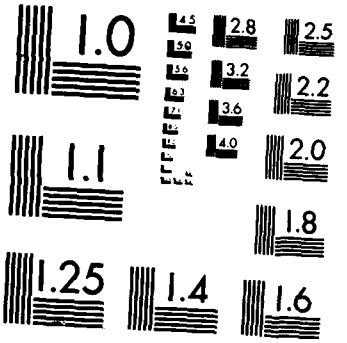
AD-A174 318 JOINT SERVICES ELECTRONICS PROGRAM(U) TEXAS UNIV AT AUSTIN ELECTRONICS RESEARCH CENTER E J POWERS 30 SEP 86 TR-33 AFOSR-TR-86-0622 F49620-82-C-0033 1/3

UNCLASSIFIED F/G 20/12 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AFOSR-TR- 86-0622

(2)

FINAL REPORT ON ELECTRONICS RESEARCH AT THE UNIVERSITY OF TEXAS AT AUSTIN

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH (AFSC)
NOTICE OF TRANSMITTAL TO DTIC
This technical report has been reviewed and is
approved for public release IAW AFR 190-12.
Distribution is unlimited.
MATTHEW J. KERPER
Chief, Technical Information Division

Approved for public release;
[illegible] unlimited.

NO. 33

For the period April 1, 1982 - March 31, 1986

JOINT SERVICES ELECTRONICS PROGRAM

Research Contract AFOSR F49620-82-C-0033

September 30, 1986

AD-A174 318

DTIC FILE COPY

DTIC
ELECTE
NOV 28 1986
S D
A

ELECTRONICS RESEARCH CENTER

Bureau of Engineering Research
The University of Texas at Austin
Austin, Texas 78712-1084

86 11 25 389

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFOSR-TR- 86-0622

2. GOVT. ACCESSION NO.: AD-A174318

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): Joint Services Electronics Program

5. TYPE OF REPORT & PERIOD COVERED: Final Report April 1, 1982-March 31, 1986

6. PERFORMING ORG. REPORT NUMBER: No. 33

7. AUTHOR(s): Edward J. Powers, Director; and other faculty and graduate research staff of the Electronics Research Center

8. CONTRACT OR GRANT NUMBER(s): ~~Contr~~. F49620-82-C-0033

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Electronics Research Center, University of Texas at Austin, Austin, Texas 78712

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F 2305/A9

11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Office of Scientific Research (AFSC) AFOSR/NE, Bolling AFB, DC 20332 NE/Witt

12. REPORT DATE: September 30, 1986

13. NUMBER OF PAGES: 192

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Same as 11

15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report): Approved for public release; distribution unlimited

18. SUPPLEMENTARY NOTES:

19. KEY WORDS (Continue on reverse side if necessary and identify by block number):

INFORMATION ELECTRONICS — QUANTUM ELECTRONICS

SOLID STATE ELECTRONICS — ELECTROMAGNETICS

20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

This report summarizes progress on projects carried out at the Electronics Research Center at The University of Texas at Austin and which were supported by the Joint Services Electronics Program. In the area of Information Electronics progress is reported for projects involving (1) nonlinear detection and estimation, (2) electronic multi-dimensional signal processing, (3) electronics time-variant signal processing, and (4) digital time series analysis with applications to nonlinear wave phenomena.

(continued next page)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

In the Solid State Electronics area recent findings in (1) interface reactions, instabilities and transport, (2) spectroscopic studies of metal/semiconductor and metal/metal oxide interfaces, (3) solid state interface reactions and instabilities, (4) electronics properties and structure of metal silicides and interfaces, and (5) implantation and interface properties of InP and related compounds are described.

In the Quantum Electronics area progress is presented for the following projects: (1) nonlinear wave phenomena, (2) structure and kinetics of excited state molecules, (3) collective effects in nonlinear optical interactions, (4) quantum effects in laser induced damage, (5) nonlinear Raman scattering from molecular ions, and (6) nonlinear optical interactions.

In the Electromagnetics area progress in (1) guided-wave devices for the far-infrared-MM-wave spectrum and (2) guided waves in composite structures is summarized.

FINAL REPORT ON ELECTRONICS RESEARCH AT THE UNIVERSITY OF TEXAS AT AUSTIN

For the period April 1, 1982 through March 31, 1986

JOINT SERVICES ELECTRONICS PROGRAM

Research Contract F49620-82-C-0033

Submitted by Edward J. Powers

on behalf of the Faculty and Staff

of the Electronics Research Center

September 30, 1986

ELECTRONICS RESEARCH CENTER

Bureau of Engineering Research
The University of Texas at Austin
Austin, Texas 78712

Approved for public release; distribution unlimited.

ABSTRACT

This report summarizes progress on projects carried out at the Electronics Research Center at The University of Texas at Austin and which were supported by the Joint Services Electronics Program. In the area of Information Electronics progress is reported for projects involving (1) nonlinear detection and estimation, (2) electronic multi-dimensional signal processing, (3) electronic time-variant signal processing, and (4) digital time series analysis with applications to nonlinear wave phenomena.

In the Solid State Electronics area recent findings in (1) interface reactions, instabilities and transport, (2) spectroscopic studies of metal/semiconductor and metal/metal oxide interfaces, (3) solid state interface reactions and instabilities, (4) electronics properties and structure of metal silicides and interfaces, and (5) implantation and interface properties of InP and related compounds are described.

In the Quantum Electronics area progress is presented for the following projects: (1) nonlinear wave phenomena, (2) structure and kinetics of excited state molecules, (3) collective effects in nonlinear optical interactions, (4) quantum effects in laser induced damage, (5) nonlinear Raman scattering from molecular ions, and (6) nonlinear optical interactions.

In the Electromagnetics area progress in (1) guided-wave devices for the far-infrared-MM-wave spectrum, and (2) guided waves in composite structures is summarized.

Accession For
NTIS
DTIC
A-1

QUALITY INSPECTED 4

PREFACE

This final report covers the period April 1, 1982 to March 31, 1986. The period April 1, 1982 to March 31, 1983 covers the last year of the 1980-1983 triennial period, and the period April 1, 1983 - March 31, 1986 covers the entire 1983 - 1986 triennial period. Since the work units and associated personnel were not identical during the two triennial periods, the work units prefixed with '82' (e.g., IE82-1) represent work done during the period April 1, 1982 - March 31, 1983, while those prefixed with '85' (e.g., IE85-1) summarize work carried out during the April 1, 1983 to March 31, 1986 period.

TABLE OF CONTENTS

		Page
Abstract		iii
Preface		v
Personnel and Research Areas		ix
Publications, Technical Presentations, Lectures and Reports		xvii
I. INFORMATION ELECTRONICS		
Res. Unit IE82-1	Nonlinear Detection and Estimation	3
Res. Unit IE82-2	Electronic Multi-Dimensional Signal Processing	9
Res. Unit IE85-1	Nonlinear Detection and Estimation	13
Res. Unit IE85-2	Electronic Time-Variant Signal Processing	19
Res. Unit IE85-3	Digital Time Series Analysis with Applications to Nonlinear Wave Phenomena	23
II. SOLID STATE ELECTRONICS		
Res. Unit SSE82-1	Interface Reactions, Instabilities and Transport	33
Res. Unit SSE82-2	Spectroscopic Studies of Metal/Semiconductor and Metal/Metal Oxide Interfaces	41
Res. Unit SSE85-1	Solid State Interface Reactions and Instabilities	47
Res. Unit SSE85-2	Electronic Properties and Structure of Metal Silicides and Interfaces	53
Res. Unit SSE85-3	Implantation and Interface Properties of InP and Related Compounds	57
III. QUANTUM ELECTRONICS		
Res. Unit QE82-1	Nonlinear Wave Phenomena	67
Res. Unit QE82-2	Structure and Kinetics of Excited State Molecules	75
Res. Unit QE82-3	Collective Effects in Nonlinear Optical Interactions	91
Res. Unit QE85-1	Quantum Effects in Laser Induced Damage	99
Res. Unit QE85-2	Nonlinear Raman Scattering from Molecular Ions	111
Res. Unit QE85-3	Nonlinear Optical Interactions	125

TABLE OF CONTENTS

Page

IV. ELECTROMAGNETICS

Res. Unit EM82-1 Guided-Wave Devices for the Far-Infrared-MM Wave Spectrum. 137

Res. Unit EM85-1 Guided Waves in Composite Structures. 143

Research Grants and Contracts

Federal Funds 155

Other Than Federal Funds. 158

Consultative and Advisory Functions 160

PERSONNEL AND RESEARCH AREAS

ELECTRONICS RESEARCH CENTER

Phone: (512) 471-3954

Administration for the Joint Services Electronics Program

Professor Edward J. Powers, Director
Professor Rodger M. Walser, Assoc. Director

Electronics Research Center Staff

Connie Finger, Administrative Assistant I
Jan White, Accountant I

Coordinators for Research Areas

Professor S.I. Marcus, Information Electronics
Professor R.M. Walser, Solid State Electronics
Professor M.F. Becker, Quantum Electronics
Professor T. Itoh, Electromagnetics

Faculty

Information Electronics:

J.K. Aggarwal, Professor, ECE, 471-1369
S.I. Marcus, Professor, ECE, 471-3265
E.J. Powers, Professor, ECE, 471-1430
J.L. Speyer, Professor, Aerospace, 471-4258

Solid State Electronics:

M.F. Becker, Associate Professor, ECE, 471-3628
R.W. Bene', Professor, ECE, 471-1225
*A.B. Buckman, Associate Professor, ECE, 471-4893
J.L. Erskine, Associate Professor, Physics, 471-1464
B.G. Streetman, Professor, ECE, 471-1754
R.M. Walser, Professor, ECE, 471-5733
*J.M. White, Professor, Chemistry, 471-3704

*With the program April 1, 1982-March 31, 1983.

PERSONNEL AND RESEARCH AREAS

Quantum Electronics:

M.F. Becker, Associate Professor, ECE, 471-3628
M. Fink, Professor, Physics, 471-5747
* L. Frommhold, Professor, Physics, 471-5100
J. Keto, Associate Profesor, Physics, 471-4151
H.J. Kimble, Associate Professor, Physics, 471-1668
E.J. Powers, Professor, ECE, 471-1430
R.M. Walser, Professor, ECE, 471-5733

Electromagnetics:

* A.B. Buckman, Associate Professor, ECE, 471-4893
T. Itoh, Professor, ECE, 471-1072

Postdoctoral Research Associates, Research Engineer Associates, and Fellow

Jae Hong, ECE, Research Engineer Associate V
Worthy Martin, ECE, Research Engineer Associate V
Marshall Onellion, Physics, Postdoctoral Research Associate
Christoph Ritz, ECE, Research Fellow
Albert T. Rosenberger, Physics, Postdoctoral Research Associate

Research Assistants

C.K. An, ECE
Jose Araya-Pochet, Physics
Craig Ballentine, Physics
John Beall, ECE
Peter Blass, Chemistry
* Tom Block, ECE
Norbert Boewering, Physics
T.L. Boyd, Physics
Robert Brecha, Physics
Mike Bruce, Physics
* Ilsub Chang, ECE
Yu-Jeng Chang, ECE
Chien-Hwei Chen, ECE
Chiun Hong Chien, ECE
Geon Choe, ECE
DooWhan Choi, ECE
Yoon-Hwa Choi, ECE
Hae-Kwon Chung, ECE
* Y.H. Ku, ECE
Winston Layne, Physics
Hong Lee, ECE
Shih-Ked Lee, ECE
Tzong Leou, ECE
* Steve Lester, ECE
Scott Levinson, ECE
Bin-Wah Lin, ECE
Jorge Castro Luengo, Physics
* Henry Luftman, Chemistry
Michael Magee, ECE
G. Joe Mauger, ECE
Richard Mawhorter, Physics
* Jabez J. McClelland, Physics
Bruce Miller, Physics
John Moretta, ECE
Raymond Munroe, Physics
* N.I. Nam, ECE

*Denotes persons who have contributed to JSEP projects, but who have not been paid out of JSEP funds (e.g., students on fellowships).

PERSONNEL AND RESEARCH AREAS

Dan Coffman, Physics

S.W. Nam, ECE

Research Assistants (continued)

Joe Comunale, Physics
John Coogan, Physics
* Mike Debner, Physics
* Hassan Ehsani, ECE
Kie Bum Eom, ECE
Craig Farley, ECE
* Steven Fry, ECE
Yoshiro Fukuoka, ECE
D.E. Grant, Physics
Jessy Grizzle, ECE
*C.C. Han, ECE
*John Hartley, Physics
*Jim Higdon, Physics
*Austin Huang, ECE
Jong Jee, ECE
Inseop Jeong, ECE
Yoon-Kyoo Jhee, ECE
Mark Kauderer, ECE
Chang Keem, Physics
Suhas Ketkar, Physics
Kyoung Il Kim, ECE
Tae Sung Kim, ECE
Taiho Koh, ECE
Tom Koonce, Physics
N. Nandhakumar, ECE
* Luis Orozco, Physics
Segeun Park, ECE
Sung Han Park, ECE
* Won Woo Park, ECE
Mark Raizen, Physics
T.D. Raymond, Physics
* Andy Ross, Physics
Michael Schore, ECE
Hyung Soon Shin, ECE
Nag Un Song, ECE
Taek Song, Aerospace
Min-Jae Tahk, Aerospace
Kathleen A. Thrush, Chemistry
Ching-Kuang Tzuang, ECE
Baba Vemuri, ECE
Lingtao Wang, ECE
* Jim Weidner, ECE
* Evan Westwood, Physics
* Cheryl White, Physics
John White, Aerospace
* Murray Wolinsky, Physics
* L.A. Wu, Physics
S. Yalamanchilli, ECE
Hwa-Yueh Yang, ECE

Advanced Degrees Awarded

Yoon-Hwa Choi, EE, M.S., May 1982, "Performance of Suboptimal Estimators for Weakly Nonlinear Estimation Problems."

Jae Young Hong, EE, Ph.D., August 1982, "Nonlinear System Transfer Functions with Applications to Nonlinear Electromagnetic Scatterers."

Taiho Koh, EE, M.S., August 1982, "Analysis of Nonsteady Signal in the Time-Frequency Plane."

Joe Mauger, EE, M.S., December 1982, "Raman Resonance Enhanced Third Harmonic Generation in CD_4."

John M. Beall, EE, Ph.D., May 1983, "The Local Wavenumber Spectrum and Its Applications in the Study of Turbulence and Noise."

Yu-Jeng Chang, Physics, Ph.D., August 1983, "Electronic Properties and Interfaced Microstructures of Nickel Silicides on Silicon Substrates."

PERSONNEL AND RESEARCH AREAS

D.E. Grant, Physics, M.S., December 1983, "Absorptive Optical Bistability with Two-Level Atoms."

Jessy W. Grizzle, EE, Ph.D., December 1983, "The Structure and Optimization of Nonlinear Control Systems Processing Symmetries."

Yen-Hui Ku, EE, M.S., August 1983, "Stress in Ultrathin Cobalt Film on Silicon."

Bih-Wan Lin, EE, M.S., December 1983, "Adaptive Control of Priority Assignment in Queueing Systems."

Bruce Reagan Miller, Physics, Ph.D., December 1983, "On The Accuracy of Molecular Structures Determined From Precise Electron Diffraction Data."

T.D. Raymond, Physics, Ph.D., August 1983, "Two Photon Spectroscopy of the 6P Manifold of Xenon."

Taek L. Song, Aerospace Engineering, Ph.D., December 1983, "A Stochastic Analysis of a Modified Gain Extended Kalman Filter."

L.A. Wu, Physics, M.S., December 1983, "The Role of Phase in Second Harmonic Generation within an Optical Cavity."

Nam-In Cho, ECE, M.S., May 1984, "Noise Properties of Ultrathin Nickel Films on Single Crystal Silicon."

DooWhan Choi, ECE, Ph.D., May 1984, "Engineering Applications of Higher-Order Spectra."

Dan Coffman, Physics, M.S., December 1984, "Electron-Atom Shadow Scattering/Does it Exist or Not?"

Y. Fukuoka, ECE, Ph.D., May 1984, "Guided Wave Phenomena in Device Structures Containing Semiconductor Materials."

Fawzi Hadjarab, Physics, M.S., May 1984, "Imaging Properties of the Spherical Analyzer."

J.K. Jhee, ECE, Ph.D., May 1984, "Charge Emission and Precursor Accumulation in the Multiple-Pulse Damage Regime of Silicon."

Maxine McBrinn-Howard, Physics, M.S., August 1984, "Construction of a Supersonic Beam Apparatus."

R. Mezenner, ECE, M.S., August 1984, "Encapsulation and Annealing of GaAs and InP."

S. Park, ECE, Ph.D., May 1984, "On Time-Variant Digital Signal Processing: Synthesis and Implementation."

H. Shin, ECE, M.S., December 1984, "Thermal Annealing Studies of Nitride Encapsulant on GaAs."

PERSONNEL AND RESEARCH AREAS

R.L. Strong, Physics, Ph.D., August 1984, "Adsorbate Structure Determination Using High-Resolution Electron Energy Loss Spectroscopy and Lattice Dynamical Calculations."

S.W. Yung, ECE, Ph.D., May 1984, "A Study of Distributed Millimeter-Wave Isolators."

Q. Zhang, ECE, M.S., May 1984, "Analysis of a Suspended Patch Antenna Excited by an Inverted Microstrip Feed."

Tak Sum Chu, ECE, M.S., May 1985, "Analysis of Microstrip Step Discontinuity".

Craig Farley, ECE, M.S., May 1985, "The Migration and Activation of Impurities in Ion-Implanted Semiconductors."

Dae Yong Kim, ECE, M.S., May 1985, "Studies of the Magnetic Properties of RF Sputtered CO-B, FE-B, and CO-FE-B Thin Films."

Taiho Koh, ECE, Ph.D., May 1985, "Non-Linear Methods in Digital Filtering and Estimation of Stationary Time Series."

Seguen Park, ECE, Ph.D., August 1985, "Ion Implantation of Polymeric Carbon Films."

Hwa-Yueh Yang, ECE, Ph.D., August 1985, "Solid State Nucleation and Growth in the Thin Film Ternary Systems (Ti/Co/Si and Co/Ti/Si): Silicon Substrates with Binary Metal Layers."

C.C. Han, ECE, M.S., December 1985, "Phase Nucleation for Aluminum and Titanium Thin Films on Single Crystal Silicon."

Austin Huang, M.S., December 1985, "Laser Induced Damage and Ion Emission of Callium Arsenide at 1.064μm."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES, AND REPORTS

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Journal Articles

* R.L. Remke, R.M. Walser and R. W. Bene, "The Effect of Interfaces on Electronic Switching in VO_2 Thin Films," Thin Solid Films 97, 129 (1982).

M.H. Kelley and M. Fink, "The Temperature Dependence of the Molecular Structure Parameters of SF_6," J. Chem. Phys. 77, pp. 1813-1817 (1982).

* R.W. Miksad, F.L. Jones, E.J. Powers, Y.C. Kim and L. Khadra, " Experiments on the Role of Amplitude and Phase Modulation During Transition to Turbulence," Journal of Fluid Mechanics, 123, pp. 1-29 (1982).

* Yu-Jeng Chang and J.L. Erskine, "Electronic Structure of $NiSi_2$," Phys. Rev. B26, 7031 (1982).

R.L. Strong, B. Firey, F. W. deWette and J.L. Erskine, Phys. Rev. B26, 3483 (1982).

* M.F. Becker, Y.C. Kim, S.R. Gautam and E.J. Powers, "Three Wave Nonlinear Optical Interactions in Dispersive Media," IEEE J. Quantum Electronics, QE-18, 113-123 (1982).

* R.M. Walser, H. Mendez, D. Finello and H.L. Marcus, "Correlation of Electronic State and Fracture Path of Aluminum-Graphite Interfaces," Scripta Met. 16, 855 (1982).

M.H. Kelley and M. Fink, "The Molecular Structure of Dimolybdenum Tetraacetate," J. Chem. Phys. 76, 1407-1416 (1982).

* A.M. Turner, Yu-Jeng Chang and J.L. Erskine, "Surface States and the Photoelectron Spin Polarization of Fe(100)," Phys. Rev. Letters 48, 348 (1982).

* M. Hazewinkel and S. I. Marcus, "On Lie Algebras and Finite Dimensional Filtering," Stochastics, vol. 7, 29-62 (1982).

A.M. Turner and J.L. Erskine, "Exchange Splitting and Critical Point Energies for Ferromagnetic Iron," Phys. Rev. B25, 1 (1982).

J.L. Erskine and R.L. Strong, "High-Resolution Electron Energy Loss Spectroscopy Study of the Oxidation of Al(111)," Phys. Rev. B25, 5547 (1982).

J.K. Aggarwal, S. Yalamanchili and W. N. Martin, "Extraction of Moving Object Descriptions via Differencing," Computer Graphics and Image Processing, No. 18, pp. 188-201 (1982).

J.A. Webb and J.K. Aggarwal, "Structure from Motion of Rigid and Jointed Objects," Artificial Intelligence , 19, pp. 107-130 (1982).

*Funded entirely or in part by the Joint Services Electronics Program.

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

J.R. Creighton and J.M. White, "Transient Low Pressure Studies of Catalytic Carbon Monoxide Oxidation: A Brief Review," Catalysis Under Transient Conditions, Alexis T. Bell and L. Louis Hegedis, eds., ACS Symposium Series 178, 33 (1982).

J.A. Schreifels, J.E. Deffeyes, L.D. Neff, and J.M. White, "An X-ray Photoelectron Spectroscopic Study of the Adsorption of N_2, NH_3, NO, and N_2O on Dysprosium," J. Electron Spectros. Relat. Phenom. 25, 191 (1982).

H.-I. Lee, B.E. Koel, W.M. Daniel, and J.M. White, "Water-Induced Effects on CO Adsorption on Ru(001)," J. Catalysis 74, (1982).

Y. Kim, J.A. Schreifels, and J.M. White, "Adsorption of N_2O on Ru(001)," Surface Sci. 114, 349 (1982).

Y. Kim, H.C. Peebles, and J.M. White, "Adsorption of D_2, CO and the Interaction of Co-Adsorbed D_2 and CO on Rh(100)," Surface Sci. 114, 313 (1982).

B.E. Koel, D.E. Peebles and J.M. White, "An Electronic Spectroscopic Study of Coadsorbed H_2 and CO on Ni(100)," J. Vac. Sci. Technol. 20, 889 (1982).

D.E. Peebles, J.A. Schreifels, and J.M. White, "The Interaction of Coadsorbed Hydrogen and Carbon Monoxide on Ru(001)," Surface Sci. 116, 117 (1982).

B.E. Koel and J.M. White, "C(KVV) Auger Lineshape of Chemisorbed CO Measured by X-ray Excited Auger Spectroscopy," J. Chem. Phys. 77, 2665 (1982).

B.E. Koel and J.M. White, "The Adsorption and Decomposition of Ethylene on Ni(100)," Chem. Phys. Lett. 88, 236 (1982).

J.A. Schreifels, D. Belton and J.M. White, "Thermal Desorption of H_2 and CO on Pt/TiO_2," Chem. Phys. Lett. 90, 261 (1982).

S.-M. Fang, B.H. Chen and J.M. White, "Photoassisted Water-Gas Shift Reaction on Platinized Titania: The Influence of Preparation Parameters," J. Phys. Chem. 86, 3126 (1982).

Bor-Her Chen and J.M. White, "Properties of Pt Supported on Oxides of Titanium," J. Chem. 86, 3534 (1982).

J.R. Creighton and J.M. White, "A Static SIMS Study of H_2O Adsorption and Reaction on Clean and Oxygen-Covered Pt," Chem. Phys. Lett. 92, 435 (1982).

J.M. White, "Constraints in Surface Science Research," guest editorial, SCIENCE 218 (1982).

J.M. White, "Photoassisted Reactions on Doped Metal Oxide Particles," Heterogeneous Atmospheric Chemistry, David R. Schryer, ed., American Geophysical Union (Washington, D.C.) p. 122 (1982).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Katsumi Tanaka and J.M. White, "Characterization of Species Adsorbed on Oxidized and Reduced Anatase," J. Phys. Chem. 86, 4708 (1982).

Katsumi Tanaka and J.M. White, "Dissociative Adsorption of CO_2 on Oxidized and Reduced Pt/TiO_2," J. Phys. Chem. 86 (1982).

* K. Hsu and S.I. Marcus, "Decentralized Control of Finite State Markov Processes," IEEE Transactions on Automatic Control, vol. AC-17, 426-431 (April 1982).

D.G. Hull and J.L. Speyer, "Optimal Reentry and Plane-Change Trajectories," The Journal of Astronautical Sciences, vol. XXX, no. 2, 117-130 (April-June 1982).

T. Itoh and B. Adelseck, "Trapped Image Guide Leaky-Wave Antenna for Millimeter Wave Applications," IEEE Trans. Microwave Theory and Techniques, vol. AP-30, no. 3, pp. 505-509 (May 1982).

* J.M. Beall, Y.C. Kim and E.J. Powers, "Estimation of Wavenumber and Frequency Spectra Using Fixed Probe Pairs," Journal of Applied Physics, vol. 53, 3933-3940 (June 1982).

* A.B. Buckman, "Polarization-Selection Lateral Waveguiding in Layered Dielectric Structures," Journal of the Optical Society of America, vol. 22, no. 6, pp. 688-691 (June 1982).

* Y.C. Shi and T. Itoh, "Analysis of Conductor-Backed Coplanar Waveguide," Electronics Letters, vol. 18, no. 12, pp. 538-540 (June 10, 1982).

N. Camilleri and T. Itoh, "Studies of Periodic Structures in Dielectric Waveguides," Int. J. Infrared and Millimeter Waves, vol. 3, no. 4, pp. 957-959 (July 1982).

* Y.C. Shih and T. Itoh, "Analysis of Printed Transmission Lines for Monolithic Integrated Circuits," Electronics Letters, vol. 18, no. 14, pp. 585-586 (July 8, 1982).

* Y. Fukuoka and T. Itoh, "Analysis of Slow-Wave Phenomena in Coplanar Waveguide on a Semiconductor Substrate," Electronics Letters, vol. 18, no. 14, pp. 589-590 (July 8, 1982).

J. Speyer, J. Krainak, F. Machell and S. Marcus, "The Dynamic Linear Exponential Gaussian Team Problem," IEEE Transactions on Automatic Control, vol. AC-27, pp. 860-869 (August 1982).

J. Speyer, J. Krainak and S. Marcus, "Static Team Problems, Part I: Sufficient Conditions and The Exponential Cost Criterion," IEEE Transactions on Automatic Control, vol. AC-27, pp. 839-848 (August 1982).

* D.E. Grant and H.J. Kimble, "Optical Bistability for Two-Level Atoms in a Standing-Wave Cavity," Optics Letters 7 (1982).

J. Krainak, J. Speyer and S. Marcus, "Static Team Problems, Part II: Affine Control Laws, Projections, Algorithms and the LEGT Problem," IEEE Transactions on Automatic Control, vol. AC-27, pp. 848-860 (August 1982).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

* T. Itoh, "Open Guiding Structures for Millimeter-Wave Integrated Circuits," Microwave Journal, vol. 25, no. 9, pp. 113-126 (September 1982).

* R.W. Bene, "First Phase Nucleation Rule for Solid State Nucleation in Metal-Metal Thin Film Systems," Applied Physics Letters, 41 (6), p. 529 (September 15, 1982).

* J.M. White, "Surface Science of Heterogeneous Reactions," Science 218, 429 (October 29, 1982 issue).

* J.-F. Miao and T. Itoh, "Hollow Image Guide and Overlayed Image Guide Coupler," IEEE Trans. Microwave Theory and Techniques, vol. MTT-30, no. 11, pp. 1826-1831 (November 1982).

M.F. Becker and R.M. Walser, "Charged Particle Exoemission from Silicon During Multi-Pulse Laser Induced Damage," 14th ASTM Laser Damage Symposium, Boulder, CO (November 1982).

M.F. Becker and R.M. Walser, "Observation of Long-Lived Metastable Excitations in Multi-Pulse Laser Damage of Silicon," 14th ASTM Laser Damage Symposium, Boulder, CO (November 1982).

W. B. Zhou and T. Itoh, "Analysis of Trapped Image Guides Using Effective Dielectric Constants and Surface Impedances," IEEE Trans. Microwave Theory and Techniques, vol. MTT-30, no. 12, pp. 2163-2166 (December 1982).

W.N. Martin and J.K. Aggarwal, "Volumetric Description from Dynamic Scenes," Pattern Recognition Letters 1, pp. 107-113 (December 1982).

A. Mitchie, B. Gil and J.K. Aggarwal, "On Combining Range and Intensity Data," Pattern Recognition Letters 1, pp. 87-92 (December 1982).

* S.N. Ketkar, M. Fink and R.A. Bonham, "High Energy Electron Scattering from Helium," Phys. Rev. A27, 806-809 (1983).

* D.E. Grant and H.J. Kimble, "Transient Response in Absorptive Bistability," Opt. Commun. 44, 415 (1983).

* R.J. Mawhorter and M. Fink, "The Vibrationally-Averaged Temperature Dependent Structure of Polyatomic Molecules II SO_2," J. Chem. Phys. 79, 3292 (1983).

J. Ganz, A. Siegel, W. Bussert, K. Harth, M.W. Ruf, H. Hotop, J. Geiger and M. Fink, "On the Ne($2p^5ns'$, nd') Autoionization Resonances: High Resolution Measurement and Quantum Defect Analysis", J. Physics B, 16, 1569-1576 (1983).

* D.J. Wolford, S. Modesti, and B.G. Streetman, "Photoluminescence of Oxygen-Induced States in $GaAs_{1-x}P_x$," pp. 501-508 in Gallium Arsenide and Related Compounds, Bristol: Inst. Phys. Conf. Ser. No. 65 (1983).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Peter Pulay, R. Mawhorter, D.A. Kohl and M. Fink, "AB INITIO Hartree-Fock Calculations of the Elastic Electron Scattering Cross Section of Sulphur Hexafluoride," J. Chem. Phys., 79, 185 (1983).

* A.T. Rosenberger, L. A. Orozco and H.J. Kimble, "Observation of Absorptive Bistability with Two-Level Atoms in a Ring Cavity," Phys. Rev. A28, 2569 (1983).

* R.J. Mawhorter, M. Fink and B.T. Archer, "An Experimental Determination of the Vibrationally-Averaged, Temperature-Dependent Structure of CO_2," J. Chem. Phys. 79, 170 (1983).

* Chien-Yu Kuo and J.W. Keto, "Dissociative Recombination of Electrons in Electron Beam Excited Argon and High Densities", J. Chem. Phys. 78, 1851 (1983).

* S.N. Ketkar, M. Fink and R.A. Bonham, "High Energy Electron Scattering from Helium," Phys. Rev. A27, 806-809 (1983).

A.M. Turner and J.L. Erskine, "Magnetic Exchange Splitting and Band Dispersion of Surface States on Fe(100)," Phys. Rev. B28, 5628 (1983).

H.A. Stevens, A.M. Turner, A.W. Donoho and J.L. Erskine, "Angle-Resolving Photoelectron Energy Analyzer: Mode Calculations, Ray Tracing, Analysis and Performance Evaluation," J. Electron Spectroscopy and Related Phenom. 32, 327 (1983).

W.N. Martin and J.K. Aggarwal, "Dynamic Scene Analysis," in the book Image Sequence Processing and Dynamic Scene Analysis, edited by T.S. Huang, Springer-Verlag, pp. 40-73 (1983).

B.M. Davies and J.L. Erskine, "Azimuthal Dependence of Impact Scattering in Electron Energy Loss Spectroscopy," J. Electron Spectroscopy and Related Phenom. 29, 323 (1983).

R.L. Strong, B. Firey, F.W. deWette and J.L. Erskine, "Adsorbate Structure Modeling Based on Electron Energy Loss Spectroscopy and Lattice Dynamical Calculations: Applications to Al(111)," J. Electron Spectroscopy and Related Phenom. 29, 187 (1983).

* Yu-Jeng Chang and J.L. Erskine, "First Phase Nickel Silicide Nucleation and Interface Structure at Si(100) Surfaces," J. Vacuum Science and Technol. A1, 1193 (1983).

* Yu-Jeng Chang and J.L. Erskine, "Diffusion Layers and the Schottky Barrier Height in Nickel Silicide-Silicon Interfaces," Phys. Rev. B28, 5766 (1983).

J. Rivera and T. Itoh, "Analysis of an Electromagnetically Coupled Patch Antenna," Electromagnetics, vol. 3, no. 4, pp. 289-298 (Fall 1983).

* R.W. Bene and H.Y. Yang, "Solid State Nucleation in the Ti-Si Ultrathin Film System," Journal of Electronic Materials 12, no. 1, pp. 1-10 (January 1983).

* A.B. Buckman, "Mode Selection with a Three-Layer Dielectric Rib Waveguide," Journal of the Optical Society of America, vol. 73, no. 1, pp. 33-36 (January 1983).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

* Y. Fukuoka and T. Itoh, "Slow-Wave Propagation on MIS Periodic Coplanar Waveguide," Electronics Letters, vol. 19, no. 2, pp. 37-38 (January 20, 1983).

K.D. Stephan, N. Camilleri and T. Itoh, "A Quasi-Optical Polarization-Duplexed Balanced Mixer for Millimeter-wave Applications," IEEE Trans. Microwave Theory and Techniques, vol. MTT-31, no. 2, pp. 164-170 (February 1983).

Y.C. Shih, T. Itoh and L.Q. Bui, "Computer-Aided Design of Millimeter-Wave E-Plane Filters," IEEE Trans. Microwave Theory and Techniques, vol. MTT-31, no. 2, pp. 135-142 (February 1983).

J.-F. Miao and T. Itoh, "Coupling Between Microstrip Line and Image Guide Through Small Apertures in the Common Ground Plane," IEEE Trans. Microwave Theory and Techniques, vol. MTT-31, no. 4, 361-363 (April 1983).

* S. Banerjee and B.G. Streetman, "Experimental Studies of Laterally Seeded Recrystallized Polysilicon on Silicon Dioxide," Proc. of 1983 IEEE Univ./Gov./Ind. Microelectronics Symposium (May 1983).

M.F. Becker, "Observations of an Incubation Period for Multipulse Laser Induced Damage," Conference on Lasers and Electro-Optics, Baltimore, MD (May 1983).

J.D. Oberstar and B.G. Streetman, "Thin Film Encapsulants for Annealing GaAs and InP," Thin Solid Films 103, 17-26 (May 13, 1983).

R.W. Miksad, F.L. Jones and E.J. Powers, "Measurements of Nonlinear Interactions During Natural Transition of a Symmetric Wake," Phys. Fluids 26, 6 (June 1983).

S. Banerjee and B.G. Streetman, "Theoretical and Experimental Study of Swept Line Electron Beam Annealing of Semiconductors," J. Appl. Phys. 54, 2947-2955 (June 1983).

* Y. Fukuoka, Y.C. Shih and T. Itoh, "Analysis of Slow-Wake Coplanar Waveguide for Monolithic Integrated Circuits," IEEE Trans. Microwave Theory and Techniques, vol. MTT-31, no. 7, pp. 567-573 (July 1983).

* G.L. Blankenship, C.-H. Liu and S.I. Marcus, "Asymptotic Expansions and Lie Algebras for Some Nonlinear Filtering Problems," IEEE Transactions on Automatic Control, vol. AC-28, 787-797 (July 1983).

A. Bhattacharyya and B.G. Streetman, "Theoretical and Experimental Study of Swept Line Electron Beam Annealing of Semiconductors," J. Physics D: Applied Physics 16, L215-L218 (November 1983).

S.K. Banerjee and B. G. Streetman, "Electron and Hole Traps in Silicon-on-Oxide Grown Using Lateral Epitaxy By Seeded Solidification," J. Phys. D: Applied Physics 16, L215-L218 (November 1983).

* O. Hernandez-Lerma and S.I. Marcus, "Adaptive Control of Service in Queueing Systems," Systems and Control Letters, vol. 3, 283-289 (November 1983).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

S.K. Banerjee, R.Y. DeJule, K.J. Soda and B.G. Streetman, "Planar Be-Implanted GaAs Junction Formation Using Swept-Line Electron Beam Annealing," IEEE Trans. Electron Dev. ED-30, 1755-1760 (December 1983).

Y.C. Shih and T. Itoh, "E-Plane Filters with Finite-Thickness Septa," IEEE Trans. Microwave Theory and Techniques, vol. MTT-31, no. 12, 1009-1013 (December 1983).

* Y. Fukuoka and T. Itoh, "Slow-Wave Coplanar Waveguide on Periodically Doped Semiconductor Substrates," IEEE Trans. Microwave Theory and Techniques, vol. MTT-31, no. 12, 1013-1017 (December 1983).

L. Su, T. Itoh and J. Rivera, "Design of an Overlay Directional Coupler by a Full-Wave Analysis," IEEE Trans. Microwave Theory and Techniques, vol. MTT-31, no. 12, pp. 1017-1022 (December 1983).

* M. Hazewinkel, S.I. Marcus and H.J. Sussmann, "Non-Existence of Finite Dimensional Filters for Conditional Statistics of the Cubic Sensor Problem," Systems and Control Letters, vol. 3, 331-340 (December 1983).

A.M. Turner, A.W. Donoho and J.L. Erskine, "Experimental Bulk Electronic Properties of Ferromagnetic Iron," Phys. Rev. B29, 2986 (1984).

W.B. Zhou and T. Itoh, "Field Distribution in the Trapped Image Guide," Electromagnetics, vol. 4, no. 1, pp. 21-34 (Spring 1984).

T.E. Dietz, K.R. Diller and J.K. Aggarwal, "Automated Computer Evaluation of Time-Varying Cryomicroscopical Images," Cryobiology, vol. 21, 200-208 (1984).

* A.M. Turner and J.L. Erskine, "Surface Electronic Properties of Fe(100)," Phys. Rev. B30 (1984).

R.L. Strong and J.L. Erskine, "A New Lens System for Surface Vibrational Spectroscopy at High Impact Energies," Rev. of Sci. Instruments 55, 1304 (1984).

* J.L. Erskine and Yu-Jeng Chang, "Selective Growth, Diffusion Layers, and the Schottky Barrier Height in Nickel Silicide-Silicon Interfaces," Mat. Res. Soc. Proc. 25, 353 (1984).

H.J. Kimble and L. Mandel, "Photoelectric Detection of Polychromatic Light," Phys. Rev. A30, 844 (1984).

* L.A. Orozco, A.T. Rosenberger and H.J. Kimble, "Intrinsic Dynamical Instability in Optical Bistability with Two-Level Atoms," Phys. Rev. Lett. 53, 2547 (1984).

J.K. Aggarwal, "Motion and Time Varying Imagery," Computer Graphics, vol. 18, no. 1, 20-21 (January 1984).

K.D. Stephan and T. Itoh, "A Planar Quasi-Optical Subharmonic Mixer Characterized by Isotropic Conversion Loss," IEEE Trans. Microwave Theory and Techniques, vol. MTT-32, no. 1, 97-102 (January 1984).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

* C.W. Farley and B.G. Streetman, "The Role of Defects in the Diffusion and Activation of Impurities in Ion-Implanted Semiconductors," J. Electr. Mater. 13, 401-436 (March 1984).

J.L. Speyer, D.G. Hull, C.Y. Tseng and S.W. Larson, "Estimation Enhancement by Trajectory Modulation for Homing Missiles," AIAA Journal of Guidance, Control, and Dynamics, vol. 7, no. 2 (March-April 1984).

D.G. Hull, W.M. Greenwell and J.L. Speyer, "Adaptive Noise Estimation for Homing Missiles," AIAA Journal of Guidance, Control and Dynamics, vol. 7, no. 3 (May-June 1984).

S.J. Levinson, J.M. Beall, E.J. Powers and Roger D. Bengtson, "Space-Time Statistics of the Turbulence in a Tokamak Edge Plasma," Nuclear Fusion, vol. 24, no. 5, 527-539 (May 1984).

* S.Park and J.K. Aggarwal, "A Simple Form Synthesis of Linear Time-Variant Digital Filters via Spectral Decomposition of its Impulse Response," Journal of the Franklin Institute, vol. 318, no. 3, pp. 151-164 (September 1984).

D.A. Kohl, P. Pulay and M. Fink, "On the Calculations of Electron Scattering Cross Sections from Molecular Wavefunctions," Theo. Chem., 108, pp. 149-159 (1984).

Shang-De Xie, M. Fink and D.A. Kohl, "Basis Set Dependence of Ab Initio SCF Elastic Born Scattering Cross Sections for Electrons on C_2H_4," J. Chem. Phys. 81, pp. 1940-1942 (1984).

* Y.K. Jhee, M.F. Becker and R.M. Walser, "Charge Emission and Accumulation in Multiple Pulse Damage of Silicon," Proc. of Laser Induced Damage in Optical Materials - NBS publ. (1984).

T.D. Raymond, N. Bowering, Chien-Yu Kuo and J.W. Keto, "Two-Photon Laser Spectroscopy of Xenon Collision Pairs," Phys. Rev. A29, pp. 721-734 (1984).

N. Bowering, T.D. Raymond and J.W. Keto, "Enhanced Quenching at Reduced Internuclear Separations of Xenon Collision Pairs," Phys. Rev. Lett. 52, pp. 1880-1883 (1984).

T.D. Raymond, Shawn T. Walsh and John W. Keto, "Narrowband Dye Laser with a Large Scan Range," Appl. Optics 23, pp. 2062-2064 (1984).

B.G. Streetman, "Solid State Electronic Devices," Collier's Encyclopedia (New York: MacMillan Publishing Co.), pp. 180-191 (1984).

* O. Hernandez-Lerma and S.I. Marcus, "Optimal Adaptive Control of Priority Assignment in Queueing Systems," Systems and Control Letters, vol. 4, pp. 65-72 (April 1984).

* C.W. Farley and B.G. Streetman, "Simulation of Anomalous Be Diffusion in Semi-Insulating InP," J. Electrochem. Soc. 131, pp. 946-947 (April 1984).

* S.K. Banerjee, B. Lee, J.E. Baker, D.A. Reed and B.G. Streetman, "Annealing of Ion-Implanted Silicon-on-Insulator Films Using a Scanned Graphite Strip Heater," Thin Solid Films 115, pp. 19-26 (May 1984).

* O. Hernandez-Lerma and S.I. Marcus, "Identification and Approximation of Queueing Systems," IEEE Trans. Automatic Control, vol. AC-29, pp. 472-474 (May 1984).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

S.W. Yun and T. Itoh, "A Distributed Millimeter-Wave Isolator Using Nonreciprocal Coupling Structure," International J. Infrared and Millimeter Waves, vol. 5, no. 6, pp. 775-792 (June1984).

* S.K. Banerjee, R.Y. Tong, B. Lee, R.Y. DeJule, B.G. Streetman and Y-W. Lam, "Implantation and Annealing Studies of Laterally Seeded Recrystallized Silicon on Silicon Dioxide," J. Electrochem. Soc. 131, 1409-1416 (June 1984).

* Y. Fukuoka and T. Itoh, "Coplanar Schottky Variable Phase Shifter Constructed on GaAs Substrate for Millimeter-Wave Applications," International J. Infrared and Millimeter Waves, vol. 5, no. 6, pp. 793-801 (June 1984).

* T.Y. Leou and J.K. Aggarwal, "Recursive Implementation of LTV Filters - Frozen-Time Transfer Function vs. Generalized Transfer Functions," IEEE Proceedings, vol. 72, no. 7, pp. 980-981 (July 1984).

* J.L. Speyer and J.E. White, "The Shiryayev Sequential Probability Ratio Test for Redundancy Management," AIAA Journal of Guidance, Control and Dynamics (September-October 1984).

K.D. Stephan and T. Itoh, "Inexpensive Short-Range Microwave Telemetry Transponder," Electronics Letters, vol. 20, no. 21, pp. 877-878 (October 11, 1984).

* S.I. Marcus, "Algebraic and Geometric Methods in Nonlinear Filtering," SIAM J. Control and Optimization, vol. 22, pp. 817-844 (November 1984).

* J.W. Grizzle and S.I. Marcus, "Optimal Control of Systems Possessing Symmetries," IEEE Trans. Automatic Control, vol. AC-29, pp. 1037-1040 (November 1984).

J.L. Speyer, J.E. White, R.K. Douglas and D.G. Hull, "MIMO Controller Design for Longitudinal Decoupled Aircraft Motion," AIAA Journal of Guidance, Control and Dynamics, vol. 7, no. 6 (Nov.-Dec. 1984).

L.Q. Bui, D. Ball and T. Itoh, "Broadband Millimeter-Wave E-Plane Bandpass Filters," IEEE Trans. Microwave Theory and Techniques, vol. MTT-32, no. 12, pp. 1655-1658 (December 1984).

* R. Sorrentino and T. Itoh, "Transverse Resonance Analysis of Finline Discontinuities," IEEE Trans. Microwave Theory and Techniques, vol. MTT-32, no. 12, pp. 1633-1638 (December 1984).

* T. Koh and E.J. Powers, "Efficient Methods to Estimate Correlation Functions of Gaussian Processes and Their Performance Analysis," IEEE Transactions on Acoustics, Speech, and Signal Processing, ASSP-33, pp. 1032-1035 (1985).

J.K. Aggarwal and S. Yalamanchili, "A System Organization for Parallel Image Processing," Pattern Recognition, vol. 18, no. 1, pp. 17-29 (1985).

J.K. Aggarwal and S. Yalamanchili, "Analysis of a Model for Parallel Image Processing", Pattern Recognition, vol. 18, no. 1, pp. 1-16 (1985).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

J.K. Aggarwal and M. Magee, "Using Multisensory Images to Derive the Structure of Three-Dimensional Objects - A Review," Computer Vision Graphics and Image Processing, vol. 32, pp. 145-157 (1985).

N. Nandhakumar and J.K. Aggarwal, "The Artificial Intelligence Approach to Pattern Recognition-A Perspective and an Overview," Pattern Recognition, vol. 18, no. 6, pp. 383-389 (1985).

R.J. Cook and H.J. Kimble, "Possible Direct Observation of Quantum Jumps," Phys. Rev. Lett. 54, 1023 (1985).

R.L. Strong and J.L. Erskine, "Adsorbate Structure Determination Using Surface Vibrational Spectroscopy," Phys. Rev. Lett. 54, 346 (1985).

Jabez J. McClelland and M. Fink, "Correlation Effects in Neon Studied by Elastic and Inelastic High Energy Scattering," Phys. Rev. A, 31, pp. 1328-1335 (1985).

* S.N. Ketkar and M. Fink, "The Structure of Dichromium Tetraacetate by Gas Phase Electron Diffraction," JACS 107, pp. 338-340 (1985).

B.G. Streetman, "Semiconductors and Transistors," Chapter 18 in Reference Data for Radio Engineers, 7th Edition (Indianapolis: Howard W. Sams & Co.)(1985).

* E.S. Kolesar and R.M. Walser, "Novel Realization of the Uniformly Distributed RC (URC) Notch Network," IEEE Trans. Educ. E-26, 173 (1985).

* S. Park and R.M. Walser, "Hydrogen Plasma Etching of Polymeric Carbon Films," CARBON 23, 701 (1985).

F. Hadjarab and J.L. Erskine, "Image Properties of the Hemispherical Analyzer Applied to Multichannel Energy Detection," J. Electron. Spect. Rel. Phen. 36, 227 (1985).

* L.A. Wu and H.J. Kimble, "Interference Effects in Second-Harmonic Generation within an Optical Cavity," J. Opt. Soc. Am. B2, 697 (1985).

J.P. Woods and J.L. Erskine, "Experimental Investigation of β1H on W(100) Using High Resolution Electron Energy Loss Spectroscopy: Bond Distances, Scattering Mechanisms and Impact, Scattering Selection Rules," Phys. Rev. Letters 55, 2595 (1985).

Bruce R. Miller and M. Fink, "The Vibrationally Averaged Temperature Dependent Structure of Polyatomic Molecules III. N_2O", J. Chem. Phys. 83, 939-944 (1985).

R.L. Strong and J.L. Erskine, "Underlayer Formation by Oxygen on Al(111) and Ti(0001)," J. Vac. Sci. Technol. A3, 1428 (1985).

Jabez J. McClelland and M. Fink, "Correlation Effects in Neon Studied by Elastic and Inelastic High Energy Scattering," Phys. Rev. A, 31, pp. 1328-1335 (1985).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

R.W. Bene', G.S. Lee and N.I. Cho, "1/f Noise in Thin Metal Films Interacting with Si Substrates," Thin Solid Films 129, 195 (1985).

C.C. Han and R.W. Bene', "Variations in Interface Compound Nucleations for Ti-Al Ultrathin Films on Si Substrates," Appl. Phys. Lett. 47 (10), 1077 (1985).

R.A. Mawhorter, M. Fink and J.G. Hartley, "An Electron Diffraction Study of Alkali Chloride Vapors", J. Chem. Phys. 83, 4418-4426 (1985).

* S.N. Ketkar and M. Fink, "The Structure of Dichromium Tetraacetate by Gas Phase Electron Diffraction," JACS 107, pp. 338-340 (1985).

J.J. McClelland and M. Fink, "Electron Correlation and Binding Effects in Measured Electron Scattering Cross Sections of CO_2", Phys. Rev. Lett. 54, 2218-2221 (1985).

M.A. Thompson and J.L. Erskine, "Electronic Properties of p(1x1)Ni Films on Cu(100)," Phys. Rev. B31, 6832 (1985).

M.F. Onellion and J.L. Erskine, "Experimental Observation of Adsorbate Orbital Splitting at Single Crystal Metal Surfaces," Phys. Rev. B33, 1 (1985).

R.L. Strong and J.L. Erskine, "A Simple Lattice Dynamical Slab Model for Interpreting Surface Vibrational Spectra: Application to Oxygen on Ni(100) and Ni(111)," Phys. Rev. B31, 6305 (1985).

* K.-C. Peng, Ling-An Wu, and H.J. Kimble, "Frequency Stabilized Nd:YAG Laser with High Output Power," Appl. Optics 24, 938 (1985).

H.J. Kimble, A. Mezzacappa, and P.W. Milonni, "Time Dependence of Photon Correlations in a Three-Level Atomic Cascade," Phys. Rev. A31, 3686 (1985).

* C.W. Farley and B.G. Streetman, "Ion Implantation and Annealing in III-V Multilayer Heterojunctions," Ion Beam Processes in Advanced Electronic Materials and Device Technology, Materials Research Society, Symposia Proceedings, Vol. 45, F.H. Eisen, T.W. Sigmon and B.R. Appleton, editors, 21-33 (1985).

B.G. Streetman, "Microelectronics," Discovery, vol. 9, no. 3, 6-9 (1985).

D.A. Coffman, M. Fink and H. Wellenstein, "Elastic Small Angle Electron Scattering by He, Ne and Ar at 35 Kev," Phys. Rev. Lett. 55, 1392-1394 (1985).

J.L. Speyer, D. Dannemiller and D. Walter, "Periodic Optimal Cruise of an Atmospheric Vehicle," AIAA Journal of Guidance, Control, and Dynamics, vol. 8, no. 1 (Jan.-Feb.1985).

* J.W. Grizzle and S.I. Marcus, "The Structure of Nonlinear Control Systems Possessing Symmetries," IEEE Trans. Automatic Control, vol. AC-30, pp. 248-258 (March 1985).

* S. Park and J.K. Aggarwal, "Recursive Synthesis of Linear Time-Variant Digital Filters via Chebyshev Approximation," IEEE Transactions on Circuits and Systems, vol. CAS-32, no. 3, pp. 245-251 (March 1985).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

* Y. Fukuoka and T. Itoh, "Field Analysis of a Millimeter-Wave GaAs Double-Drift IMPATT Diode in the Traveling-Wave Mode," IEEE Trans. Microwave Theory and Techniques, vol. MTT-33, no. 3, pp. 216-222 (March 1985).

T.S. Chu and T. Itoh, "Modified Residue Calculus Technique for Microstrip Discontinuities," Electronics Letters, vol. 21, no. 7, pp. 257-258 (March 28, 1985).

* S.K. Banerjee and B.S. Streetman, "Planar Junctions in Silicon-on-Oxide Grown Using Lateral Epitaxy by Seeded Solidifications," IEEE Trans. Electron Devices ED-32, 850-853 (April 1985).

A. Mitichie and J.K. Aggarwal, "Image Segmentation by Conventional and Information Integrating Techniques: A Synopsis," Image and Vision Computing, vol. 3, no. 2, pp. 50-62 (May 1985).

Y. Fukuoka, Q. Zhang, D.P. Neikirk and T. Itoh, "Analysis of Multilayer Interconnection Lines for a High Speed Digital Integrated Circuit," IEEE Trans. Microwave Theory and Techniques, vol. MTT-33, no. 6, pp. 527-532 (June 1985).

S.W. Yun and T. Itoh, "Nonreciprocal Wave Propagation in a Hollow Image Guide with a Ferrite Layer," IEE Proc. -H Microwaves, Antennas and Propagation, vol. 132, no. 4, pp. 222-226 (July 1985).

Q. Zhang, Y. Fukuoka and T. Itoh, "Analysis of a Suspended Patch Antenna Excited by an Electromagnetically Coupled Inverted Microstrip Feed," IEEE Trans. Antennas and Propagation, vol. AP-33, no. 8, pp. 895-899 (August 1985).

* Y.K. Jhee, M.F. Becker and R.M. Walser, "Charge Emission and Precursor Accumulation in the Multiple-Pulse Damage of Silicon," The Journal of the Optical Society of America, Part B, vol. 2, pp. 1626-1633 (October 1985).

T.C. Mu, H. Ogawa and T. Itoh, "Characteristics of Coupled Slow-Wave Microstrip Lines," Electronics Letters, vol. 21, no. 20, pp. 946-947 (September 26, 1985).

* S.S. Chan, B.G. Streetman and J.E. Baker, "Redistribution and Electrical Properties of S Implanted in GaAs," J. Electrochem. Soc. 132, 2467-2472 (October 1985).

T.S. Chu and T. Itoh, "Analysis of Microstrip Step Discontinuity by the Modified Residue Calculus Technique," IEEE Trans. Microwave Theory and Techniques, vol. MTT-33, no. 10, pp. 1024-1028 (October 1985).

T.S. Chu, T. Itoh and Y.C. Shih, "Comparative Study of Mode-Matching Formulations for Microstrip Discontinuity Problems," IEEE Trans. Microwave Theory and Techniques, vol. MTT-33, no. 10, pp. 1018-1023 (October 1985).

N. Camilleri and T. Itoh, "A Quasi-Optical Multiplying Slot Array," IEEE Trans. Microwave Theory and Techniques, vol. MTT-33, no. 11, pp. 1189-1195 (November 1985).

J.K. Aggarwal, M. Magee, B. Boyter and C.H. Chien, "Experiments in Intensity Guided Range Sensing Recognition of Three-Dimensional Objects," Pattern Analysis Machine Intelligence Transactions, vol. PAMI-7, no. 6, pp. 629-637 (November 1985).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Y.C. Shih, L.Q. Bui and T. Itoh, "Millimeter-Wave Diplexers with Printed Circuit Elements," IEEE Trans. Microwave Theory and Techniques, vol. MTT-33, no. 12, pp. 1465-1469 (December 1985).

S. Yalamanchili and J.K. Aggarwal, "Reconfiguration Strategies for Parallel Architectures," IEEE Computer Society COMPUTER, vol. 18, no. 12, pp. 44-61 (December 1985).

B. Boyter and J.K. Aggarwal, "Recognition of Polyhedra from Range Data," IEEE Computer Society IEEE EXPERT, vol. 1, pp. 47-59 (Spring 1986).

R.A. Bonham and M. Fink, "Small Angle Elastic Electron Scattering and Moments of the Molecular Charge Density," Phys. Rev. A33, 1569-1577 (1986).

H. Ehsani and R.W. Bene', "Interface Reactions at Cu-$Hg_{1-x}Cd_xTe$ Contacts," J. Appl. Phys. 59(8), 2808 (1986).

N. Bowering, Michael Bruce and J. W. Keto, "Collisional Deactivation of Two-Photon Excited Xenon 5p56p Atoms: II. Lifetimes and Quench Rates," J. Chem. Phys. 84, 715 (1986).

N. Bowering, Michael Bruce and J.W. Keto, "Collisional Deactivation of Two Photon Excited Xenon 5p56p Atoms: I. State-to-State Reaction Rates," J. Chem. Phys. 84, 709 (1986).

Hwa-Yueh Yang and R.W. Bene', "Variations in the Nucleated Products of Ultrathin Films of Ti-Co on Si Substrates with Processing Changes," J. Appl. Phys. 59(5), 1525 (1986).

* S.D. Lester and B.G. Streetman "Materials Issues Underlying Compound Semiconductor Devices," Superlattices and Microstructures (January 1986).

* T.R. Block, C.W. Farley, T.S. Kim, S.D. Lester and B.G. Streetman, "Heating of GaAs and InP by Incoherent Radiation," Proceedings of the 1986 Society of Photo-Optical Instrumentation Engineers SPIE (January 1986).

G.E. Crook and B.G. Streetman, "Laser-Based Structure Studies of Silicon and Gallium Arsenide," IEEE Circuits and Devices 2, 25-31 (January 1986).

T.S. Chu and T. Itoh, "Generalized Scattering Matrix Method for Analysis of Cascaded and Offset Microstrip Step Discontinuities," IEEE Trans. Microwave Theory and Techniques, vol. MTT-34, no. 2, pp. 280-284 (February 1986).

* T.R. Block, C.W. Farley and B.G. Streetman, "Temperature Response of GaAs in a Rapid Thermal Annealing System," J. Electrochem. Soc. 133, 442-443 (February 1986).

A. Mitiche and J.K. Aggarwal, "Multiple Sensor Integration/Fusion Through Image Processing: A Review," Optical Engineering, vol. 25, no. 3, pp. 380-386 (March 1986).

D.L. Brower, N.C. Luhmann, Jr., W.A. Peebles, Ch.P. Ritz and E.J. Powers, "The Application of Homodyne Spectroscopy to the Study of Low-Frequency Microturbulence in the TEXT Tokamak," International Journal of Infrared and Millimeter Waves, 7, no. 3, 447-457 (March 1986).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Jacek Borysow, Roger Taylor and J.W. Keto, "Raman Induced Kerr Gain Spectroscopy," to be published.

L.H. Breaux and J.L. Erskine, "Optimization of a Six-MeterToroidal Grating Monochromator," Nucl. Inst. Methods (in press).

D.W. Choi, E.J. Powers, R.D. Bengtson, G. Joyce, D.L. Brower, N.C. Luhmann, Jr. and W.A. Peebles, "Digital Complex Demodulation Applied to Interferometry," Review of Scientific Instruments (in press).

* K.I. Kim and E.J. Powers, "Identification of Nonlinear Systems in the Walsh Sequency Domain," IEEE Transactions on Electromagnetic Compatibility (in press).

Ch.P. Ritz and E.J. Powers, "Estimation of Nonlinear Transfer Function for Fully Developed Turbulence," Physica D'Nonlinear Phenomena' (in press).

M.F. Onellion, C.L. Fu, M.A. Thompson, J.L. Erskine and A.J. Freeman, "Electronic Structure and Properties of Epitaxial fe on Cu(100): Theory and Experiment," Phys. Rev. B (Rapid Communication)(in press).

J.P. Woods and J.L. Erskine, "Surface Vibrational Resonances and the Order-Disorder Transformation at the W(100) Surface," J. Vac. Sci. Technol. (in press).

J.L. Erskine, "High-Resolution Electron Energy Loss Spectroscopy: Explored Regions and the Frontier", J. Vac. Sci. Technol. (in press).

J.L. Erskine, "Advanced Electron Optics for Vibrational Spectroscopy," J. Electron Spectroscopy Rel. Phenom. (in press).

S. Varma, Y.J. Kim, P.A. Dowben, M.F. Onellion and J.L. Erskine, "Resonant Photoemission at the 5p and 4f Thresholds of Mercury," Phys. Lett. A (in press).

M.F. Onellion, J.L. Erskine, Y. Kim, S. Varma and P.A. Dowben, "Structure Induced Electronic States for Hg Overlayers on Ag(100)," (in press).

M. Fink, Y. Zhang and R.A. Bonham, "Charge Deformation Maps, Molecular Moments and High Energy Electron Scattering," accepted in Int. J. of Quantum Chem.

M.F. Onellion, M.A. Thompson, J.L. Erskine, A. Patten, and C.B. Duke, "Epitaxial Growth of fcc Fe on Cu(100)," submitted to Surface Science.

* C.W. Farley and B.G. Streetman, "Simulation of Anomalous Acceptor Diffusion in Compound Semiconductors," submitted to J. Electrochem.Society.

* S.D. Lester, T.S. Kim and B.G. Streetman, "Factors Influencing the Photoluminescence Intensity of InP," submitted to J. Electrochem. Society.

R.W. Bene', "A Kinetic Description of Solid State Silicide Nucleation," submitted to J. Appl. Phys.

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

H. Ehsani and R.W. Bene', "Interfacial Nucleation in Thin Film Co-$Hg_{1-x}Cd_xTe$ Contacts", submitted to J. Appl. Phys.

* C.W. Farley, T.S. Kim, B.G. Streetman, R.T. Laureau and P. Williams, "Encapsulation and Annealing Studies of Semi-Insulating InP," submitted to Thin Solid Films.

* S. Park and R.M. Walser, "Ion Implantation of Polymeric Carbon Thin Films," submitted to J. Appl. Phys.

Jacek Borysow, Lothar Frommhold and J.W. Keto, "Theoretical Stimulated Raman Gain Spectrum of the Argon Dimer," submitted to Mol. Phys.

Jacek Borysow, Hossein Golnabi and J.W. Keto, "An Innovative Technique for Measuring Small Gains," submitted to Optical Communications.

A.L. Huang, M.F. Becker and R.M. Walser, "Laser Induced Damage and Ion Emission of GaAs at 1.06 Microns," submitted to Applied Optics.

* C.W. Farley and B.G. Streetman, "Simulation of Anomalous Diffusion of Acceptors in Compound Semiconductors," submitted to J. Electrochem. Soc.

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Technical Presentations

183rd National ACS Meeting
Las Vegas, Nevada
April 1, 1982

J.M. White, J.A. Schreifels, D.N. Belton, and B -H. Chen, "Properties of Pt on Ti and Its Oxides."

B.E. Koel and J.M. White, "C(KVV) and 0(KVV) Auger Lineshapes of Chemisorbed CO on Ni(100) Measured by XAES."

Colloquia
Indiana University
Bloomington, Indiana
April 2, 1982

M. Fink, "Electron Diffraction, A New Way to Study Force Fields."

Surface Chemistry Seminar
University of Texas
Austin, Texas
April 26, 1982

* R. M. Walser, "Picosecond Pulse Laser Damage of Crystalline Silicon."

DOE Workshop
BES Atomic Physics Program
Williamsburg, VA.
May 1982

J.W. Keto, "Kinetic Studies Following State Selective Laser Excitations."

*Funded entirely or in part by the Joint Services Electronics Program.

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

1982 Offshore Technology Conference
Houston, Texas
May 3-6, 1982

D.W. Choi, R.W. Miksad, E.J. Powers and F.J. Fischer, "Determination of Nonlinear Drift Force Quadratic Transfer Functions by Digital Cross-Bispectral Analysis."

IEEE International Conference on
Acoustics, Speech and Signal Processing
Paris, France
May 3-5, 1982

A. Mitchie and J.K. Aggarwal, "Detection of Edges Using Range Information."

W.N. Martin and J.K. Aggarwal, "Dynamic Scenes and Object Descriptions."

188th Annual Symposium of the
New Mexico Chapter of the
American Vacuum Society
May 5, 1982

J.A. Schreifels, D.N. Belton and J.M. White, "Thermal Desorption of H_2 and CO on Pt/TiO_2."

IEEE International Symposium on Circuits and Systems
Rome, Italy
May 10-12, 1982

* T. Itoh, "Open Guided Wave Structures for Millimeter-Wave Integrated Circuits."

IEEE
South Central Italy Section
May 13, 1982

T. Itoh, "Comparative Study of Millimeter-Wave Transmission Lines."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Electrical Engineering Seminar
University of Naples
May 14, 1982

T. Itoh, "Microwave Research at The University of Texas."

NATO Advanced Study Institute
on Image Sequence Processing
and Dynamic Scene Analysis
Braunlage, West Germany
June 1982

J.K. Aggarwal, "Dynamic Scene Analysis."

J.K. Aggarwal, "Three-Dimensional Description of Objects."

J.K. Aggarwal, "3-D Motion Analysis."

Imperial College of Science and Technology
London, England
June 1982

* S.I. Marcus, "Lie Algebraic and Approximation Methods in Nonlinear Filtering."

1982 IEEE MTT-S International Microwave Symposium
Dallas, Texas
June 14-18, 1982

W.B. Zhou and T. Itoh, "Analysis of Trapped Image Guides Using Effective Dielectric Constants and Surface Impedance."

Y.C. Shih, T. Itoh and L.Q. Bui, "Computer-Aided Design of Millimeter-Wave E-Plane Filters."

K.D. Stephan, N. Camilleri and T. Itoh, "Quasi-Optical Polarization-Duplexed Balanced Mixer."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

AVS Symposium
Dallas, Texas
June 18, 1982

J.L. Erskine, "Recent Developments in Silicide Research."

Electronic Materials Conference
Ft. Collins, Colorado
June 23-25, 1982

*R.W. Bene, "Solid State Nucleation in Ti-Si Ultrathin Film Systems."

NATO Advanced Study Institute
on Image Sequence Processing
and Dynamic Scene Analysis
Braunlage, West Germany
July 1982

J.K. Aggarwal, "Dynamic Scene Analysis - A Panel Discussion."

1st International Summer School on
Advanced Coal Techniques
Calabria, Italy
July 1-7, 1982

*J.M. White, "Models for the Interaction of CO and H_2 on Transition Metal Surfaces."

Fritz-Haber-Institut der
Max-Planck-Gesellschaft
Berlin, West Germany
July 9, 1982

* J.M. White, "Coadsorption of CO and H_2 on Ni, Rh and Ru Single Crystal Surfaces."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Deutsche Forschung und
Versuchsanstalt fur
Luft-und Raumfahrt (DFLVR)
Munich, West Germany
July 9, 1982

J.K. Aggarwal, "Dynamic Scene Analysis."

Bundeskriminal Amt (BKA)
Wiesbaden, West Germany
July 16, 1982

J.K. Aggarwal, "Dynamic Scene Analysis."

NATO Advanced Study Institute
on Cohesive Properties of
Semiconductors Under Laser
Irradiation
Cargese, Corsica
July 19-31, 1982

*R.M. Walser, "Picosecond Pulse Laser Damage of Crystalline Silicon."

Workshop on Multi-Resolution
Image Processing and Analysis
Leesburg, VA.
July 19-21, 1982

L. Mahaffey, L.S. Davis and J.K. Aggarwal, "Region Correspondence in Multi-Resolution Images Taken from Dynamic Scenes."

Mexican Polytechnic Institute
Mexico City, Mexico
July 28, 1982

* S.I. Marcus, "Nonlinear Filtering: Pathwise Solutions, Finite Dimensional Filters, and Approximations."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Argonne National Laboratory
August 1982

J.W. Keto, "Two-Photon Spectroscopy of Xenon."

Workshop on Computer Vision,
Representation and Control
Rindge, N.H.
August 1982

J.A. Webb and J.K. Aggarwal, "Shape and Correspondence."

Department of Electrical Engineering
Texas A&M University
College Station, Texas
August 23, 1982

J.K. Aggarwal, "Dynamic Scene Analysis."

Fourth American Physical Society
Topical Conference on High Temperature
Plasma Diagnostics
Boston, Massachusetts
August 25-27, 1982

S.J. Levinson, J.M. Beall, E.J. Powers, R.D. Bengtson and G.R. Joyce, "Estimating of $S(k,\omega)$ from Fixed Probe Pairs on the PRETEXT Tokamak."

12th European Microwave Conference
Helsinki, Finland
September 13-17, 1982

* J.-F. Miao and T. Itoh, "Hollow Image Guide for Millimeter-Wave Integrated Circuits."

* Y.C. Shih and T. Itoh, "Analysis of Printed Transmission Lines for Monolithic Integrated Circuits."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

International Conference: Semiconductors in the
Vacuum UV, Applications of Synchrotron Radiation
Berlin, West Germany
September 13-15, 1982

J.L. Erskine, "Systematic Studies of Nickel Silicide Formation on Si(100) and Si(111) Surfaces," invited paper.

University of New Orleans
New Orleans, Louisiana
October 1, 1982

M. Fink, "Experimental Charge Densities of Small Molecules."

McGill University
Department of Electrical Engineering
Montreal, Canada
October 4, 1982

J.K. Aggarwal, "Three-Dimensional Information from Image and Motion Analysis."

University of Texas
Austin, Texas
October 6, 1982

M. Fink, "Schopenhauer, Quantum Mechanics and Electron Diffraction."

RADAR '82 International Conference
London, England
October 18-20, 1982

* J.Y. Hong and E.J. Powers, "Digital Signal Processing of Scattering Data from Nonlinear Targets."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

1982 Annual Meeting of the
Optical Society of America
Tucson, Arizona
October 18-20, 1982

* D.E. Grant, P.D. Drummond and H.J. Kimble, "Evolution of Hysteresis in Absorptive Bistability."

* H.J. Kimble and D.E. Grant, "Transient Response in Absorptive Optical Bistability."

Meeting of Southwest Division
of American Physical Society
Austin, Texas
November 1982

T.D. Raymond, N. Bowering, Chien-Yu Kuo and J.W. Keto, "Classical Phase Shift Analysis of Some Two Photon Absorption Profiles of Xenon."

24th Annual Meeting of the
Division of Plasma Physics
New Orleans, Louisiana
November 1-5, 1982

T. Kochanski, B. Richards, P. Phillips, W. Rowan, T. Boyd, J. Snipes, E.J. Powers and S.B. Kim, "MHD Mode Structure and Activity in the TEXT Tokamak."

S.B. Kim, T.P. Kochanski, E.J. Powers, J.A. Snipes and G.R. Joyce, "Time Dependent MHD Mode Identification in TEXT."

G.R. Joyce, E.J. Powers, R.D. Bengtson and Sung Bae Kim, "MHD Activity During the Current Rise on the PRETEXT Tokamak."

* S.J. Levinson, J.M. Beall, E.J. Powers and R.D. Bengtson, "Experimental Studies of Potential and Density Fluctuations in the Limiter Region of the PRETEXT Tokamak."

Seminar
Abilene Christian University
Abilene, Texas
November 5, 1982

* H.J. Kimble, "The Facts of Light."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

14th ASTM Laser Damage Symposium
NBS
Boulder, Colorado
November 16-17, 1982

* M.F. Becker and R.M. Walser, "Charged Particle Exoemission from Silicon During Multi-Pulse Laser Induced Damage."

* M.F. Becker and R.M. Walser, "Observation of Long-Lived Metastable Excitations in Multi-Pulse Laser Damage of Silicon."

II Conference on Image
Analysis and Processing
Selva di Fasano
Brindisi, Italy
November 18, 1982

J.K. Aggarwal, "Three Dimensional Description of Objects and Dynamic Scene Analysis."

Laser Seminar
Texas A&M University
College Station, Texas
November 19, 1982

H.J. Kimble, "Optical Bistability for Two-Level Atoms."

35th Annual Meeting
Division of Fluid Dynamics
New Brunswick, New Jersey
November 21-23, 1982

R.W. Miksad, F.L. Jones and E.J. Powers, "Experiments on Nonlinear Interactions During Natural Transition of a Wake."

Los Alamos National Laboratory
Los Alamos, New Mexico
December 6, 1982

E.J. Powers, "Applications of Digital Time Series Analysis to Plasma Fluctuation Diagnostics."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Poster Presentation
Venture Research Unit Science Meeting
British Petroleum Int.
London, England
December 8, 1982

* H.J. Kimble, "Nonequilibrium Phase Transitions in Optical Systems."

* H.J. Kimble, "Optical Bistability for Two-Level Atoms."

Seminar
Hughes Aircraft Co.
Canoga Park, CA.
January 6, 1983

* T. Itoh, "Microwave and Millimeter-Wave Research at The University of Texas."

Naval Research Lab
Washington, D.C.
January 10, 1983

* R.M. Walser, "Thin Film Magnetodielectrics."

Electrical Engineering Seminar
Pennsylvania State University
State College, PA.
January 12, 1983

* R.M. Walser, "Laser Damage of Silicon."

Third New Zealand Symposium on
Laser Physics
New Zealand
January 17-23, 1983

* H.J. Kimble, D.E. Grant, A.T. Rosenberger and P.D. Drummond, "Optical Bistability with Two-Level Atoms."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

7th International Conference on
Infrared and Millimeter Waves
Marseilles, France
February 14-18, 1983

S.W. Yun and T. Itoh, "Eigenvalue Analysis of Nonreciprocal Coupling Structure."

Dallas Chapter of
Electrochemical Society
Dallas, Texas
February 24, 1983

R.W. Bene, "First Nucleation in Solid State Thin Film Systems."

University of Texas at Arlington
Dallas, Texas
March 2, 1983

M. Fink, "Molecular Charge Densities Studied by Electron Diffraction."

ACM Siggraph/Sigart Workshop on
Motion Representation and Perception
Toronto, Canada
April 1983

J.K. Aggarwal, "3-D Computer Vision - An Introduction."

NASA Symposium on Computer Aided
Geometry Modeling
Hampton, VA
April 1983

W.N. Martin, B. Gil and J.K. Aggarwal, 'Volumetric Representation for Object Model Acquisition."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Seminar
University of Texas at Dallas
April 8, 1983

H.J. Kimble, "Optical Bistability with Intracavity Atomic Beams."

1983 IEEE International Conference
on Acoustics, Speech and Signal Processing
Boston, Massachusetts
April 14-16, 1983

Taiho Koh and E.J. Powers, "Adaptive Nonlinear Digital Filter with Lattice Orthogonalization."

Colloquium of the Electrical
Engineering Department
University of Notre Dame
South Bend, Indiana
April 25, 1983

* S.I. Marcus, "Nonlinear Filtering: Pathwise Solutions, Finite Dimensional Filters and Approximations."

Conference on Lasers and Electro-Optics
Baltimore, Maryland
May 1983

* M.F. Becker, Y.-K. Jhee, M. Bordelon and R.M. Walser, "Charged Particle Exoemission from Silicon During Multi-Pulse Laser Induced Damage."

Offshore Technology Conference
Houston, Texas
May 2-5, 1983

R.W. Miksad, D. W. Choi, E.J. Powers and F.J. Fischer, "Applications of Digital Complex Demodulation Techniques to Low Frequency Nonlinear Drift Forces in Irregular Seas."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

1983 IEEE International Conference
on Plasma Science
San Diego, California
May 23-25, 1983

S.B. Kim, T.P. Kochanski, J.A. Snipes, G.R. Joyce and E.J. Powers, "Observation of Nonlinear Mode Coupling of a Low Frequency MHD Oscillation in TEXT."

E.J. Powers, "Applications of Digital Time Series Analysis to Plasma Fluctuation Diagnostics."

S.J. Levinson, J.M. Beall, E.J. Powers and R. D. Bengtson, "Edge Turbulence in the PRETEXT Tokamak."

1983 International Microwave Symposium
Boston, Massachusetts
May 31-June 3, 1983

* Y. Fukuoka and T. Itoh, "Slow Wave Coplanar Waveguide on Periodically Doped Semiconductor Substrates."

Trends and Application 1983 Conference
Gaithersburg, MD
May 1983

J. Courtney and J.K. Aggarwal, "Robot Guidance Using Computer Vision."

1983 International Symposium on
Antennas and Propagation
Houston, Texas
May 23-26, 1983

J. Rivera and T. Itoh, "Analysis of an Electromagnetically Coupled Patch Antenna."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

1983 International Microwave Symposium
Boston, Massachusetts
May 31-June 3, 1983

Y.C. Shih and T. Itoh, "E-Plane Filters with Finite-Thickness Septa."

L. Su, T. Itoh and J. Rivera, "Design of An Overlay Directional Coupler by a Full-Wave Analysis."

W.B. Zhou and T. Itoh, "Field Distributions in the Trapped Image Guide."

IEEE Computer Society Conference
on Computer Vision and Pattern Recognition
Washington, D.C.
June 1983

C.H. Chien and J.K. Aggarwal, "A Normalized Quadtree Representation."

M. Magee and J.K. Aggarwal, "Intensity Guided Range Sensing Recognition of Three-Dimensional Objects."

Y.C. Kim and J.K. Aggarwal, "Rectangular Coding of Binary Images."

Invited Talk
Fifth Rochester Conference on
Coherence and Quantum Optics
and Topical Meeting on
Optical Bistability
Rochester, New York
June 13-17, 1983

H.J. Kimble, "Optical Bistability with Two-Level Atoms."

III-V Research Strategy
Workshop for Digital IC Applications
Research Triangle Park, N.C.
June 14, 1983

B.G. Streetman, "Ion Implantation Research."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

1983 Electronic Materials Conference (AIME)
Burlington, VT
June 23, 1983

B.G. Streetman, "The Role of Defects in the Diffusion of Impurities in Ion Implanted Semiconductors."

Colloquia
University of Kaiserslautern
Germany

M. Fink, "Temperature Dependent Molecular Structure Parameters."

Naval Underwater Systems Center
New London, Connecticut
July 12, 1983

E.J. Powers, "Application of Higher-Order Spectra in Analyzing and Interpreting *Nonlinear Time Series Data.*"

UCLA Short Course on Advanced Scattering
Analysis of Microwave Networks with Applications
UCLA Extension Course No. Engineering 881.61
Los Angeles, CA.
July 25-29, 1983

* T. Itoh, "Generalized Scattering Matrix Technique."

International Society for
Optical Engineering
Annual Symposium
San Diego, CA.
August 1983

S. Yalamanchili and J.K. Aggarwal, "A Model for Parallel Image Processing."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

3-D Workshop of the American Association
for Artificial Intelligence
Washington, D.C.
August,1983

M. Magee and J.K. Aggarwal, "Intensity Guided Range Sensing Recognition of Three-Dimensional Objects."

SPIE
San Diego, CA.
August 22-26, 1983

K.D. Stephan and T. Itoh, "Quasi-Optical Planar Mixers for Millimeter-Wave Imaging Applications."

13th European Microwave Conference
Nurnberg, West Germany
September 5-8, 1983

* Y. Fukuoka and T. Itoh, "Design Consideration of Uniform and Periodic Coplanar Schottky Variable Shifter."

S.W. Yun and T. Itoh, "A Novel Distributed Millimeter-Wave Isolator."

BRASIL OFFSHORE '83
International Symposium on Offshore Engineering
Rio de Janeiro, Brazil
September 12-16, 1983

* T. Koh, E.J. Powers, R.W. Miksad and F.J. Fischer, "An Approach To Time Domain Modelling of Nonlinear Drift Oscillations in Random Seas."

Colloquium
Invited Talk
Heriod-Watt University
Edinburg, Scotland
September 15, 1983

H.J. Kimble, "Atomic Cooperativity in Optical Bistability."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Instituto de Fisica
Universidade Federal Fluminense
Rio de Janeiro, Brazil
September 19, 1983

E.J. Powers, "Applications of Digital Time Series Analysis to Plasma Fluctuation Diagnostics."

16th Annual Electronics and
Aerospace Conference and Exposition
Washington, D.C.
September 19-21, 1983

* J.Y. Hong and E.J. Powers, "Detection of Weak Third Harmonic Backscatter from Nonlinear Metal Targets."

Instituto de Fisica
University of Sao Paulo
Sao Paulo, Brazil
September 20, 1983

E.J. Powers, "Applications of Digital Time Series Analysis to Plasma Fluctuation Diagnostics."

Venture Research Science Meeting
Sponsored by British Petroleum, Int.
London, England
September 20-21, 1983

H.J. Kimble, "Nonequilibrium Phase Transition in Optical Systems."

Instituto de Fisica
University of Campinas
Campinas, Brazil
September 21, 1983

E.J. Powers, "Application of Digital Time Series Analysis to Plasma Fluctuation Data."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Physics Colloquium
Texas A&M University
College Station, Texas
October 1983

J.W. Keto, "Laser Probes of Reactions in Half-Collision."

1983 Annual Meeting of the
Optical Society of America
New Orleans, Louisiana
October 17-20, 1983

H.J. Kimble, A. Mezzacappa and P.W. Milonni, "Time Dependence of Photon Correlations in a Three-Level Atomic Cascade."

H.J. Kimble, L.A. Orozco and A.T. Rosenberger, "Evolution of Hysteresis in Dispersive Bistability with Two-Level Atoms."

H.J. Kimble, A.T. Rosenberger and L.A. Orozco, "Anomalous Behavior on the Upper Branch in Optical Bistability."

15th ASTM Laser Damage Symposium
Boulder, CO.
November 1983

* M.F. Becker, F.E. Domann, A.F. Stewart and A.H. Guenther, "Charge Emission and Related Precursor Events Associated with Laser Damage."

Colloquium
University of Arkansas
November 4, 1983

H.J. Kimble, "Optical Bistability with Two-Level Atoms: Theory Meets Experiment."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

25th Annual Meeting of the
Division of Plasma Physics
Los Angeles, California
November 7-11, 1983

S.B. Kim, T.P. Kochanski, J. Snipes, E.J. Powers and P. Phillips, "Evolution of MHD Mode Structure in TEXT."

S.J. Levinson, J. Beall, E.J. Powers, Roger D. Bengtson and K. Nelin, "Edge Turbulence in TEXT and PRETEXT."

Ch.P. Ritz, S.J. Levinson, E.J. Powers and Roger D. Bengtson, "An Approach to Estimate Wave-Wave Nonlinear Coupling Coefficients in a Turbulent Plasma."

Electrical and Computer Engineering
Department Seminar
University of Massachusetts
Amherst, MA
November 15, 1983

* T.Itoh, "MIC Transmisison Lines with Composite Materials."

Invited Talk
Venture Research Material Sciences Meeting
London, England
November 23, 1983

H.J. Kimble, "Nonequilibrium Phase Transition in Optical Systems."

Invited Talk
Royal Signals and Radar Establishment
Malvern, England
November 25, 1983

H.J. Kimble, "Optical Bistability with Intracavity Atomic Beams."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

IEEE Conference on Decision and Control
San Antonio, Texas
December 1983

* T.Y. Leou and J.K. Aggarwal, "Difference Equation Implementations of Time Variant Digital Filters."

MCC Presentation
Austin, Texas
December 6, 1983

R.W. Bene, "Systematics of Solid State Interface Development Between Thin Metal Films and Semiconductor Substrates."

8th International Conference on
Infrared and Millimeter Waves
Miami Beach, Florida
December 12-17, 1983

K.D. Stephan and T. Itoh, "Isotropic Conversion Loss as a Measure of Quasi-Optical Mixer Efficiency."

Invited Talk
1984 Joint APS/AAPT Meeting
San Antonio, Texas
January 30, 1984

M. Fink, "Correlation and Binding Effects in Molecule Studies by High Energy Electron Diffraction."

2nd International Modal Analysis Conference
Orlando, Florida
February 6-9, 1984

DooWhan Choi, Jung-Hua Chang, R.O. Stearman and E.J. Powers, "Bispectral Identification of Nonlinear Mode Interactions."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Department Colloquium
University of Texas at Arlington
Arlington, Texas
February 22, 1984

J.L. Erskine, "Electron Energy Loss Studies of Ordered Structures at Metal Surfaces."

JSEP Electronics Program Research Review
University of Texas at Austin
March 9, 1984

* R.W. Bene, "Solid State Interface Reactions and Instabilities,"

IEEE International Conference
on Acoustics, Speech and Signal Processing
San Diego, California
March 19-21, 1984

* Taiho Koh and E.J. Powers, "Efficient Maximum Entropy Spectral Estimation Using Non-Multiplication Methods."

Universita di Roma La Sapienze
Rome, Italy
March 13, 1984

T. Itoh, "Quasi-TEM Analysis by the Spectral Domain Technique."

Universita di Roma 'Tor Vergata'
and IEEE AP-MTT Rome Chapter
Rome, Italy
March 14, 1984

* T. Itoh, "Open Guided Wave Structures."

* T. Itoh, "Transmission Lines on Semiconductor Substrate."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Universita di Roma La Sapienze
Rome, Italy
March 15, 1984

T.Itoh, "Full-Wave Analysis by the Spectral Domain Technique".

Universita di Roma 'Tor Vergata'
and IEEE MTT Rome Chapter
Rome, Italy
March 16, 1984

T. Itoh, "Quasi-Optical Planar Mixers."

T. Itoh, "E-Plane and Finline Techniques."

Physics Colloquium
University of Texas at Austin
Austin, Texas
March 28, 1984

J.W. Keto, "Dynamics of Multiphoton Excited Atoms."

Texas Instruments
Dallas, Texas
April 1984

* R.W. Bene, "The Systematics of Metal-Compound Semiconductor Interfacial Reaction in the Solid State."

University of Texas at Austin
Physics Department
Austin, Texas
April 4, 1984

* John W. Keto, "Dynamics of Multiphoton Excited Atoms".

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Distinguished Lecturer Series
Department of Electrical Engineering
University of Houston
Houston, Texas
April 9, 1984

* S.I. Marcus, "Recent Developments in Nonlinear Estimation Theory."

General Motors Research Laboratory
Warren, Michigan
April 23, 1984

E.J. Powers, "Applications of Digital Time Series Analysis."

American Vacuum Society Lecture
Texas A&M University
College Station, Texas
April 24, 1984

J.L. Erskine, "Surface Vibrational Spectroscopy of Ordered Overlayers on Crystal Surfaces."

SPIE Technical Symposium East '84
Arlington, VA.
April 29-May 4, 1984

* T. Itoh, "Recent Development of Dielectric Waveguide Technology."

1st Annual Research Review
Dept of Electrical Engineering
University of Texas at Austin
Austin, Texas
May 1984

* R.W. Bene', "Systematics of Interface Solid State Reactions."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Electrophysics Seminar
University of Maryland
College Park, Maryland
May 4, 1984

* T. Itoh, "Dielectric Waveguide Technology for Microwave and Millimeter-Wave Applications."

107th Meeting of the
Acoustical Society of America
Norfolk, Virginia
May 6-10, 1984

E.J. Powers, D. Choi, J-H. Chang and R.O. Stearman, "Bispectral Analysis of Parametric and Nonlinear Phenomena."

1984 International Symposium on
Circuits and Systems
Montreal, Canada
May 7-10, 1984

* S.H. Park and J.K. Aggarwal, "Recursive Synthesis of Linear Time-Variant Digital Filters."

16th Annual Offshore Technology Conference
Houston, Texas
May 7-9, 1984

T. Koh, E.J. Powers, R.W. Miksad and F.J. Fischer, "Applications of Nonlinear Digital Filters to Modeling Low-Frequency, Nonlinear Drift Oscillations of Moored Vessels in Random Seas."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

1984 IEEE International Conference
on Plasma Science
St. Louis, Missouri
May 14-16, 1984

S.B. Kim, T.P. Kochanski, J. Snipes and E.J. Powers, "Characteristics of Double Sawteeth and Sawtooth-Like Oscillations on TEXT."

S.J. Levinson, E.J. Powers, Ch.P. Ritz and Roger D. Bengtson, "Space-Time Statistics and Particle Transport."

Ch.P. Ritz, S.J. Levinson, E.J. Powers and R.D. Bengtson, "Wave-Wave Coupling and Energy Flow in a Tokamak Edge Plasma."

Users Group
Austin, Texas
May 23, 1984

R.L. Strong and J.L. Erskine, "Use of Electron Energy Loss Spectroscopy to Determine Positions of Adsorbates."

Phillips Petroleum Company
Bartlesville, OK
May 24, 1984

E.J. Powers, "Applications of Digital Time Series Analysis to Nonlinear Wave Phenomena."

1984 IEEE MTT-S International
Microwave Symposium
San Francisco, CA
May 30-June 1, 1984

L.Q. Bui, D. Ball and T. Itoh, "Broadband Millimeter-Wave E-Plane Bandpass Filters."

* R. Sorrentino and T. Itoh, "Transverse Resonance Analysis of Finline Discontinuities."

* Y. Fukuoka and T. Itoh, "Field Analysis of Millimeter-Wave GaAs Double-Drift IMPATT Diode in the Traveling-Wave Mode."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Optical Society of America
Topical Meeting on Ultrafast Phenomena
Monterrey, CA
June 1984

* M.F. Becker and Y.K. Jhee, "Subthreshold Picosecond Laser Damage in Silicon Associated with Charge Emission."

International IEEE VLSI
Multilevel International Conference
New Orleans, LA
June 21-22, 1984

Y. Fukuoka, Q. Zhang, D. Neikirk and T. Itoh, "Analysis of Multilayer Interconnection Lines for a High Speed Digital Integrated Circuit."

1984 IEEE AP-S
Symposium/National Radio Science Meeting
Boston, MA
June 25-28, 1984

T. Itoh, "CAD-Oriented Field and Network Analysis - Overview."

U.S. Army Harry Diamond Laboratory
Adelphi, MD
June 29, 1984

* T. Itoh, "Microwave Research at University of Texas."

Korean Science and Technology Symposium
Seoul, Korea
July 2-6, 1984

* J.Y. Hong and E.J. Powers, "Nonlinear Radar Systems Based on Digital Higher-Order Spectral Techniques."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

International Union of Theoretical
and Applied Mechanics Second Symposium
on Laminar-Turbulent Transition
Novosibirsk, USSR
July 9-13, 1984

F.L. Jones, R.W. Miksad and E.J. Powers, "Wave Modulations and Nonlinear Interactions During Transition to Turbulence of a Wake."

Colloquia
University of Wurzburg
Germany
July 12, 1984

M. Fink, "Studies of the Metal-Metal Bonding by Gas Phase Electron Diffraction."

Sandia National Labs
Albuquerque, New Mexico
August 1984

J.L. Speyer, "Guidance Law Synthesis for Hypersonic Gliders."

UCLA Short Course
Los Angeles, CA
August 15, 1984

T. Itoh, "Generalized Scattering Parameter Methods."

XVIth International Congress of
Theoretical and Applied Mechanics
Lyngby, Denmark
August 19-25, 1984

R.W. Miksad, F.L. Jones and E.J. Powers, "The Generation of Low-Frequency Fluctuations by Nonlinear Interactions During Transition to Turbulence."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

XXIst General Assembly of URSI
Florence, Italy
August 28-September 5, 1984

* T. Itoh, "Survey of New Waveguides."

* T. Itoh, "Fin-Line and E-Plane Structures for Millimeter Wave Circuits."

International Conference on
Digital Signal Processing
Florence, Italy
September 5-8, 1984

* L. Khadra, E.J. Powers and Y.C. Kim, "Digital Complex Demodulation of Nonstationary Time Series."

Technische Hochschule Aachen
Aachen, W. Germany
September 7, 1984

* T. Itoh, "Millimeter-Wave Research at University of Texas."

14th European Microwave Conference
Liege, Belgium
September 10-13, 1984

S.W. Yun and T. Itoh, "Nonreciprocal Wave Propagation in a Hollow Image Guide with a Ferrite Layer."

14th European Microwave Conference
Liege, Belgium
September 10-13, 1984

Q. Zhang, Y. Fukuoka, T. Itoh and L. Su, "Analysis of a Suspended Patch Antenna Excited by an Electromagnetically Coupled Inverted Microstrip Feed."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

AFOSR Workshop on Metastable Helium
AFRPL, Edwards Air Force Base
Pasadena, California
September 4, 1984

J.W. Keto, "Optical Pumping of He_2a^3E in Liquid Helium."

Tenth International Conference on
Plasma Physics and Controlled
Nuclear Fusion Research
International Atomic Energy Agency
London, U.K.
September 12-19, 1984

D.L. Brower, ..., E.J. Powers, et al., "Tokamaks-Description of Turbulence and the First Test of an Ergodic Magnetic Limiter."

Fern Universitat Hagen
Iserlohn, W. Germany
September 13, 1984

* T. Itoh, "Millimeter-Wave Research at University of Texas."

Technische Universitat Braunschweig
Braunschweig, W. Germany
September 13, 1984

* T. Itoh, "Millimeter-Wave Research at University of Texas."

Technische Universitat Hamburg
Hamburg, W. Germany
September 14, 1984

* T. Itoh, "Millimeter-Wave Research at The University of Texas."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

North Jersey IEEE MTT-AP
Chapter Meeting
Nutley, NJ
September 18, 1984

* T. Itoh, "Transmission Lines for Microwave and Millimeter-Wave Circuits."

Seminar
RCA David Sarnoff Research Center
Princeton, NJ
September 19, 1984

* T. Itoh, "Microwave and Millimeter-Wave Research at The University of Texas."

Seminar
NASA Lewis Research Center
Cleveland, OH
September 24, 1984

T. Itoh, "Microwave Transmission Structures."

Atomic and Molecular Seminar
Physics Department
University of Texas at Austin
Austin, Texas
September 28, 1984

* J. Keto and Roger Taylor, "Stimulated Raman Gain Spectroscopy and the Search for Sensitivity."

Sandia National Laboratories
Albuquerque, NM
October 1984

* M.F. Becker, "Charge Emission and Accumulation of Damage for Multi-Pulse Laser Irradiation of Silicon."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

16th ASTM Laser Damage Symposium
Boulder, CO
October 1984

* M.F. Becker, "Charge Emission and Accumulation in Multiple-Pulse Damage of Silicon."

* M.F. Becker, "Surface Potential as a Laser Diagnostic."

Invited Talk
Research and Development Center
Grumman Aerospace Corp.
Bethpage, NY
October 9, 1984

R.M. Walser, "Thin Film Magnetodielectrics."

Seminar
University of Colorado
Boulder, Colorado
October 19, 1984

* H.J. Kimble, "Optical Bistability with Two-Level Atoms."

1984 International Symposium on
Noise and Clutter Rejection in
Radars & Imaging Sensors
Tokyo, Japan
October 22-24, 1984

* J.Y. Hong and E.J. Powers, "Simulation Study of Detection of Nonlinear Metallic Targets in Sea Clutter Type Noise."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

9th International Conference on
Infrared and Millimeter Waves
Takarazuka, Japan
October 22-26, 1984

* Y. Fukuoka and T. Itoh, "Travelling-Wave Characteristics of Millimeter-Wave IMPATT Diode."

S.W. Yun and T. Itoh, "Bias Dependence of a Hollow Image Guide Type Isolator."

Invited Talk
Southeastern Section of American Physical Society
Memphis, Tennessee
October 26, 1984

* H.J. Kimble, "Optical Bistability and Dynamical Instability Using Two-Level Atoms."

Tokyo Chapter of IEEE
MTT-S Meeting
Uniden Corporation
Ichikawa, Japan
October 29, 1984

* T. Itoh, "Recent Trends in Millimeter-Wave Research."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

26th Annual Meeting
Division of Plasma Physics
Boston, Massachusetts
October 29-November 2, 1984

T.L. Rhodes, Roger D. Bengtson, E.J. Powers and Ch.P. Ritz, "Two-Dimensional Structure of the Turbulence in the Edge Plasma of TEXT."

Ch.P. Ritz, Roger D. Bengtson and E.J. Powers, "Observation of Wave-Wave Interaction in the Edge Plasma of TEXT."

Roger D. Bengtson, Ch.P. Ritz, S.J. Levinson and E.J. Powers, " Turbulent Structure in the Edge Plasma of the TEXT Tokamak."

R.C. Cross, T.P. Kochanski, J.A. Snipes, S.B. Kim and E.J. Powers, "A Typical Magnetic MHD Activity in TEXT."

S.B. Kim, J.A. Snipes, T.P. Kochanski and E.J. Powers, "Soft X-Ray Imaging of Giant Sawteeth and Other Phenomena on TEXT."

Invited Presentation
ONR Contracts Workshop
Naval Research Laboratory
Washington, DC
October 29, 1984

R.M. Walser, "Magnetic Materials Research at The University of Texas."

Seminar
Matsushita Research Institute
Kawasaki, Japan
October 30, 1984

T. Itoh, "Research Operations in the U.S. Universities."

* T. Itoh, "Millimeter Wave Research."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Colloquia
Rice University
Houston, Texas
November 6, 1984

M. Fink, "Studies of Metal-Metal Bonding By Gas Phase Electron Diffraction."

Colloquia
University of Houston
Houston, Texas
November 7, 1984

M. Fink, "Studies of Metal-Metal Bonding by Gas Phase Electron Diffraction."

Washington IEEE MTT-S
Chapter Lecture Series
College Park, MD
November 13, 1984

T. Itoh, "Millimeter Wave Transmission Lines."

EE Seminar
University of Virginia
Charlottesville, VA
November 14, 1984

* T. Itoh, "Millimeter Wave Research at University of Texas."

EE Seminar
University of Texas at Arlington
Arlington, TX
November 15, 1984

* T. Itoh, "Microwave and Millimeter-Wave Research at University of Texas at Austin."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Optical Society of America
San Diego, CA
October 30-November 2, 1984

* Kun-Chi Peng, Ling-An Wu and H.J. Kimble, "Frequency-Stabilized Nd:YAG Lasers."

* Lung-An Wu and H.J. Kimble, "Role of Phase in Second-Harmonic Generation within an Optical Cavity."

* A.T. Rosenberger, L.A. Orozco and H.J. Kimble, "What is the Best Measure of Cavity Loss in Optical Bistability?"

* L.A. Orozco, A.T. Rosenberger and H.J. Kimble, "Observation of the Single-Mode Instability in Optical Bistability."

* H.J. Kimble and L. Mandel, "Theory of Photoelectric Detection of Polychromatic Light."

Electrochemical Society Symposium
on Compound Semiconductors
New Orleans, LA
October 7-12, 1984

* B.G. Streetman, "Simulation of Concentration-Dependent Diffusion During the Annealing of Ion-Implanted Compound Semiconductors."

Dept. of Aerospace and Ocean Engineering
Virginia Polytechnic Institute
and State University
Blacksburg, Virginia
November 1984

J.L. Speyer, "Optimal Periodic Control."

Colloquium
Laser Science Division
Sandia National Research Labs
November 1, 1984

* John W. Keto, "Dynamics of Two-Photon Excited Xenon Atoms."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Dallas IEEE MTT/AP
Chapter Meeting
Dallas, Texas
November 15, 1984

* T. Itoh, "Microwave Research at The University of Texas."

Dallas IEEE MTT/AP Chapter
Dallas, Texas
November 16, 1984

T. Itoh and T.W. Kennedy, "Problems and Avenues in University -Industry Research Cooperation."

Invited Talk
International Conference on Lasers
San Francisco, California
November 27, 1984

H.J. Kimble, A.T. Rosenberger and L.A. Orozco, "Optical Bistability and Dynamical Instability with Two-Level Atoms."

ARO Workshop on Near Millimeter
Wave Communication Technology
New York Institute of Technology
Glenn Cove, NY
December 5-9, 1984

* T. Itoh, "Millimeter Wave Transmission Lines."

Semiconductor Research Corporation
Post-Shrink Silicon Device Workshop
Chappel Hill, North Carolina
January 10-11, 1985

* J.L. Erskine, "Experiments, Theory and Predictive Modeling in Relation to 'Post-Shrink Silicon Devices'".

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

3rd International Modal Analysis Conference
Orlando, Florida
January 29-31, 1985

D.W. Choi, R.O. Stearman and E.J. Powers, " Identification of Aeroelastic Phenomenon Employing Bispectral Analysis Techniques."

Wright Patterson AFB
Wright Patterson AFB, OH
February 1985

* J.L. Speyer, "Fault Tolerant Digital Flight Control Systems."

Advanced Development Group Seminar
McDonnell-Douglas, Inc.
St. Louis, MO
February 7, 1985

R.M. Walser, "Thin Film Magnetodielectrics."

Colloquia
Texas A&M University
College Station, Texas
February 12, 1985

M. Fink, "Studies of Metal-Metal Bonding by Gas Phase Electron Diffraction."

Aerospace Corporation
Los Angeles, CA
March 1985

* J.L. Speyer, "The Modified Extended Kalman Filter with Applications."

Southwest Conference on Optics
Albuquerque, NM
March 1985

* M.F. Becker, "Surface Potential as a Laser Damage Diagnostic."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Invited Talk
Texas Section of APS Meeting
Rice University
Houston, Texas
March 7, 1985

* H.J. Kimble, "Optical Bistability."

EE Seminar
Texas A&M University
College Station, Texas
March 7, 1985

* T. Itoh, "Microwave and Millimeter Wave Research at The University of Texas ."

Texas Section of American Physical Society
Rice University
Houston, Texas
March 8-9, 1985

J. Hartley and M. Fink, "A New Gas Phase Raman Spectrometer."

R.J. Mawhorter, J. Hartley and M. Fink, "The Structure of Alkali Chloride Dimer Clusters."

J.D. Coffman and M. Fink, "Shadow Scattering/Does It Exist or Not?"

Hughes Torrance Research Center
Torrance, CA.
March 14, 1985

T. Itoh, "Microstrip Discontinuity Problems."

Invited Talk
American Physical Society
Baltimore, MD
March 25-29, 1985

* Ben G. Streetman and C.W. Farley, "Materials Properties of GaAs and Related Compounds."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Workshop on the Estimation and
Control of Stochastic Systems
Dept. of Mathematics
Mexican Polytechnic Institute
Mexico City, Mexico
March 27, 1985

* S.I. Marcus, "Analysis of an Adaptive Estimation Algorithm Arising in the Adaptive Estimation of Markov Chains."

UT Dept. of Electrical
and Computer Engineering
2nd Annual Research Review
Austin, Texas
April 6, 1985

R.M. Walser, "Synthesis and Applications of Inhomogeneous Electromagnetic Media."

Martin Marietta Laboratories
Baltimore, MD
April 8, 1985

T. Itoh, "Recent Advances in Millimeter Wave Research at The University of Texas."

SPIE Technical Symposium East '85
Arlington, VA
April 8-12, 1985

T. Itoh, "Survey of Millimeter-Wave Guiding Structures."

NSF Site Review Committee
Austin, Texas
April 9, 1985

R.M. Walser, "Magnetic Microstructures."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Materials Research Society
San Francisco, CA
April 14-16, 1985

B.G. Streetman, "Ion Implantation and Annealing in III-V Multilayer Heterojunctions."

Physics Seminar
Cornell University
Ithaca, New York
April 24, 1985

J.L. Erskine, "Thin Film Magnetism: New Interest in an Old Subject."

Bell Labs
Murray Hill, New Jersey
April 26, 1985

J.L. Erskine, "Experimental Studies of Epitaxial Magnetic Films."

Colloquium
University of Wurtzburg, West Germany
May 7, 1985

J.W. Keto, "Dynamics of Multiphoton Excited Xenon Atoms."

The Electrochemical Society
Toronto, Canada
May 12-17, 1985

Ben G. Streetman, "Ion Implantation in Compound Semiconductors."

SFB Colloquium
University of Kaiserslautern, West Germany
May 23, 1985

J.W. Keto, "Laser Switched Electronic Energy Transfer."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Annual Meeting of the
Division of Atomic, Molecular,
and Optical Physics
May 29-31, 1985

H.J. Kimble, "Cooperant Atomic Dynamics in Optical Bistability with Two-Level Atoms."

Texas A&M University
College Station, Texas
June 3, 1985

J.L. Erskine, "Studies of MBE Grown Monolayer Magnetic Films Using Synchrotron Radiation and Photoelectron Spectroscopy."

1985 IEEE MTT-S International
Microwave Symposium
St. Louis, MO
June 4-6, 1985

Y.C. Shih, L.Q. Bui and T. Itoh, "Millimeter-Wave Diplexers with Printed Circuit Elements."

Y.C. Shih, T.S. Chu and T. Itoh, "Comparative Study of Mode Matching Formulations for Microstrip Discontinuity Problems."

Whitney Symposium on Science and Technology
Schenectady, NY
June 11-14, 1985

Ben G. Streetman, "Ion Implantation in Semiconductors."

1985 North American Radio Science/IEEE
AP-S Symposium
Vancouver, Canada
June 17-21, 1985

C. Tzuang and T. Itoh, "Analysis of Coplanar Waveguide with Finite Conductor Thickness and a Substrate with a Lossy Layer."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

International Meeting on Instabilities
and Dynamics of Lasers and Nonlinear
Optical Systems
Rochester, New York
June 18-21, 1985

* R.J. Brecha, L.A. Orozco, A.T. Rosenberger, H.J. Kimble and H.J. Carmichael, "Period Doubling Bifurcation from a Linear (Empty) Cavity."

Seminar
CNRS-ORSAY
Universite Paris-Nord
Villetaneuse, France
June 19, 1985

J.W. Keto, "Dynamics of Multiphoton Excited Xenon Atoms."

Seminar
CNRS
Grenoble, France
June 21, 1985

J.W. Keto, "Laser Physics in Austin, Texas."

1985 IEEE VLSI Multilevel
Interconnection Conference
Santa Clara, CA
June 24-26, 1985

C-K C. Tzuang and T. Itoh, "Pulse Transmission in an Interconnection Line on a Semiconductor Substrate with a Lossy Layer."

Science Conference of the
Venture Research Unit of
BP International
London, England
June 25-26, 1985

H.J. Kimble, "Is Quantum Noise a Friend or a Foe?"

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Seminar
Physics Dept.
University of Bielefeld, West Germany
July 12, 1985

J.W. Keto, "Dynamics of Multiphoton Excited Xenon Atoms."

1985 International Symposium on
Microwave Technology in
Industrial Development
Campinas, Brazil
July 22-25, 1985

T. Itoh, "New Waveguide Structures for Microwave and Millimeter Circuits."

Institute of Electronics
Chinese Academy of Sciences
Beijing, China
August 9, 1985

T. Itoh, "Comparison of Transmission Lines."

T. Itoh, "Full-Wave Analysis at Microstrip Lines."

Nanjing Institute of Technology
Nanjing, China
August 12, 1985

T. Itoh, "Quasi-TEM Analysis and Techniques."

T. Itoh, "Comparison of Millimeter-Wave Transmission Lines."

T. Itoh, "Microwave Research and Education at The University of Texas."

T. Itoh, "Full-Wave Analysis of Microstrip Lines."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Nanjing Institute of Technology
Nanjing, China
August 14-15, 1985

T. Itoh, "Dielectric Waveguide Analysis and Techniques."

T. Itoh, "E-Plane Techniques."

1985 International Symposium on
Antennas and Propagation
Kyoto, Japan
August 20-22, 1985

N. Camilleri and T. Itoh, "Frequency Multiplying Active Slot Array."

Radio Research Laboratory
Matsushita Electric
Osaka, Japan
August 21, 1985

T. Itoh, "Recent Trends in Millimeter-Wave Research."

Millimeter Wave Workshop at
Institut National des Sciences Appliquees
Rennes, Britagny, France
September 16, 1985

T. Itoh, "Comparison of Millimeter Wave Transmission Line."

T. Itoh, "E-Plane Techniques."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

International Symposium on
Offshore Engineering
BRASIL OFFSHORE '85
Rio de Janeiro, Brazil
September 16-20, 1985

K.I. Kim, E.J. Powers, Ch.P. Ritz and R.W. Miksad, "Modeling of Nonlinear Systems in Offshore Engineering for Non-Gaussian Inputs."

Texas Instruments
Dallas, Texas
September 18, 1985

R.W. Bene', "Solid State Reactions at Metal-MCT and Metal-CdTe Contacts."

15th European Microwave Conference
Paris, France
September 19-21, 1985

N. Camilleri and T. Itoh, "Frequency Multiplying Power-Combining Slot Array."

C-K C. Tzuang and T. Itoh, "Pulse Transmission on a Slow-Wave MIS and Schottky Coplanar Waveguide with Finite Conductor Thickness."

* N.U.Song and T. Itoh, "Accurate Simulation of MESFET by Finite Element Method Including Energy Transport and Substrate Effects."

T. Itoh, "An Overview on Numerical Techniques for Modeling Miniaturized Passive Components."

T.S. Chu and T. Itoh, "Analysis of Offset Microstrip Step Discontinuity by the Generalized Scattering Matrix Techniques."

Department of Physics
University of Texas
Austin, Texas
October 1985

J.L. Erskine, "Surface Magnetism."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

17th ASTM Laser Damage Symposium
Boulder, Colorado
October 1985

M.F. Becker, "N-on-1 Damage Testing of Single Crystal Metal Surfaces at 1.06 Microns."

M.F. Becker, "Laser Induced Ion Emission and Damage of GaAs at 1.06 Microns."

Symposium on Surface Chemical Processes
Chemistry Dept.
University of Texas
Austin, Texas
October 3, 1985

J.L. Erskine, "Research in Surface Physics."

1985 Annual Meeting of the
Optical Society of America
Washington, D.C.
October 14-18, 1985

H.J. Kimble and R.J. Cook, "Monitoring Quantum Transition in a Three-Level Atom."

* L.A. Orozco, A.T. Rosenberger and H.J. Kimble, "Experimental Test of the Single-Gaussian Mode Theory of Optical Bistability."

Xiao Min, H.J. Kimble, and H.J. Carmichael, "Quantum Theory of Optical Bistability with a Spatially Varying Field Mode in the Good Cavity Limit."

MIT Workshop on Squeezed States of Light
MIT
October 21, 1985

H.J. Kimble and J.L. Hall, "Intracavity Harmonic Conversion for the Generation of Squeezed States."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

1985 Fall Meeting of the
Division of Plasma Physics
San Diego, California
November 4-8, 1985

D.L. Brower, Ch.P. Ritz, W.A. Peebles, N.C. Luhmann, Jr. and E.J. Powers, "Asymmetries in the Distribution of Microturbulence on TEXT."

S.B. Kim, T.P. Kochanski and E.J. Powers, "Studies of Double Sawtooth Oscillations and Heat Pulse Propagation on TEXT."

S.J. Levinson, B. Rogers, E.J. Powers and Roger D. Bengtson, "Space-Time Statistics of the Magnetic Turbulence in PRETEXT."

T. Rhodes, D.L. Brower, Ch.P. Ritz, Roger D. Bengtson, N.C. Luhmann, Jr., W.A. Peebles and E.J. Powers, "Characterization of the TEXT Edge Turbulence with Probe and Far-Infrared Scattering."

Ch.P. Ritz, T. Rhodes, Roger D. Bengtson, E.J. Powers and A. Wootton, "Particle Transport in the Edge of TEXT."

Seminar
Institut National Polytechnique
Grenoble, France
November 8, 1985

T. Itoh, "Microstrip Discontinuity Problems."

Texas Section Meeting
of the American Physical Society
College Station, Texas
November 8-9, 1985

* R.J. Brecha, L.A. Orozco, A.T. Rosenberger and H. J. Kimble, "Transient Behavior of an Empty Optical Cavity."

* L.A. Orozco, K.A. Jones, A.T. Rosenberger and H.J. Kimble, "Instability Boundaries of the Single-Mode Instability of Optical Bistability."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Joint Fall Meeting
APS and AAPT
Texas A&M University
College Station, Texas
November 9, 1985

J.L. Erskine and M. Onellion, "Photoelectron Spectroscopy Studies of Surface Magnetism."

Seminar
Ecole Polytechnique Federal de Lausanne
Lausanne, Switzerland
November 11, 1985

T. Itoh, "Discontinuities in Microstrip Lines - Analysis by the Technique of Residues."

ITU Expert Lecture at Telebras
Campinas, Brazil
November 18-22, 1985

T. Itoh, "Millimeter Wave Transmission Lines."

T. Itoh, "Quasi-TEM Analysis of Microstrip Lines."

T. Itoh, "Full-Wave Analysis of Microstrip Lines."

T. Itoh, "Dielectric Waveguide Technology."

T. Itoh, "E-Plane Techniques."

32nd National Symposium of the
American Vacuum Society
Houston, Texas
November 18-22, 1985

J.L. Erskine, "High-Resolution Electron Energy Loss Spectroscopy: Explored Regions and the Frontier."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Invited Talk
First International Laser Science Conference
of the American Physical Society
November 20, 1985

J.W. Keto, "Observation of Curve Crossings in Radiative Collisions of Xenon Atoms."

Department Colloquium
Montana State University
Bozeman, Montana
November 22, 1985

J.L. Erskine, "The Renaissance in Research on Surface Magnetism."

38th Annual Meeting of
The Division of Fluid Dynamics
Tucson, Arizona
November 24-27, 1985

F.L. Jones, C.P. Ritz, R.W. Miksad and E.J. Powers, "The Influence of Nonlinear Interactions on Space/Time Statistics of Instability Waves."

Programs in Mathematical Sciences
University of Texas at Dallas
Dallas, Texas
November 26, 1985

* S.I. Marcus, "Recent Developments in Nonlinear Estimation Theory."

1985 Materials Research Society Meeting
Boston, Massachusetts
December 1985

R.M. Walser, "Origin of Anisotropy in Sequential RF Co-Sputtered Amorphous CoB and CoFeB Magnetic Thin Films."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Seminar
General Electric Company
Syracuse, New York
December 2, 1985

T. Itoh, "Millimeter Wave Research at The University of Texas."

Syracuse Chapter of IEEE
MTT/AP
Syracuse, New York
December 2, 1985

T. Itoh, "Millimeter Wave Transmission Lines."

International Meeting on
Optical Bistability
Tucson, Arizona
December 22-24, 1985

* H.J. Kimble, A.T. Rosenberger, L.A. Orozco and M.G. Raizen, "Optical Bistability with Two-State Atoms: Steady States and Dynamical Instabilities."

* A.T. Rosenberger, L.A. Orozco, R.J. Brecha and H.J. Kimble, "Influence of Cavity Properties on the Interpretation of Experimental Results in Bistability."

10th International Conference on
Infrared and Millimeter Waves
Lake Buena Vista, FL
December 9-13, 1985

T. Itoh, "Comparative Study of Millimeter-Wave Guided Structure."

P. Cheung, D. Fun, D. Miller, K-C C. Tzuang, D.P. Neikirk and T. Itoh, "Optically Controlled Coplanar Waveguide Millimeter Wave Phase Shifter."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

24th IEEE Conference on Decision and Control
Ft. Lauderdale, FL
December 10-13, 1985

* A. Arapostathis and S.I. Marcus, "Analysis of an Identification Algorithm Arising in the Adaptive Estimation of Markov Chains."

Malvern Symposium on Frontiers
in Quantum Optics
Malvern, England
December 16-20, 1985

H.J. Kimble, "The Dynamic Character of Quantum Electrodynamics in Quantum Optics."

IEC-ESA Workshop on
Millimeter Wave Radiometry
Madrid, Spain
December 17-19, 1985

T. Itoh, "Waveguide and Receivers in Space."

NSF Workshop on Future Research
Opportunities in Electromagnetics
Arlington, Texas
January 29-31, 1986

T. Itoh, "Applications of Electromagnetics to New Millimeter-Wave Components."

4th International Symposium on
Quantum Optics
Hamilton, New Zealand
February 10-15, 1986

H.J. Kimble and J.L. Hall, "Intracavity Frequency Doubling for the Generation of Squeezed States of Light."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Los Angeles Chapter of IEEE MTT
Los Angeles, California
February 18, 1986

T. Itoh, "Quasi-Optical Mixers and Components."

Electrical Engineering Seminar
University of California Santa Barbara
Santa Barbara, California
February 19, 1986

T. Itoh, "Applications of Electromagnetics to Millimeter-Wave Components."

Workshop on Particle
and Impurity Transport
University of Texas at Austin
Austin, Texas
February 26-28, 1986

Ch.P. Ritz, T. Rhodes, R. Bengtson, E. Powers and A. Wootton, "Fluctuation Induced Particle Transport in the Edge of TEXT."

Seminar
Department of Physics
University of Florida
Gainesville, Florida
March 4, 1986

J.L. Erskine, "The Renaissance in Research in Magnetism."

Electromagnetics Laboratory Seminar
University of Illinois
Urbana, Illinois
March 5, 1986

T. Itoh, "Applications of Electromagnetics to Millimeter-Wave Components."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

26th Anniversary Sanibel Symposia 1986
March 6-15, 1986

M. Fink, "Molecular Charge Densities and Their Moments as Seen by High Energy Electron Scattering."

Sixth Topical Conference on
High Temperature Plasma Diagnostics
Hilton Head, South Carolina
March 9-13, 1986

D.L. Brower, C.P. Ritz, W.A. Peebles, N.C. Luhmann, Jr. and E.J. Powers, "Resolving the Propagation Direction of Tokamak Microturbulence via Homodyne Spectroscopy."

J.Y. Hong, E.J. Powers and Ch.P. Ritz, "The Development of a Plasma Fluctuation Diagnostic Software Tool."

E.J. Powers, Roger D. Bengtson, D.L. Brower, D. Choi, G. Joyce, N.C. Luhmann, Jr. and W.A. Peebles, "Digital Complex Demodulation Applied to Interferometry."

MCC Workshop
Process and Device Simulation
Austin, TX
March 17-18, 1976

S.D. Lester and Ben G. Streetman, "III-V Compound Processing."

Energy Technology Conference
Washington, D.C.
March 17-19, 1986

J.Y. Hong, E.J. Powers, and Ch.P. Ritz, "The Development of a Plasma Fluctuation Diagnostic Tool."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Electromagnetics and
Solid State Seminar
University of California Berkeley
Berkeley, California
March 21, 1986

T. Itoh, "Application of Electromagnetics to Millimeter-Wave Components."

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Conference Proceedings

* A.M. Turner, Yu Jeng Chang and J.L. Erskine, "Bulk and Surface Electronic Structure of Iron," Bull. American Physical Soc. 27, 210, 1982.

R.L. Strong and J.L. Erskine, "Off-Specular EELS Studies of Adsorbates on Ni(100)," Bull. Am. Phys. Soc. 27, 372 , 1982.

D.G. Hull and J.L. Speyer, "Optimal Reentry and Plane-Change Trajectories," Proceedings of the AAS/AIAA Astrodynamic Conference, Lake Tahoe, Nevada, August 1982, accepted for publication in the Journal of Astronautical Sciences, vol. XXX, no. 2, April-June1982.

E.J. Powers, D.W. Choi, R.W. Miksad and F.J. Fischer, "Determination of Nonlinear Drift Force Quadratic Transfer Functions by Digital Cross Bispectral Analysis," Proceedings of the 14th Annual Offshore Technology Conference, Houston, Texas, pp. 759-767, May 3-6, 1982.

* J.K. Aggarwal and N. Huang, "A Comparison Between Time-Varying Signal Processing," Proceedings of International Conference on Acoustics, Speech and Signal Processing, Paris, France, May 3-5, 1982.

J.K. Aggarwal and A. Mitchie, "Detection of Edges Using Range Information," Proceedings of International Conference on Acoustics, Speech and Signal Processing, Paris, France, May 3-5, 1982.

J.K. Aggarwal and W.N. Martin, "Dynamic Scenes and Object Descriptions," Proceedings of International Conference on Acoustics, Speech and Signal Processing, Paris, France, May 3-5, 1982.

* J.K. Aggarwal, S. Park and N. Huang, "One-Dimensional Linear Shift-Variant Digital Filtering Using Two-Dimensional Techniques," Proceedings of the 1982 International Symposium on Circuits and Systems, Rome, Italy, May 10-12, 1982.

* T. Itoh, "Open Guided Wave Structures for Millimeter-Wave Integrated Circuits," IEEE International Symposium on Circuits and Systems, Rome, Italy, pp. 957-959, May 10-12, 1982.

* J.K. Aggarwal and N. Huang, "Synthesis and Implementation of Recursive Linear Shift-Variant Digital Filters", Proceedings of the 1982 International Symposium on Circuits and Systems, Rome, Italy, May 10-12, 1982.

* J.K. Aggarwal and N. Huang, "Time-Varying Digital Signal Processing: A Review," Proceedings of the 1982 International Symposium on Circuits and Systems, Rome, Italy, May 10-12, 1982.

J.L. Speyer and D.G. Hull, "Estimation Enhancement by Trajectory Modulation for Homing Missiles," Proceedings of the 1982 American Control Conference, Arlington, Virginia, June 1982.

J.K. Aggarwal, "Dynamic Scene Analysis," NATO Advanced Study Institute on Image Sequence Processing and Dynamic Scene Analysis, Braunlage, W. Germany, June 1982.

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

W.B. Zhou and T. Itoh, "Analysis of Trapped Image Guides Using Effective Dielectric Constants and Surface Impedances," 1982 IEEE MTT-S International Microwave Symposium, Dallas, Texas, pp. 295-297, June 14-18, 1982.

* Yu-Jeng Chang and J.L. Erskine, "LEED, Auger and Angle Resolved Photoelectron Emission Studies of Nickel Silicide Formation on Si(111) and Si(100)," Forty-Second Annual Conference on Physical Electronics, Atlanta, Georgia, June 14-16, 1982.

K.D. Stephan, N. Camilleri and T. Itoh, "Quasi-Optical Polarization-Duplexed Balanced Mixer," 1982 IEEE MTT-S International Microwave Symposium, Dallas, Texas, pp. 376-378, June 14-18, 1982.

Y.C. Shih, T. Itoh and L.Q. Bui, "Computer-Aided Design of Millimeter-Wave E-Plane Filters," 1982 IEEE MTT-S International Microwave Symposium, Dallas, Texas, pp. 471-473, June 14-18, 1982.

J.L. Speyer, W.M. Greenwell and D.G. Hull, "Adaptive Noise Estimation and Guidance for Homing Missiles," Proceedings of the AIAA Guidance and Control Conference, August 1982.

J.L. Speyer and J.E. White, "The Shiryayev Sequential Probability Ratio Test for Redundancy Management," Proceedings of the AIAA Guidance and Control Conference, August 1982.

R. Mawhorter, Peter Pulay and M. Fink, "Ab Initio Calculations for N_2 and SF_6 and Electron Scattering Factors," 2nd International Conference on Molecular Structure, Tubingen, August 16-18, 1982.

J.K. Aggarwal and J. Webb, "Shape and Correspondence," Proceedings of Workshop on Computer Vision, Representation and Control, Ridge, N.H., August 23-25, 1982.

B.M. Davies and J.L. Erskine, "Azimuthal Dependence of Impact Scattering in Electron Energy Loss Spectroscopy," Third International Conference on Vibrations at Surfaces," California, September 1-4, 1982.

R.L. Strong, B. Firey, F.W. deWette and J.L. Erskine, "Adsorbate Structure Modeling Based on Electron Energy Loss Spectroscopy and Lattice Dynamical Calculations," Third International Conference on Vibrations at Surfaces," California, September 1-4, 1982.

* J.-F. Miao and T. Itoh, "Hollow Image Guide for Millimeter-Wave Integrated Circuits," Proc. 12th European Microwave Conference, Helsinki, Finland, pp. 520-525, September 13-17, 1982.

* Y.C. Shih and T. Itoh, "Analysis of Printed Transmission Lines for Monolithic Integrated Circuits," Proc. 12th European Microwave Conference, Helsinki, Finland, pp. 301-305, September 13-17, 1982.

* J.Y. Hong and E.J. Powers, "Digital Signal Processing of Scattering Data from Nonlinear Targets," Proceedings of the International Conference - RADAR '82, London, U.K., pp. 266-270, October 18-20, 1982.

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

* Yu-Jeng Chang and J.L. Erskine, "First Phase Nickel Silicide Nucleation and Interface Structure at Si(100) Interfaces," Paper SSThA-17, 29th National Vacuum Symposium, American Vacuum Society, Baltimore, Md., November 16-19, 1982.

B. Hanzon and S.I. Marcus, "Riemannian Metrics on Spaces of Stable Linear Systems, with Applications to Identification," Proc. 21st IEEE Conf. on Decision and Control, Orlando, Florida, pp. 1119-1124, December 1982.

* M. Bordelon, R.M. Walser, M.F. Becker and Y.-K. Jhee, "Observation of Long-Lived Metastable Excitations in Multi-Pulse Laser Damage of Silicon," 14th ASTM Laser Damage Symposium, NBS Special Publications, Boulder, Co., 1983.

N. Bowering, T.D. Raymond, Chien-Yu Kuo and J.W. Keto, "Spectral Line Shapes from Two Photon Excitation of Xenon," 6th International Conference on Spectral Line Shapes, 1982 to be published in Spectral Lineshapes Vol. 2, K. Burnett, ed., Debruyer, Berlin, 1983.

* M.F. Becker, Y.-K. Jhee, M. Bordelon and R.M. Walser, "Charged Particle Exoemission from Silicon During Multi-Pulse Laser Induced Damage," 14th ASTM Laser Damage Symposium, NBS Publication, Boulder, Co., 1983.

H.J. Kimble, P.D. Drummond, D.E. Grant and A.T. Rosenberger, "Optical Bistability with Two-Level Atoms," in Laser Physics, eds. J.D. Harvery and D.F. Walls, Lecture Notes in Physics, vol. 182 (Springer Verlag, Berlin), 14-40, 1983.

* M.F. Becker, H.-K. Jhee, M. Bordelon and R.M. Walser, "Observations of an Incubation Period for Multi-Pulse Laser Induced Damage," Proc. of the Conference on Lasers and Electro-Optics, (CLEO), Optical Society of America, Washington, D.C., 1983.

D.J. Wolford, S. Modesti and B.G. Streetman, "Photoluminescence of Oxygen-Induced States in $GaAs_{1-x}P_x$," in Gallim Arsenide and Related Compounds, Bristol: Inst. Phys. Conf. Ser. 65, 501-508, 1983.

J.W. Keto, M. Bowering and T.D. Raymond, "Laser Enhanced Quenching of Xenon $6p[5/2]_2$, APS DEAP Meeting, Bull. Am. Phys. Soc. 28, 810, 1983.

S.W. Yun and T. Itoh, "Eigenvalue Analysis of Nonreciprocal Coupling Structures," Digest of the *International Conference on Infrared and Millimeter Waves," Marseille, France, p. 111*, February 14-18, 1983.

W.N. Martin, B. Gil and J.K. Aggarwal, "Volumetric Representation for Object Model Acquisition," Proceedings NASA Symposium on Computer Aided Geometry Modeling, NASA Conference Publication No. 2272, 87-94, April 1983.

T. Koh and E.J. Powers, "An Adaptive Nonlinear Digital Filter with Lattice Orthogonalization," Proceedings of the IEEE International Conference on Acoustics, Speech and Signal Processing, Boston, Massachusetts, vol. , pp. 37-40, April 1983.

T.D. Raymond, N. Bowering and J.W. Keto, "Lineshape Analysis of Some Two-Photon Absorption Profiles of Xenon, "DEAP Conf., Mul. Am. Hys. Soc. 28, 809, May 1983.

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

S. Banerjee and B.G. Streetman, "Experimental Studies of Laterally Seeded Recrystallized Polysilicon on Silicon Dioxide," Proc. of 1983 Univ./Gov./Ind. Microelectronics Symposium, 79-83, May 1983.

J. Courtney and J.K. Aggarwal, "Robot Guidance Using Computer Vision," Proceedings of IEEE Computer Society Conference on Trends and Applications, Gaithersburg, MD, 57-62, May 1983.

R.W. Miksad, D.W. Choi and E.J. Powers, "Application of Complex Demodulation Techniques to Low-Frequency Nonlinear Drift Forces in Irregular Seas," Proceedings of the 1983 Offshore Technology Conference, Paper OTC 4489, Houston, Texas, pp. 399-404, May 2-5, 1983.

J. Rivera and T. Itoh, "Analysis of an Electromagnetically Coupled Patch Antenna," 1983 International Symposium Digest Antennas and Propagation, vol. 1, 190-193, Houston, Texas May 23-26, 1983.

W.B. Zhou and T. Itoh, "Field Distributions in the Trapped Image Guide," 1983 International Microwave Symposium Digest, Boston, Massachusetts, 227-229, May 31-June 3, 1983.

Y. Fukuoka and T. Itoh, "Slow-Wave Coplanar Waveguide on Periodically Doped Semiconductor Substrates," 1983 International Microwave Symposium Digest, Boston, Massachusetts, 399-401, May 31-June 3, 1983.

Y.C. Shih and T. Itoh, "E-Plane Filters with Finite-Thickness Septa," 1983 International Microwave Symposium Digest, Boston, Massachusetts, 157-159, May 31-June 3, 1983.

L. Su, T. Itoh and J. Rivera, "Design of an Overlay Directional Coupler by a Full-Wave Analysis," 1983 International Microwave Symposium Digest, Boston, Massachsuetts, 427-429, May 31-June 3, 1983.

Y.C. Kim and J.K. Aggarwal, "Rectangular Coding of Binary Images," Proceedings of IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Washington, D.C., 108-113, June 1983.

C.H. Chien and J.K. Aggarwal, "A Normalized Quadtree Representation," Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Washington, D.C., 121-126, June 1983.

M. Magee and J.K. Aggarwal, "Intensity Guided Range Sensing Recognition of Three-Dimensional Objects," at the IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Washington, D.C., 550-552, June 1983.

P.Pulay, R. Mawhorter, D.A. Kohl and M. Fink, "The Elastic Electron Scattering Cross Section of SF_6 by ab initio Calculation," 13th International Conference on the Physics of Electronic and Atomic Collisions, Berlin, July 27-August 2, 1983.

M. Fink, R. Mawhorter and J.J. McClelland, "Elastic High Energy Electron Scattering as a Tool to Study Bonding and Correlation in Atoms and Molecules," 13th International Conference on the Physics of Electronic and Atomic Collisions, Berlin, July 27-August 2, 1983.

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

S. Yalamanchili and J.K. Aggarwal, "A Model for Parallel Image Processing," at the International Society for Optical Engineering Annual Symposium, San Diego, CA, August 1983.

T. Itoh and K.D. Stephan, "Quasi-Optical Planar Mixers for Millimeter-Wave Imaging Applications," Proceedings of the SPIE, San Diego, CA, August 22-26, 1983.

* Y. Fukuoka and T. Itoh, "Design Consideration of Uniform and Periodic Coplanar Schottky Variable Phase Shifter," 13th European Microwave Conference Proceedings, Nurnberg, West Germany, 278-282, September 5-8, 1983.

S.W. Yun and T. Itoh, "A Novel Distributed Millimeter-Wave Isolator," 13th European Microwave Conference Proceedings, Nurnberg, West Germany, 174-178, September 5-8, 1983.

T. Koh, E.J. Powers, R.W. Miksad and F.J. Fischer, "An Approach to Time Domain Modelling of Nonlinear Drift Oscillations in Random Seas," Proceedings of the BRASIL OFFSHORE '83 International Symposium on Offshore Engineering, Rio de Janeiro, Brazil, September 12-16, 1983.

* J.L. Erskine and Yu-Jeng Chang, "Selective Growth Diffusion Layers and the Schottky Barrier Height in Nickel Silicide-Silicon Interfaces," Proceedings of the Materials Research Society, Boston, Massachusetts, November 13-18, 1983 (invited talk).

* J.Y. Hong and E.J. Powers, "Detection of Weak Third Harmonic Backscatter from Nonlinear Metal Targets," Proceedings of the 16th Annual Electronics and Aerospace Conference and Exposition, Washington, D.C., pp. 169-175 (IEEE Catalog No. 83CH1967-9), September 19-21, 1983.

* O. Hernandez-Lerma and S.I. Marcus, "Priority Assignment in Queueing Systems with Unknown Parameters," Proc. IEEE Mexicon '83, Cuernavaca, Mexico, November 23-25, 1983.

K.D. Stephan and T. Itoh, "Isotropic Conversion Loss as a Measure of Quasi-Optical Mixer Efficiency," 8th International Conference on Infrared and Millimeter Waves Digest," Miami Beach, Florida, No. TH3.3, December 12-17, 1983.

* J.W. Grizzle and S.I. Marcus, "Symmetries in Nonlinear Control Systems," Proceedings 22nd IEEE Conf. on Decision and Control, San Antonio, Texas, 1384-1388, December 14-16, 1983.

H.J. Kimble, A.T. Rosenberger and P.D. Drummond, "Optical Bistability with Two-Level Atoms," Optical Bistability II, eds. C.M. Bowden, H.M. Gibbs and S.L. McCall (Plenum, New York), 1984.

* M.F. Becker, F.E. Domann, A.F. Stewart and A.H. Guenther, "Charge Emission and Related Precursor Events Associated with Laser Damage," 15th ASTM Laser Damage Symposium, NBS Special Publication, 1984.

* A.T. Rosenberger, L.A. Orozco, and H.J. Kimble, "Optical Bistability: Steady State and Transient Behavior," in Fluctuations and Sensitivity in Nonequilibrium Systems, eds. W. Horsthemke and C. Kondepudi, Springer-Verlag, pp. 62-69 (1984).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

* B.G. Streetman and C.W. Farley, "Simulation of Concentration-Dependent Diffusion During Annealing of Ion-Implanted Compound Semiconductors," Journal of Electrochemical Society 131, 468C (1984).

* Y.K. Jhee, M.F. Becker and R.M. Walser, "Subthreshold Picosecond Laser Damage in Silicon Associated with Charge Emission," Ultrafast Phenomena, C.V. Shank, et. al., (eds.) Springer-Verlag, New York (1984).

* S.H. Park and J.K. Aggarwal, "Recursive Synthesis of Linear Time-Variant Digital Filters," Proceedings of the 1984 International Symposium on Circuits and Systems, Montreal, Canada.

R.J. Mawhorter, M. Breitenstein, H. Meyer, A. Schweig and M. Fink, "Vibrational Effects on Electron-Molecule Scattering for Polyatomics in the First Born Approximation," 1984 Joint APS/AAPT Meeting, San Antonio, Texas, January 30-February 2, 1984.

DooWhan Choi, Jung-Hua Chang, R.O. Stearman and E.J. Powers, "Bispectral Identification of Nonlinear Mode Interactions," Proceedings of the 2nd International Modal Analysis Conference, vol. II, Orlando, Florida, pp. 602-609, February 7-9, 1984.

J.L. Erskine, "Surface Vibrational Spectroscopy," Proc. of the Conf. on High-Energy Excitations in Condensed Matter, Los Alamos, New Mexico, February 13-15, 1984.

Taiho Koh and E.J. Powers, "Efficient Maximum Entropy Spectral Estimation Using Non-Multiplication Methods," Proceedings of the IEEE International Conference on Acoustics, Speech and Signal Processing, San Diego, CA., March 19-21, 1984.

J.L. Erskine, "High Resolution Electron Energy Loss Study of Ordered Structures at Metal Surfaces," 20th Annual Symposium, The New Mexico Chapter of the American Vacuum Society, Albuquerque, NM (April 17-19, 1984).

* T. Itoh, "Recent Development of Dielectric Waveguide Technology," SPIE Technical Symposium East '84, Arlington, VA, paper no. 477-14, pp. 90-93 (April 29-May 4, 1984).

J.W. Keto, N. Bowering and M.R. Bruce, "Lifetimes and Collisional Deactivation Rates for Xenon $5p^5 6p$", DEAP Meeting of the Amer. Phys. Soc. (May 1984).

T. Koh, E.J. Powers, R.W. Miksad and F.J. Fischer, "Applications of Nonlinear Digital Filters to Modeling Low-Frequency, Nonlinear Drift Oscillations of Moored Vessels in Random Seas," Proceedings of the 16th Annual Offshore Technology Conference, Houston, Texas, pp. 309-314 (May 7-9, 1984).

S B. Kim, T.P. Kochanski, J. Snipes, and E.J. Powers, "Characteristics of Double Sawteeth and Sawtooth-like Oscillations on TEXT," Proceedings of the 1984 IEEE International Conference on Plasma Science, IEEE Catalog No. 84CH1958-8, p. 43, St. Louis, MO. (May 14-16, 1984).

S.J. Levinson, E.J. Powers, Ch.P. Ritz and Roger D. Bengtson, "Space-Time Statistics and Particle Transport," Proceedings of the 1984 IEEE International Conference on Plasma Science, IEEE Catalog No. 84CH1958-8, p. 118, St. Louis, MO. (May 14-16, 1984).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Ch.P. Ritz, S.J. Levinson, E.J. Powers and R.D. Bengtson, "Wave-Wave Coupling and Energy Flow in a Tokamak Edge Plasma," Proceedings of the 1984 IEEE Conference on Plasma Science, Catalog No. 84CH1958-8, p. 118, St. Louis, MO (May 14-16, 1984).

L.Q. Bui, D. Ball and T. Itoh, "Broadband Millimeter-Wave E-Plane Bandpass Filters", 1984 IEEE MTT-S International Microwave Symposium Digest, pp. 236-237, San Francisco, CA (May 30-June 1, 1984).

* R. Sorrentino and T. Itoh, "Transverse Resonance Analysis of Finline Discontinuities," 1984 IEEE MTT-S International Microwave Symposium Digest, pp. 414-416, San Francisco, CA (May 30-June 1, 1984).

* Y. Fukuoka and T. Itoh, "Field Analysis of Millimeter-Wave GaAs Double-Drift IMPATT Diode in the Travelling-Wave Mode," 1984 IEEE MTT-S International Microwave Symposium Digest, pp. 169-171, San Francisco, CA (May 30-June 1, 1984).

J.L. Erskine, "A Status Report on the Texas/Cornell/Sandia Synchrotron Radiation Beam Line Project," Annual Symposium on Thin Film Processes and Characterization Tools, Dallas, Texas (June 4-5, 1984).

J.L. Erskine, "Adsorbate Structure Determination Using Electron Energy Loss Spectroscopy and a Parameterized Lattice Slab Model," Forty-Fourth Annual Conference on Physical Electronics, Princeton, NJ (June 18-20, 1984).

Y. Fukuoka, Q. Zhang, D. Neikirk and T. Itoh, "Analysis of Multilayer Interconnection Lines for a High Speed Digital Integrated Circuit," International IEEE VLSI Multilevel Interconnection Conference Digest, pp. 246-251, New Orleans, LA (June 21-22, 1984).

* T. Itoh, "CAD-Oriented Field and Network Analysis - Overview," 1984 IEEE AP-S Symposium/National Radio Science Meeting Digest, p. 61, Boston, MA. (June 25-28, 1984).

Ch.P. Ritz, S.J. Levinson, E.J. Powers, Roger D. Bengtson and K.W. Gentle, "Turbulence and Energy Cascading in the Edge Plasma of the TEXT Tokamak," Proceedings of the 1984 International Conference on Plasma Physics, vol. 1, p. 73, Lausanne, Switzerland (June 27-July 3, 1984).

* S.I. Marcus and E.K. Westwood, "On Asymptotic Approximations for Some Nonlinear Filtering Problems," Proc. IFAC Triennial Congress, vol. VII, pp. 36-41, Budapest, Hungary (July 2-6, 1984).

R.W. Miksad, F.L. Jones and E.J. Powers, "Experiments on Nonlinear Interactions in Wake Transition," Proceedings of the International Union of Theoretical and Applied Mechanics Second Symposium on Laminar-Turbulent Transition, 11 pages, Novosibirsk, USSR (July 9-13, 1984).

* T. Itoh, "Survey of New Waveguides," XXIst General Assembly of URSI Digest, p. 294, Florence, Italy (August 28-September 5, 1984).

* T. Itoh, "Fin-Line and E-Plane Structures for Millimeter Wave Circuits," XXIst General Assembly of URSI Digest, p. 434, Florence, Italy (September 5, 1984).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

S.W. Yun and T. Itoh, "Nonreciprocal Wave Propagation in a Hollow Image Guide with a Ferrite Layer," 14th European Microwave Conference Proceedings, pp. 341-343, Liege, Belgium (September 10-13, 1984).

Q. Zhang, Y. Fukuoka, T. Itoh and L. Su, "Analysis of a Suspended Patch Antenna Excited by an Electromagnetically Coupled Inverted Microstrip Feed," 14th European Microwave Conference Proceedings, pp. 613-618, Liege, Belgium (September 10-13, 1984).

D.L. Brower, ..., E.J. Powers, et al., "Tokamaks - Description of Turbulence and the First Test of an Ergodic Magnetic Limiter," Proceedings of the International Atomic Energy Agency Tenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, London, UK (September 12-19, 1984).

* Jae Y. Hong and E.J. Powers, "Simulation Study of Detection of Nonlinear Metallic Targets in Sea Clutter-Type Noise," Proceedings of the 1984 International Symposium on Noise and Clutter Rejection in Radars and Imaging Sensors, Tokyo, Japan (October 22-24, 1984), North Holland, Amsterdam and New York.

* Y. Fukuoka and T. Itoh, "Travelling-Wave Characteristics of Millimeter-Wave IMPATT Diode," 9th International Conference on Infrared and Millimeter Waves Digest, p. 528, Takarazuka, Japan (October 22-26, 1984).

S.W. Yun and T. Itoh, "Bias Dependence of a Hollow Image Guide Type Isolator," 9th International Conference on Infrared and Millimeter Waves Digest, p. 529, Takarazuka, Japan (October 22-26, 1984).

J.L. Erskine, "Inelastic Electron Scattering from Surfaces, Explored Regions and Frontiers," Molecular Dynamics and Surface Chemistry Contractors Conference, p. 45, Albuquerque, New Mexico (October 23-25, 1984).

S. Balakrishnan and J.L. Speyer, "A Coordinate-Transformation Based Filter for Improved Target Tracking," Proceedings of the IEEE Decision and Control Conference (December 1984).

J.L. Speyer and C. Chuang, "Periodic Optimal Hypersonic Scramjet Cruise," Proceedings of the IEEE Decision and Control Conference (December 1984).

R.L. Strong and J.L. Erskine, "Investigation of Underlayer Formation by Oxygen on Al(111) and Ti(001) by High Resolution Electron Energy Loss Spectroscopy and Lattice Dynamical Calculations," 31st National Symposium of the American Vacuum Soc., Reno, Nevada (December 4-7, 1984).

* J.W. Grizzle and S.I. Marcus, "A Jacobi-Liouville Theorem for Hamiltonian Control Systems," Proc. of the 23rd IEEE Conf. on Decision and Control, pp. 1598-1602, Las Vegas, Nevada (December 12-14, 1984).

N. Bowering, T.D. Raymond and J.W. Keto, "Quench Enhancement During Half-Collisions of Laser Excited Xenon Atoms," in Spectral Line Shapes," Vol. 2, Proc. of the 7th International Conference, New York (1985).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

N. Bowering and J.W. Keto, "Selective Quenching During Half-Collisions of Laser Excited Xenon Atoms," in Proc. of the Int. Conf. on Lasers '84, W.C. Stalley edt., (STS Press) (1985).

* M.F. Becker, J.A. Kardach, A.F. Stewart and A.H. Guenther, "Surface Potential as a Laser Damage Diagnostic," 16th ASTM Laser Damage Symposium, NBS Special Publication, Boulder, CO (1985).

* M.F. Becker, Y.-K. Jhee and R.M. Walser, "Charge Emission and Accumulation in Multiple-Pulse Damage of Silicon," 16th ASTM Laser Damage Symposium, NBS Special Publication, Boulder, CO (1985).

* M.F. Becker, J.A. Kardach, A.F. Stewart and A.H. Guenther, "Surface Potential as a Laser Damage Diagnostic," Proceedings of the Southwest Conference on Optics, SPIE, Bellingham, WA (1985).

J.H. Chang, R.O. Stearman, D. Choi and E.J. Powers, "Identification of Aeroelastic Phenomenon Employing Bispectral Analysis Techniques," Proceedings of the 3rd International Modal Analysis Conference, Orlando, Florida, pp. 956-964 (January 28-31, 1985).

B.G. Streetman, "Materials Properties of GaAs and Related Compounds," Bulletin of American Physical Society 30, 450 (1985).

M. Onellion and J.L. Erskine, "Experimental Observation of Adsorbate Orbital Splitting at Single Crystal Surfaces," Bull. Am. Phys. Soc. 30, 516 (1985).

H.J. Kimble and J.L. Hall, "Investigation of Intracavity Harmonic Conversion for the Generation of Squeezed States," Proceedings of the MIT Endicott House Workshop on Squeezed States of Light, eds. J.H. Shapiro and P. Kumar.

* A.T. Rosenberger, L.A. Orozco and H.J. Kimble, "Intrinsic Dynamical Instability in Optical Bistability with Two-Level Atoms," Proceedings of the International Meeting on Instabilities and Dynamics of Lasers and Nonlinear Optical Systems, eds. R.W. Boyd, M.G. Raymer and L.M. Narducci (Cambridge University Press, Cambridge, 1985), 325.

M.R. Bruce, N. Bowering and J.W. Keto, "Collisional Deactivation of Two-Photon Laser Excited Xenon $5p^5 6p$," Texas Sectional Meeting of the Amer. Phys. Soc. (March 1985).

J. Hartley and M. Fink, "A New Gas Phase Raman Spectrometer," Proceedings of the Texas Section of the American Physical Society, Rice University, Houston, Texas (March 8-9, 1985).

J.D. Coffman and M. Fink, "Shadow Scattering/Does It Exist or Not?", Proceedings of the Texas Section of the American Physical Society, Rice University, Houston, Texas (March 8-9, 1985).

R.J. Mawhorter, J. Hartley and M. Fink, "The Structure of Alkali Chloride Dimer Clusters," Proceedings of the Texas Section of the American Physical Society, Rice University, Houston, Texas (March 8-9, 1985).

T. Itoh, "Survey of Millimeter-Wave Guiding Structures," SPIE Technical Symposium East '85, Arlington, Virginia (April 8-12, 1985).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

Y.C. Shih, L.Q. Bui and T. Itoh, "Millimeter-Wave Diplexers with Printed Circuit Elements," 1985 IEEE MTT-S International Microwave Symposium Digest, pp. 567-569 (June 4-6, 1985).

Y.C. Shih, T.S. Chu and T. Itoh, "Comparative Study of Mode Matching Formulations for Microstrip Discontinuity Problems," 1985 IEEE MTT-S International Microwave Symposium Digest, pp. 435-438 (June 4-6, 1985).

M.A. Thompson, M. Onellion and J.L. Erskine, "Electronic Structure of Epitaxial Monolayer Magnetic Films," 45th Annual Conference on Physical Electronics, Milwaukee, Wisconsin (June 17-19, 1985).

C. Tzuang and T. Itoh, "Analysis of Coplanar Waveguide with Finite Conductor Thickness and a Substrate with a Lossy Layer," 1985 North American Radio Science/IEEE AP-S Symposium Digest, Vancouver, Canada, p. 179 (June 17-21, 1985).

C-K C. Tzuang and T. Itoh, "Pulse Transmission in an Interconnection Line on a Semiconductor Substrate with a Lossy Layer," 1985 IEEE VLSI Multilevel Interconnection Conference Proceedings, pp. 424-430 (June 24-26, 1985).

T. Itoh, "New Waveguide Structures for Microwave and Millimeter Circuits," 1985 International Symposium on Microwave Technology in Industrial Development - Brazil, Campinas, Brazil, pp. 205-208 (July 22-25, 1985).

D. Coffman, M. Fink, and H. Wellenstein, "Elastic Small Single Electron Scattering by He, Ne and Ar at 35 KeV," Proceedings of the 14th Int. Conference on the Physics of Electronic and Atomic Collisions, Stanford University, Palo Alto, California, (July 24-30, 1985).

L.H. Breaux and J.L. Erskine, "Design Optimization of a Six-Meter Toroidal Grating Monochromator," International Conference on X-ray and VUV Instrumentation, Stanford, California (July 29-August 2, 1985).

N. Camilleri and T. Itoh, "Frequency Multiplying Active Slot Array," Proc. of 1985 International Symposium on Antennas and Propagation, pp. 739-742, Kyoto, Japan (August 20-22, 1985).

T. Itoh, "Comparison of Transmission Lines," International Symposium on Antennas and EM Theory, Beijing, China (August 24-26, 1985).

C-K C. Tzuang and T. Itoh, "Pulse Transmission on a Slow-Wave MIS and Schottky Coplanar Waveguide with Finite Conductor Thickness," 15th European Microwave Conference, pp. 225-230, Paris, France (September 9-12, 1985).

T. S. Chu and T. Itoh, "Analysis of Offset Microstrip Step Discontinuity by the Generalized Scattering Matrix Techniques," 15th European Microwave Conference, pp. 814-819, Paris, France (September 9-12, 1985).

T. Itoh, "An Overview on Numerical Techniques for Modeling Miniaturized Passive Components," 15th European Microwave Conference, pp. 1059-1063, Paris, France (September 9-12, 1985).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

N. Camilleri and T. Itoh, "Frequency Multiplying Power-Combining Slot Array," 15th European Microwave Conference, pp. 194-197, Paris, France (September 9-12, 1985).

* N.U. Song and T. Itoh, "Accurate Simulation of MESFET by Finite Element Method Including Energy Transport and Substrate Effects," 15th European Microwave Conference, pp. 245-250, Paris, France (September 9-12, 1985).

J.L. Erskine, "New Instrumentation for Studying EELS Impact Scattering Cross Section," Vibrations at Surfaces IV, Bowness-on-Windermere, England (September 15-19, 1985).

K.I. Kim, E.J. Powers, Ch.P. Ritz and R.W. Miksad, "Modeling of Nonlinear Systems in Offshore Engineering for Non-Gaussian Inputs," Proceedings of the International Symposium on Offshore Engineering, BRASIL OFFSHORE '85, Rio de Janeiro, Brazil, September 16-20, 1985, Pentech Press, London (in press).

J.L. Erskine, "High Resolution Electron Energy Loss Spectroscopy of Surface and Subsurface Adsorbate Complexes," AFOSR Conference on Chemical Dynamics, Dayton, Ohio (November 4-6, 1985).

J.P. Woods and J.L. Erskine, "Surface Vibrational Resonances and the Order-Disorder Transformation at the W(100) Surface," 32nd National Symposium of the American Vacuum Society, Houston, Texas (November 18-22, 1985).

Ch.P. Ritz, E.J. Powers, D.L. Brower, T. Rhodes, R.D. Bengtson, N.C. Luhmann and W.A. Peebles, "Digital Bispectral Analysis - A Diagnostic for Fusion Research," Proceedings of the 11th Symposium on Fusion Engineering, Austin, Texas (November 18-22, 1985).

D.L. Brower, N.C. Luhmann, Jr., W.A. Peebles, Ch.P. Ritz and E.J. Powers, "The Application of Homodyne Spectroscopy to the Study of Low-Frequency Microturbulence in the TEXT Tokamak," Proceedings of the 10th International Conference on Infrared and Millimeter Waves , Orlando, Florida (December 1985).

R.M. Walser and D.Y. Kim, "Origin of Magnetic Anisotropy in Sequential RF Co-Sputtered Amorphous Thin Films," Proc. 1985 Materials Research Soc. Meeting, Boston, Massachusetts (December 1985).

R.M. Walser and S. Park, "Ion Implantation In Polymeric Carbon Thin Films," Proc. 1985 Materials Research Society Meeting, Boston, Massachusetts (December 1985).

T. Itoh, "Comparative Study of Millimeter-Wave Guided Structures," 10th International Conference on Infrared and Millimeter Waves Digest, pp. 232-233, Lake Buena Vista, Florida (December 9-13, 1985).

P. Cheung, D. Fun, D. Miller, C-K C. Tzuang, D.P. Neikirk and T. Itoh, "Optically Controlled Coplanar Waveguide Millimeter Wave Phase Shifter," 10th International Conference on Infrared and Millimeter Waves Digest, pp. 303-304, Lake Buena Vista, Florida (December 9-13, 1985).

* A. Arapostathis and S. I. Marcus, "Analysis of an Identification Algorithm Arising in the Adaptive Estimation of Markov Chains," Proc. 24th IEEE Conf. on Decision and Control, Ft. Lauderdale, Fl., pp. 208-211 (December 10-13, 1985).

PUBLICATIONS, TECHNICAL PRESENTATIONS, LECTURES AND REPORTS

* M.F. Becker, Yong Jee and R.M. Walser, "N-on-1 Damage Testing of Single Crystal Metal Surfaces at 1.06 Microns," 17th ASTM Laser Damage Symposium, NBS Special Publication, Boulder, Co. (1986).

* M.F. Becker, A.L. Huang and R.M. Walser, "Laser Induced Ion Emission and Damage of GaAs at 1.06 Microns," 17th ASTM Laser Damage Sympoisum, NBS Special Publication, Boulder, Co. (1986).

H. Li, M. Robrecht, B.P. Tonner, M. Onellion and J.L. Erskine, "Photoelectron Spectroscopy of Monolayer Melting," Bull. Am. Phys. Soc. 31, 537 (1986).

S. Varma, K. Kim, P.A. Dowben, M. Onellion and J.L. Erskine, "Structure Induced Electronic States for Hg Overlayers on Ag(100)," Bull. Am. Phys. Soc. 31, 675 (1986).

M. Onellion, M.A. Thompson and J.L. Erskine, "Structural and Electronic Properties of Epitaxial Fe Layers on Cu(100)," Bull. Am. Phys. Soc. 31, 674 (1986).

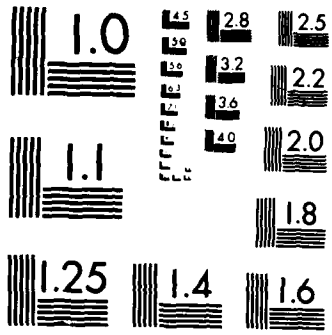
Y. Li, J.L. Erskine and A. Diebold, "High Resolution Electron Energy Loss Spectroscopy Studies of the Interaction of H with Nb(100)," Bull. Am. Phys. Soc. 31, 272 (1986).

M.A. Thompson, M. Onellion and J.L. Erskine, "Electronic Structure and Magnetic Exchange Splitting of p(1x1) Ni Layers on Ag(100)," Bull. Am. Phys. Soc. 31, 675 (1986).

I. INFORMATION ELECTRONICS

AD-A174 318 JOINT SERVICES ELECTRONICS PROGRAM(U) TEXAS UNIV AT AUSTIN ELECTRONICS RESEARCH CENTER E J POWERS 30 SEP 86 TR-33 AFOSR-TR-86-0622 F49620-82-C-0033 2/3

UNCLASSIFIED F/G 20/12 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE82-1 NONLINEAR DETECTION AND ESTIMATION

Principal Investigators: Professor S.I. Marcus (471-3265)
Professor J.L. Speyer (471-1356)

Graduate Students: Jessy Grizzle, Kie-Bum Eom, Taek Song, John White, and Yoon-Hwa Choi

A. OBJECTIVES AND PROGRESS: This research unit is concerned with several aspects of the statistical properties of nonlinear systems. Specifically, the design and analysis of optimal and suboptimal nonlinear estimators, the problem of detecting and identifying failure modes in fault tolerant systems, and the decentralized estimation and control of multiaccess broadcast networks have been investigated.

1. Nonlinear Estimation

The nonlinear estimation problem involves the estimation of a signal or state process $x=\{x_t\}$ which cannot be observed directly. Information concerning x is obtained from observations of a related process $y=\{y_t\}$ (the observation process). The objective is the computation, for each t, of least squares estimates of functions of the signal x_t given the observation history $\{y_s, 0\leq s\leq t\}$ -- i.e., the computation of conditional expectations of the form $E[\phi(x_t)|y_s, 0\leq s\leq t]$, or perhaps even the computation of the entire conditional distribution of x_t given the observation history. These state estimates are generated by passing the measurements through a nonlinear system. Optimal state estimators have been derived for very general classes of nonlinear systems, but these are in general infinite dimensional. That is, it is usually not possible to recursively generate the conditional mean of the system state given the past observations. The basic objective here is the design, analysis, and implementation of high-performance optimal and suboptimal estimators which operate recursively in real time. There are few known cases aside from the linear (Kalman) filtering problem in which the conditional mean (the minimum variance estimate) of the system state given the past observations can be computed recursively in real time with a filter of fixed finite dimension. However, in [1] we have proved that for certain classes of discrete-time and continuous-time systems, described either by a finite Volterra series or by certain types of state-affine realizations, the minimum variance estimator is recursive and of fixed finite dimension.

Benes [2] has recently given an explicit solution for the conditional density for a class of nonlinear filtering problems with nonlinear state equations and linear observations. In [3] we have extended his results and our results of [1] in the following way. In [1] we found finite dimensional filters for the conditional moments for problems involving linear systems feeding forward into nonlinear

systems; in [3], we have studied problems in which systems of Benes type feed forward into nonlinear systems of the type considered in [1]. We have derived recursive filtering equations for the conditional moments of the Benes' problem and used these to derive new finite dimensional optimal filters for the class of nonlinear systems described above.

By means of an algebraic approach to nonlinear estimation, we have in [4] shown that for some problems, including a linear system with cubic observations of the state plus white noise, no nontrivial statistics of the form $E[\phi(x_t)\ y_s, 0\leq s\leq t]$ can be computed exactly with recursive finite dimensional filters; this is the first such result in the literature. However, these results do not address the issue of non-exact but high-performance suboptimal filters; this issue is addressed in [5] and [6]. In these papers, we have considered linear estimation problems with small nonlinear perturbations. A typical such system is of the form

$$\begin{aligned} dx_t &= ax_t dt + dw_t, \\ dz_t^{\varepsilon} &= [x_t + \varepsilon h(x_t)]dt + dv_t, \end{aligned} \tag{1}$$

where h is a polynomial function. In general, such problems do not possess finite dimensional filters for the conditional statistics, and approximate filters are sought. The approach is to expand the unnormalized conditional density $\rho(t,x)$ in powers of ε

$$\rho^{\varepsilon}(t,x) = \rho_0(t,x) + \varepsilon\rho_1(t,x) + \varepsilon^2\rho_2(t,x) + \ldots. \tag{2}$$

In order for this expansion to result in a useful suboptimal filter, we first showed that the error

$$\rho^{\varepsilon}(t,x) - \sum_{i=0}^{n} \varepsilon^i \rho_i(t,x)$$

is of the order of ε^{n+1} for ε small; i.e., (2) is a true asymptotic expansion. Then the same result was shown to be true for approximations of the normalized conditional density and conditional means.

Even if (2) is an asymptotic expansion, it is not of much use in nonlinear estimation unless each term in (2) can be computed with a finite dimensional recursive filter. It is in this phase of the investigation that Lie algebraic methods are useful, because they can provide guidance into the computation of such filters. In [5] and [6], it is shown that the individual terms in (2), and hence the conditional mean, can indeed be computed with finite dimensional filters. The mean-square errors of the resulting filters in the case

of the zero-th and first order approximations were compared via Monte-Carlo simulation to the extended Kalman filter (EKF) and the Bobrovsky-Zakai lower bound [6],[10]. The behavior found in all the simulations was the following: the zero-th order filter performs worse than the EKF, but the first order filter performs better than the EKF (which is the most widely used suboptimal filter).

A different approach to nonlinear estimation problems has been pursued in [7]; the problems in this paper have the property that in spherical coordinates the measurements are linear and Gaussian but the state dynamics are nonlinear, whereas in rectangular coordinates the state dynamics are linear and the observations are nonlinear. In the noiseless case a nonlinear transformation produces in rectangular coordinates a pseudo-linear measurement consisting of a matrix function of the original measurements multiplying the state vector. In this case, a linear observer structure has been developed through the minimization of an integral quadratic form. The resulting observer, called the pseudo-measurement observer (PMO), is shown to have the property that the estimation errors converge to zero. The PMO performance has been compared to that of the EKF used as an observer. It is shown via simulation that the EKF performance degrades and even diverges with large initial state estimation error, whereas the PMO is guaranteed to be globally stable. In a noisy environment, the structures of the observers are retained, and the observers become filters. The resulting filters are the PMF and the usual EKF; in addition, a new filter, the modified gain extended Kalman filter (MGEKF) is formulated. A simulation study in the noisy environment shows the PMF is biased while the MGEKF shows excellent filtering performance under various conditions. The EKF still shows erratic behavior except for the case where initial errors are small. The bias of the PMF for the system with both process noise and measurement noise is analyzed and upper and lower bounds for the bias and actual covariance are obtained.

In related work, a survey of recent methods in nonlinear estimation was presented in [8]; emphasis was placed on the use of the unnormalized version of the conditional density.

The research in this area is continuing and has been complemented by Grant AFOSR-79-0025 from the Air Force Office of Scientific Research and Grant ECS-8022033 from the National Science Foundation.

2. Fault Detection and Identification

An essential aspect in the design of fault tolerant digital flight control systems is the design of failure detection and redundancy management systems. Design considerations are concerned with the trade-off between the cost of hardware redundancy and the complexity and robustness of the software for analytic redundancy. In

analytic redundancy dissimilar instruments are combined through analytic relations to achieve redundancy. Since these relations contain system parameters, additional uncertainty may be introduced beyond that present in the sensors. The processing of the outputs of these relations to produce adequate fault detection and isolation performances may require complex decision and estimation software. A decision rule, the Shiryayev sequential probability ratio test (SPRT), is used in [9] to detect failures between similar instruments, as well as between dissimilar instruments through analytic redundancy. Unlike the Wald SPRT, which tests for the presence of failure or no failure in the entire data sequence, the Shiryayev SPRT detects the occurrence of a fault in the data sequence in minimum time if certain conditions are met. The performance of the Shiryayev SPRT in detecting a failure between two rate gyros as compared to standard fixed interval schemes is presented, as is the performance for a single accelerometer failure using translational kinematic equations to form a parity relation for analytic redundancy.

The research in this area is continuing and is complemented by a grant from General Dynamics, Fort Worth Division.

3. Decentralized Estimation and Control of Multiaccess Broadcast Networks

Our earlier methodology for decentralized stochastic control problems [11] is applied in [12] to multiaccess broadcast communication problems. The objective of multiaccess broadcast communication is the efficient sharing of a single communication medium among many users, while giving each access to the full bandwidth of the channel. In the so-called Aloha-type schemes, a terminal sends a new message immediately upon receipt; if two terminals send simultaneously, a "collision" occurs, and each terminal retransmits after a random delay. When terminals are able to gather some information about the state of the network, feedback control policies (centralized, decentralized, or adaptive) may be implemented to improve performance. A number of such control schemes have been proposed in the literature. On the other hand, this problem fits precisely into the decentralized control framework discussed in [11]. In [12] we have applied the optimal decentralized control policies derived in [11] to problems of this type. It is shown that the optimal policy is nonrandomized, stationary, and extreme. Optional policies can be calculated via the policy iteration algorithm, and the complexity of the algorithm is reduced by using equivalence relations on the state space. For many-user systems, the computations are infeasible, so a class of suboptimal policies (conjectured to be optimal) is proposed and shown to perform well. We compared the results with those of previously proposed algorithms. Tradeoffs between the information available to each terminal and the value of

the performance index were examined in detail.

B. REFERENCES

1. S.I. Marcus, S.K. Mitter, and D. Ocone, "Finite-Dimensional Nonlinear Estimation for a Class of Systems in Continuous and Discrete Time," in Analysis and Optimization of Stochastic Systems, O.L.R. Jacobs, et. al. (eds), Academic Press, New York, pp. 387-406, (1980).

2. V.E. Benes, "Exact Finite Dimensional Filters for Certain Diffusions with Nonlinear Drift," Stochastics, vol. 5, pp. 65-92, (1981).

3. D.L. Ocone, J.S. Baras, and S.I. Marcus, "Explicit Filters for Diffusions with Certain Nonlinear Drifts," Stochastics, vol. 8, pp. 1-16, (1982).

4. M. Hazewinkel and S.I. Marcus, "On Lie Algebras and Finite Dimensional Filters," Stochastics, vol. 7, pp. 29-62 (1982).

5. S.I. Marcus, C.-H. Liu, and G.L. Blankenship, "Lie Algebraic and Approximation Methods for Some Nonlinear Filtering Problems," in Advances in Filtering and Optimization Stochastic Control, W.H. Fleming and L.G. Gorostiza (eds.), Springer-Verlag, New York, pp. 225-238 (1982).

6. G.L. Blankenship, C.-H. Liu, and S.I. Marcus, "Asymptotic Expansions and Lie Algebras for Some Nonlinear Filtering Problems," IEEE Trans. Automatic Control, vol. AC-28, May 1983.

7. T.L. Song and J.L. Speyer, "A Stochastic Analysis of the Pseudo-measurement Filter and a Modified Gain Extended Kalman Filter," submitted to IEEE Trans. Automatic Control.

8. S.I. Marcus, "An Introduction to Nonlinear Filtering and Functional Integration," Proc. 20th IEEE Conf. on Decision and Control, San Diego, California, pp. 573-574, (December 16-18, 1981).

9. J.L. Speyer and J.E. White, "The Shiryayev Sequential Probability Ratio Test for Redundancy Management," Proc. 1982 AIAA Guidance and Control Conf., San Diego.

10. Y.-H. Choi, Performance of Suboptimal Estimators for Weakly Nonlinear Estimation Problems, M.S. Thesis, Dept. of Electrical Engineering, University of Texas at Austin, May 1982.

11. K. Hsu and S.I. Marcus, "Decentralized Control of Finite State Markov Processes," IEEE Trans. Automatic Control, vol. AC-27, pp. 426-431, (April 1982).

12. J.W. Grizzle, K. Hsu and S.I. Marcus, "A Decentralized Control Strategy for Multiaccess Broadcast Networks," Large Scale Systems, vol. 3, pp. 75-88 (May 1982).

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE82-2 ELECTRONIC MULTI-DIMENSIONAL SIGNAL PROCESSING

Principal Investigator: Professor J. K. Aggarwal (471-1369)

Graduate Students: S. Park and T. Leou

A. PROGRESS: The broad objective of the research unit is to develop new and efficient techniques for the processing of multi-dimensional signals. The current research focuses on the analysis, synthesis and implementation of linear time-variant (LTV) digital filters in both time and frequency domains. Significant progress has been achieved in the analysis, synthesis and implementation of LTV digital filters, as described in the following.

As reported earlier in [1], we have developed a framework for the analysis and synthesis of time-variant one-dimensional digital filters, and investigated the interrelationships among the three characterizations of linear time-variant digital filters; namely the impulse response, the generalized transfer function and the time-variant difference equation. Also as documented in [2], we have proposed an efficient technique to determine the generalized frequency characteristics of LTV digital filters from the short-time Fourier transform properties. The developed technique allows spectral modification properties of the filter to vary with the changing frequency content of the desired sequence. The overall advantage is that the resultant bandwidth of the LTV digital filter is much narrower than that of a linear time-invariant digital filter.

Complementing the above results, we have recently published the paper [3] where problems associated with the synthesis and implementation of recursive time-variant filters are investigated. In this work, we describe two techniques to approximate a given impulse response as a degenerate sequence that is realizable as a recursive difference equation. Both techniques use a least-squares error criterion to minimize the difference between the given and the approximated impulse responses. Numerical examples illustrating and comparing results of these techniques are also included in [3]. In addition we present several recursive structures for the implementation of both causal and non-causal degenerate impulse responses.

The above publications [1,2,3] present a comprehensive set of results for time-variant digital filters. In particular, they present fundamental results on the nature of time-variant digital filters; they discuss the properties of the responses in terms of short-time Fourier transform; and they document implementation procedures and structures for the filters.

In addition, we have investigated the implementation of one-dimensional (1D) linear time-variant digital filter as two-dimensional (2D) linear time-invariant (LTI) digital filter. These results have

been accepted for publication in Circuits and Systems [4]. We have shown in this paper that by mapping 1D input/output sequences into 2D sequences, we may approximately implement the 1D LTV filter as 2D LTI filter. The advantages and disadvantages of this implementation technique are also discussed.

Continuing our work on the frequency domain, the filter performance and computation requirements of the technique are compared with those of conventional time domain criterion. Our result demonstrates that the frequency domain technique is efficient in computation time but yields suboptimal filter, as presented in [5].

The above work is being continued. In particular, we are investigating the recursive realization of rational generalized transfer function as linear time-variant difference equation. The purpose is to derive a system of overdetermined set of linear equations relating coefficients of the transfer function and the difference equation. Hopefuly, the minimax solution of the overdetermined system by numerical method will yield a solution to provide an approximate realization. Several other interesting avenues of research are being pursued as outlined in the renewal proposal for period April 1, 1983-March 31, 1986. In the past year, the following presentations were made [5,6,7,8].

B. REFERENCES

1. N.C. Huang and J.K. Aggarwal, "On Linear Shift-Variant Digital Filters," IEEE Transactions on Circuits and Systems, CAS-27, no. 8, pp. 672-679 (August 1980).

2. N.C. Huang and J.K. Aggarwal, "Frequency Domain Consideration of LSV Digital Filters," IEEE Transactions on Circuits and Systems, CAS-28, no. 4, pp. 279-287 (April 1981).

3. N.C. Huang and J.K. Aggarwal, "Synthesis and Implementation of Recursive Linear Shift-Variant Digital Filters," IEEE Transactions on Circuits and Systems, CAS-30, no. 1, pp. 29-36, (January 1983).

4. S.H. Park, N.C. Huang and J.K. Aggarwal, "One-Dimensional Linear Shift-Variant Digital Filtering Using Two-Dimensonal Techniques," IEEE Transactions on Circuits and Systems, CAS-30, no. 3, pp. 172-176 (March 1983).

5. N.C. Huang and J.K. Aggarwal, "A Comparison Between Time and Frequency Domain Techniques for Time-Varying Signal Processing," IEEE International Conference on Acoustics, Speech and Signal

Processing, Paris, France, pp. 1341-1344 (May 3-5, 1982).

6. N.C Huang and J.K. Aggarwal, "Time-Varying Digital Signal Processing: A Review," IEEE International Symposium on Circuits and Systems, Rome, Italy, pp. 659-662 (May 10-12, 1982).

7. N.C. Huang and J.K. Aggarwal, "Synthesis and Implementation of Recursive Linear Shift-Variant Digital Filters," International Symposium on Circuits and Systems, Rome, Italy, pp. 788-791, (May 10-12, 1982).

8. S.H. Park, N.C. Huang and J.K. Aggarwal, "One-Dimensional Linear Shift-Variant Digital Filtering Using Two-Dimensional Techniques," IEEE International Symposium on Circuits and Systems, Rome, Italy, pp. 89-92 (May 10-12, 1982).

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE85-1 NONLINEAR DETECTION AND ESTIMATION

Principal Investigators: Professor S.I. Marcus (471-3265)
Professor J.L. Speyer (471-4258)

Graduate Students: Jessy Grizzle, Hong Gi Lee, Bih-Wan Lin, Taek Song, Evan Westwood and John White

A. RESEARCH OBJECTIVES: Several problems in the area of nonlinear estimation and detection are considered in this research unit. The area of nonlinear state estimation is concerned with the extraction of information about the state of a nonlinear stochastic dynamical system from nonlinear noisy measurements. The state cannot be observed directly; instead, we have access to an observation or measurement process which is contaminated by noise and which is related to the state via a stochastic model. The objective is the calculation of either the entire conditional distribution of the state given the past measurements or some particular estimate, such as the conditional mean (which is the minimum mean square error estimator). In addition, it is desired that the state estimate or conditional distribution be calculated recursively; *that is, the observations are being received continuously, and it is required that the estimate be* continuously revised to take into account the new data. Thus the state estimate is generated by passing the measurements through a nonlinear system (also called a filter or estimator). The basic objective here is a study of the design, analysis, and implementation of high-performance optimal and suboptimal estimators which operate recursively in real time.

Failure detection and identification in dynamical systems are important parts of overall system design. These are especially critical in the design of highly accurate estimation and control systems, given the possibility of abrupt but infrequent system changes. The task of the failure detection monitor is the detection that a failure has occurred, the identification of the faulty hardware, and the estimation of the extent of the failure. Our objective is to develop and analyze implementable fault detection and identification schemes. A related approach to systems with unknown or changing parameters is that of adaptive estimation and control. Our objective in adaptive estimation and control is the study of recursive adaptive algorithms which simultaneously identify the unknown parameters and estimate the state or control the system.

B. PROGRESS: In a Lie algebraic approach to nonlinear filtering [1]-[6], we have studied the (Zakai) stochastic partial differential equation for an unnormalized conditional density $\rho(t,x)$ of the state x_t given the past observations $\{z_s, 0 \leq s \leq t\}$:

$$d\rho(t,x) = L_0\rho(t,x)dt + L_1\rho(t,x)dz_t, \tag{1}$$

where L_0 and L_1 are certain differential operators. The major idea of the approach is that, if L is the Lie algebra generated by $L_0 - 1/2\, L_1^2$ and L_1, and if a recursive finite dimensional estimator for some statistic of the state exists, then there should be a Lie algebra homomorphism from L to the Lie algebra F of the finite dimensional filter. F is a Lie algebra of vector fields on a finite

dimensional manifold, so the representability of L or quotients of L by vector fields on a finite dimensional manifold is closely related to the existence of finite dimensional recursive filters.

The structure and representability properties of L are analyzed for several interesting classes of problems in [1]. It is shown that, for certain nonlinear filtering problems, L is given by the Weyl algebra $W_n = R < x_1,...,x_n, \partial x_1,...,\partial x_n >$ of all polynomial differential operators. These problems include the cubic sensor problem (linear system with cubic observations) and some examples of mixed linear-bilinear type. It is proved that neither W_n nor any quotient of W_n can be realized with C^∞ or analytic vector fields on a finite dimensional manifold, thus suggesting that for these problems, no statistic of the conditional density can be computed with a finite dimensional recursive filter. This work, together with the analytical results of [4], implies that for some problems (including the cubic sensor), no nontrivial statistics can be computed recursively with finite dimensional filters; this is the first such result in the literature. For another class of problems, it is shown that L is a certain type of filtered Lie algebra. The algebras of this class are of a type which suggests that many statistics are exactly computable. In [5], we have given a comprehensive synthesis and exposition of algebraic and geometric methods in nonlinear estimation. In [2],[3],[6], Lie algebraic techniques are used along with asymptotic expansions to design high-performance suboptimal estimators for systems having no exact finite dimensional filters for conditional statistics. In particular, linear systems with small polynomial nonlinearities are considered in [2],[3]. Lie algebraic methods are used to elucidate the structure of the problem and to derive approximate filters. Then the performance of the approximate filters is, for the first time in the literature, analyzed precisely and proved to be close to optimal for small polynomial *nonlinearities*. We studied the application of similar methods to the problem of estimation in linear systems with infrequently jumping parameters [6]; this represented a new approach to a problem of fault detection and identification.

A new globally convergent nolinear observer, called the modified gain extended Kalman observer (MGEKO), has been developed for a special class of systems [7]-[10]. This special class of systems is characterized by special nonlinearities in either the dynamics or measurements, called modifiable nonlinearities. The globally convergent property of the associated nonlinear observer is found by using a quadratic Lyapunov function of the estimation errors. If this observer is used in a noisy environment, then biased estimates result. This is because both the residual and the gain are functions of the present measurement and, therefore, are correlated. To avoid this effect, the algorithm is modified so that the gain is not a function of the present measurement. Although some reasonable but uncheckable assumptions are required, the filter, called the modified gain extended Kalman filter (MGEKF), is shown under certain side conditions to be exponentially bounded in mean square.

Although the class of modifiable functions is quite small, it does include some important engineering estimation problems. In [7],[8], the bearings-only measurement problem is described; in this problem, the angle measurements are linear in a spherical coordinate frame and the dynamics are linear in a rectangular coordinate frame. Although the bearings-only measurement in two dimensions is modifiable in a rectangular coordinate frame, the vector bearings-only measurement is approximately modifiable in three dimensions. Nevertheless, simulations revealed stable and unbiased behavior in the noisy measurement case, thus showning superior performance with respect to existing filter mechanizations. In [9],[10], the problem of state and parameter identification is shown to fit into the class of modifiable functions. Choice of the coordinate frame is shown to be crucial. The results show dramatic improvement over previously published results for the extended Kalman filter.

In the area of fault detection and identification, a decision rule, the Shiryayev sequential probability ratio test (SPRT), has been used in [11],[12] to detect failures between similar instruments, as well as between dissimilar instruments through analytic redundancy. Unlike the

Wald SPRT, which tests for the presence of a failure or no failure in the entire data sequence, the Shiryayev SPRT detects the occurrence of a fault in the data sequence in minimum time if certain conditions are met. The performance of the Shiryayev SPRT in detecting a failure between two rate gyros as compared to standard fixed interval schemes is presented, as is the performance for a single accelerometer failure using translational kinematic equations to form a parity relation for analytical redundancy. The results of [11],[12] have been extended to include the derivation of a relatively simple algorithm for testing multiple failure hypotheses against a single unfailed hypothesis.

Detection filter theory constitutes a technique for generating closed-loop residuals which have directional characteristics that are useful for fault detection and identification (FDI). A detection filter acts in a closed-loop fashion to fix the output error direction associated with a set of plant and/or actuator failures, while restricting the output error direction of sensor failures in the set to lie in a plane. The output error direction(s) can then be employed to detect and identify the failure source by association with the design failure direction set. The concept of the detection filter was introduced by Beard [13]; a new derivation for the determination of detection filters has been developed by using an eigensystem assignment approach [14]. This approach is not only conceptually simpler, but by building on the filter closed-loop eigenvalues and eigenvectors explicitly, the physical interpretation of the performance of the detection filter is much more transparent.

Closely related to the parameter identification and fault identification problems discussed above are problems involving queueing systems with unknown parameters. In such problems, parameter identification algorithms are of interest; even more important is the on-line use of these algorithms in adaptive control algorithms. In [15], the problem of adaptively controlling the service rate in an M/G/1 queueing system in the presence of unknown parameters has been considered. An optimal adaptive policy is determined using recently developed results on parameter estimation and adaptive control of semi-Markov processes.

In [16],[17], we consider the priority assignment (or dynamic scheduling) problem in a queueing system with unknown arrival and service rates, and average cost criterion with linear cost rates. An optimal adaptive policy is determined via the direct, elementary approach of a naive feedback controller. We have considered in [18] discounted-reward finite state Markov decision processes which depend on unknown parameters. An adaptive policy inspired by the nonstationary value-iteration scheme of Federgruen and Schweitzer [19] is proposed. This policy is briefly compared with the "principle of estimation and control" recently obtained by Schal [20]. In related work, we have in [21] presented a distance-measures approach to the problems of identification and approximation of queueing systems. This approach combines ideas from statistical robustness, information-type measures and parameter-continuity of stochastic processes. In [22], the adaptive estimation problem is studied. A new adaptive estimation algorithm for finite state Markov processes with incomplete observations is developed. This algorithm is then analyzed via the Ordinary Differential Equation (ODE) Method. That is, it is shown that the convergence of the parameter estimation algorithm can be analyzed by studying an "averaged" ordinary differential equation.

In related work on nonlinear systems, the structure of nonlinear control systems possessing symmetries is studied in [23]-[25]. It is shown, under various technical conditions, that nonlinear control systems with symmetries admit local and/or global decompositions in terms of lower dimensional subsystems and feedback loops. It is shown in [26] that a symmetry in an optimization problem induces a decomposition of the optimal feedback control law into factors. One factor can be calculated algebraically and depends only on the symmetry; the other factor corresponds to a lower dimensional optimization problem. This gives *a priori* information about the structure of the optimal feedback control law and indicates a possibly more efficient method for optimizing such systems.

The research in this area is continuing and has been complemented by Grant AFOSR-86-0029 from the Air Force Office of Scientific Research and Grant ECS-8412100 from the National Science Foundation.

PUBLICATIONS

1. M. Hazewinkel and S. I. Marcus, "On Lie Algebras and Finite Dimensional Filters," Stochastics, vol. 7, pp. 29-62 (1982).

2. G. L. Blankenship, C.-H. Liu and S. I. Marcus, "Asymptotic Expansions and Lie Algebras for Some Nonlinear Filtering Problems," IEEE Trans. Automatic Control, vol. AC-28, pp. 787-797 (July 1983).

3. S. I. Marcus, C.-H. Liu and G. L. Blankenship, "Lie Algebraic and Approximation Methods for Some Nonlinear Filtering Problems," in Advances in Filtering and Optimal Stochastic Control, W. H. Fleming and L. G. Gorostiza (eds.), Springer-Verlag, New York, pp. 225-238 (1982).

4. M. Hazewinkel, S. I. Marcus and H. J. Sussmann, "Non-Existence of Finite Dimensional Filters for Conditional Statistics of the Cubic Sensor Problem," Systems and Control Letters, vol. 3, pp. 331-340 (1983).

5. S. I. Marcus, "Algebraic and Geometric Methods in Nonlinear Filtering," SIAM J. Control and Optimization, vol. 22, pp. 817-844 (November 1984).

6. S. I. Marcus and E. K. Westwood, "On Asymptotic Approximations for Some Nonlinear Filtering Problems," Proc. IFAC Triennial Congress, vol. VII, pp. 36-41, Budapest, Hungary (July 2-6, 1984).

7. T. L. Song and J. L. Speyer, "A Stochastic Analysis of a Modified Gain Extended Kalman Filter with Applications to Estimation with Bearings-Only Measurements," IEEE Trans. Automatic Control, vol. AC-30, pp. 940-949 (October 1985).

8. T. L. Song and J. L. Speyer, "A Stochastic Analysis of a Modified Gain Extended Kalman Filter with Applications to Estimation with Bearings-Only Measurements," Proc. IEEE Conference on Decision and Control (December 1983).

9. T. L. Song and J. L. Speyer, "The Modified Gain Extended Kalman Filter and Parameter Identification in Linear Systems," Automatica (January 1986).

10. T. L. Song and J. L. Speyer, "The Modified Gain Extended Kalman Filter and Parameter Identification in Linear Systems," Proc. American Control Conference (June 1984).

11. J. L. Speyer and J. E. White, "The Shiryayev Sequential Probability Ratio Test for Redundancy Management," AIAA Journal of Guidance, Control and Dynamics (September-October 1984)

12. J. L. Speyer and J. E. White, "The Shiryayev Sequential Probability Ratio Test for Redundancy Management," Proc. 1982 AIAA Guidance and Control Conference, San Diego.

13. R. V. Beard, "Failure Accomodation in Linear Systems Through Self-Reorganization," Report No. MUT-71-1, Man-Vehicle Laboratory, M.I.T., Cambridge, MA (February 1971).

14. J. E. White and J. L. Speyer, "Detection Filter Design by Eigensystem Assignment," Proc. 1985 American Control Conference (June 1985).

15. O. Hernandez-Lerma and S. I. Marcus, "Adaptive Control of Service in Queueing Systems," Systems and Control Letters, vol. 3, pp. 382-389 (1983).

16. O. Hernandez-Lerma and S. I. Marcus, "Optimal Adaptive Control of Priority Assignment in Queueing Systems," Systems and Control Letters, vol. 4, pp. 65-72 (April 1984).

17. O. Hernandez-Lerma and S. I. Marcus, "Priority Assignment in Queueing Systems with Unknown Parameters," Proc. IEEE Mexicon '83, Cuernavaca, Mexico, November 23-25, 1983.

18. O. Hernandez-Lerma and S. I. Marcus, "Adaptive Control of Discounted Markov Decision Chains," to appear in J. Optimization Theory and Applications (March 1987).

19. A. Federgruen and P. J. Schweitzer, "Nonstationary Markov Decision Problems with Converging Parameters," J. Optimization Theory and Applications, vol. 34, pp. 207-241 (1981).

20. M. Schal, "Estimation and Control in Discounted Stochastic Dynamic Programming," University of Bonn, Institute of Applied Mathematics, Preprint No. 428 (1981).

21. O. Hernandez-Lerma and S. I. Marcus, "Identification and Approximation of Queueing Systems," IEEE Trans. Automatic Control, vol. AC-29, pp. 472-474 (May 1984).

22. A. Arapostathis and S. I. Marcus, "Analysis of an Identification Algorithm Arising in the Adaptive Estimation of Markov Chains," Proc. 24th IEEE Conf. Decision and Control, Ft. Lauderdale, Florida, pp. 208-211 (December 10-13, 1985).

23. J. W. Grizzle and S. I. Marcus, "The Structure of Nonlinear Control Systems Possessing Symmetries," IEEE Trans. Automatic Control, vol. AC-30, pp. 248-258 (March 1985).

24. J. W. Grizzle and S. I. Marcus, "Symmetries in Nonlinear Control Systems," Proc. 22nd IEEE Conf. Decision and Control, San Antonio, Texas, pp. 1384-1388 (December 14-16, 1983).

25. J. W. Grizzle and S. I. Marcus, "A Jacobi-Liouville Theorem for Hamiltonian Control Systems," Proc. 23rd IEEE Conf. Decision and Control, Las Vegas, Nevada, pp. 1598-1602 (December 12-14, 1984).

26. J. W. Grizzle and S. I. Marcus, "Optimal Control of Systems Possessing Symmetries," IEEE Trans. Automatic Control, vol. AC-29, pp. 1037-1040 (November 1984).

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE85-2 ELECTRONIC TIME-VARIANT SIGNAL PROCESSING

Principal Investigator: Professor J.K. Aggarwal (471-1369)

Graduate Students: T. Leou, N. Nandhakumar and S. Park

A. OBJECTIVES AND PROGRESS: The scientific objectives of this research unit are to explore the basic properties of linear time-variant (LTV) systems and to develop efficient techniques for processing time-variant signals. Our research efforts have been directed towards the analysis, synthesis and implementation of LTV filters in both time and frequency domains. In particular, we have developed new structures for realizing LTV filters aimed at reducing the complexity of the synthesis and implementation algorithms. The progress of this research unit is summarized in the following.

We have established the framework for the analysis and synthesis of LTV digital filters by investigating the interrelationships among the three common characterizations of LTV filters; the time-variant impulse response, the generalized transfer function and the time-variant difference equation [1]. It has been shown that a time-variant impulse response is realizable via a time-variant difference equation if and only if it is expressed as a separable causal sequence. As documented in [2], we have studied the frequency-domain characterization of LTV digital filters based upon the notion of spectral modification. We have shown that the use of an LTV filter in processing time-variant signals may significantly reduce the bandwidth of the filter. Further, we have developed two synthesis techniques for recursive LTV filters based upon the minimization of the squared difference between the desired and the synthesized impulse responses [3]. The first technique is formulated as a spectral decomposition of the desired impulse response, and the second one is based upon a nonlinear minimization algorithm. We have also developed a technique to implement a one-dimensional (1-D) LTV filter with a two-dimensional (2-D) linear time-invariant (LTI) filter by appropriately mapping 1-D input/output sequences into 2-D sequences [4]. Therefore, a 1-D LTV synthesis problem may be solved by the synthesis techniques develped for 2-D LTI filters.

In [5], [6], we have highlighted the misconception of synthesizing a recursive LTV filter based on the idea of the frozen-time transfer function. A typical example of the recursive LTV filter has been selected to illustrate the difference between the desired transfer function and the synthesized transfer function. We have also identified the special cases where the frozen-time synthesis technique produces satisfactory results.

Continuing our research on the synthesis of LTV digital filters via time-variant difference equations, we have studied the relationship between a rational generalized transfer function (GTF) and the corresponding difference equation based upon a difference equation representation of the GTF [7], [8]. The synthesis of a rational GTF via a time-variant difference equation has been formulated by minimizing a Chebyshev norm of a residual vector which represents the difference between the desired GTF and the GTF realizable via an LTV difference equation. The necessary conditions for the realization of a generalized transfer function can also be derived from this formulation. We have shown that there always exists an exact realization for a GTF having constant denominator coefficients. A simple two-stage structure for implementing a rational GTF having constant denominator coefficients has been proposed, where the coefficients of the recursive structure are in one-to-one correspondence with those of the GTF.

As reported in [9], the problem of synthesizing a time-variant impulse response via an LTV difference equation can be formulated by assuming that the desired impulse response satisfies a

LTV difference equation with a small error term added. Then the filter coefficients can be derived from a set of linear equations which are formulated by minimizing the error term in the least-squares sense. This formulation has avoided the numerical difficulties in obtaining the spectral decomposition of a large matrix and in calculating the solution of a nonlinear minimization.

Further, we have also investigated new synthesis structures in addition to the LTV difference equation. In [9], [10], LTV filters are synthesized as a parallel combination of a finite number of LTI filters each followed by a time-variant multiplier. The desired impulse response is first decomposed into a sum of products of two sets of orthogonal sequences through the use of spectral decomposition. Then a small number of dominant terms in the sum of products are chosen as an approximation of the desired impulse response. The filter structure is further simplified by replacing the parallel combination of LTI filters with a cascade connection of first- and second-order recursive LTI filter sections.

We have explored a structure-independent approach to the analysis and synthesis of recursive LTV filters based upon the state-space representation of LTV filters [11]. A systematic algorithm has been developed to select a time-dependent state transformation which can map an LTV filter to an equivalent filter having diagonal state-feedback matrices. Due to the structural simplicity of diagonal systems, the time-dependent state transformation is a convenient tool for analyzing recursive LTV filters. The properties of the impulse responses realized via several different structures have been investigated using the diagonalizing state transformation technique. Based upon the separable properties of the impulse responses, we have developed an efficient suboptimal algorithm for synthesizing desired impulse responses via a major class of recursive LTV filters.

Recently, we have been invited to contribute a chapter on time-varying systems and signal processing to The Encyclopedia of *Physical Science and Technology [12]. In this chapter, we* have presented the framework for representing and analyzing LTV systems based upon our research in this area. Further, we have reviewed a number of widely-used techniques for processing time-varying signals. We have also discussed several areas of current research interest in the scope of time-varying systems and signal processing.

B. REFERENCES

1. N.C. Huang and J.K. Aggarwal, "On Linear Shift-Variant Digital Filters," IEEE Transactions on Circuits and Systems, vol. CAS-27, pp. 672-679 (August 1980).

2. N.C. Huang and J.K. Aggarwal, "Frequency-Domain Considerations of LSV Digital Filters, "IEEE Transactions on Circuits and Systems, vol. CAS-28, no. 4, pp. 279-287 (April 1981).

3. N.C. Huang and J.K. Aggarwal, "Synthesis and Implementation of Recursive Linear Shift-Variant Digital Filters," IEEE Transactions on Circuits and Systems, vol. CAS-30, pp. 29-36 (January 1983).

4. S.H. Park, N.C. Huang and J.K. Aggarwal, "One-Dimensional Linear Shift-Variant Digital Filtering Using Two-Dimensional Techniques," IEEE Transactions on Circuits and Systems,vol. CAS-30, pp. 172-176 (March 1983).

5. T.Y. Leou and J.K. Aggarwal, "Difference Equation Implementation of Time-Variant Digital Filters," Proceedings of IEEE Conference on Decision and Control, San Antonio, Texas, pp. 1356-1357 (December 14-16, 1983).

6. T.Y. Leou and J.K. Aggarwal, "Recursive Implementation of LTV Filters---Frozen-Time Transfer Function Versus Generalized Transfer Function," Proceedings of The IEEE, vol. 72, no. 7, pp. 980-981 (July 1984).

7. S.H. Park and J.K. Aggarwal, "Recursive Synthesis of Linear Time-Variant Digital Filters," 1984 International Symposium on Circuits and Systems, Montreal, Canada (May 7-10, 1984).

8. S.H. Park and J.K. Aggarwal, "Recursive Synthesis of Linear Time-Variant Digital Filters via Chebyshev Approximation," IEEE Transactions on Circuits and Systems, vol. CAS-32, no. 3, pp. 245-251 (March 1985).

9. S.H. Park, "Realization of Generalized Impulse Response," Proceedings of Midwest Symposium on Circuits and Systems, Puebla, Mexico, pp. 198-202 (August 15-16, 1983).

10. S.H. Park and J.K. Aggarwal, "A Simple Form Realization of Linear Time-Variant Digital Filter via Spectral Decomposition of Its Impulse Response," Journal of the Franklin Institute, vol. 318, no. 3, pp. 151-164 (September 1984).

11. T.Y. Leou and J.K. Aggarwal, "A Structure-Independent Approach to the Analysis and Synthesis of LTV Digital Filters," to appear in IEEE Transactions on Circuits and Systems.

12. N.C. Huang, T.Y. Leou and J.K. Aggarwal, "Control, Time-Varying Systems and Signal Processing," to appear in The Encyclopedia of Physical Science and Technology by Academic Press.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
INFORMATION ELECTRONICS

Research Unit IE85-3 DIGITAL TIME SERIES ANALYSIS WITH APPLICATION TO NONLINEAR WAVE PHENOMENA

Principal Investigator: Professor E.J. Powers (471-3954)

Research Associate: Dr. Christoph Ritz

Graduate Students: K.I. Kim and Taiho Koh

A. SCIENTIFIC OBJECTIVES: The overall scientific objective of this research unit is to conceive and implement unique digital time series analysis techniques that may be used to analyze and interpret nonlinear wave fluctuation data in such a way as to provide new experimental and physical insight into a variety of important nonlinear wave phenomena. Our approach is multidisciplinary and rests upon synthesizing appropriate knowledge from the fields of nonlinear waves, nonlinear systems, and digital signal processing. Particular emphasis is placed upon modelling the linear and nonlinear relationships between two (or more) time series in the frequency domain via a hierarchy of linear and nonlinear transfer functions. Such transfer functions are closely related to the relevant physics in that the transfer functions are a measure of the "efficiency" with which various spectral components in the input mix to transfer energy to new spectral components in the output. Although the primary focus of this research unit has been on frequency domain modelling of nonlinear systems, time-domain models based on second-order Volterra filters have also been investigated. We anticipate that the results of this research will continue to impact on many important scientific and technological problems, some of which are discussed in this report.

B. PROGRESS: During the three year period covered by this report we have focused on detecting and modelling the linear and nonlinear relationships (if any) between two time series of fluctuation data. This is basically a problem in nonlinear systems modelling. In the following paragraphs we indicate that our approach has been to model the relationship in terms of a hierarchy of linear and nonlinear transfer functions. We have focused on frequency domain modelling because the transfer functions are most easily related to the nonlinear wave physics of most problems. In order to demonstrate the validity of our approach we have applied these results to several problems which will be summarized in this section.

Nonlinear Systems Modelling in the Frequency Domain: One of the principal characteristics of any nonlinear system is the introduction of new frequency components, e.g., harmonics and intermodulation products. The "efficiency" with which these new spectral components are generated is given by an interaction or coupling coefficient. In the case of nonlinear systems where one can define an "input" and "output", the "efficiency" with which the new spectral components are generated is described by nonlinear transfer functions. For quadratically nonlinear interactions, the coupling coefficients or transfer functions are two-dimensional functions of frequency. For cubic interactions, the corresponding coupling coefficients or transfer functions are three-dimensional functions of frequency. This clearly suggests that higher-order (i.e., multi-dimensional functions of frequency) spectral densities must be utilized to appropriately analyze and interpret fluctuation data associated with nonlinear

physical systems. For quadratically and cubically nonlinear systems, the bispectrum $B(\omega_1,\omega_2)$ and the trispectrum $T(\omega_1,\omega_2,\omega_3)$ are the appropriate spectral densities, respectively.

We have developed a conceptual nonlinear system model [1,2] in the frequency domain that corresponds to the Fourier transform of an orthogonalized Volterra functional series model in the time domain, previously described by Barrett. This model is valid for zero-mean Gaussian inputs with arbitrary spectral density. The model consists of a parallel combination of linear, quadratic, cubic, etc., transfer functions such that when the actual input is applied to the model, the model output approximates the output of the actual physical system very well. In particular the concept of coherency has been extended to quantify the goodness of the model. Of particular importance is the fact that the linear, quadratic, and cubic transfer functions may be estimated by computing the cross-power, cross-bispectrum, and cross-trispectrum, respectively, given the actual input and output time series data.

The validity of the model and the computer software have been validated by applying them to a variety of scientific and technological problems, some of which are described in the following paragraphs.

It is well known that many man-made metallic objects (aircraft, motor vehicles, etc.) exhibit electromagnetic nonlinearities (primarily cubic) which are associated with the nonlinear current-voltage characteristic of various junctions that are formed by oxide layers in the vicinity of various metallic joints. Depending on the spectral composition of the incident radar signal, the scattered signal will be characterized by a variety of harmonics and intermodulation products. On the basis of our work in nonlinear systems we have been able to generalize the radar equation (normally valid for linear targets) to nonlinear targets. Furthermore, the nonlinear scattering features of the target may be quantitatively described in terms of a hierarchy of linear, quadratic, and cubic radar cross sections [3].

Of particular interest is the result that the cubic nature of a target may be detected and investigated by appropriately processing the return at the fundamental frequency, rather than at the third harmonic. For a target containing both linear and cubic features, the return at the fundamental frequency ω_o will consist of two parts. The first is due to the linear nature of the target, the second due to the cubically generated degenerate component at ω_o (i.e., the ω_o component in the expansion of $\cos^3\omega_o t$). We have demonstrated how digital cross-trispectral analysis may be used to isolate not only weak third harmonics, but also the degenerate signal at ω_o from the linear return, even though both components are at the same frequency and the degenerate component is considerably weaker than the linear component [4]. Furthermore, we have, in a series of papers published in conference proceedings, demonstrated that cross-trispectral analysis is capable of detecting the presence of both the weak third-harmonic and the weak degenerate (at the fundamental) backscattered signals when they are as much as 20 db below the noise level [5,6].

Another application of our work in nonlinear system modelling in the frequency domain involves the modelling of the nonlinear response of moored-vessels to random sea-wave excitation. It is relatively well known that vessels moored in random seas can undergo large-amplitude low-frequency oscillations at or near the undamped natural frequency of the vessel-mooring system. Since such low-frequency excursions are significantly below dominant frequencies associated with the incident sea waves, a nonlinear mechanism is at play. In refs. [2,7,8,9] we indicate how digitally implemented cross-bispectral analysis techniques may be utilized to model the quadratically nonlinear response of moored vessels subject to random seas. The model consists of a linear and quadratic transfer function in parallel. The goodness of the

model is quantified by comparing the actual power spectrum of the moored vessel response with that "predicted" by the model. The agreement is very good indeed.

In a project supported principally by the National Science Foundation, digital higher order spectral analysis techniques (particularly, the bispectra), originally developed under JSEP auspices, have been utilized in experimental studies of transition to turbulence. In refs. [10,11,12], it was shown that these digital techniques are capable of providing extensive insight into the various nonlinear wave interactions that result in spectral energy redistribution, a common feature of transition to turbulence.

Another important application area involves the use of digital bispectral analysis techniques in studies of parametric and nonlinear mode interactions in structures, such as high performance aircraft. When a structure is subjected to random forcing functions, the classical normal mode spectrum of the response may be contaminated by auto parametric and nonlinear phenomena. We have demonstrated [13] how digital bispectral analysis techniques may be utilized to identify and detect the autoparametric and nonlinear responses from among the classical normal mode responses. In ref. [14] these bispectral analysis techniques are used to experimentally identify different classes of auto-parametric responses and finally the onset of flutter-type instabilities. In particular, a new subcritical flutter testing technique, based on bispectral analysis, was proposed and tested.

Nonlinear System Modelling in the Time-Domain: The representation of nonlinear system models in terms of Volterra functional series is well known [15]. While most of the current signal processing techniques are based on linear system models, there has been a growing interest in utilizing Volterra series in digital filtering and estimation of stationary time series. A major problem in the use of Volterra-type nonlinear digital filters is the computational complexity associated with the design and implementation of such filters. The complexity is rather formidable due to their multi-dimensional convolutional structure and higher-order statistical characteristics. We have investigated the problem of second-order Volterra filtering with emphasis on reducing the computational complexity where possible. A simple solution for the Volterra filter has been obtained based on the assumption that the filter input is Gaussian [16,17]. The practical usefulness of these techniques have been demonstrated in terms of an offshore engineering problem [18,19] involving modelling and predicting the nonlinear low-frequency large-amplitude oscillations of moored vessels subject to random sea waves.

Space-Time Statistics of Turbulent Fluctuation Fields: While the dispersion relation for undamped waves, which do not couple with each other, can be deterministic, this is no longer the case for turbulent fluctuations. Due to the wave-wave coupling, the dispersion relation is broadened and must be described by the joint wavenumber-frequency power spectrum $S(k,\omega)$. In principle, $S(k,\omega)$ may be found by Fourier transforming the space-time correlation function describing the second-order space-time statistics of the fluctuation field. In most practical situations such a space-time correlation function is not available. Under earlier JSEP (partial) sponsorship, we developed a procedure whereby $S(k,\omega)$ may be estimated by appropriately processing the fluctuation data observed at two spatial points [20].

In work supported principally by DOE, we have utilized our two-point scheme to investigate the space-time statistics of plasma turbulence observed in the edge of the PRETEXT and TEXT tokamaks located on The University of Texas campus [21,22,23]. Another advantage of the digital approach lies in its flexibility. Specifically, once one has $S(k,\omega)$ stored in the computer one can calculate other quantities of interest, such as the wavenumber power

spectrum, S(k), the statistical dispersion relation (average value of k for a given ω), and the degree of turbulent broadening (the variance of k for a given ω).

Efficient Correlation Function Estimator of Gaussian Processes: The computation of correlation function estimates is an important task in time series modelling since they provide crucial statistical information which is required in many time series modelling techniques. While conventional approaches require a large number of multiplications in estimating the correlation functions, several researchers proposed new methods in which the correlation function estimates are computed with additions only [24]. These methods employ a nonlinear distortion to exploit the prior knowledge of Gaussian statistics and are very suitable for digital implementation due to the non-multiplicative property. However, while the computational merit of these methods seems quite encouraging, their detailed performance has not been fully understood until recently. In ref. [25] a comparative performance evaluation between the new and conventional methods was carried out and the performance of these new methods compares favorably to the conventional approaches. In addition, we developed an extension of the previous non-multiplication correlation function estimators and showed that this method is useful in fast computation of maximum entropy spectra [26].

C. FOLLOW-UP STATEMENT: This work is continuing. As previously discussed our most recent work has focused on nonlinear system modelling in the frequency domain and serves as the basis of the approach of our new work which is to measure three-wave coupling coefficients directly from observations of the fluctuation field at two or more spatial points. Experimental determination of such coupling coefficients is important since the physics of the nonlinear interaction is imbedded in the coupling coefficient. Experimental measurements of the coupling coefficient are necessary to compare with theory, and determination of the coupling coefficient is necessary in order to quantify energy cascading between modes due to three-wave interactions.

Heretofore our work on nonlinear system modelling, and most of that carried out elsewhere, has been limited to input signals characterized by Gaussian statistics. The assumption of Gaussian input statistics renders a difficult nonlinear problem tractable. However, many noisy or turbulent physical systems do not allow such a restrictive assumption for the "input" signal. In order to gain experimental insight into the role of nonlinear three-wave interactions in various media, we will monitor the fluctuation field at two points and analyze the change in spectra between these two points. No matter which point we consider to be the input, the fluctuating waveform to be observed will, in general, be non-Gaussian due to its nonlinear history. Thus, if we are to be successful in measuring complex three-wave coupling coefficients, via the measurement of nonlinear transfer functions, it is essential that our past work in modelling of nonlinear systems be extended to non-Gaussian inputs. The preliminary results [27] are quite encouraging.

For these reasons, then, our future program of work will include:

1. Modelling of nonlinear systems in the frequency domain for non-Gaussian inputs,

2. Development of a procedure, including a computer algorithm, which enables one to determine complex three-wave coupling coefficients from the two channels of raw fluctuation data (information on linear growth (or damping) rates and dispersion is also to be provided).

3. Further development of an algorithm that will permit one to quantify the energy cascading between modes in the incoherent fluctuation spectrum as a result of three-wave interactions, and

4. Validation of the approach via computer simulations and by application to data from real physical systems.

D. REFERENCES

1. J.Y. Hong, Y.C. Kim and E.J. Powers, "On Modeling the Nonlinear Relationship Between Fluctuations with Nonlinear Transfer Functions," Proceedings of the IEEE (Letter), 68, 1026-1027 (1980). See also errata, Proceedings of the IEEE, 70, 93 (1982).

2. DooWhan Choi, R.W. Miksad, E.J. Powers and F.J. Fischer, "Application of Digital Cross-Bispectral Analysis Techniques to Model the Non-Linear Response of a Moored Vessel System in Random Seas," Journal of Sound and Vibration, 99, 309-326 (1985).

3. E.J. Powers, J.Y. Hong and Y.C. Kim, "Cross Sections and Radar Equation for Nonlinear Scatterers," IEEE Transactions on Aerospace and Electronic Systems, AES-17, 602-605 (1981).

4. Jae Y. Hong and Edward J. Powers, "Digital Signal Processing of Scattering Data from Nonlinear Targets," Proceedings of the International Conference RADAR-82, October 1982, London, England, 11pp.

5. J.Y. Hong and E.J. Powers, "Detection of Weak Third Harmonic Backscatter from Nonlinear Metal Targets," Proceedings of IEEE EASCON '83 - 16th Annual Electronics and Aerospace Conference and Exposition, September 1983, Washington, D.C., pp. 169-175.

6. Jae Y. Hong and Edward J. Powers, "Simulation Study of Detection of Nonlinear Metallic Targets in Sea Clutter-Type Noise," Proceedings of the 1984 International Symposium on Noise and Clutter Rejection in Radars and Imaging Sensors, Editors: T. Musha, T. Suzuki, H. Ogura, October 1984, Tokyo, Japan, pp. 351-356.

7. E.J. Powers, D.-W. Choi, R.W. Miksad and F.J. Fischer, "Determination of Nonlinear Drift Force Quadratic Transfer Functions by Digital Cross-Bispectral Analysis," Paper OTC 4440, Proceedings of the 1982 Offshore Technology Conference, May 1982, Houston, Texas, pp. 759-767.

8. R.W. Miksad, E.J. Powers, Y.C. Kim, F.L. Jones and R.S. Solis, "Applications of Digital Time Series Techniques to Determine Nonlinear Drift Forces," in Offshore Engineering Vol. 3, Editors: F.L.L.B. Carneiro, A.J. Ferrante, and R.C. Batista, Pentech Press, London, 1982, 273-280.

9. Edward J. Powers, Richard W. Miksad, DooWhan Choi and F. Joseph Fischer, "Applications of Digital Complex Demodulation Techniques to Low-Frequency Nonlinear Drift Forces in Irregular Seas," Paper OTC 4489, Proceedings of the 1983 Offshore Technology Conference, May 1983, Houston, Texas, pp. 399-404.

10. R.W. Miksad, F.L. Jones, E.J. Powers Y.C. Kim and L. Khadra, "Experiments on the Role of Amplitude and Phase Modulations During Transition to Turbulence," Journal of Fluid Mechanics, 123, 1-19 (1982).

11. R.W. Miksad, F.L. Jones and E.J. Powers, "Measurements of Nonlinear Interactions During Natural Transition of a Symmetric Wake," Physics of Fluids, 26, 1402-1409 (1983).

12. R.W. Miksad, F.L. Jones and E.J. Powers, "Experiments on Nonlinear Interactions in Wake Transitions," in Laminar-Turbulent Transition, V.V. Kozlov, Editor, pp. 397-409, Springer-Verlag, Berlin, 1985.

13. DooWhan Choi, Jung-Hua Chang, Ronald O. Stearman and Edward J. Powers, "Bispectral Identification of Nonlinear Mode Interactions," Proceedings of the 2nd International Modal Analysis Conference, February 1984, Orlando, Florida, pp. 602-609.

14. J.H. Chang, R.O. Stearman, D. Choi and E.J. Powers, "Identification of Aeroelastic Phenomena Employing Bispectral Analysis Techniques," Proceedings of the 3rd International Modal Analysis Conference, January 1985, Orlando, Florida, pp. 956-964.

15. M. Schetzen, The Volterra and Wiener Theories of Nonlinear Systems, John Wiley and Sons, New York (1980).

16. T. Koh and E.J. Powers, "Second-Order Volterra Filtering and Its Application to Nonlinear System Identification," IEEE Transactions on Acoustics, Speech and Signal Processing, ASSP-33, 1445-1455 (December 1985).

17. Taiho Koh and Edward J. Powers, "An Adaptive Nonlinear Digital Filter with Lattice Orthogonalization," Proceedings of ICASSP '83 - IEEE International Conference on Acoustics, Speech and Signal Processing, Vol. 1, April 1983, Boston, Massachusetts, pp. 37-40.

18. T. Koh, E.J. Powers, and R.W. Miksad, "An Approach to Time Domain Modelling of Nonlinear Drift Oscillations in Random Seas," Offshore Engineering Vol. 4, Editors: F.L.L.B. Carneiro, A.J. Ferrante, and R.C. Batista, Pentech Press, London, 1984, 137-153.

19. T. Koh, E.J. Powers, R.W. Miksad and F.J. Fischer, "Application of Nonlinear Digital Filters to Modelling Low-Frequency Nonlinear Drift Oscillations of Moored Vessels in Random Seas," Paper OTC 4812, Proceedings of the 1984 Offshore Technology Conference, May 1984, Houston, Texas, pp. 309-314.

20. J.M. Beall, Y.C. Kim and E.J. Powers, "Estimation of Wavenumber and Frequency Spectra Using Fixed Probe Pairs," Journal of Applied Physics 53, 3933-3940 (1982).

21. S.J. Levinson, J.M. Beall, E.J. Powers and R.D. Bengtson, "Space/Time Statistics of the Turbulence in a Tokamak Edge Plasma," Nuclear Fusion 24, 527-539 (1984).

22. Ch.P. Ritz, Roger D. Bengtson, S.J. Levinson and E.J. Powers, "Turbulent Structure in the Edge Plasma of the TEXT Tokamak," Physics of Fluids 27, 2956-2959 (1984).

23. Ch.P. Ritz, E.J. Powers, D.L. Brower, T. Rhodes, R.D. Bengtson, N.C. Luhmann, and W.A. Peebles, "Digital Spectral Analysis - A Diagnostic for Fusion Research," Proceedings 11th

Symposium on Fusion Engineering, pp. 1185-1188, November 1985 (IEEE Catalog No. CH2251-7).

24. See for example D. Hertz, "A Fast Digital Method of Estimating the Autocorrelation of a Gaussian Stationary Process," IEEE Trans. on Acoust., Speech, Signal Process., ASSP-31, 1023-1025 (1982).

25. Taiho Koh and Edward J. Powers, "Efficient Methods to Estimate Correlation Functions of Gaussian Processes and Their Performance Analysis," IEEE Transactions on Acoustics, Speech and Signal Processing, ASSP-33, 1032-1035 (August 1985).

26. Taiho Koh and Edward J. Powers, "Efficient Maximum Entropy Spectral Estimation Using Non-Multiplication Methods," Proceedings ICASSP '84 - IEEE International Conference on Acoustics, Speech and Signal Processing, Vol. 1, March 1984, San Diego, California, pp. 13.2.1-4.

27. Kyoung Il Kim and Edward J. Powers, "Digital Estimation of Linear/Quadratic Transfer Functions with a General Random Input," Proceedings of the International Conference on Acoustics, Speech, and Signal Processing, pp. 2727-2730, April 1986 (IEEE Catalog No. 86-CH2243-4).

II. SOLID STATE ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE82-1 INTERFACE REACTIONS, INSTABILITIES AND TRANSPORT

Principal Investigators: Professor M.F. Becker (471-3628)
Professor R.W. Bene' (471-1225)
Professor A.B. Buckman (471-4893)
Professor R.M. Walser (471-5733)

Graduate Students: Mark Bordelon, E. Ehsani, Y.K. Jhee, Y.H. Ku, Segeun Park, J. Wiedner and H.Y. Yang

A. SCIENTIFIC OBJECTIVES: One principal objective of this research unit is to understand and model the instabilities and interactions which develop at interfaces. In the long range we wish to do this at microscopic level and with the generality necessary to allow us to design interface systems with specific structures and electronic properties useful in advanced microelectronics and other emerging technologies. We have made significant progress in the last few years in our limited objective of understanding the nucleation of structures in binary thin film systems and one of our specific objectives in the next proposal period is to extend these results to ternary systems. The basic increase in complexity in these systems is that of the generalization of the supply of the elements in the reaction process. We plan to achieve this objective using two types of systems; 1) Si substrate with controlled series/parallel deposition of 2 different transition metals and 2) single metal deposition upon compound semiconductor substrates. Another objective is to increase our understanding of the binary systems to a greater level. Generally this will involve a more microscopic understanding as well as the fit of individual systems into the overall scheme.

Another objective of this unit is to increase our microscopic understanding of ordering processes at phase transitions in solids beyond that provided by strictly thermodynamic perspectives. The long range goal of these studies would, for example, suggest how radiation and particle beams can be intelligently used to beneficially modify electronic material properties or to synthesize desirable metastable phases. Most of the JSEP sponsored research to date has been to develop and apply picosecond laser reaction kinetic techniques for inducing and monitoring non-equilibrium structural transformations in solids. We initially applied these techniques to the study of martensitic shear transformations and successfully demonstrated the ability to induce and monitor nonequilibrium phases in vanadium dioxide [1].

The current thrust of this research is to study the mechanism of laser induced damage in solids. Emphasis will be on semiconductors (mainly silicon) and metal surfaces. Our viewpoint is that laser damage is a first order phase transition; and when it is induced by

picosecond laser pulses, it is non-equilibrium in nature. Experimental techniques which probe the state of the target materials just below the picosecond laser pulse damage threshold will be used to determine the characteristics of the precursors to the phase transition. Study of exoemitted charges in addition to conventional morphology and statistical studies will be employed to determine the nature of the first detectible phase after damage is nucleated.

B. PROGRESS: Over the past year we have continued our study of the systematics of first nucleation in binary systems. In particular we have studied the Ti-Si system in detail; partly because this is one of the end phases in our recently begun investigations into the systematics of ternary phase formation.

In particular, it is part of the study of Ti-Co-Si and Ti-Ni-Si systems. The Ti-Si system is interesting in its own right technologically, because it is a possible metallization for new gates and interconnects and scientifically because it has been recently reported that the TiSi phase is nucleated prior to the predicted $TiSi_2$ phase. We have studied this system using transmission election diffraction (TED) as well as bright field TEM X-ray diffraction, resistivity and Auger spectroscopy and find that the phase found prior to the equilibrium $TiSi_2$ phase is a nonequilibrium phase founded by ordering of the interstitial diffusion of Ti into the Si substrate. This work has been reported at the Electronic Materials Conference in Ft. Collins (1982) and published in the Journal of Electronic Materials [2].

Some initial TED results on the Ti-Co-Si system indicates that for certain preparation conditions this nonequilibrium superstructure phase may be suppressed and that $CoTi_2$ may precede either Co_2Si or $TiSi_2$ formation. More measurements are needed to map out the nucleation path with changes in sample preparation conditions including supply of the transition metals.

In related work, we have extended our modeling considerations to metal-metal thin film systems. We have found that the overwhelming majority of binary systems satisfy a metal-metal rule (Rule MM) which states that first nucleation in metal-metal thin film reactions is the phase immediately adjacent to the low temperature eutectic in the binary phase diagram. This rule, in conjunction with our previous rule for metal-covalent semiconductor systems (Rule MC), indicates quite clearly the barrier to nucleation encountered in metallic glass forming regions near deep eutectics of metal-covalent semiconductor systems. This leads to "phase skipping" in these systems. This work has been recently published in Applied Physics Letters [3].

We have begun studying the ternary systematics of metals deposited on compound semiconductors with a review of work on metals deposited on GaAs. Generally this work can be characterized as inconclusive or ambiguous as far as first phase identification for

first phase nucleation is concerned [4,5,6,7]. The reason is probably because relatively thick films were studied using techniques which are not particularly sensitive for phase identification in the ultrathin film regime. We have thus began a TED study of thin films of metals deposited on GaAs substrates. Our work to date has concentrated on determining the best etchants to use in the prethinning and jet thinning techniques and a determination of the best system (metal) to begin the study. At present the etchants have been determined by trial and error and we have started measurements on the Pd:GaAs system. We are not ready to report the results yet, however.

Finally, we have begun making measurements of stress of ultrathin films of metals deposited on Si substrates. These measurements are just beginning, but using the laser technique we have initially seen that very thin Co films on Si are highly compressive prior to nucleation of Co_2Si. Thicker films of Co_2Si and other silicides are known to be tensile on Si substrates. At least one of the newer theories [8] on glass or noncrystalline alloy formation relies critically on stress build up due to topological constraints and it would be very useful to see if we can observe any systematics of stress build up in the prenucleation regime.

This information, in conjunction with the noise fluctuation work being pursued with NSF support, could be very useful in determining the microscopic structural changes along the reaction path.

During the past year we have also conducted detailed experimental studies of picosecond laser induced damage as a non-equilibrium phase transition and proposed a new damage mechanism. This model, which includes energy transfer by resonant surface plasmons on small charge density droplets, is corroborated by our existing experimental data. Experimental data has been taken which demonstrates the nucleation and growth aspects of the laser damage process [10,11].

The motivation for this work has its origin in several facts. First, the picosecond time domain results in several simplifications due to the elimination of transport during the pulse duration. Near band-gap excitation of 1.06μm limits the heating of the sample by fast phonon decay of hot electrons. Silicon, a covalent material, was chosen for the absence of polar optical coupling mechanisms and the absence of an electron collision time sufficiently short to allow avalanche ionization. Finally, experience gained in the excitation of VO_2 through a non-equilibrium, semiconducting-metallic phase transition in the first such study [1] led to a conceptual framework for these types of experiments.

We have performed an experimental demonstration of the heterogeneous nature of the nucleation and growth of laser damage in crystalline silicon. The samples of single crystal silicon were prepared from low resistivity <100> and <111> wafers with high resistivity 1.5 or 2.5μm epitaxial layers. To obtain the very thin samples used

in some experiments, the wafers were masked and electrochemically etched, exposing about $0.5cm^2$ of epitaxial membrane [9,10].

The damage nucleation and growth was studied by monitoring the transmission of the irradiated region at 633nm while multiple pulse damage was initiated at a prf of 5Hz. The laser pulses were supplied by a passively mode-locked 1.06μm Nd:YAG laser. Single pulses were selected with an average FWHM duration of 38psec.

The sample transmission could then be related to a percent of the spot area transformed to the final state of damage. The results of this measurement showed an incubation period, a sigmoidal shape, and have been fit to the Avrami equation for the behavior of nucleation and growth. These results strongly suggested that this damage process is a (micro) heterogeneously nucleated first order phase transformation process. This in turn suggested that a morphological study of the nucleation process would be beneficial.

A systematic study of the morphology of laser damage of silicon has been conducted. The multiple pulse damage threshold represents the point of closest approach to the phase transition where the morphology of nucleation may be studied. This method avoids the catastropic damage characteristics of single pulse damage which tends to destroy evidence of its early formation stages.

An automatic translation stage was constructed for the sample which would count laser pulses and give a sequence of irradiations at increasing powers of 2 or single pulses. A high resolution SEM study showed the development of the coherent damage morphology with increasing numbers of pulses. The nucleation of the damage appears first as oval pits with their long axis orthogonal to the optical electric field. Subsequently and simultaneously formed pits are regularly spaced along single rows. Parallel rows of pits finally form into grating structure. Clearly the first phase of the damage process self-consistently selects pit formation at a specified distance from another pit, orthogonal to the optical field. The second phase of damage is the formation of regular spaced rows of pits (grooves). The grooves are spaced by the free space wavelength, suggesting that they are formed by the constructive interference of a scattered surface wave. This second process is consistent with the damage observed to propagate from pre-existing linear structures such as scratches oriented normal to the optical field.

All of the damage we observed in these experiments was at the front surface. Even the optically thin 1.5μm thick films damaged first at the front surface. Near threshold, only front surface damage was observed. Since our silicon samples were extremely thin compared to the absorption length, this observation indicates that the damage could not have been initiated by the optical electric field, which by simple Fresnel arguments, is a maximum on the exit surface.

Silicon, with a band gap of 1.11ev at 300K, has a linear absorption constant of only $10cm^{-1}$ for 1.06μm (1.17ev) laser pulses. At intensities approaching the multi-pulse damage threshold, our experimentally measured transmission data indicates the presence of an additional two photon absorption. Assuming that an indirect two photon process dominates, we obtained a two photon absorption constant β=52cm/GW by fitting the data.

Using this absorption process for 38 psec 1.06μm pulses at an intensity of $1GW/cm^2$ only 10^{18} to 10^{19} charge pairs are produced per cm^3. In addition, the computed temperature rise during the pulse is less than one degree K. Although free carrier absorption was omitted from these calculations, it is not expected to increase the refractive index or temperature jump significantly.

These extrapolated values of ΔT and Δn are much too small to initiate catastrophic damage which is, of course, the basic scientific enigma found in nearly all studies of laser damage in nearly-transparent media. Note that electronic avalanche ionization is not a highly probable process at the high excitation frequency of the Nd:YAG laser and, is ruled out by our observation of entrance face damage in thin samples.

To circumvent these difficulties we have proposed a new laser damage mechanism suggested by the morphological studies of the early damage nucleation regime [12,13]. This work suggests that, despite the apparent absence of avalanching, locally high absorption in some highly excited, small, charge density "embryos" is the precursor to damage. Furthermore, the consistent observation of coherently interfering "embryos" indicates that these are of intrinsic or homogeneous origin and not due to the presence of highly absorbing extrinsic heterogeneities.

We are led to suggest that an electronic spinodal separation occurs near the damage threshold when the average excited charge density approaches $\sim 10^{19}/cm^3$. Inside the spinodal the electron and hole excitations are subject to spontaneous clustering under the influence of some unknown driving force.

The proposed damage mechanism involves the resonant absorption of incident photons by the collective electronic oscillations (surface plasmons) of embryo regions having near-critical radii and excited charge density approaching that of the liquid. This model is consistent with the evidence of cooperative interaction between damage sites. The direction and separation of the sites are those expected of a coherent, dipolar radiative interaction between resonant surface plasmons on adjacent sites just prior to liquid phase nucleation. Subsequent resonant absorption, in the presence of Auger or other fast decay processes, will rapidly heat the site to a liquid vapor instability and cause pit formation.

While normally incident light will not couple to the planar surface plasmons of a solid, it will couple efficiently to any charge

density droplets that form. The coupling will be resonant for a droplet size and charge density such that $\omega_{sp}=\omega_0$. Damage will nucleate at the lowest intensity for which coherent radiative coupling occurs between the resonant surface plasmons of two or more droplets.

A small, compared to lambda, spherical charge droplet will support a number of surface plasmon modes. Our calculations show that the lowest mode will be resonant in energy with the laser photons as a density of $n=2\times10^{22}$ cm^{-3}. From the classical theory of radiating dipoles, we have computed the in phase and quadrature components of the radiated field in a direction orthogonal to the optical field. The minimum spacing for which the radiative fields will constructively interfere is at a separation of $1.2\lambda_{Si}$ or about 375nm. This interaction distance compares favorably with the 350-380nm values obtained from our SEM experiments.

The proposed mechanism should result in a large increase in the laser energy deposited micro-heterogeneously at the surface near the damage threshold. It is not clear, however, how the material will relax such an intense, fast, local electronic excitation.

In summary our studies of the isointensity laser damage kinetics of crystalline silicon, while still continuing, have led to the following conclusions:

(1) Multiple picosecond pulse laser damage of silicon is a first order phase transformation which may be accessed by laser induced charge density jumps at intensities near to those required for homogeneous melting.

(2) Multiple pulse damage transformation kinetics indicate that large area damage is a micro-heterogeneously nucleated process. This data suggests that a relevant phase diagram for silicon contains a metastable region in which charge density clusters can be elevated to or beyond the liquid phase.

(3) The identification of a new, and possible widespread, laser damage mechanism, in which energy transfer is by resonant surface plasmons on small charge density clusters.

C. FOLLOW-UP STATEMENT: All of the work involving the study of reaction paths at metal-semiconductor interfaces described in the preceding section is continuing under the new 3 year JSEP contract.

The research involving the use of picosecond laser techniques to both excite and study non-equilibrium phase transitions in solids will, however, be split between Research Units SSE83-1 and QE83-1 in the next 3 year program. SSE83-1 is the continuation of the present unit and the laser kinetic research in this unit will be focused on (1) exploring the use of laser kinetic techniques to probe the non-equilibrium phase diagram of semiconductors and (2) monitoring the recrystallization reaction kinetics of glassy and amorphous semiconductors.

Since the experimental techniques developed in the past 3 years appear to be especially productive in shedding new light on the difficult problem of understanding laser-induced damage in solids we will, in Research Unit QE83-1, expand these techniques and apply them to the study of laser-induced damage in a wider variety of materials to include metals and insulators.

D. REFERENCES

1. M.F. Becker, R.M. Walser and R.W. Gunn, "Fast Laser Excitations in VO_2 at the Semiconducting-Metallic Phase Transition," in Picosecond Phenomena, C.V. Shank et al eds., Springer-Verlag, New York, 1978; and "Fast Laser Kinetic Studies of the Semiconducting-Metal Phase Transition in VO_2 Thin Films," in Laser-Solid Interactions and Laser Processing 1978, S.D. Ferris et al. eds, A.I.P., New York, 1979.

2. R.W. Bene' and H.Y. Yang, "Solid State Nucleation in the Ti-Si Ultrathin Film System," J. Electron. Mater. 12, no. 1, pp. 1-10, Jan. 1983.

3. R.W. Bene', "First Nucleation Rule for Solid-State Nucleation in Metal-Metal Thin Film Systems," Appl. Phys. Lett. 41 (6), pp. 529-531, September 15, 1982.

4. S.D. Mukherjee, C.J. Palmstrom, and J.G. Smith, "The Thermal Stability of Thin Layer Transition and Refractory Metallizations on GaAs," J. Vac. Sci. Technol. 17 (5), pp. 904-910, Sept./Oct. 1980.

5. J.O. Olowalafe, P.S. Ho, H.J. Hovel, J.E. Lewis and J.M. Woodall, "Contact Reactions in Pd/GaAs Junctions," J. Appl. Phys. 50 (2), pp. 955-962, Feb. 1979.

6. A. Oustry, M. Caumont, and A. Escant, "Intensities of Evaporated Palladium Thin Films with GaAs," Thin Solid Films 79, pp. 251-256, 1981.

7. J.R. Waldrop and R.W. Grant, "Interface Chemistry of Metal-GaAs Schottky-barrier Contacts," Appl. Phys. Lett. 34 (10), pp. 630-634, May 15, 1979.

8. J.C. Phillips, "Topology and Structure of Non-Crystalline Solids," Cambridge Structure of Glass Conference 1982, to be published.

9. M.F. Becker, R.M. Walser, J.G. Ambrose, and D.Y. Sheng, "Picosecond 1.06μm Laser-Induced Amorphous Phases in Thin, Single Crystal Silicon Membranes," Picosecond Phenomena II, R.M. Hochstrasser, et al, eds. Springer-Verlag, Berlin, pp. 290-293 (1980).

10. R.M. Walser, M.F. Becker, J.G. Ambrose and D.Y. Sheng, "Heterogeneous Nucleation of Spatially Coherent Damage Structures in Crystalline Silicon with Picosecond 1.06μm and 0.53μm Laser Pulses," Laser and Electron-Beam Solid Interactions and Materials Processing, J.F. Gibbons, et al, eds., Elsevier North-Holland, Inc. pp. 177-184 (1981).

11. D.Y. Sheng, R.M. Walser, M.F. Becker and J.G.Ambrose, "Heterogeneous Nucleation of Damage in Crystalline Silicon with Picosecond 1.06μm Laser Pulses," Appl. Phys Lett., 38, 99 (1981).

12. R.M. Walser, M.F. Becker and D.Y. Sheng, "Laser Damage of Crystalline Silicon by Multiple 1.06μm Picosecond Pulses," in Proceedings of the 13th Symposium on Optical Materials for High Power Lasers, Boulder, Colorado (1981).

13. M.F. Becker, R.M. Walser, Y.K. Jhee and D.Y. Sheng, "Picosecond Laser Damage Mechanisms at Semiconductor Surfaces," Proceedings of SPIE Laser 82 Symposium on Picosecond Lasers and Applications, Los Angeles, California (Jan. 1982).

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE82-2 SPECTROSCOPIC STUDIES OF METAL/SEMICONDUCTOR AND METAL/METAL OXIDE INTERFACES

Principal Investigators: Professor J.L. Erskine (471-1464)
Professor J.M. White (471-3949)

Graduate Students: Y. Chang, S. Shi, H. Peebles, P. Blass and K. Thrush

A. OBJECTIVES: The scientific objective of this research unit is to investigate atomic and molecular level properties associated with selected solid surfaces and solid state interfaces. The work is divided into three related subareas: 1) metal/semiconductor interfaces, 2) metal and semiconductor surface/adsorbate systems, 3) metal/metal and metal/metal oxide systems.

Research on metal/semiconductor interfaces is focused on understanding the electronic structure and composition of silicide structures which form when metal atoms deposited on a semiconductor surface react to form an interface. Particular emphasis is being directed towards understanding structural, metallurgical and electronic properties of the silicide interfaces which affect selective growth processes and electrical characteristics, namely the Schottky barrier height. This work utilizes Auger electron spectroscopy (AES), to characterize near surface composition, low energy electron diffraction (LEED) to determine geometrical structure, angle resolved photoelectron emission spectroscopy (ARPS) to study electronic properties of the constituent atoms, x-ray photoelectron spectroscopy (XPS) to study the chemical state of silicon and the deposited metal, and transmission electron diffraction (TED) to study interface crystal structure and composition.

Research on surface/adsorbate systems is primarily oriented towards supporting our work on metal/semiconductor interfaces and on metal/metal oxide interfaces. In preparing any solid state interface, impurity atoms and molecules are incorporated from the background of atomic and molecular species in the vacuum chamber. These impurities can chemisorb at surfaces where interfaces are being formed and can influence the growth kinetics, electronic properties, and crystal structure of the interface. Our research includes investigations of the structure and composition of selected adsorbates on semiconductor, metal and metal oxide surfaces with emphasis on materials used in interface systems being investigated under metal/semiconductor and metal/metal oxide headings. Several state-of-the-art experimental techniques are available to accomplish this work. These include the capability to obtain the vibrational spectra of atoms and molecules at surfaces using high resolution electron energy loss spectroscopy (EELS). These capabilities provide an opportunity to obtain detailed structural information related to species adsorbed at solid surfaces.

Research on metal/metal oxide interfaces is focused on the development of depth profiling and analysis methods of studying the top most atomic layers that form when a clean metal is exposed to oxygen. This work utilizes electron spectroscopy, particularly XPS, to obtain substrate core level intensities. Of great interest are satellite intensities of core levels which reflect changes in the metal/metal oxide interactions.

B. PROGRESS: We have made significant progress in several subareas indicated in Section A which summarizes our objectives. This section outlines scientific progress in these subareas and describes current efforts to improve the instrumentation required for our research.

1. Metal Semiconductor Interface

Our last progress summary reported that we had successfully produced high quality epitaxial films of NiSi on Si(111) and Si(100) substrates and had obtained the first detailed description of the electronic structure using angle resolved photoemission [1]. Our results were useful in checking several recent calculations [1-3].

We have recently studied the low coverage interaction of Ni atoms with Si(100) surfaces and have discovered that it is possible to form a diffusion layer of Ni atoms in the Si lattice with novel properties [4]. We believe that the diffusion layer is characterized by Ni atoms in interstitial voids of the Si lattice, and that these Ni interstitial defects can account for selective growth processes based on a model proposed by Tu [5]. The diffusion layer is not depleated by prolonged annealing, and the stoichiometry of the layer is $NiSi_2$.

Our work on the diffusion layer and bulk electronic properties has provided the basis for careful studies of interface formation and growth. We have obtained a detailed picture of the room temperature growth of silicide-Ni contacts at Si surfaces using Auger and photoemission spectroscopy, and by measuring work function changes [6].

Interface formation studies were extended to higher temperatures and these experiments have yielded what appears to be an important discovery. All interfaces we have studied to date show evidence of having an ordered Si-rich stoichiometric phase at the interface. We believe that this ordered phase is the diffusion layer phase which we discussed previously [4]. Our UPS studies have established that a Si rich silicide is always present during the initial phase of interface formation. This phase can be identified along with the stoichiometric phases which nucleate and grow by selective growth at various temperatures (Ni_2Si at 200 C and NiSi at 430 C). Transmission electron diffraction (TED) shows that the silicon rich phase is ordered and corresponds to an fcc superlattice of Ni atoms. This result has important implications [7]. First, it provides a basis for accounting for the constant Schottky barrier height in Ni silicide interfaces

independent of the silicide phase which forms the "metal" contact. Second, it suggests that either the interface phase can bypass selective growth to form $NiSi_2$ or that the diffusion layer (which has the same stoichiometry but different crystal structure) forms. If the actual structure is the diffusion layer structure as we have suggested, then this result can account for selective growth.

2. Metal/Metal Reactions

The addition of small (submonolayer) amounts of potassium (K) on metal substrates has generally been characterized with a decrease in binding energies of core and valence electrons of the substrate and an increase in such energies for K due to electron donation by the alkali to the conductor. We have completed preliminary studies on the effect of variable amounts of K dosed onto the surface of single crystal Si using AES and XPS. XPS results indicate no shift in the core electron levels of K and Si as a function of K doseage, but AES shows an increase in the binding energy (or decrease in relaxation) for the Si valence orbitals. At greater K coverages, probably corresponding to multilayer formation, Si energies cease to change while K evinces an increase in valence binding energies. This, with the unexpected ability of Si to support multilayers of K, suggest future spectroscopic work to probe further the physical properties of this system as well as to explore changes in Si surface chemistry with K adaptions.

We have also continued work involving Ag deposition on Rh(100) with particular emphasis on the growth of epitaxial layers and the coadsorption of CO and H_2 on this system. Parts of this work are being published in a feature article in the Journal of Physical Chemistry [10].

3. New Instrumentation

We have received information from the National Science Foundation (Division of Materials Research) that our synchrotron radiation beam line will be funded. This project will provide support to establish two beam lines at the Aladdin storage ring facility in Stoughton, Wisconsin. The beam lines will consist of a 6-meter torrodial grating monochromator (photon energy 10-200 eV) and an extended range grasshopper monochromator (photon range 20 eV - 1500 eV). This instrumentation will increase tremendously the range of material science research we are able to conduct through our JSEP center.

Local high resolution x-ray photoelectron spectroscopy facilities are needed to conduct some of our planned experiments. We have recently had visitors from Leybold-Heraeus (Dr. Martin Wilmers) who came to Austin to discuss application of the capabilities we have developed in electron optics to help design a high resolution multichannel detection x-ray photoelectron spectrometer. DoD instrument

program funding would make it possible to pursue this state-of-the-art instrument.

C. CURRENT RESEARCH: The overall scientific objective of our current and planned research program remains unchanged. We are working toward establishing accurate interface models for selected metal silicon interfaces. In addition, our work is aimed at understanding nucleation and growth mechanisms, transport phenomena and reaction kinetics which lead to interface structures and which also have bearing on the stability and electrical characteristics of the interfaces.

Based on our recent results on nickel silicide-silicon interfaces we plan to pursue several new directions. One of our first priorities is to investigate the evolution of the Ni silicide interface using high resolution valence band XPS. The reaction layer which is formed when Ni interacts with Si to form a silicide is approximately equal to the escape depth of electrons (about 12 Å) for photon energies we have available in our lab (resonance lamp sources 16-48 eV). The escape depth for electrons at 1400 eV is considerably larger, and will permit the actual interface to be probed. Valence band XPS results when compared with corresponding UPS studies will yield important information related to the interface composition and electronic properties which is not available by other techniques.

We are also planning to correlate Schottky barrier heights measured on our own samples with the structural, compositional and electronic properties we are obtaining for these interfaces. The barrier height may be deduced from core level photoemission data, and may also be measured directly from threshold photoconductivity measurements. Our recent work indicates that the barrier height in Ni silicides is closely related to the interface structure and stoichiometry. If we can obtain relationships between the structural and compositional properties of the interfaces and the barrier height, it may be possible to make progress towards a general description of barrier heights in reactive metal contacts.

We have not succeeded in forming truly thin epitaxial silicide layers, however there is now some evidence that this is possible [8]. We are continuing our efforts to produce interfaces having an ordered silicide overlayer thin enough (10 Å) to permit study of the electronic structure of the interface by UPS. We would like to search for interface electronic states, and also use UPS and XPS to investigate impurity migration and interface stability under annealing and other perturbations.

Future plans include work of a similar nature on other silicide systems. we are currently examining the prospects of studying Co and W silicides and are looking at some of the silicides which have already been studied fairly thoroughly such as Pt and Pd. Some ordered phases of these silicides have been reported to occur by selective growth [9] and there is a possibility that ordered

structures exist at the interface as we have shown in the case of Ni on Si(100).

D. REFERENCES

1. Yu-Jeng Chang and J.L. Erskine, Phys. Rev. B26, 7031 (1982).

2. D.M. Bylander, L. Kleinman, K. Mednick and W.R. Grise, Phys. Rev. B26, 6379 (1982).

3. Y.J. Chabal, D.R. Hamann, J.E. Rowe, and M. Schluter, Phys. Rev. B26, 7598 (1982).

4. Yu-Jeng Chang and J.L. Erskine, Phys. Rev. B26, 4766 (1982).

5. K.N. Tu, Appl. Phys. Lett. 27, 221 (1975).

6. Yu-Jeng Chang and J.L. Erskine, J. Vac. Sci. Technol., in press.

7. Yu-Jeng Chang and J.L. Erskine, submitted to Phys. Rev. B.

8. R.T. Tung, J.M. Gibson, and J.M. Poate, Phys. Rev. Lett. 50, 429 (1983).

9. G. Ottaviana, J. Vac. Sci. Technol. 16, 1112 (1979).

10. J.M. White, J. Phys. Chem., in press.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE85-1 SOLID STATE INTERFACE REACTIONS AND INSTABILITIES

Principal Investigators: Professor R.W. Bene' (471-1225)
Professor R.M. Walser (471-5733)

Graduate Students: H. Ehsani,Segeun Park , Won Woo Park and H.Y. Yang

A. RESEARCH OBJECTIVES: The common research objective of the work reported in this unit is to gain a detailed understanding of the kinetic selectivity of the condensed phase. We are concerned with the study of how materials are destabilized by non-equilibrium and far- from-equilibrium excitation and the relationships between the excitation and the selection of unstable and metastable states available to them.

The distinguishing feature of kinetic selectivity is the observation that the excited state is relaxed by a metastable, or possibly, unstable state. A good example of this is in silicide formation where, according to our model [1-3], the surface excited states produced by deposition are relaxed, initially by the formation of a 2D glassy state, and eventually through the formation of a silicide when this glassy layer itself becomes kinetically unstable. The process kinetically selects a silicide which is not necessarily the lowest free energy silicide in the system, but instead is related to the kinetically induced glassy state through its internal structure. One possible way of selecting the kinetics is through the maximization of the excess free energy degradation rate as discussed in reference 3. Of course, it is possible that the specific kinetics of the process fortuitously correspond to equilibrium, or energetic, silicide selectivity in isolated cases.

Kinetic selectivity is of extreme importance in microelectronics processing where virtually every interface in, for example, a silicon integrated circuit, is not at equilibrium. The electronic properties of the ~2D metastable states at the interfaces dominate the performance of ohmic contacts, Schottky barriers, FET's, etc. In addition, the thermodynamic proximity of these states to other metastable or stable states is the origin of most reliability problems in microelectronics.

The specific objectives of the first study are to develop a set of rules for predicting the first nucleation product in solid state reactions, to understand the kinetic selection criteria underlying these rules, and to measure properties of the interface region undergoing the evolution to first nucleation. The properties measured are structure and topology using transmission electron microscopy and diffraction (TEM/TED), stress, surface resistance, noise, dielectric response, and magnetic properties. The interfacial systems under study are those between semiconductor substrates (Si, GaAs, CdTe, $Hg_xCd_{1-x}Te$) and metals (Cu, Co, Ni, Ti, Pd, Pt, V, etc.).

Another objective of this work has been to understand the effect of small impurity concentrations on the stability of amorphous materials and on amorphous-crystalline interfaces. Small traces of impurities in concentrations of less than 1 at.% have profound influence on the kinetics of recrystallization of amorphous materials and on phase transitions that occur in them. Impurity effects of this type are among the most prevalent and important problems in materials science and there is at present only an unsatisfactory empirical understanding of the problem. Progress in this area has been primarily limited by the experimental difficulties of (1) controlling the type and amount of impurities present in the experiment and, (2) conducting in-situ studies of the dynamics of the impurity modified processes. Ion implantation offers an interesting way to overcome the first set of problems and can be used to introduce a known distribution of impurities away from the surface in locations where solid phase reactions can be studied free from undesirable surface contamination.

We have conducted two studies of the effects of small implanted impurity concentrations on the stability of amorphous materials. The first was concerned with the effect of impurities on solid phase epitaxal (SPE) regrowth of self-ion amorphitized crystalline silicon. The objective of this work was to analytically characterize and model the "electronic effects" of electrically active impurities on the kinetics of SPE. This effect is important for understanding and controlling the annealing of implantation damage produced in silicon wafers during integrated circuit processing. The electronic impurity effect is one in which the effect of an impurity in accelerating or retarding the SPE rate is completely compensated by introducing an identical concentration of an impurity of the opposite conductivity type. The effect is regarded as one in which the chemical effect of interest is equivalent to a shifting of the electronic Fermi level. Previous studies of the electronic impurity effect in SPE produced only qualitative results and lacked the experimental precision to allow the processes to be analytically modeled. To overcome this we developed a new, one sample, in-situ technique to measure the kinetic parameters of SPE. This technique utilized an CW laser interferometer to study SPE kinetics during furnace annealing.

The second study was somewhat different because we were concerned with observing the effects of an implanted impurity on inducing and modifying an electronic phase transition in a model material. Our objective was to systematically study a phase transition produced by the energy transferred to an amorphous material from the impurity during implantation. The problem is of practical interest, for example, in understanding how organic materials are beneficially modified by ion implantation for applications such as; ion beam lithography; and ion beam induced, conductive polyimide vias. In our research we compared the effects of implantation of a relatively heavy ion (^{28}Si) on the pyrolysis of polymeric carbon thin films, with those produced by a light ion (^{1}H). The specific objective was to assess the possible selective roles of nuclear (dominant in stopping ^{28}Si) and electronic energy transfer (dominant in stopping ^{1}H) in altering the course of the insulator-metal phase transition that occurs in the ion induced pyrolysis of a model organic material. In our work we used optical (FTIR, UV/VIS) spectroscopy, Auger spectroscopy, TEM, field effect and conductivity measurements, to characterize the difference in the changes produced in the chemical bonding, microstructure, and electronic conductivity.

B. PROGRESS: The progress we have made in understanding metal-semiconductor contacts is quite substantial and of a diverse nature. We developed rules for systematically categorizing and predicting phase nucleation based upon the concept that thin film nucleation is a kinetic process. We have done this for both metal-elemental semiconductor cases[1] and metal-metal cases[2]. We have developed a kinetic model based upon kinetic selection by the maximum energy degradation rate of the system. In most cases this process is expected to agree with the previous rules, but modification of these rules based upon this kinetic model appears to improve the agreement(4) with experiments. Also, the kinetic model allows us to make predictions of new phase and/or better thin film morphology upon specific changes in processing of silicides. We are presently pursuing two possible variations for the production of better $TiSi_2$ films on Si substrates.

Measurement of the properties of the ultrathin layers of metals deposited on Si prior to silicide nucleation have indicated that: a semiconducting/metallic transition occurs in the thin intermixed film prior to nucleation in several films [5,6,7]: excess noise increases enormously prior to the transition, whereupon a precipitous drop takes place (8): and, stress changes relatively slowly [9]. In addition, measurements on Ti/Co/Si [10] and Ti/Al/Si [11] thin film systems show the interaction of two closely spaced interfaces on phase formation and nucleation temperatures. Both systems show formation of metastable silicide phases [10,11,12], and in the Ti/Al/Si case, Ti-Al metastable phases which depend on the spacing of the Ti-Al and Al-Si interfaces.

Interfacial compound phase formation has also been studied for Cu [13], Co [14], Ni [15] on CdTe and MCT. Two results stand out; the formation at the interface is dominated by kinetic behavior; and the initial phase is higher in energy than the metal/CdTe or the metal/MCT abrupt

interface. By doing the measurements for both r-f sputtering and e-beam evaporation it is seen that the condensation energy alone is sufficient to cause this effect. It is thought that the initial kinetic rate limitation is the extremely low thermal conductivity of CdTe and MCT (~1/50 that of Si). In addition, it is found that compound selection follows the "MC" rule [2] in the binary metal-Te system.

We have made substantial progress in characterizing the effects of implanted boron impurities on the kinetics of intrinsic (100) silicon. We are collecting the data with CW laser interferometric measurements made continuously, in-situ, during annealing in a high vacuum RF heated graphite furnace. This system (reported in the previous annual report) is capable of resolving the the position of the recrystallizing amorphous-crystalline interface, near the surface, to within 10 Å. This is a substantial improvement over previously reported techniques (RBS and conventional TEM with typical position accuracy of 100-200 Å) which utilize multiple samples and isochronal annealing. With this system we are able to resolve the activation energy (E_a) of silicon SPE to within +/- 87 meV compared to the estimated +/- 200 meV accuracy of previously reported techniques. We measured(16) the activation energy of intrinsic (100) silicon at 2.69 +/- 0.09 eV; a value which is nearly the mean of all previously reported values which ranged from 2.3 eV to 2.9 eV. The precise value of this energy is important in helping to identify the fundamental atomic rearrangements (activated states) that rate-limit recrystallization. Since the maximum change in E_a produced by the impurities of interest is < 0.5 eV, it is apparent that the physics of the process could not be resolved without the increased precision.

In addition we have shown that the variation of E_a produced by a change in the impurity concentration can be resolved by the CW laser interferometer with an accuracy of +/- 23 meV. The increased precision is achieved by removing systematic errors through the use of a one-sample, in-situ measurement. We were thus able to accurately measure the change in the regrowth rate and activation energy produced by precisely known concentrations of implanted boron impurities over the concentration range from 5×10^{18} cm^{-3} to 3×10^{20} cm^{-3}. These results were reported in reference [17] and show that the regrowth velocity depends non-linearly on the boron concentration over this range. For smaller concentrations (< 10^{19} cm^{-3}) a linear relationship is found and supports, in this concentration range, a simple Fermi level shifting model for the origin of the electronic impurity effect.

With the increased precision of our measurements we were able, for the first time, to separate out the effect of impurities in changing the activation entropy (ΔS) of SPE from changes in the activation enthalpy (E_a) [17]. The results are surprising and, for boron, show that the two changes are of about the same magnitude and negatively correlated. There is an inflection point in the change of the regrowth velocity with boron concentration, below which the process is dominated by reductions in E_a and, above which it is dominated by increases in ΔS. The inflection point occurs near the boron concentration that corresponds to the estimated solubility limit.

More recently we have been studying intrinsic and boron impurity modified SPE in (111) silicon. With the CW laser interferometer we have observed and reported(18) the roughening transition that attends the non-planar SPE regrowth on the (111) plane. We have been able to measure the average regrowth velocity and activation energy of intrinsic (111) silicon. Our value of E = 2.67 eV agrees reasonably well with previously reported values and confirms that the activation energy of intrinsic silicon SPE is, apparently, independent of the substrate orientation. We also reported the first measurements of the effect of impurities on (111) SPE. Boron, in the same concentration range used in the (100) SPE experiments, produced a reduction in the activation energy of (111) SPE comparable to that produced in (100) SPE. All of the work to date will be comprehensively reviewed in the near future [19-20].

We have also recently completed, and reported the results [21-23] of, a study of the chemical, structural, and electronic changes produced by implantation in polymeric carbon thin films. Our motivation was to study the type of damage-induced, insulator-conductor phase transitions observed in various polymeric and non-polymeric organic thin films. These are characterized by large (10^{14} to 10^{15}) increases in electrical conductivity, the destruction of molecular structure and modification of polymer chains, carbonization, and the release of gaseous by-products. All of the prior investigations utilized high energy (MeV) or intermediate range energies (100-250 keV), heavy ion beams which deposit high energies along the ion tracks. In this work we explored the use of low energy (20 keV) light ion ($^{1}H^{+}$) beams for which the energy deposition was insufficient for converting the organic film into a high conductive state for doses as high as 10^{17} ions/cm^{2}. The films used were polymeric carbon films prepared from ultrapure furfuryl alcohol, and used in this study because of their purity and because their pyrolysis has been the subject of extensive prior research.

In the experiments we compared the effect of various implanted doses of a heavy ion ($^{28}Si^{+}$) with those produced by light $^{1}H^{+}$ ion doses on the properties of polymeric carbon thin films pre-pyrolyzed at various temperatures in the vicinity of the 600-700 °C critical temperature for the insulator-conductor carbonization phase transition. The results, interpreted from the measured temperature-dependent electrical conductivity, and FTIR/UV/VIS optical spectroscopies, unambiguously show that low energy, light ion implantation can alter the conduction mechanism of the pre-pyrolyzed films without significantly changing the magnitude of the conductivity. This conclusion is based on a comparison with the changes produced by the heavy ion implantation and from the change in the exponent of the thermally activated conductivity. The change in the exponent suggests that the conduction mechanism was changed from a 3D variable range hopping transport to a more 1D process.

The results of these experiments suggest that the electronic energy transfer from the light $^{1}H^{+}$ ions may selectively excite non-thermal bond rearrangements (possibly by the selective reduction of cross linking) that can modify the dominant conduction paths, without dramatically increasing their density. In contrast, the energy transfer from heavy ion beams is observed to produce changes in the chemical bonding and electronic conductivity that is nearly the same as in thermal pyrolysis.

C. FOLLOW-UP STATEMENT: The research in this unit is being terminated at the conclusion of the three year program ending in March 31, 1986. The scope of the research is now very substantial and various parts of the work will be continued (or are proposed for continuation) as separate research projects under different sponsors. In the following we describe the follow-on efforts of each of the separate parts of the continuing research.

The part of this work dealing with Silicide processing is being continued under the TATRP project entitled "Novel Approaches to Growth of Refractory Metal Silicides," and the part on metal-MCT interfaces is continuing with Texas Instruments support under a contract entitled "A Study of Structures which occur at the interfaces between $Hg_{1-x}Cd_xTe$ and other materials."

The research on solid phase epitaxy in semiconductors is now being sponsored by the State of Texas as part of the Texas Advanced Technology Research Projects program at the University of Texas. It is funded for two years (through the 1986/87 academic year) as part of a research unit concerned with the transient annealing of semiconductors. In addition, a proposal for conducting a fundamental study of the effects of impurities in solid phase interface reactions is in preparation and will be submitted to the NSF in the Fall of 1986.

D. REFERENCES

1. R.M. Walser and R.W. Bene', Appl. Phys. Lett. 28, 624 (1976).

2. R.W. Bene', Appl. Phys. Lett. 41(6), 529 (1982).

3. R.W. Bene', "A Kinetic Model for Solid State Silicide Nucleation," submitted to J. App. Phys.

4. H.G. Nam and R.W. Bene', in preparation.

5. R.W. Bene', R.M. Walser, G.S. Lee, and K.C. Chen, J. Vac. Sci. Technol. 17, 911 (1980).

6. N.I. Cho, Masters Thesis, unpublished.

7. El-Saied M. Aly and J.P. Stark, J. Appl. Phys. 53(4), 3063 (1982).

8. R.W. Bene', G.S. Lee, and N.I. Cho, Thin Solid Films, 129, 195 (1985).

9. Y.H. Ku and R.W. Bene', in preparation.

10. H.Y. Yang and R.W. Bene', J. Appl. Phys. 59(5), 1525 (1986).

11. C.C. Han and R.W. Bene', Appl. Phys. Lett. 47(10), 1077 (1985).

12. R.W. Bene' and H.Y. Yang, J. Electron. Mater. 12(1), 1 (1983).

13. H. Ehsani and R.W. Bene', J. Appl. Phys. 59(8), 2808 (1986).

14. H. Ehsani and R.W. Bene', submitted for publication to J. Appl. Phys.

15. H. Ehsani and R.W. Bene', in preparation.

16. W. W. Park and R. M. Walser, submitted to J. Mater. Res., June, 1986.

17/18. W. W. Park and R. M. Walser, 2 papers submitted to Appl. Phys. Lett, June, 1986.

19. W. W. Park and R. M. Walser, to be submitted to J. Appl. Phys., June, 1986.

20. R. M. Walser, Abstract submitted for Materials Research Conf., Boston, Dec. 1986. June (1986).

21. S. Park and R. M. Walser, Carbon 23, 701 (1985).

22. S. Park and R. M. Walser, submitted to J. Appl. Phys., June, 1986.

23. S. Park and R. M. Walser, "Ion Implantation of Polymeric Carbon Thin Films," presented at Symposium on Transport and Excitations in Polymers, Materials ResearchSoc.,Boston,Dec.1985.

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE85-2 ELECTRONIC PROPERTIES AND STRUCTURE OF METAL SILICIDES AND INTERFACES

Principal Investigator: Professor J.L. Erskine (471-1464)

Graduate Students: Jose Araya, Craig Ballentine and Joe Comunale

A. OBJECTIVES: The scientific objective of this research unit is to investigate the structure and electronic properties associated with selected solid surfaces and solid state interfaces. Particular emphasis in our program during the current three year grant period has been directed toward developing new experimental probes to study surface reconstruction, diffusion at surfaces and interfaces and the electronic properties of ultra-thin metal overlayer systems deposited onto various substrates. Our present goal is to develop instrumentation which will enable our group to combine important new sample preparation methods such as molecular beam epitaxy (MBE) with powerful probes of electronic properties, magnetic properties and surface structure based on electron spectroscopic techniques. This combination of sample preparation and analysis will enable us to address a broad range of new issues related to interface formation and growth of a variety of metal and semiconductor interface systems as well as ultra-thin magnetic systems.

B. PROGRESS

1. Metal Semiconductor Interfaces

We have studied the low coverage interaction of Ni atoms with Si(100) surfaces and have reported that it is possible to form a diffusion layer of Ni atoms in the Si lattice with novel properties [1]. We believe that the diffusion layer is characterized by Ni atoms in interstitial voids of the Si lattice, and that these Ni interstitial defects can account for selective growth processes based on a model proposed by Tu [2]. The diffusion layer is not depleted by prolonged annealing, and the stoichiometry of the layer is $NiSi_2$. Several other groups are now studying thicker films of this system using LEED [3], surface EXAFS [4] and TEM [5]. These groups also find a $NiSi_2$ stoichiometry interface, but believe that the crystal structure is the CaF_2 structure of $NiSi_2$ rather than our proposed diffusion layer structure [6,7]. The $NiSi_2$ structure has an excellent lattice match to the Si lattice substrate, but can grow in one of two rotational twin structures called type A and type B lattices. Interfaces of type A and type B yield different Schottky barrier heights [5]. We have attempted (unsuccessfully) to grow $NiSi_2$ layers sufficiently thin on Si(111) and Si(100) substrates to investigate these interesting interfaces using electron spectroscopy. Such studies using angle resolved photoelectron emission spectroscopy will provide a direct determination of the electronic structure of the interface, and should provide important insight into the origin of the difference in Schottky barrier height for the type A and type B silicide layers. Co-evaporation of metal and silicon under precisely controlled MBE conditions permits fabrication of the very thin silicide interfaces needed for these studies. We are currently constructing a MBE reactor coupled to an electron spectrometer which will permit such interface studies. Had we been able to purchase some equipment based on our supplemental proposal, our group might have been able to perform the first such experiments. Another group has the same idea, and is beginning to exploit it [8].

2. Rare Gas Atoms on Surfaces

Recent experimental [9] and theoretical [10] results suggest that the binding energy of electronic states associated with rare-gas atoms on surfaces exhibit important features which are related to the work function appropriate to microscopically small regions of a substrate. The chemical activity associated with small regions such as steps and corners, and the site specific nucleation of phases during metal deposition on semiconductor surfaces makes the determination of the local work function potentially very important. We have completed an extensive study of Xe, Ar and Kr gas physisorbed on βNiAl(110) - a crystalline alloy surface with well known stoichiometry. We have observed interesting new phenomena asociated with the local surface crystal field (splitting of the excited state spectral lines) [11] and have also shown that the binding energy of the electronic states do not necessarily lead directly to an appropriate value for the average surface work function [12].

3. New Instrumentation

Ray tracing studies for our 6-meter toroidal grating monochromator are complete [13] and good progress has been made in constructing the instrument.

The final construction phase involving the exit slit carriage and mirror mounts is also in progress and we expect to complete the project by December 1986. This instrument will be installed at the NSLS facility at Brookhaven National Labs and will provide a valuable new instrumentation resource for materials science research at The University of Texas.

We have also completed a feasibility study [14] of new multichannel detection electron optics which will be used in our studies of semiconductor surfaces. A prototype analyzer has been constructed and will be tested during the next six months. Based on our feasibility analysis, our track record of designing and constructing state-of-the-art instrumentation, and the important new research this new instrument will make possible, our group has been awarded a University/DoD research grant. If this analyzer is successful, it will revolutionize an important area of electron spectroscopy.

C. CURRENT RESEARCH: We have recently shown (under AFOSR sponsorship) that high resolution electron energy loss spectroscopy (EELS) can be used to determine the surface phonon bands throughout the two-dimensional Brillouin zone [15,16]. Surface vibrational properties are closely related to surface structure, and lattice dynamical calculations [16] permit structural models to be tested based on vibrational data. Recent theoretical studies of semiconductor surface vibrational properties suggest that surface phonon measurements can provide direct information related to the mechanisms responsible for surface reconstruction [17-19]. We are planning to apply electron scattering spectroscopy to the Si(111) and Si(100) reconstructed surfaces to investigate these predictions.

Recent experimental work using electron scattering (EELS) and photoelectron emission has indicated that the reconstructed surfaces of several semiconductors are metallic [20,21] and exhibit novel dielectric properties. One of the first experiments we plan to conduct using our new high-resolution electron spectrometer is to investigate the metallic-like states at the Fermi level of reconstructed silicon and germanium surfaces.

Finally, we have begun a new program in which the magnetic properties of ultra-thin magnetic films grown on a variety of substrate materials are being investigated. Preliminary experimental results by our group [22], and some results involving two cooperative experimental and theoretical efforts [23,24] have demonstrated that this work is very promising. The experiments involve novel materials synthesis based on MBE and analysis of the structure, electronic and magnetic properties based on various electron spectroscopic probes. Theoretical/numerical support based on LEED structure analysis and first principal predictions of

the electronic and magnetic properties add a dimension to our work which permits us to address fundamental questions associated with the physical behavior of ultra-thin films, interfaces, and superlattices. This type of collaborative program appears to represent the most productive direction for our JSEP sponsored work to take in the future.

D. REFERENCES (JSEP sponsored work indicated by *)

1. * Yu-Jeng Chang and J.L. Erskine, Phys. Rev. B26, 4766 (1982).

2. K.N. Tu, Appl. Phys. Lett. 27, 221 (1985).

3. W.S. Yang, F. Jona and P.M. Marcus, Phys. Rev. B28, 7377 (1983).

4. F. Comin, J.E. Rowe and P.H. Citrin, Phys. Rev. Lett. 51, 2402 (1983).

5. R.T. Tung, J.M. Gibson and J.M. Poate, Phys. Rev. Lett. 50, 429 (1983).

6. * Yu-Jeng Chang and J.L. Erskine, Phys. Rev. B28, 5766 (1983).

7. * J.L. Erskine and Yu-Jeng Chang, Mat. Res. Soc. Symp. Proc. 25, 353 (1984).

8. R.J. Hauenstein, T.E. Schlesinger, T.C. McGill, B.D. Hunt and L.J. Schowalter, Appl. Phys. Lett. 47, 853 (1985).

9. J. Kuppers, H. Michel, F. Nitschke, K. Wandelt and G. Ertl, Surface Science 89, 361 (1979); J. Kuppers, K. Wandelt and G. Ertl, Phys. Rev. Lett. 43, 928 (1979).

10. N.D. Lang and A.R. Williams, Phys. Rev. B25, 2940 (1982).

11. * M. Onellion and J.L. Erskine, Bull. Am. Phys. Soc. 30, 516 (1985); Phys. Rev. B33, 1440 (1985).

12. * M. Onellion and J.L. Erskine (submitted to Surface Science).

13. Louis Breaux, M.S. Thesis, University of Texas (1985); L.H. Breaux and J.L. Erskine, Nucl. Inst. Methods (in press).

14. F. Hadjarab, M.S. Thesis, Univ. of Texas (1984); F. Hadjarab and J.L. Erskine, J. Electron. Spectros. Rel. Phenom. 36, 277 (1985). (Also see 16 below).

15. R.L. Strong, Ph.D. Thesis, Univ. of Texas (1984).

16. * R.L. Strong and J.L. Erskine, Phys. Rev. Lett. 54, 346 (1985); Phys. Rev. B31, 6503 (1985); also Technical Report: "Advanced Electron Optics for Surface Vibrational Spectroscopy," Interim Rel. Phenom. Report 2, AFOSR-83-0131 (1983); J.L. Erskine, J. Electron. Spect. (in press).

17. W. Goldammer and W. Ludwig, J. de Physique 43, C5-119 (9184).

18. W. Goldammer, W. Ludwig, W. Zieran and C. Falter, Surf. Sci. 141, 139 (1984).

19. D.C. Allan and E.J. Mele, Phys. Rev. Lett. 53, 826 (1984).

20. S.D. Kevan, (private communication).

21. B.J.N. Persson and J.E. Demuth, Phys. Rev. B30, 5968 (1984).

22. M.A. Thompson and J.L. Erskine, Phys. Rev. B37, 6832 (1985) (rapid communication).

23. M.F. Onellion, M.A. Thompson, J.L. Erskine, A. Patten and C.B. Duke, (submitted to Surface Science).

24. M.F. Onellion, C.L. Fu, M.A. Thompson, J.L. Erskine and A.J. Freeman, Phys. Rev. B33, (1985) (rapid communication).

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
SOLID STATE ELECTRONICS

Research Unit SSE85-3 IMPLANTATION AND INTERFACE PROPERTIES OF INP AND RELATED COMPOUNDS

Principal Investigator: Professor Ben G. Streetman (471-1754)

Graduate Students: C. Farley, T. Kim, S. Lester, and H. Shin

A. RESEARCH OBJECTIVES

Several important materials properties of InP make it particularly attractive for use in high-speed field effect transistors (FETs) and integrated circuits, as well as in optoelectronic systems. InP has excellent electron transport properties, very attractive surface electronic properties, and a higher thermal conductivity than GaAs. These materials characteristics make InP a good candidate for use in high-speed field-effect transistors. However, these inherent advantages cannot be exploited in electronic devices and systems without considerable understanding of effects occuring during processing. This information is currently unavailable or is too incomplete to be useful for device fabrication. The objective of this research is to provide a better understanding of two of the most important issues facing a reliable InP FET technology: (a) impurity migration and activation during various implantation and annealing procedures, and (b) formation of a stable InP/insulator interface with a low density of interface states.

In the implantation and annealing studies, our objective is to develop procedures for obtaining controllable donor and acceptor distributions with good electrical activation. Since previous work has shown that considerable migration of impurities occurs during conventional thermal annealing of implanted InP, some form of transient annealing is required. This study includes work on transient and conventional furnace annealing techniques. Surface protection methods including dielectric encapsulation [1] and proximity techniques are studied. Impurity distributions, donor or acceptor activation, interactions with compensating impurities, and effects associated with dual implantation techniques are studied. Since comparisons of these effects in GaAs and InP are important to the interpretation, implantation and annealing studies are made on both of these materials.

Research on InP surface properties include basic studies of ambient/InP interactions and studies of the properties of various interfaces between InP and deposited dielectrics. Investigations of InP surfaces include studies of the interaction of InP with chemical etching solutions, gas ambients, and vacuum environments. Studies of dielectric interfaces include a number of SiO_2 and Si_3N_4 based dielectric systems. Also, the effects of surface preparation and post-dielectric deposition processing on the properties of InP/dielectric interfaces are investigated. This work should improve the current understanding of InP interfaces and help to advance the state-of-the-art InP FET technology.

B. PROGRESS

1. Implantation Studies

a. Simulations

To improve the interpretation of impurity migration and activation, we have developed several computer simulation programs to account for effects of impurity concentration and

damage in the redistribution of implanted impurities. [5,16] This work was motivated by the desire to explain various anomalous diffusion effects such as that observed for implanted Be and Mg. Diffusion simulation is accomplished with a Crank-Nicholson transformation of Fick's second law. [6] The general form of the model for the diffusion coefficient was suggested by the qualitative resemblance of the profiles of Be in InP to those of other acceptors implanted in GaAs and InP.

Using these simulations, we have developed a model for the diffusion coefficient of Be in InP, which gives results similar to those observed experimentally for Be-implanted InP. The resulting profiles suggest that Be and Mg may diffuse by an interstitial mechanism in InP and demonstrate that diffusion at and near the peak of the profile is a critical determinant of the final distribution. It appears that the depletion of Fe and Cr in the regions of fast Be diffusion is related to solid solubility, and it is believed that the presence of Fe and Cr on the In sublattice contributes to the concentration-dependent diffusion. This would explain why the effect was seen in compensated semi-insulating substrates and not in VPE material.

In addition to its application in the specific InP:Be problem, this model can be used as an analytical/predictive tool for estimating impurity migration of multiple implants. Once the diffusion coefficient is found for a single implant, the impurity profiles resulting from annealing multiple implants can be approximated.

b. Furnace Annealing

Much of the ion implantation work has concentrated on the activation behavior of moderate to high dose Si implants. Si activation during furnace annealing was studied for implant doses of 10^{14} to 10^{15} cm^{-2} at an energy of 150keV. Hall effect and PL measurements show that for a 30 minute furnace anneal time, a temperature of 750°C is necessary to produce complete annealing and activation, and at an anneal temperature of 750°C, 20 to 30 minutes is needed. Co-implants of 1×10^{14} cm^{-2}, 150keV Si + P were investigated as a means of controlling substrate stoichiometry to reduce autocompensation of Si donors by Si acceptors. We investigated several variables in this co-implantation study including the energy and dose of the P implant and we observe decreased compensation for co-implanted samples compared to those in which Si alone is implanted. The post-anneal carrier concentration profile is found to depend heavily on the energy of the P co-implant. When the projected range of the P is on the surface side of the Si projected range the P implant results in higher carrier concentrations near the surface. When the P is placed on the bulk side of the Si implant, activation is enhanced deeper in the bulk. This suggests that the P co-implant influences the site selection of Si and causes a larger fraction of the Si to reside on In sites.

We also investigated effects of the dose of the co-implant and found that the maximum benefit is achieved when the co-implant dose is approximately the same as the Si dose. When the P dose is ten times less than the Si dose, the enhancement of Si activation is marginal. Increasing the P dose to ten times the Si dose increases Si activation efficiency; however, it also reduces the sheet mobility so that there is no decrease in sheet resistance. The lower mobility observed for samples with the highest P doses suggests that there may be incomplete annealing of implantation damage and possible formation of P precipitates. We have also studied 10^{14} cm^{-2}, 150keV Si + N co-implants to see if the compensation of Si by N observed in GaAs occurs in InP. A surprising result was that in InP, the activation of Si + N was higher than when Si was implanted alone. This result is being investigated further to determine the nature of this effect.

The influence of compound stoichiometry on the activation behavior of Si implanted into GaAs has also been studied for both furnace and rapid thermal anneals. Si activation is higher in As-rich LEC substrates than in Ga-rich LPE substrates, which is expected since more Si is expected to reside on As sites and act as acceptors in the LPE material. In all cases carrier

concentrations saturate at a maximum value of about 1 x 10^{19} cm^{-3}, and measurements of low temperature mobility indicate very strong compensation of Si donors by Si acceptors.

c. Rapid Thermal Annealing

The activation of Si implanted into InP using an incoherent rapid thermal annealing (RTA) system [11,12] has been studied. Isochronal anneals of 1 x 10^{15} cm^{-2}, 150keV implants have been performed and evidence of the effects of unequal recoil of In and P atoms during implantation has been seen. For samples annealed between 550 and 750°C, a region on the surface side of the projected range with anomalously low carrier concentrations is found. This can be explained by the unequal recoil of In and P during implantation. Phosphorus, which is much lighter than In, recoils much deeper during Si implantation and as a result, there is a net excess of In on the surface side of the projected range of the implant and a net excess of P on the bulk side of R_p. These stoichiometric fluctuations influence the site selection of Si, causing more compensation on the surface side of R_p and less on the bulk side. As the anneal temperature increases, carrier concentration profiles extend further into the bulk, even in 30 seconds anneal times. This suggests that Si begins to diffuse even at 750°C. SIMS profiles of these samples are being taken to confirm this.

The effects of rapid thermal annealing heating cycles on the activation of Si in InP was also investigated. Sample anneal times were varied from 0 seconds to 10 seconds, where 0 seconds corresponds to heating the sample to the anneal temperature, then immediately cooling it down. We found ~25% activation efficiency for 0 second anneals and only an increase to 50% for 10 second anneals. This shows that a significant amount of annealing and activation occurs during the ~5 seconds in which the temperature is raised from 300°C to 750°C. Maximum activation efficiency is reached for high dose implants in about ten seconds, whereas lower dose implants take up to 30 seconds. This demonstrates the difficulties involved in comparing anneal times of conventional furnace anneals where the samples are very slowly heated to their final anneal temperature and times for rapid thermal anneals. Fortunately, RTA anneal times are much less than the three to five minutes needed to produce significant doping of the substrate from the encapsulant. [14]

We have also investigated the proximity cap annealing method for rapid thermal anneals. In this method, an InP wafer is placed in contact with another wafer (generally, but not necessarily InP) which presumably prevents P from evaporating from the InP wafer during annealing. Several interesting results are observed. First, very little dependence on the type of wafer used as the proximity cap is found. We compared Si, GaAs, and InP and found that the activation efficiency of 1 x 10^{15} cm^{-2}, 150 keV implants was the same within experimental uncertainty for all three capping materials. This is understandable when one considers the second unexpected result of these experiments. Carrier concentration profiles of these implants show a 500Å thick p-type region at the InP surface for all proximity capping materials. This demonstrates that even for InP in close contact with another InP wafer, enough P evaporates during annealing that Si atoms near the surface tend to occupy more P than In sites. This result suggests that proximity annealing techniques are insufficient for protecting InP during high temperature annealing. Co-implants of Si + P and Si + Al were also proximity annealed and it was found that the effect of the P implants on the activation of Si was less than in the encapsulated case and that Al co-implants had essentially no effect on the Si activation efficiency. This is not surprising since a significant loss of P during annealing would overwhelm the effects of co-implanted dopants in determining the site selection behavior of Si.

We also investigated the use of pre-anneal heating cycles to remove structural damage prior to high temperature dopant activation. An enhancement of activation efficiency has been

reported for pre-annealing of Si implants in GaAs. All anneals were carried out in a 10% H_2 in N_2 atmosphere. In these experiments, a sample is brought to an elevated temperature (100-600°C) for 30 seconds and then to the anneal temperature (in this case, 750°C) for the specified anneal time. In contrast to results seen in GaAs, no direct correlation is observed between the pre-anneal temperature and the electrical activation of 1×10^{15} cm^{-2}, 150 keV Si implants. Slightly lower sheet resistances are observed for 500°C pre-anneals, but we believe that the high implant doses may mask the effects of a pre-anneal cycle and this experiment might be more appropriate for lower Si implant doses.

In summary, studies of Si activation using furnace and rapid thermal annealing and the effects of co-implantation on implant activation have been performed. It has been demonstrated that P co-implantation can effectively increase Si activation in furnace and rapid thermal anneals. The energy and dose of the P implants are important since activation is enhanced where the P concentration is greatest, but too much or too little P results is higher sheet resistances. These co-implantation results point out that substrate stoichiometry is of fundamental importance in determining the site selection of Si in InP. This is further demonstrated by the fact that Si activation is found to depend on crystal growth conditions and by the fact that a single Si implant can result in the formation of a p-n junction if insufficient care is taken to prevent P evaporation from the InP surface during annealing. It has also been shown that Si can be effectively activated using RTA for times <30 seconds; however, even for these short times proximity annealing techniques are insufficient for protecting the substrate surface from decomposition (regardless of the proximity cap material).

Finally, as an alternative doping technique, the diffusion of Ge into GaAs from a thin elemental source using rapid thermal processing has been investigated. [13] Several types of encapsulants and substrates have been examined. The diffusion and activation of Ge have been found to depend on both the encapsulant and substrate growth conditions. Photoluminescence indicates that Ga vacancies may control dopant diffusion and activation. Very shallow n^+ junctions and nonalloyed ohmic contacts to semi-insulating GaAs have been formed.

2. Surface Studies

Surface studies have been pursued along two lines: (a) basic studies of InP surfaces and ambient/surface interactions, and (b) development and characterization of FET processing techniques. The former studies involved the use of PL as a probe of InP surfaces. It was found that the intensity of the band-edge transition in InP is very sensitive to surface conditions. [15,17] In-situ measurements of room temperature PL intensity have been made in a variety of environments typically encountered during the fabrication of MIS devices. These environments include vacuum, chemical etching solutions, and gas ambients. PL measurements were sometimes combined with conductivity measurements on ion implanted resistor structures in order to better determine the mechanisms responsible for PL intensity changes. Such conductivity measurements allow for the determination of the surface Fermi level position and thus make it possible to separate the effects of band bending from the effects of surface recombination velocity in determining the PL intensity.

The gas ambient experiments involve sequentially exposing InP to oxygen or nitrogen (or some other gas) atmospheres. It was found that room temperature band edge PL intensity of n-type material reversibly increases in N_2 and decreases in O_2. For p^+ material, the PL intensity responds in the opposite sense, increasing in O_2 and decreasing in N_2. Fe-doped InP and p^+ InP under high illumination levels, respond to ambient changes like n-type material does. These PL intensity changes have been correlated with resistance changes measured on n- and p-type resistor structures exposed to changing ambients. These resistance measurements, performed

in the dark and under laser illumination, show that the position of the surface Fermi level is reversibly changed by the adsorption and desorption of oxygen on the InP surface. A comparison of these results with similar experiments on GaAs suggests that the surface state density on these materials is reversibly changed by oxygen adsorption/desorption. This in turn suggests that there are surface states on InP and GaAs which are associated with the satisfaction of bonding requirements between the semiconductor and overlayers and not with semiconductor intrinsic defects, surface stoichiometry, or surface disorder as suggested in the literature.

Research involving the development of InP metal-insulator-semiconductor field-effect transistors (MISFETs) has centered on finding suitable processes for preparing InP surfaces for dielectric deposition, developing suitable dielectric structures and dielectric deposition procedures, and assessing the effects of post-deposition annealing on the electrical characteristics of InP/ dielectic interfaces.

As a tool for removing the native oxide layer prior to plasma-enhanced dielectric deposition, we have studied the effect of H_2 plasma etching in InP. InP was etched by a hydrogen plasma in a plasma-enhanced chemical vapor deposition (PECVD) reactor prior to the in-situ deposition of Si_3N_4 films. Sample surfaces were found to be covered with micron-size agglomerates after silicon nitride deposition. Auger depth profiling revealed that the H_2 etching resulted in a 10nm thick In-rich layer at the interface between the nitride and the InP. XPS was then used to determine the chemical identity of the In-rich layers. This measurement revealed that the In-rich layer contained metallic In. These observations indicate that H_2 plasma etching produces In-rich surface layers which result in the formation of In agglomerates during subsequent silicon nitride deposition. Therefore, H_2 etching is not well suited for in-situ surface preparation of InP.

For dielectric deposition, a PECVD system was developed with the important feature of having the plasma dicharge region located in a part of the reactor remote from the sample. This system allows for the low temperature deposition of dielectric films without problems associated with plasma damage. This system has been used to deposit SiO_2, Si_3N_4, phosphorus-doped SiO_2 and Si_3N_4, and sandwich structures consisting of doped and undoped layers. These P-doped layers were investigated as a means of preventing phosphorus evaporation from the InP surface during the initial stages of dielectric deposition. [10] The presence of P in the dielectric was found to be very helpful in reducing the interface state density at the InP/dielectric interfaces, and interface state densities in the low 10^{11} cm^{-2} eV^{-1} range were fabricated.

Post-deposition annealing of these dielectric layers was also investigated. It was found that relatively low temperature (~400 °C) annealing in forming gas reduces the interface state density of InP/SiO_2 interfaces while high temperature annealing (>600 °C) results in severe degradation of the interface. For InP/Si_3N_4 structures, interface state densities are generally very high; however, high temperature annealing results in significant improvements. The lowest interface state densities are found on InP/SiO_2 structures which incorporate phosphorus in the SiO_2 near the InP surface and which have been annealed at low temperatures.

C. FOLLOW-UP STATEMENT

This work will be continued under JSEP sponsorship. Surface and interface studies will be devoted to the fundamental understanding of InP and GaAs surface effects and their implications for device fabrication. The implant and annealing studies will focus on two issues which are critical to the development of a competitive InP FET technology: activation of low dose channel implants (~10^{12} ions/cm^{-2}) with minimal redistribution of background and compensating

impurities, and activation of shallow (<100 keV) high dose source-drain implants (~10^{15} ions/cm^{-2}) with high activation efficiency, high mobility, and minimal redistribution of other impurities. It is clear from work by our group over the last three years that rapid thermal annealing (RTA) using an incoherent light source will best address these issues. Changes in compound stoichiometry strongly affect impurity activation and migration, and we have begun to study various methods of controlling compound stoichiometry during implant processing. Current work on this research unit has identified the major issues to be addressed and has given us the methods for studying them. In future research we will be able to use these techniques to join theoretical and experimental methods to finally understand these important problems, which have thus far been elusive.

D. REFERENCES

1. J.D. Oberstar and B.G. Streetman, "Thin Film Encapsulants for Annealing GaAs and InP," Thin Solid Films 103, 17-26 (13 May, 1983).

2. S. Banerjee and B.G. Streetman, "Theoretical and Experimental Study of Swept Line Electron Beam Annealing of Semiconductors," J. Appl. Phys. 54, 2947-2955 (June, 1983).

3. A. Bhattacharyya and B.G. Streetman, "Theoretical Considerations Regarding Pulsed Laser Annealing of a-Ge Layers on GaAs," J. Physics D: Applied Physics 16, 2033-2037 (October, 1983).

4. S.K. Banerjee, R.Y. DeJule, K.J. Soda, and B.G. Streetman, "Planar Be-Implanted GaAs Junction Formation Using Swept-Line Electron Beam Annealing," IEEE Trans. Electro. Dev. ED-30, 1755-1760 (December, 1983).

5. C.W. Farley and B.G. Streetman, "The Role of Defects in the Diffusion and Activation of Impurities in Ion-Implanted Semiconductors," J. Electron. Mater. 13, 401-436 (March, 1984).

6. C.W. Farley and B.G. Streetman, "Simulation of Anomalous Be Diffusion in Semi-Insulating InP," J. Electrochem. Soc. 131, 946-947 (April, 1984).

7. C.W. Farley and B.G. Streetman, "Ion Implantation and Annealing in III-V Multilayer Heterojunctions," Ion Beam Processes in Advanced Electronic Materials and Device Technology, Materials Research Society, Symposia Proceedings Vol. 45, F.H. Eisen, T.W. Sigmon, and B.R. Appleton, editors, 21-33 (1985).

8. S.S. Chan, B.G. Streetman, and J.E. Baker, "Redistribution and Electrical Properties of S Implanted in GaAs," J. Electrochem. Soc. 132, 2467-2472 (October, 1985).

9. G.E. Crook and B.G. Streetman, "Laser-Based Structure Studies of Silicon and Gallium Arsenide," IEEE Circuits and Devices 2, 25-31 (January, 1986).

10. S.D. Lester, and B.G. Streetman, "Materials Issues Underlying Compound Semiconductor Devices," Superlattices and Microstructures, to appear (January, 1986).

11. T.R. Block, C.W. Farley, T.S. Kim, S.D. Lester, and B.G. Streetman, "Heating of GaAs and InP by Incoherent Radiation," Proceedings of the 1986 Society of Photo-Optical Instrumentation Engineers SPIE (January, 1986).

12. T.R. Block, C.W. Farley, B.G. Streetman, "Temperature Response of GaAs in a Rapid Thermal Annealing System," J. Electrochem. Soc. 133, 442-443 (Feb. , 1986).

13. S.D. Lester, C.W. Farley, T.S. Kim, B.G. Streetman, and J.M. Anthony, " Pulse Diffusion of Ge into GaAs," Applied Physics Letters 48, 1063-1065 (April 21, 1986).

14. C.W. Farley, T.S. Kim, B.G. Streetman, R.T. Laureau, and P. Williams, "Encapsulation and Annealing Studies of Semi-Insulating InP," submitted to Thin Solid Films.

15. S.D. Lester, T.S. Kim, and B.G. Streetman, "Factors Influencing the Photoluminescence Intensity of InP," submitted to J. Electrochem. Society.

16. C.W. Farley and B.G. Streetman, "Simulation of Anomalous Acceptor Diffusion in Compound Semiconductors," submitted to J. Electrochem. Society.

17. S.D. Lester, T.S. Kim, and B.G. Streetman, "Ambient-induced Surface Effects on InP and GaAs," in preparation.

18. C.W. Farley, T.R. Block, B.G. Streetman, and M. Anthony, "Suppression of Si Diffusion into Semi-Insulating Fe-Doped InP Using Rapid Thermal Annealing," in preparation.

III. QUANTUM ELECTRONICS

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE82-1 NONLINEAR WAVE PHENOMENA

Principal Investigators: Professor M.F. Becker (471-3628)
Professor E.J. Powers (471-1430)

Graduate Students: J. Beall, J. Hong, J.G. Mauger and Y. Twu

A. PROGRESS: This research unit is concerned with analytical and experimental studies of nonlinear wave interactions in physical systems. The work may be subdivided into two areas: (1) the development of digital time series analysis techniques useful in analyzing and interpreting fluctuation data generated by nonlinear interactions in various media, and (2) nonlinear optics in the infrared spectral region in molecular gases.

1. Nonlinear Wave Interactions: The objective of this work is to develop digital time series analysis techniques that enable one to properly analyze and accurately interpret experimental fluctuation data associated with nonlinear and/or nonstationary wave phenomena in a variety of media. One of the principal characteristics of any nonlinear system is the introduction of new frequency components, e.g., harmonics and intermodulation products. The "efficiency" with which these new spectral components are generated is given by an interaction or coupling coefficient. In the case of nonlinear systems where one can define an "input" and "output", the "efficiency" with which the new spectral components are generated is described by nonlinear transfer functions. For quadratically nonlinear interactions, the coupling coefficients or transfer functions are two-dimensional functions of frequency. For cubic interactions, the corresponding coupling coefficients or transfer functions are three dimensional functions of frequency. This clearly suggests that higher-order (i.e., multi-dimensional functions of frequency) spectral densities must be utilized to appropriately analyze and interpret fluctuation data associated with nonlinear physical systems. For quadratically and cubically nonlinear systems, the bispectrum $B(\omega_1,\omega_2)$ and the trispectrum $T(\omega_1,\omega_2,\omega_3)$ are the appropriate spectral densities, respectively. During the past year our research efforts have focused on the following topics summarized in subsequent paragraphs.

a. Nonlinear System Modelling in the Frequency Domain. Following the successful development of modelling a nonlinear system in terms of a hierarchy of continuous orthogonalized Volterra-like transfer functions [1,2] we have focused on the following topics. First, a discrete version of the orthogonalized Volterra series model has been developed since the continuous model provides a conceptual framework

but the actual computation of such transfer functions will be carried out on a digital computer. Second, the sensitivity of the digital approach to both weak and strong external noise has been investigated in a preliminary fashion.

As discussed in our previous work [1], our modelling has been based on the "black box" approach where the nonlinear system is modelled in terms of a parallel combination of such black boxes, with each box being characterized by an appropriate linear or nonlinear transfer function. This approach is particularly appropriate when one has only the input and output time series data to work with, but no, or very incomplete, knowledge of the nonlinear system equations. Of particular importance is the fact that the nonlinear transfer functions may be determined directly from the input-output data by computing the higher-order cross spectra, (e.g., cross bispectrum, cross trispectrum, etc.) [1].

To apply these concepts to digitized input-output data we developed a discrete orthogonalized Volterra series model which incorporates new definitions of the relevant higher-order spectra and which takes into account the effects of finite record length. Based on this discrete model we have implemented a computer algorithm to estimate the nonlinear transfer functions directly from the raw digitized input-output data [2,3]. This algorithm has been applied in studies of the nonlinear response of moored vessels to random ocean waves [4,5] and electromagnetic wave scattering from nonlinear metallic targets [6]. This latter work is JSEP supported and will be described further in subsequent paragraphs.

It is well known that nonlinear electrical phenomena are associated with metallic joints in man-made objects. Experimentally it is observed that the I-V characteristics of such metal junctions exhibit an asymmetrical nonlinearity with third order predominating. This property is utilized by harmonic radar to achieve selective detection of metal targets, especially when concealed by natural clutter. Specifically harmonic radar detects metal targets by sensing only the third harmonic frequency component in the backscattered field. If this signal component is contaminated due to natural, intentional or inadvertent interference, the performance of this type of radar may be severely degraded.

Recently, we proposed a conceptual model which enables one to systematically characterize a nonlinear target in terms of a hierarchy of linear, quadratic, cubic, etc. radar cross sections [7]. The harmonic radar turns out to be a special case of this model. With the aid of high-order spectral density functions, these nonlinear cross sections can be digitally computed from the transmitted and scattered signals [6].

Our most recent work has been concerned with investigating how one can detect the third-order characteristics of a metallic target,

when the strength of the third harmonic frequency component is far below that of the external noise or intentional jamming signal. The key idea of our approach lies in the fact that the digital third-order cross trispectrum used to detect the third harmonic is primarily sensitive to the phase coherence between the transmitted fundamental and relatively weak backscattered third harmonic, rather than on the amplitude of the third harmonic. On the basis of a computer simulation we have demonstrated the feasibility of using digital cross trispectrum analysis to detect weak (S/N ratio$\approx$-20db) third harmonic signals. These initial results will be described in a forthcoming conference paper [8].

b. Applications of the Local Wavenumber Spectrum in the Study of Turbulence. Many theories modelling turbulent fields in solids, liquids, gases, and plasmas, model the turbulent field $\phi(x,t)$ as a superposition of approximately linear modes. Due to nonlinear interactions between the modes, energy is redistributed in wavenumber and frequency space. In the steady state, the fluctuations arrive at a characteristic spectral density $S(k,\omega)$. Recently we developed a method for estimating $S(k,\omega)$ (formerly denoted by $P(k,\omega)$) of a turbulent fluctuation using fixed pairs of probes. The quantity we actually estimate, called the local wavenumber spectrum $S(K,\omega)$, is a good estimate of the conventional spectrum if the fluctuation is a superposition of oscillatory plane waves with slowly varying amplitudes and wavenumbers:

$$\phi(x,t) = \int d\omega a(\omega) e^{i(k(\omega)x-\omega t)} \tag{1}$$

with

$$\left| \frac{1}{a(\omega)} \frac{d^n a(\omega)}{dx^n} \right| = (\ell_a^{(n)}(\omega))^{-1} << k^n(\omega) \tag{2}$$

$$\left| \frac{1}{k(\omega)} \frac{d^n k(\omega)}{dx^n} \right| = (\ell_k^{(n)}(\omega))^{-1} << k^n(\omega) \tag{3}$$

For n=1, the last two conditions simply mean that the length scales $\ell_a^{(1)}(\omega)$ and $\ell_k(1)(\omega)$ of wave amplitude and wavenumber variation are much longer than the wavelength $\lambda=2\pi/k$. The idea that the wave amplitudes $a(\omega)$ and the wavenumbers $k(\omega)$ may be slowly varying functions of space is in the same spirit as the WKB approximation method used in the solution of differential equations with slowly varying coefficients; henceforth, we refer to Eqs. (2) and (3) as the WKB assumptions.

An important question in the study of turbulence is whether or not expansions of the form of Eq. (1) are in fact valid. Estimates of the spectral density $S(k,\omega)$ in plasmas using laser or microwave scattering techniques have revealed that fluctuations with a given

wavenumber k are broadly distributed in frequency space; in fact, the width $\sigma_\omega(k)$ of the distribution is of the same order as the mean frequency $\bar{\omega}(k)$. Intuitively, this would seem to indicate that the plane wave expansion of the form of Eq. (1), involving modes which at any given time and place have a well defined dispersion relation $k(\omega)$, no longer makes sense. The coherence time $\tau_c = \sigma_\omega^{-1}(k)$ is on the same order as the mean period of oscillation $T = 2\pi/\bar{\omega}(k)$, which would seem to imply a violation of the WKB assumptions. We have found, on the other hand, that short correlation times (or in the spatial dimension, coherence lengths ℓ_c short compared to a wavelength) do not necessarily imply a violation of the WKB assumptions. The spectral broadening and concommittant reduction in coherence times or lengths can be a result of slow, random variations in the dispersion characteristics of the turbulent medium which are still consistent with the WKB assumptions.

One way of testing the WKB assumptions is to compare the local and conventional wavenumber and frequency spectra. If the length scales $\ell_k^{(n)}(\omega)$ and $\ell_a^{(n)}(\omega)$ are short compared to a wavelength, $S(k,\omega)$ will tend to have a larger spectral width $\sigma_k(\omega)$ than $S_\ell(K,\omega)$. In [9], we demonstrate using two probe data, that it is possible to estimate the spectral widths $\sigma_k(\omega)$ and $\sigma_K(\omega)$ of both conventional and local wavenumber spectra. The two estimates agree quite well for turbulence observed in an RF-discharge [9] and in the edge turbulence in the pre-text tokamak [10]. The difference in the spectral widths $\sigma_k(\omega)$ and $\sigma_K(\omega)$ is sensitive to the 1st order derivative in Eq. (2); if $\ell_a^{(1)}(\omega)$ is small compared to a wavelength, $\sigma_k(\omega)$ will be large compared to $\sigma_K(\omega)$. In ref. [11] the comparison of higher order moments, in order to test Eqs. (2) and (3) to higher order, is discussed. More recently, using a four probe arrangement, we have tested Eq. (2) to 4th order and Eq. (3) to 2nd order by making direct estimates of the length scales $\ell_a^{(n)}(\omega)$ and $\ell_k^{(n)}(\omega)$. The WKB assumptions appear to be well satisfied, despite the fact that the large spectral widths we observe might suggest otherwise. These results and the significance of the WKB approximation in turbulence will be discussed in a forthcoming publication.

2. Nonlinear Optics: The objective of the research program in nonlinear optics has been to study new types of resonant optical nonlinearities in molecules at infrared wavelengths. This research has employed third harmonic generation (THG), multi-photon absorption, and degenerate four-wave mixing (DFWM) to measure the nonlinear properties of two classes of molecules; those with a single two-photon resonance and those that are approximately triply resonant at one, two, and three photon energies. When these techniques are used with a

step-tunable CO_2 laser, the spectral dependence of the nonlinear susceptibility, its magnitude, and the influence of limiting processes can be measured. This has been the final year of work on this project and the work consisted of concluding and writing up the study of THG in CD_4 gas. This case emphasizes a two-photon resonance which is unusually sharp and strong.

Progress in Nonlinear Optics has been in four general areas over the last several years: multi-photon absorption and THG in SF_6 [12,13], three wave parametric interactions in dispersive media [14], DFWM in SF_6 [15], and THG in CD_4 [16,17,18]. The first three areas have been concluded and covered in previous annual reports. The fourth area was concluded this year and is covered in the three publications noted above. The major conclusions of this fourth area will be summarized here along with their interpretation.

It is known that the Raman susceptibility and the THG susceptibility are closely related. The molecule CD_4 was selected because of its strong, narrow Raman line at 4.7 microns. This is two-photon resonant with CO_2 laser photons in the 9.4 micron band. The THG conversion of CD_4 was measured and found to be as large as CO at room temperature. When the gas temperature was lowered to 193K at a constant gas density, the THG conversion efficiency of CD_4 increased fivefold. The increase is due to two predicted effects. First, the absorption of the fundamental laser wavelength is reduced substantially. The room temperature absorption was due to highly excited rotational states which were depopulated as the temperature was lowered. The second contributing effect is that the two-photon resonant states are of low rotational energy, and their population increased as the temperature was lowered.

At pressures below 300 torr and at a temperature of 193K, the THG conversion efficiency was substantially larger than CO (a standard at this wavelength). However, the conversion efficiency of CD_4 failed to increase with increasing pressure above 300 torr. We believe this is due to residual absorption at the fundamental wavelength which remains even at 193K. In conclusion, the THG susceptibility was found to be high as predicted from the Raman susceptibility, but THG conversion efficiency was found to be limited by residual absorption at 9.4 microns.

3. Follow-up Statement: This unit will not appear in future Annual Reports. The work on nonlinear wave interactions will be continued as Research Unit IE83-3 "Digital Time Series Analysis with Applications to Nonlinear Wave Phenomena." The work in nonlinear optics has been concluded and will not continue in subsequent proposals. Future work in a related area concerns the effect of nonlinear and other quantum processes in solids on the laser induced damage of these materials.

This latter work will be described in future Annual Reports under Research Unit QE83-1 "Quantum Effects in Laser Induced Damage."

B. REFERENCES

1. J.Y. Hong, Y.C. Kim, and E.J. Powers, "On Modelling the Nonlinear Relationship Between Fluctuations with Nonlinear Transfer Functions," Proc. IEEE, 68, pp. 1026-1027 (August 1980).

2. J.Y. Hong, "Nonlinear Transfer Functions with Application to Nonlinear Electromagnetic Scatterers," Ph.D. dissertation, The University of Texas at Austin, August 1982.

3. J.Y. Hong and E.J. Powers, "On Modelling Nonlinear Systems in the Frequency Domain," in preparation.

4. R.W. Miksad, E.J. Powers, Y.C. Kim, F.L. Jones, R.S. Solis and F.J. Fischer, "Applications of Digital Time Series Analysis Techniques to Determine Nonlinear Drift Forces," in Offshore Engineering, vol. 3, Pentech Press, London, 1982, pp. 273-289, (F.L. Carneiro, A.J. Ferrante, and R.C. Batista, editors).

5. E.J. Powers, D.W. Choi, R.W. Miksad, and F.J. Fischer, "Determination of Nonlinear Drift Force Quadratic Transfer Functions by Digital Cross-Bispectral Analysis," Paper OTC 4440, Proceedings of the Offshore Technology Conference, Houston, Texas, pp. 759-767 (May 3-6, 1982).

6. J.Y. Hong and E.J. Powers, "Digital Signal Processing of Scattering Data from Nonlinear Targets," Proceedings of the IEE Int. Conf. RADAR-82, pp. 266-270, London, Oct. 18-20, 1982.

7. E.J. Powers, J.Y. Hong, and Y.C. Kim, "Cross Sections and Radar Equation for Nonlinear Scatterers," IEEE Transactions on Aerospace and Electronic Systems, AES-17, 602-605 (1981).

8. J.Y. Hong and E.J. Powers, "Detection of Weak Third Harmonic Backscatter from Nonlinear Metal Targets," to be presented at EASCON, Washington, D.C., September 21-23, 1983.

9. J.M. Beall, Y.C. Kim and E.J. Powers, "Estimation of Wavenumber and Frequency Spectra Using Fixed Probe Pairs," J. Appl. Phys. 53, 3933 (June 1982).

10. S.J. Levinson, J.M. Beall, E.J. Powers, R.D. Bengtson and G.R. Joyce, "Estimation of $S(k,\omega)$ from Fixed Probe Pairs on the PRETEXT Tokamak," presented at the Fourth APS Topical Conference

on High Temperature Plasma Diagnostics, Boston, Massachusetts, August 25-27, 1982.

11. John M. Beall, "The Local Wavenumber Spectrum and Its Applications in Turbulence and Noise," Ph.D. Dissertation, The University of Texas at Austin, May 1983.

12. M.F. Becker, K.M. Chung and G.J. Stevens, "Investigation of Multiphoton Absorption in SF_6 by Third Harmonic Generation," Europhysics Study Conference on Multiphoton Processes, Benodet, France (June 1979).

13. K.M. Chung, G.J. Stevens and M.F. Becker, "Investigation of Multiphoton Absorption in SF_6 by Third Harmonic Generation," IEEE J. of Quantum Electronics, QE-15, 874-878 (1979).

14. M.F. Becker, Y.C. Kim, S.R. Gautam and E.J. Powers, "Three-Wave Nonlinear Optical Interactions in Dispersive Media," IEEE J. of Quantum Electronics, QE-18, 113-123 (1982).

15. Yihjye Twu, Phase Conjugation via Resonantly Enhanced Degenerate Four-Wave Mixing,, Masters Thesis, The University of Texas at Austin, (December 1981).

16. M.F. Becker, G.J. Mauger, and Y. Twu, "Raman-Resonance Enhanced Third Harmonic Generation in CD_4," Optical Society of America Annual Meeting, Chicago, IL (October 1980).

17. M.F. Becker, G.J. Mauger, and Y. Twu, "Raman-Resonance Enhanced Third Harmonic Generation in CD_4, J. of the Optical Soc. of Am., 70, 1582 (1980).

18. George Joseph Mauger, Raman Resonance Enhanced Third Harmonic Generation in CD_4, Masters Thesis, The University of Texas at Austin (December 1982).

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE82-2 STRUCTURE AND KINETICS OF EXCITED STATE MOLECULES

Principal Investigators: Professor M. Fink (471-5747)
Professor L. Frommhold (471-5100)
Professor J.W. Keto (471-4151)

Graduate Students: Suhas Ketkar, Richard Mawhorter and Bruce Miller

A. RESEARCH OBJECTIVES: The experiments to be proposed emphasize structural and dynamical studies of molecular systems using non-linear interactions with electromagnetic radiation for detection or state selective excitation. The scientific objectives are (1) contributions to the knowledge of the basic process of non-linear interaction of matter with light, (2) development of non-linear techniques as dynamical probes, (3) structural studies of excited states of molecules and ions previously unavailable for study, (4) studies of energy transfer processes in both collisional and collision-free environments. These objectives will be pursued under three research efforts: non-linear scattering of electromagnetic radiation, inelastic and superelastic scattering of electrons from excited states produced selectively by laser excitation, and dynamical studies of excited molecules produced by multiphoton excitation.

Collisional Pairs of Atoms or molecules are capable of absorbing and scattering light in ways that go beyond the familiar absorption and scattering by non-interacting atoms (molecules). Collisional pairs ("diatoms") acquire "collision-induced" properties, such as an electric dipole moment (if dissimilar pairs are considered) of a gas or gas mixture. These interact with electro-magnetic radiation in linear and other ways and give rise to second and higher-order virial dielectric properties of the real gases. In recent years, ab initio calculations of the collision-induced properties at all levels of sophistication have appeared. It is the goal of our work to provide new, often the first, measurements of collision-induced quantities for a direct comparison with the fundamental theory, and thus to obtain an understanding of the interactions of light with real gases at the molecular level.

Superelastic Scattering

The extensive studies of the molecular properties of many systems in the electronic ground state have led to the vast capabilities of today's chemical industry. As our knowledge grows, more efficient ways are found to produce compounds and to control reaction paths during the formation of products. Due to the availability of a large variety of lasers which produce high energy photons at an ever

diminishing cost, a second thrust in the production of exotic compounds can be predicted for the near future. Critical for this progress is a good understanding of molecules in an excited electronic, vibrational and rotational state. It is in this transient mode where the crucial reactions will take place. As an example how ground and excited state properties are different, consider the rare gases. In the ground state they are exceedingly inert, while the excitation of an outer electron generates an alkali like system with its core and valance electron and subsequent strong reactivity.

The bulk of the new data on excited species comes from absorption and fluorescence spectroscopy. The know-how accumulated so far has already lead to some new chemical processes not otherwise possible. But as in the discharge of laser tubes, the excited molecules have several avenues to distribute the excitation energy internally. These escape channels have been known for a long time and are identified as radiationless transitions. The problem with molecules undergoing such a transition is that they often change the symmetry of their state and become inaccessible to studies in the fluorescence spectrum due to the restrictions imposed by the selection rules.

Our scientific objective is to take advantage of low energy electron scattering to probe the excited molecules. Electrons interact with the target much more strongly than photons, breaking selection rules in the scattering process and increasing the sensitivity of the detection to optical resonance extinction coefficients. The scattered electrons can be grouped into three categories: the elastic scattered electrons (analogous to Rayleigh scattering for photons), the inelastic scattered electrons (analogous to the Stokes photons), and the superelastic scattered electrons (analogous to the anti-Stokes photons). It is the last group of electrons which we intend to use as a diagnostic tool. The basic principal of this method had been demonstrated on laser excited Na [1] and Ba [2], and with the extension of this method to molecules a new sensitive and very versatile tool will become available for the new and promising field of laser chemistry.

Energy Transfer Reactions are being studied at high densities. This research has involved two areas: 1. reactions of excited atoms and molecules following state-selective multiphoton excitation of atoms and molecules, and 2. ion-molecule reactions at high densities. The former experiments are similar in spirit to those done at synchrotrons using resonance absorption except two-photon transitions offer the advantages: 1) greater choice of final states, 2) better time resolution, 3) better energy resolution, 4) the absorption length on resonance is significantly longer, and 5) higher energies can be reached when pumping through windows. This research program using non-linear photoexcitation was initiated by JSEP support in the past

three year contract, is now producing exciting data, and has attracted support from the Department of Energy.

In previous units studying molecular reactions, we were motivated to understand the chemistry of excimer lasers; and in those studies found that at high densities many reactions are termolecular. At high pressures molecules react fundamentally differently than at low pressures; yet research studying reactions at pressures near or above atmosphere is relatively new. In research studying ion-molecule reactions at high pressures [3,4,5,6], we are greatly hampered by the lack of a probe which can even distinguish the ion type. For unambiguous studies it is necessary first to develop a selective probe applicable in high pressure discharges.

The probes for such studies must have high sensitivity, and good spectral and temporal resolution. Temporal resolution is required so that the decay rates can be used to measure reaction rates. We are interested in reactions such as association, recombination, and charge transfer. Nonlinear optical probes based on coherent Raman scattering used in conjunction with high power pulsed lasers potentially meet all these criteria. Two techniques currently under consideration are coherent antistokes resonant Raman spectroscopy and gain modulated Raman spectroscopy. The spectral and temporal characteristics of these techniques are governed by the characteristics of the lasers employed. A continuing goal of this research unit is to demonstrate experimentally that such probes have the necessary sensitivity. When successful, these experiments will represent the first Raman spectra of molecular ions and will greatly aid in the understanding of polyatomic molecules and high pressure discharges.

Polyatomic ions of interest include Xe_3^+, Ar_3^+ and $Xe_n Cl^+$ which are relevant to excimer lasers. Other molecular ions for which there exists a need for experimental analysis include those formed in atmospheric discharges; H_3^+, N_3^+, N_4^+, O_3^+ and O_4^+ all fall into this category. The results from such studies will be applicable to the problem of particle beam transport in the atmosphere. Of particular fundamental interest is H which is the simplest nonlinear polyatomic molecule. Data gathered on it may be compared directly to ab initio calculations.

B. Progress: Our electron diffraction work with high energy electrons has continued with extensive data compilation on molecules at elevated temperatures [7,8,9,10]. Also, our studies on the theoretical background of the diffraction work have lead to several new results [11,12]. Since this research is now supported by the NSF, the JSEP funding is shifted toward the development of the most accurate low energy electron diffraction unit currently in operation in the world.

We have continued to build up the superelastic scattering unit from three aspects: the laser excitation source, the electron beam,

and the gas jet. As for the laser, a linear dye laser was modified to incorporate a Michelson interferometer [13]. This leads to two advantages: first, the laser runs single mode with the same output power and therefore multifold spectral density, and second, one arm in the spectrometer contains a beam waist, which is excellently positioned to allow intracavity photon frequency doubling.

The peripheral equipment was extended by Hansch-type wavemeter [14] and a 75 MHz etalon which is used as a marker generator to keep track of the frequency as it is tuned through the rotational-vibrational spectrum. As for the gas jet, we are making progress but several problems still remain. Our quadrupole spectrometer is in place and working and in Fig. 1 a well resolved spectrum of NO_2 and its fragmentation products is reproduced. The problems lie with the peaks not seen in the mass spectrum. According to the thermodynamics of the reactions

$$2NO_2 \rightleftharpoons N_2O_4$$

we should have a strong N_2O_4 peak in our spectrum, given the conditions under which the nozzle system is run [15]. Since the optical quenching cross sections are in general very large, the N_2O_4 can act as a perturber in our jet and must be taken into account in the interpretation of the scattering data. Most NO_2 studies suffer under this handicap, and it might provide a simple explanation for the often contradictory results in the literature in regard to NO_2. We hope that the appearance potential of the fragments will give use more insight.

The scattering apparatus itself is finished and ready to take data [16]. Not only will we be able to measure the total energy spectrum at every scattering angle between 1-150°, but we have the ability to measure the cross sections better than 0.1% on a relative scale. This will lead to very sensitive comparisons with theory, particularly in the elastic channel. These data will then tell us much more about charge cloud polarization [17], exchange effects [18], intramolecular multiple scattering [19], and spin contributions [20]. The inelastic data, when maintained at that high accuracy, will show the correlation effects in the Comption profiles from the individualized subshells of the target molecules. Finally, when the laser is introduced into the scattering process, the dynamics of intramolecular relaxation can be studied.

In a previous report [21] we reviewed our work on collision-induced laser light scattering, a relatively weak two-photon progress arising from the polarizability change induced by molecular interactions [22-24]. Since that report was written we have expanded the scope of our work, in cooperation with Dr. G. Birnbaum at the National Bureau of Standards, Washington, D.C., by considering the dipole

moments induced in non-polar gases by molecular collisions [25]. Induced dipoles interact with radiation, usually by absorption in the infrared. Two mechanisms are known that induce dipoles. The overlap-induced dipole arises from electronic rearrangement of the collisional complex if dissimilar molecules interact [26,27], e.g. He and H_2. The multipole-induced dipole, on the other hand, relies on polarization of a molecule in the electric multipole field of another molecule nearby [28], e.g. the electric field of H_2 polarizing a collisional partner in the vicinity. The infrared absorption spectra of induced dipoles feature broad continua of characteristic shapes. Multipole-induced dipole spectra usually show broad structures at the rotational/vibrational frequencies of the monomers. All essential features of the infrared spectra induced by binary collisions can be computed from an adiabatic theory [29], provided two functions describing the molecular interactions are known: the interaction potential, V(R), and the induced dipole moment, M(R). We were able to show that, conversely, potential and dipole function are rather critically defined over a certain range of separations by accurate measurements of induced spectra, preferably at a variety of temperatures. The spectral profiles with their gentle change of slope and curvature with wavenumber apparently contain significantly more information than was hitherto utilized. The new device employed in our analysis of the measurements is an adiabatic line shape computer program, presumably the only one presently available for such work. The systems studied are selected for their astrophysical interest [26-28, 30-32] (H_2, He, Ch_4, etc); but rare gas mixtures (He-Ar, Ne-Ar, Ar-Kr) were also considered [33] for critical comparisons with the fundamental theory, which predicts these functions V(R), M(R), for many systems, with varying degrees of accuracy. In general, a satisfying, very close agreement with the ab initio theory is observed except in Ne-Ar, where the ab initio dipole moment was shown to be in error [34]. Empirical induced dipole functions [29,33], and for the first time a potential function [30,34], presumably improvements over the ones computed from first principles, could be obtained for several molecular systems which allow a most reliable computation of the absorption spectra even at temperatures that are different from those of the measurements, an important consideration particularly in the physics of planetary atmospheres. New insights are obtained concerning the role of dimers, i.e. diatomic molecules bound together by the weak van der Waals forces, which affect the optical properties of the dense systems more than commonly expected, particularly if heavy systems (e.g. those involving species other than hydrogen or helium) are considered. Surprisingly, dimers affect the optical properties of dense gases even at temperatures of 300K and higher in several important cases [28,32].

Progress: Energy Transfer Reactions: Initial experiments studying reactions of excited species have begun with studies of collisions of

xenon $5p^5 6p$ following two-photon laser excitation. Excitation spectra have been measured from 76,000 to 82,000 cm while observing laser induced fluorescence (LIF) from the lowest bound xenon excimer (radiation at 172 nm) and atomic transitions in the infrared. We illustrate the two-photon pumping process in Fig. 2. At pressures above 50 Torr excimers are rapidly produced by association of $5p^5 6s$ states which are radiation trapped. All states excited to $5p^5 6p$, whether they radiate or are collisionally deactivated to $5p^5 6s$, produce fluorescence at 172 nm.

With laser excitation, a large flux of photons reaches the photodetector. The flux produced is large enough that the response time of the photomultiplier makes single photon counting techniques impossible, but small enough to make usual analogue techniques impractical. We have developed a detection scheme based on digitizing the charge at the photodetector for the first 100 nsec following excitation. This charge is divided by the mean charge for a single photon event and added to individual photons counted at later times. This enables the detection of up to 900 photons per laser pulse. This signal is limited by the linearity of the photomultiplier. We have found the precision of this detection system to be limited by Poisson statistics for signals from 10-2 to 900 photons per laser pulse. Our noise levels are limited by scattered light to levels of 5x10 photons per laser pulse.

We have measured the laser induced fluorescence near 828 nm produced by excitation of 6p[1/2] at various pressures. Similarly we have observed fluorescence of 6p[3/2] near 823 nm and 6p[5/2] near 905nm. In Table 1 we list both the calculated two photon transition rates for these states in the dipole-dipole approximation for several intermediate states and the measured transition rates. The experimental cross sections have been measured using laser induced fluorescence both in the infrared and in the vacuum u.v. In the infrared, the optical detector system is absolutely calibrated using an NBS traceable standard lamp. In the vacuum u.v. we do not have standard lamps available, hence we have measured the two photon coefficients relative to the known Rayleigh scattering cross section, $d\sigma/d = 6\times10^{-26}$ cm^2 for the scattering geometry, polarizations, and laser frequencies of our experiment.

The absolute measured rates are in reasonable agreement with theory when errors are taken into account. We observe ratios of two photon coefficients in Table 1 of 8:4:1 for 6p[1/2] : 6p[5/2] : 6p[3/2] . The accuracy of these relative rates is 10%. These ratios are in significant disagreement with ratios of 2.5:2:1 when using a single intermediate state. We note in Table 1 that there is a significant contribution to theoretical transition rates from 5d[3/2], and 7s[3/2], intermediate states; hence a single intermediate state model gives only an order of magnitude estimate and a sum over intermediate states is required for accurate calculations.

Table 1. Two-Photon Coefficients

The calculated values are given for specific intermediate states.

	α for given li >, (cm^4/J2)			Experiment
le>	$6s[3/2]_1$	$5d[3/2]_1$	$7s[3/2]_1$	
$6p[1/2]_0$	100	73	12	43
$6p[3/2]_2$	43	7.7	19	4.5
$6p[5/2]_2$	92	4.2	17	22.4

Precision excitation spectra of $6p[1/2]_0$, $6p[3/2]_2$ and $6p[5/2]_2$ have been measured over a broad pressure range. These data demonstrate a significant advantage of multiphoton spectroscopy for lineshape studies-- since the absorption length is large, data are accurate both in the line core and line wings. In Fig. 3 we show an example of high resolution data obtained in the line core. Szudy and Baylis [36] have derived a unified pressure broadening model applicable in both the line core and line wing. This model predicts a simple asymmetric Lorentzian for the line shape when a single interaction potential is assumed. The model predicts the pressure dependence of the shifts, widths, and asymmetry are related to the strength and order m of the interaction potential, Cm/R^m. The measured shifts, widths, and asymmetry [35] are in agreement with the model for pressures of 1 to 1000 Torr when the single potential C_5/R^5 is used for J=2 states and when C_6/R^5 is used for J=0 states.

We have also obtained precise spectra in the far line wings. Various lineshape theories have been applied to the analysis of these data. The quasistatic theory and the unified statistical theory by Szudy and Baylis have been used to analyze the linewing in order to extract numerical potentials for internucleation separations from 3.7 A to 10.0 A. As described, the long range interaction potential is obtained from measurements of the line core at low pressures. The two potentials were smoothly joined to generate an analytical representation of the potential over the full range of internuclear separations. Calculations using this potential in the Anderson-Talman theory [37,38] were compared with the data over the full line profile. A comparison of the calculations and data are shown in Fig. 4.

In addition to determining the interaction potentials for states of $5p^56p$ we have begun reaction studies. While exciting on resonance, we have measured the branching fractions for product states. With experiments now in progress measuring the time dependence of

fluorescence from these states, we will determine collision cross sections for fine structure changing collisions on a state-to-state basis.

Experiments to obtain coherent Raman scattering were begun during the past year. To date these experiments have been in the building stage and significant progress has been made. Two N_2 pumped dye lasers have been constructed which provide 50 kw peak power with bandwidth less than 1 GHz. These lasers will be used to probe the N_2 laser discharge. Because of the time delay in producing the dye laser beams a long-pulse (10 nsec) N_2 laser was constructed. Initial experiments have obtained gain modulated Raman spectra of CCl_4. More sensitive electronics for monitoring the gain or absorption of the probe laser are being constructed. When the electronics are complete, tests will be made on low pressures of air prior to attempts to observe signals from the N_2 discharge. For studies using CARS, we have designed an unique prism monochromator (93% transmission with 20 cm^{-1} bandpass) for extracting the colinear CARS beam from the pump lasers. This device is being constructed in the machine shop. The prism monochromator, combined with the sensitive technique for photon counting described earlier will provide a sensitivity significantly better than current state of the art.

C. FOLLOW-UP STATEMENT

Our research supported by the JSEP program has gained such momentum that additional federal funding could be secured. The electron diffraction work is now sponsored by the NSF, and the high gas density reaction kinetics studies are financed by the DoE. This provided the ideal moment to reorganize our groups QE82-2 and QE2-3. The diatom work is close to completion, it has been summarized in last years significant accomplishments. Therefore, we formed two new groups for the next trianium: QE83-2 and QE83-3, emphasizing the new ideas we plan to pursue in the coming years. Hopefully, this project will again lead to significant results to attract new federal support.

D. REFERENCES

1. I.V. Hertel and W. Stoll, J. Phs. B 7, 583 (1974).

2. D.F. Register, S. Trajmar, S.W. Jensen and R.T. Poe, Phys. Rev. Lett. 41, 749 (1978).

3. J.W. Keto, C.F. Hart and Chien-Yu Kuo, "Electron Beam Excited Mixtures of Argon Doped with O_2: I. Spectroscopy," J. Chem. Phys. 74, 4433 (1981).

4. J.W. Keto, "Electron Beam Excited Mixtures of Argon Doped with O_2 II. Electron Distribution Functions and Excitation Rates," J. Chem. Phys. 74, 4445 (1981).

5. J.W. Keto, C.F. Hart and Chien-Yu Kuo, "Electron Beam Excited Mixtures of Argon Doped with O_2: III. Energy Transfer Reactions," J. Chem. Phys. 74, 4450 (1981).

6. Chien-Yu Kuo and J.W. Keto, "Dissociative Recombination of Electrons in Electron Beam Excited Argon at High Densities," J. Chem. Phys. 78, 1851 (1983).

7. M.H. Kelley and M. Fink, "J. Chem. Phys. 77, 1813 (1982).

8. R.J. Mawhorter, M. Fink and B.T. Archer, "The Vibrational-Averaged, Temperature-Dependent Structure of Polyatomic Molecules I CO_2", J. Chem. Phys. (in press).

9. R.J. Mawhorter and M. Fink, "The Vibrational-Averaged, Temperature-Dependent Structure of Polyatomic Molecules II SO_2", J. Chem. Phys. (in press).

10. S.N. Ketkar, M. Fink and R.A. Bonham, Phys. Rev. A 27, 806 (1983).

11. P. Pulay, R.J. Mawhorter, D.A. Kohl and M. Fink, "Ab Initio Hartree-Fock Calculations of the Elastic Electron Scattering Cross Section of Sulphur Hexafluoride," J. Chem. Phys. (in press).

12. D.A. Kohl, P. Pulay and M. Fink, "On the Calculation of Electron Scattering Cross Sections from Molecular Wavefunctions - CF_4 and CH_4", J. Mol. Struct. Theo. Chem., submitted.

13. S. Liberman and J. Pinard, Appl. Phys. Lett. 24, 142 (1974).

14. H.R. Xia, S.V. Benson and T.W. Hansch, Laser Focus 17, 54 (1981).

15. W.F. Giauque and J.D. Kemp, J. Chem. Phys. 6, 40 (1938).

16. J.J. McClelland, J.M. Ratliff and M. Fink, J. Appl. Phys. 52, 7039 (1981).

17. K. Jost, D. Hermann and M. Fink, J. Chem. Phys. 64, 1 1976.

18 D. Gregory and M. Fink, J. Phys. B, L310 (1975).

19. B. Miller and M. Fink, J. Chem. Phys. 75, 5326 (1981).

20. D. Gregory and M. Fink, Phys. Rev. A7, 1251 (1973).

21. Significant Accomplishments, 1979.

22. L. Frommhold, Adv. Chem. Phys. 46, 1-72 (1981).

23. M.H. Proffitt, J.W. Keto, L. Frommhold, Canadian J. Phys. 59, 1459-74 (1981).

24. P.D. Dacre, L. Frommhold, J. Chem. Phys. 76, 3447-60 (1982).

25. G. Birnbaum, B. Guillot, S. Bratos, Adv. Chem. Phys. 51, 50-112 (1982).

26. R.L. Matcha, R.K. Nesbet, Phys. Rev. 160, 72 (1967).

27. A.J. Lacey, W. Byers Brown, Mol. Phys. 27, 1013 (1974).

28. J. van Kranendonk, Physica 24, 347 (1958).

29. G. Birnbaum, Shi-I Chu, A. Dalgarno, L. Frommhold, E.L. Wright, "Theory of Collision-Induced Translation-Rotation Spectra of H_2-He, submitted to Phys. Rev. A.

30. E.R. Cohen, L. Frommhold, G. Birnbaum, "Analysis of the Far Infrared H_2-He Spectrum," J. Chem. Phys., 77, 4933 (1982).

31. G. Birnbaum, L. Frommhold, in preparation.

32. L. Nencini, L. Frommhold, G. Birnbaum, submitted to Chem. Phys. Letters.

33. G. Birnbaum, M.S. Brown, L. Frommhold, Canadian J. Phys. 59, 1544-54, (1981).

34. L. Frommhold, G. Birnbaum, J. Chem. Phys., in press.

35. J.W. Keto, T.D. Raymond, Chien-Yu Kuo and H. Bowering, "Spectral Line Shapes from Two Photon Excitation of Xenon," 6th International Conference on Spectral Line Shapes, 1982, proceedings to be publihsed Spectral Lineshapes vol. 2, K. Burnett, ed., De Gruyer, Berlin, 1983.

36. J. Szudy and W. Baylis, J. Quant. Spectros. Radiat. Transfer 15, 641 (1975); ibid JQRST 17, 681 (1977).

37. P.W. Anderson, Phys. Rev. 86, 809 (1952).

38. N. Allard and J. Kielkopf, Rev. Mod. Phys. 54, 1103 (1982).

(Page 12, Res. Unit QE82-2 "Structure and Kinetics of Excited State Molecules")

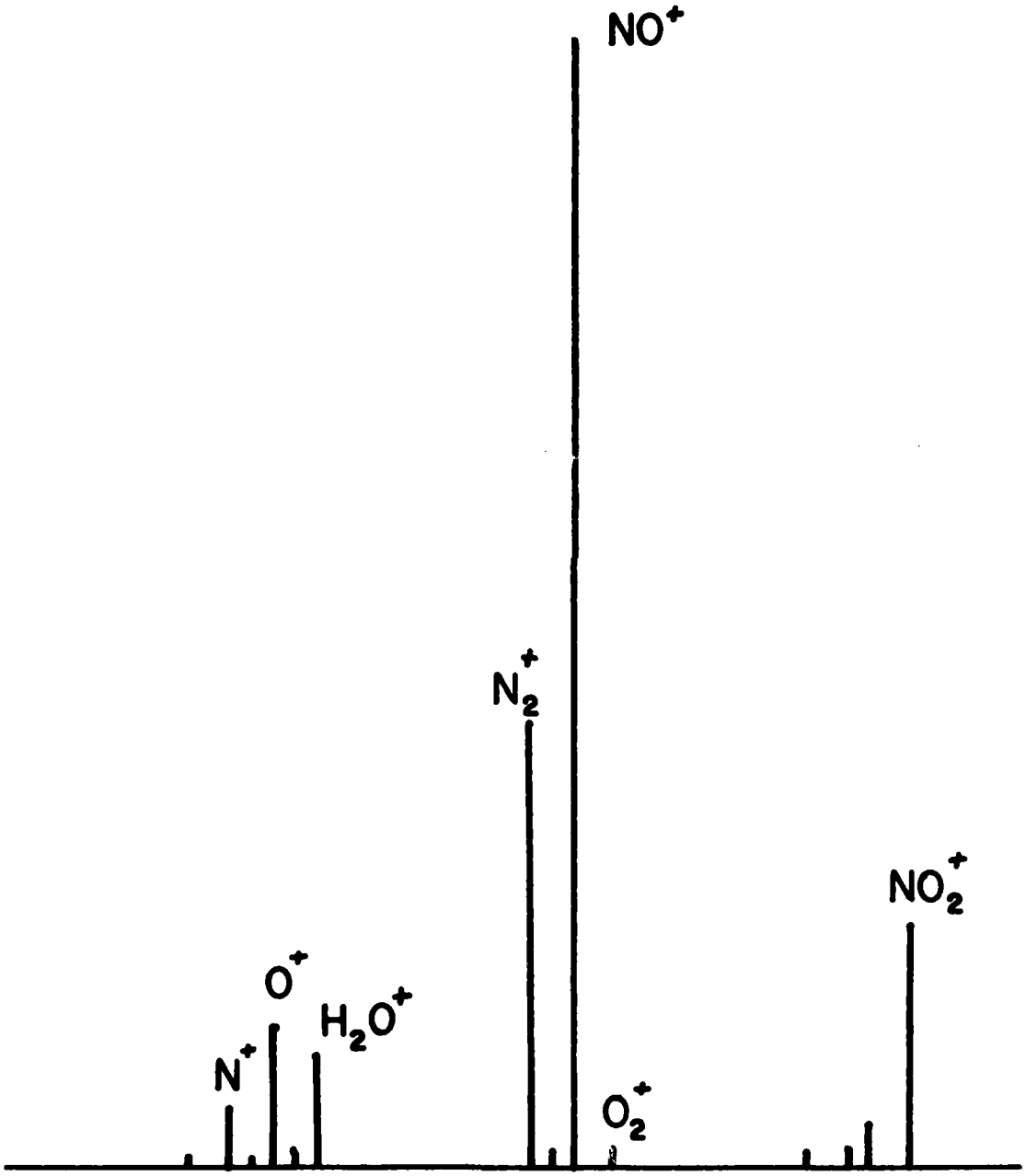


Fig. 1 Mass Spectrum of NO_2 and $N_2)_4$ (-30°C)

(Page 13, Res. Unit QE82-2 "Structure and Kinetics of Excited State Molecules")

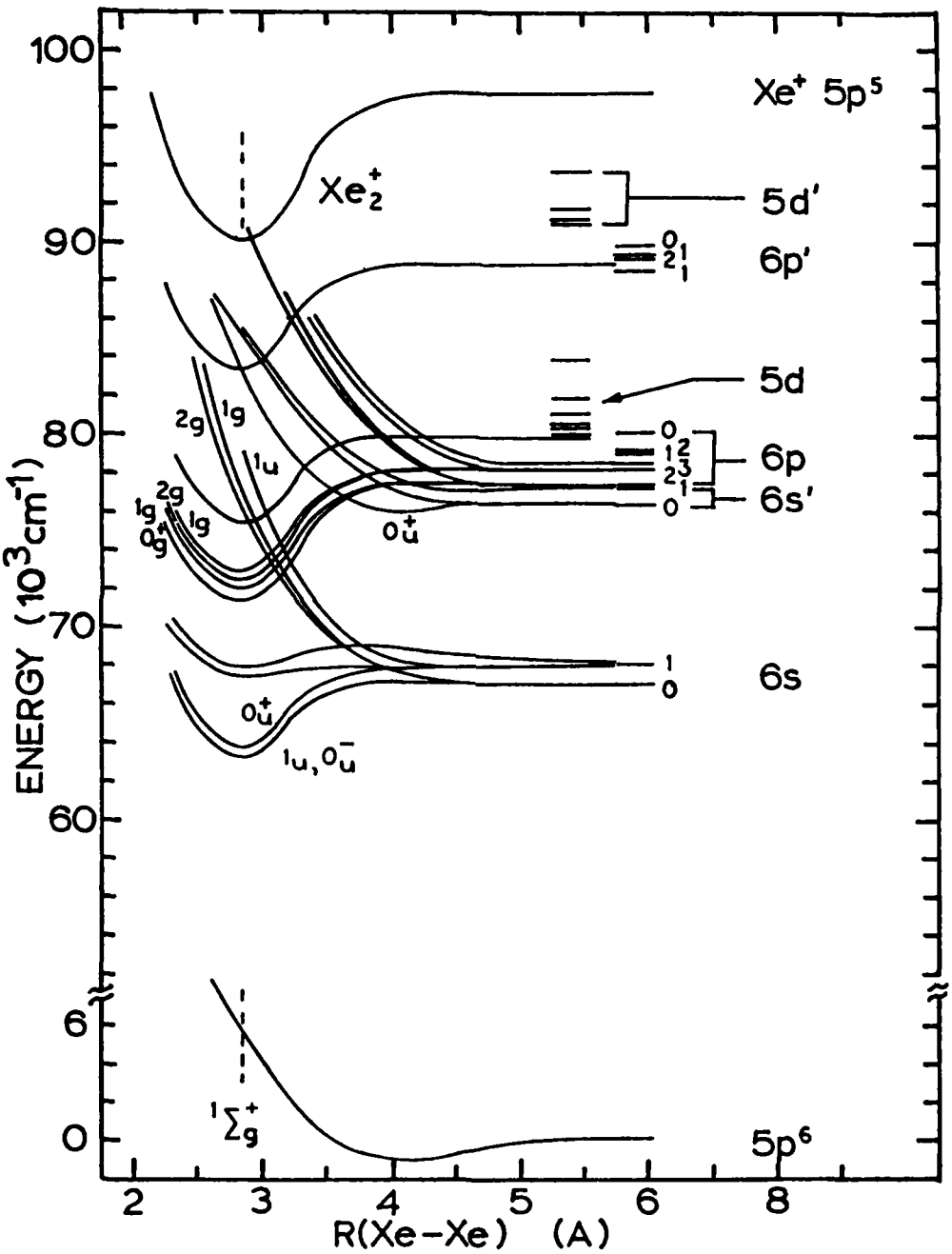


Fig. 2 The states of the 6p manifold are excited via two photon absorption. The molecular curves drawn are based on the estimates by Mulliken.

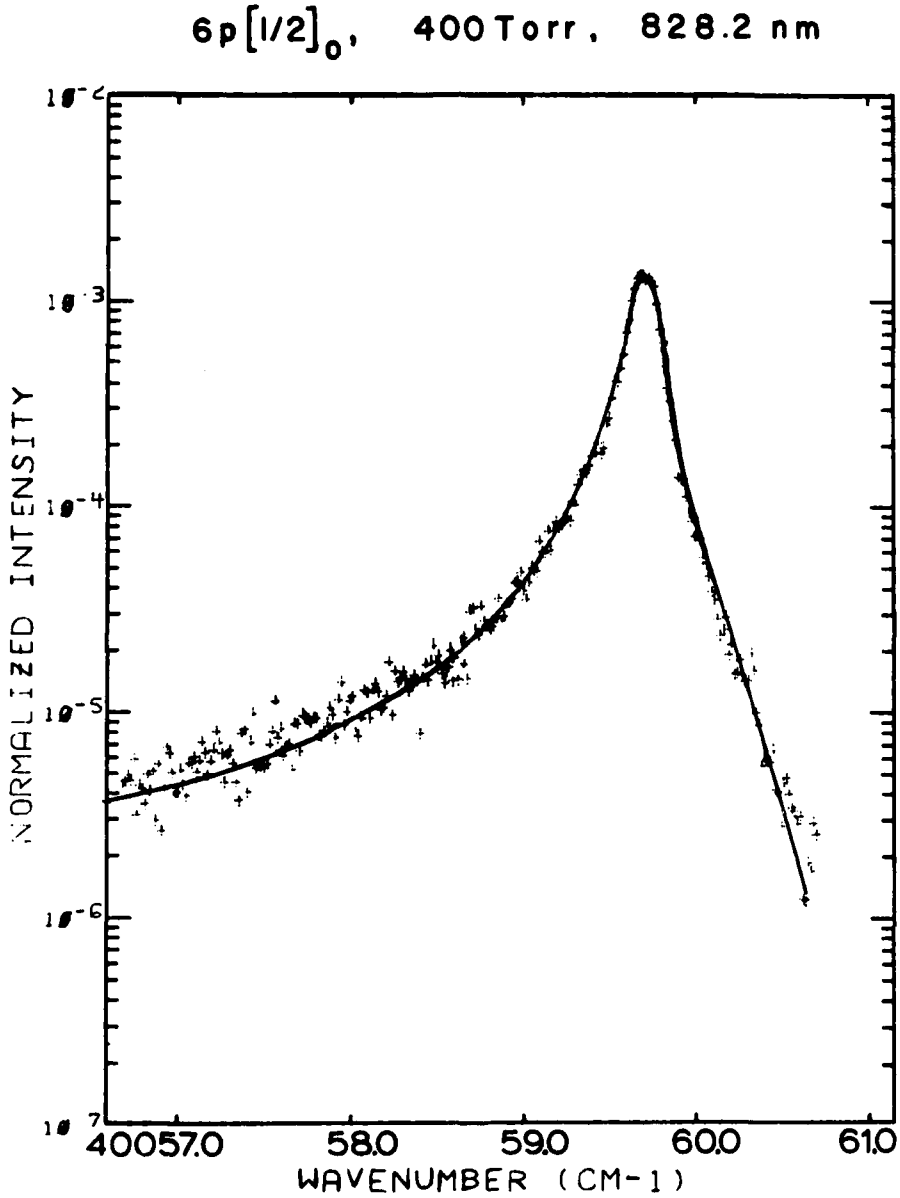


Fig. 3 The narrowband laser was used to obtain this absorption spectra of $6p[1/2]_0$ at 400 Torr. The transition of this state to the lower lying $6s[3/2]_1$ state (8282 Å) was used as the fluorescence monitor. The solid curve is the least squares fit of an asymmetric Lorentzian to the data.

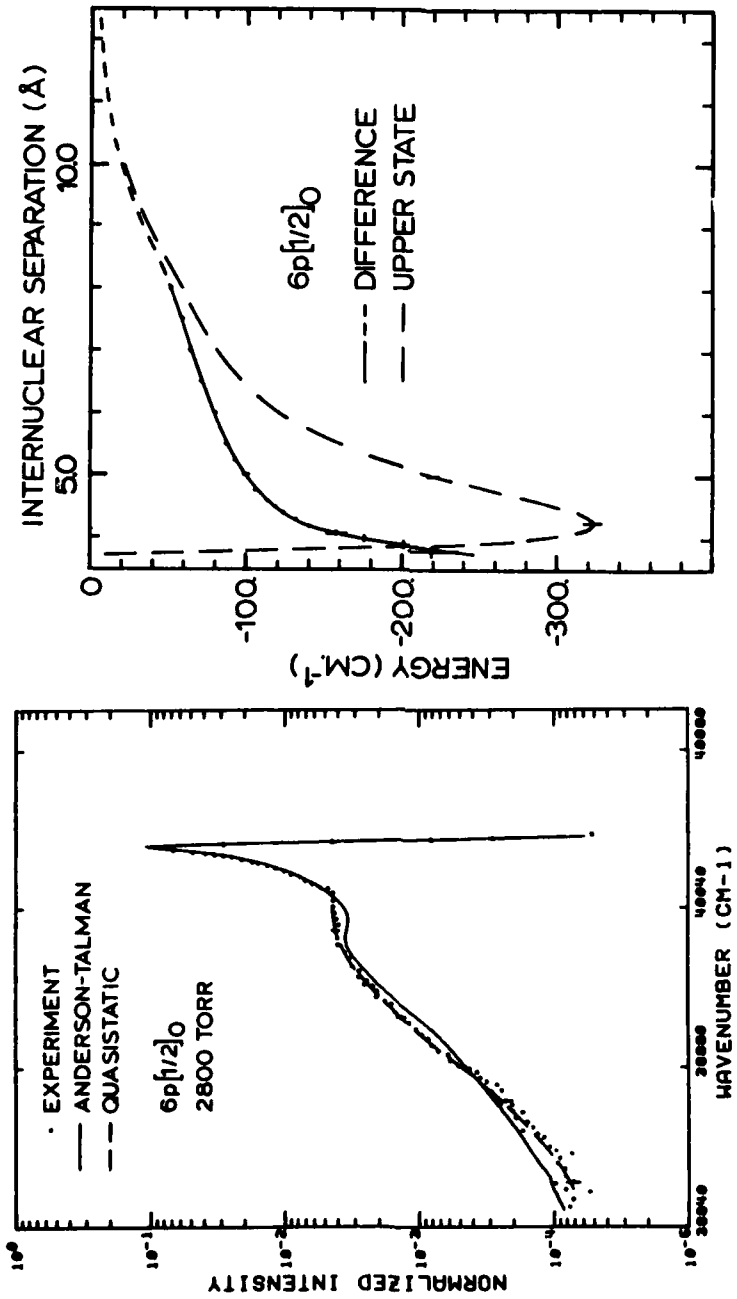


Fig. 4 Experimentally measured and calculated line shapes for xe $6p[1/2]_0$. At left are experimentally measured points compared with the calculated line shapes, while on the right we show the potentials used in the calculation.

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE82-3 COLLECTIVE EFFECTS IN NONLINEAR OPTICAL INTERACTIONS

Principal Investigators: Professor H.J. Kimble (471-1668)
Dr. A. T. Rosenberger

Graduate Students: David Grant, Luis Orozco, Murray Wolinsky, L.A. Wu

A. RESEARCH OBJECTIVES: The objective of this research unit is to investigate the behavior of nonlinear optical systems that are strongly coupled. The dynamics of such systems are not explicable in a simple way based upon perturbative analyses. Rather, the coupling is such that one must deal with the combined system as a new dynamical entity, as for example in the interaction of gas phase atoms and resonant electromagnetic radiation discussed below. In general our efforts are devoted to the study of physical systems that are on the one hand amenable to detailed microscopic analysis while on the other hand experimentally realizable. The intent is to investigate both the range of dynamical behavior exhibited and as well the possible role played by quantum fluctuations in the atom-field coupling.

Within this general context we have initiated over the past three years with the support of JSEP a project to study optical bistability. In our experiments an atomic beam passes through the intracavity field of a high finesse interferometer. As the intensity of the laser incident upon the optical cavity is varied we record the transmitted laser power and intracavity fluorescent intensity. For zero intracavity atomic density, the input-output characteristic is a straight line. As the atomic beam density increases the transmission function develops a region of differential (ac) gain. Beyond some critical point a hysteresis cycle emerges in the input-output curve. The onset and growth of the hysteresis cycle can be characterized by a parameter C known as the atomic cooperativity parameter. C is defined as the ratio of intracavity atomic loss $\alpha\ell$ to the linear loss of the cavity π/F, with F equal to the cavity finesse. (C is analogous to the pump parameter of laser theory, which is defined as the ratio of atomic gain to cavity loss and which describes the onset of laser action).

By conducting experiments in the system described above, we are making an investigation of optical bistability free from certain "complicating" features such as inhomogeneous broadening, optical pumping, or other nonradiative relaxation mechanisms. The theoretical descriptions for such a system of "two-level" atoms are numerous and predict a wide range of phenomena which are of relevance to the study of cooperative interactions in atomic and molecular physics, to the study of the fluctuation and relaxation processes for nonlinear systems driven far from thermal equilibrium, and to potential applications in optical signal processing. However in spite of the rather advanced state of development of the theory, almost no experimental

information is available. The intent of our research is to address experimentally several questions that until now have been treated only theoretically for bistability in the "simple" arrangement of two-level atoms inside an optical resonator.

B. PROGRESS: In the last Annual Report (1981-1982) we discussed our preliminary measurements of optical bistability [1]. Those measurements still represent the first and only systematic study of the onset and growth of hysteresis in absorptive bistability. Over the past year we have extended this work to analyze in detail the role of each of the following in optical bistability: (1) Inhomogeneous (Doppler) broadening - Experiments have been carried out both with and without appreciable inhomogeneous broadening. (2) Cavity-mode structure - Experiments have been performed in both Fabry-Perot (standing wave) and ring (travelling wave) geometries to investigate the importance of variations in the longitudinal and transverse structure of the intracavity field. (3) Transient response - Our experiments in an all optical system have systematically explored the dependence of switching time on the size of the switching increment in the vicinity of the hysteresis cycle [1-4]. In addition to the experimental program, a collaborative effort has been ongoing with Dr. P.D. Drummond of the University of Rochester to analyze our data in the light of current theories of optical bistability. In this section we will deal with each aspect (1)-(3) of the research program.

As has been discussed by many authors [5-7], the behavior of many nonlinear optical systems is analogous to that of systems that undergo equilibrium phase transitions. Of course the optical systems, such as those in optical bistability, are driven far from thermal equilibrium by some pumping mechanism. Nonetheless formal associations between the variables of a thermodynamic process and those of an optical process can be made. This has been done in the case of optical bistability [8-9]. In the language of equilibrium phase transitions, one is then interested in examining the bistable system for the "critical" onset of bistability and for the characteristics of the system above and below this critical point. In optical bistability the values of the critical atomic cooperativity parameter C_0 and of the actual switching powers depend upon the resonator structure and on the detailed nature of the intracavity nonlinearity. The intracavity media in most bistable systems that have been studied in the past are sufficiently complex in their own right that it has not been in general possible to make detailed comparisons between theory and experiment. Our experiment is unique in that the intracavity medium behaves to a good approximation as a simple "two-level" atom [10] with a single nondegenerate ground state and single nondegenerate excited state (in this regard, see also the work of reference [11]). We are then able to investigate not only the dependence on geometric factors

or susceptibility but as well the higher order processes in optical bistability.

Inhomogeneous broadening has a large effect on the characteristics observed in optical bistability. Even in the cases where a homogeneously broadened system has been obtained by collisional broadening or phonon processes, actual observations are far removed from the fundamental radiative relaxation mechanism. In our experiments we have studied optical bistability both without appreciable broadening of any kind other than purely radiative relaxation and with inhomogeneous (Doppler) broadening amounting to three times the natural linewidth. As predicted [12,13,16] we see marked changes in both the values of the critical cooperativity parameter and of the incident switching intensities. With inhomogeneous broadening the critical density for observing optical bistability increases two-fold in a fixed finesse cavity, while the incident switching intensities are raised by 50% relative to their expected values for bistability in the Doppler free case. The theoretical analysis of the experiments carried out by Dr. Drummond has demonstrated the need to analyze the broadening mechanism as not simply inhomogeneous but rather as due to the moving atoms in our atomic beams. The motion of the atoms through the standing-wave pattern of the intracavity field tends to "wash out" the maxima in the pattern and hence to increase the incident power required for switching [1,3,16].

Our experiments have also investigated the role of Gaussian beams in optical bistability. The radial distribution of intensities of an incident laser beam and of the intracavity field greatly alters the response of a bistable system as compared to the results obtained from a plane-wave analysis [14,15,17]. Critical values of the cooperativity parameter C and of switching intensities are increased several fold. As well the rate of growth of hysteresis with increasing intracavity atomic density is drastically reduced [3]. Stated somewhat differently, a fixed intracavity nonlinearity and range of incident laser power that would be sufficient to observe optical bistability in the plane-wave theory would be insufficient for bistability in our experiments. Overall we have obtained good agreement with the Gaussian beam theory of our experiments, but some remaining discrepancies are being investigated.

In order to eliminate the effects of standing waves and inhomogeneous broadening, we have recently made major alterations in our apparatus. For the first time in this field we are now studying optical bistability in a ring resonator with an intracavity medium that is nearly free of inhomogeneous broadening. We have constructed a new interferometer that operates in a ring or travelling wave configuration. Such an interferometer and intracavity medium represent a bistable system in which not only the deterministic effects in optical bistability but as well as many of the dynamical processes can

be studied. With this arrangement we hope to record certain of the higher order correlation functions in optical bistability. For example, measurements of average incident and transmitted intensities can be understood from a knowledge of the (static) nonlinear susceptibility of the intracavity medium. On the other hand, the spectral density of the fluorescent or transmitted light involves quantum and other fluctuations of the resonator-atomic system.

We also plan to search for the occurrence of "self-pulsing" instabilities in optical bistability [19,20]. Parts of the steady-state hysteresis cycle that were thought to be stable are in fact predicted to be unstable against small perturbations. The nature of the new "stable" states that evolve is one in which continuous-wave incident light is converted by the (passive) bistable device to time-dependent, oscillatory transmitted light. The instability (transition from continuous-wave output to oscillatory output) arises from the strong coupling of atomic and cavity dynamics so that neither atoms nor cavity can be thought of as slightly perturbed by the presence of the other. While the observation of such instabilities would be of scientific interest, it would also be of possible significance for the use of bistable devices as elements in optical signal processing. Recent numerical simulations of the Maxwell-Bloch equations indicate the possibility of observing these instabilities in our experiment [21].

Our preliminary work with the ring cavity and nearly Doppler-free system have been directed toward a comparison with the usual steady-state theories of optical bistability [4]. As in the standing wave cavity we have recorded the onset and growth of the hysteresis cycle as a function of atomic cooperativity. Values of both incident and transmitted intensities have been measured. A detailed comparison of our data with theory is in progress, but in general terms our results agree with the standard steady-state theories in the mean-field limit in the region around the critical onset of bistability. However for $C>40$, corresponding to a well-developed hysteresis cycle, we have observed features in the input-output characteristics that are greatly different from the usual theories of optical bistability. In particular, the hysteresis cycle appears to be gradually truncated as C increases from 40 to 50. Unexplained structure develops in the hysteresis cycle not only in the region between the turning points but also for incident intensities well above the upper turning point.

We are currently exploring several possible causes for this behavior. They are as follows: (1) Existence of dynamical instabilities on the upper branch of the hysteresis cycle can cause premature precipitation to the lower branch [19,20]. (2) The mean-field theory might not be applicable to our experiments at high values of C due to the large intracavity absorption and resulting longitudinal and

transverse variation of the intracavity field. (3) Switching between the fundamental and higher order transverse modes of the interferometer might occur due to its mode-degenerate (confocal) nature. (4) The approximation of an intracavity medium composed of two-level atoms might break down at the high intensities within the cavity. These intensities are 10^3-10^4 times the saturation intensity of the medium and are comparable to or greater than the hyperfine spacings of the atomic levels. Both additional experiments and numerical investigations are underway in an attempt to explain the behavior that we have observed.

In a separate set of measurements in the standing-wave cavity with a Doppler-broadened intracavity medium we have investigated transient response in absorptive bistability [2]. In these measurements the bistable system is subjected to an input that turns on from zero to some final value in a time that is short compared to cavity or atomic relaxation times. The evolution in time of the output of the cavity is recorded as the transmitted field builds from zero to a final steady-state value. The time taken by the output to reach steady-state is determined for various amplitudes of the input pulse to the cavity. For switching from zero to a final value large compared to the turning points of the hysteresis cycle, the output of the cavity evolves as if there were no intracavity medium. However as the switching increment above the upper turning point of the hysteresis cycle diminishes, the time taken for the output to reach steady state increases rapidly. More than a ten fold increase in switching time has been observed for switching within a few percent of the upper turning point. This phenomenon has been predicted theoretically [23] and seen in a hybrid device [24] previously. However, our measurement is one of only two direct observations of "critical slowing down" in all optical bistable systems [2,25]. The slowing of response to changes in driving field can be related to a change in the dynamical behavior of the system based upon the thermodynamic analogies discussed earlier. Such slowing down would have to be considered in any device application.

C. FOLLOW-UP STATEMENT: The work that has been outlined in the previous section is to be continued, and the research program is outlined in the most recent JSEP proposal. Principle funding for the research will however be shifted. The program in optical bistability that was begun three years ago under the sponsorship of the JSEP has attracted funding from the National Science Foundation and from the Venture Research Unit of British Petroleum, Int. While JSEP support will continue to be acknowledged in future publications from the work, several new projects have been discussed in the 1983-86 JSEP proposal and are being developed. The general area of the project is still

that of cooperative or collective effects in nonlinear optical systems.

D. REFERENCES

1. D.E. Grant and H.J. Kimble, Optics Lett. 7, 353 (1982).

2. D.E. Grant and H.J. Kimble, Opt. Commun. 44, 415 (1983).

3. H.J. Kimble, P.D. Drummond, D.E. Grant and A.T. Rosenberger, Proceedings of the Third New Zealand Symposium on Laser Physics, eds. D.F. Walls and J. Harvey, (Springer-Verlag, New York, 1983).

4. A.T. Rosenberger, L.A. Orozco, and H.J. Kimble, Phys. Rev. A, submitted (1983).

5. H. Haken, Synergetics (Springer-Verlag, New York, 1978).

6. F.T. Arecchi, in Order and Fluctuations in Equilibrium and Nonequilibrium Statistical Mechanics, XVIIth International Solvay Conference in Physics, eds. G. Nichols, Gug Dewel and John W. Turner (Wiley, New York, 1981), pp. 107-157.

7. Optical Bistability, eds. C.M. Bowden, M. Ciftan, and H.R. Robl (Plenum Press, New York, 1981).

8. G.S. Agarwal, L.M. Narducci, Da Huuan Feng and R. Gilmore, Coherence and Quantum Optics IV, eds. L. Mandel and E. Wolf (Plenum, New York, 1978), p. 281.

9. R. Bonifacio, M. Gronchi, and L.A. Lugiato, Phys. Rev. A18, 2266 (1978).

10. L. Allen and J.H. Eberly, Optical Resonance and Two-Level Atoms, (John Wiley and Sons, New York 1975).

11. K.G. Weyer, H. Widenmann, M. Rateike, W.R. MacGillivray, P. Meystre, and H. Walther, Opt. Commun. 37, 426 (1981).

12. H.J. Carmichael and G.P. Agrawal, in ref. 7, above, p. 237.

13. S. Stenholm and W.E. Lamb, Jr., Phys. Rev. 181, 618 (1969); B.J. Feldman and M.S. Feld, Phys. Rev. A1, 1375 (1970); J.H. Shirley, Phys. Rev. A8, 347 (1973); V.S. Letokhov and V.P. Chebotayev, Nonlinear Laser Spectroscopy, (Springer, Berlin 1977).

14. P.D. Drummond, IEEE J. Quantum Electron. QE-17, 301 (1981).

15. R.J. Ballagh, J. Cooper, M.W. Hamilton, W.J. Sandle, and D.M. Warrington, Opt. Commun. 37, 143 (1981).

16. S.L. McCall and H.M. Gibbs, Opt. Commun 33, 335 (1980).

17. R. Bonifacio and L.A. Lugiato, Opt. Commun. 19, 172 (1976).

18. H.J. Carmichael and J.A. Hermann, Z. Physik B38, 365 (1980).

19. M. Gronchi, V. Benza, L.A. Lugiato, P. Meystre, and M. Sargent III, Phys. Rev. A24, 1419 (1981).

20. L.A. Lugiato, L.M. Narducci, D.K. Bandy, and C.A. Pennise, Opt. Commun. 43, 281 (1982) and 44, 207 (1983).

21. L.M. Narducci, private communication.

22. P.W. Smith and W.J. Tomlinson, IEEE Spectrum 18, 26 (1981); E. Abraham and S.D. Smith, Rep. Prog. Phys. 45, 815 (1982).

23. R. Bonifacio and P. Meystre, Opt. Commun. 27, 147 (1978); G.S. Agarwal, L.M. Narducci, R. Gilmore, and Da Hüsan Feng, Phys. Rev. A18, 620 (1978); V. Benza and L.A. Lugiato, Lett. Nuovo Cimento 26, 405 (1979).

24. J.A. Goldstone, P.-T. Ho, and E. Garmire, in ref. 7 above, p. 187.

25. K.Y. Lau, C. Harder, and A. Yariv, Appl. Phys. Lett. 40, 198 (1982).

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE85-1 QUANTUM EFFECTS IN LASER INDUCED DAMAGE

Principal Investigators: Professor M.F. Becker (471-3628)
Professor R.M. Walser (471-5733)

Graduate Student: Yong Jee

A. RESEARCH OBJECTIVES: The major objective of this research unit is to study the mechanisms of laser induced surface damage in solids. Recent emphasis has been placed on single crystal metal surfaces. Diagnostic techniques which probe the state of the material surface at laser intensities near the damage threshold fluence will be used to determine the nature of the precursors to multi-pulse laser damage. Such precursors have been found to include accumulation, charge emission, cleaning, hardening, and conditioning. The goal of this program is to determine non-destructively where a particular sample is on its life curve or where its damage threshold is at a particular time. This will perhaps be possible when the events leading to multi-pulse damage are known.

The current project in this area is the study of multi-pulse damage of single crystal copper, aluminum, and nickel surfaces prepared by chemical, electro-chemical, and single point diamond machining methods.

B. PROGRESS: The interaction of high power laser beams with metal surfaces has a variety of damage phenomena such as slip band formation, melting and evaporation. The difficulty of making the determination of a unique damage phenomenon has led to the study of the effect of spot-size [1,2] and pulse width [3] on the single shot damage of metal mirrors.

Several models were proposed to analyze these damage mechanisms. Sparks and Loh's thermodynamic model has been successfully applied to analyze these damage mechanisms. Sparks and Loh's thermo-dynamic model has been successfully applied to analyze 1-on-1 damage testing data [3]. But the accumulation effect has not been studied fully on metal surfaces, particularly at 1.06 μm. Lee, Koumvakalis and Bass have studied the accumulation effect on diamond machined Cu at 10.6 μm and proposed a model based on plastic deformation damage. Musal's model [4] was another, similar explanation which related damage to the thermal stress field induced by the laser pulse at the metal surface. Figueira et al. [5,6] have also investigated N-on-1 damage to metal surfaces at 10.6 μm and have observed anomalous, reversible fluence dependent damage.

The purpose of the present work is to measure single and multiple pulse damage thresholds for metal surfaces of single crystal Cu, Al and Ni under 1.06 μm irradiation. Because of the close relation of damage to surface preparation, we have also studied the effect of different polishing methods on the damage of single crystal surfaces. We have examined the slope of damage probability curves with several different polishing conditions, and have studied the accumulation effect by varying the incident number of pulses. Damage morphologies near threshold with various incident number of pulses will be discussed. Finally, the correlation between the cumulative effect of laser damage on metal surfaces and the linear slope regions of the accumulation curves will be investigated. The accumulation curves are plots of log ($F_N N$) vs. log N

where F_N is N-pulse damage threshold fluence and N is the incident number of pulses. From accumulation curves and damage morphologies, N-pulse damage can be explained in terms of a cumulative process which is dependent on the incident number of pulses. The metal samples were found to have a storage cycle dependent on preceding pulses if the incident energy was larger than the plastic yield threshold.

EXPERIMENTAL PROCEDURES

The laser source used in these experiments was a Q-switched Nd:YAG laser with a 20 nsec pulse width and with pulse energy fluctuations of less than 3%. Incident pulses were attenuated by a rotating half-wave plate followed by a polarizer, and monitored by an energy meter whose output value was recorded by the computer. This energy meter was calibrated using a second energy meter before and after each testing session. The incident number of pulses was selected by an electro-mechanical shutter whose open and close operation was also automatically controlled. The laser was operated at a pulse repetition frequency of 10-20 Hz. The beam spatial profile was measured with the knife-edge scanning method at the beginning and at the end of each session [7]. The actual operating beam spot diameter was around 200 μm, with a measurement error less than 3%.

In the damage testing process, a predetermined number of laser pulses were incident on the sample surface, the energy of each pulse was recorded, and the laser beam was blocked by the shutter. A new site was then selected by the step-motor stage controlled by the computer system. Testing sites were separated by 0.7-1 mm in order to avoid overlap. As it was tested, each site was viewed under an 80X optical microscope mounted on the experimental apparatus. Finally the sample was removed from the sample holder and examined under a 200X optical Nomarski microscope to determine whether there was a permanent change on the metal surface. The damage features were also examined using a scanning electron microscope (SEM). All damage thresholds presented here correspond to the energy fluence on-axis of a focused beam and represent 50% damage probability thresholds as determined by examination under the 200X optical Nomarski microscope.

The prepared samples were single point diamond machined, chemically polished and electro-polished single crystal Al, Cu and Ni surfaces. The single point diamond machined samples were prepared at the Los Alamos National Laboratory. Chemically polished and electro-polished samples were prepared in our laboratory.

In order to investigate the surface crystal quality, electron channeling patterns (ECP), a Laue camera and an X-ray diffractometer were used. Since the electron channeling pattern can provide crystal orientation and crystal perfection information from a surface layer less than 50nm thick, sample surfaces can be checked effectively with this instrument [8]. The X-ray beam of the diffractometer and Laue camera penetrates more deeply into the material, up to 20 μm. An X-ray diffractometer or a Laue camera is recommended for examining bulk crystals. Chemically polished or electro-polished surfaces exhibited good single crystal quality for either the ECP, X-ray diffractometer or Laue camera. However, when we examined single point diamond machined surfaces with ECP, they did not exhibit good single crystal qualities within a 0.1 μm depth. Only with X-ray techniques could we see their single crystal quality.

EXPERIMENTAL DATA

When each sample was damage tested, we determined the damage probability curve which plotted damage probability versus incident fluence. Damaged and undamaged data points are overlapped within the interval between the maximum nondamaged and minimum damaged fluences. A linear curve is obtained from these overlapped data points by a least square curve fit. From this linear fit, we obtain the 50% damage threshold (F_N) for N pulses, and the damage onset, which is the zero intercept fluence for the linear fit for later correlation with the surface defect density [1].

We have repeatedly tested samples at different incident numbers of pulses, taken similar damage probability curves, and put the 50% probability threshold data on the damage accumulation curve. This accumulation curve is used to examine the effect of cumulative laser action on metal surfaces. The y-axis is the log of the product of the N-pulse damage threshold, F_N, and the incident number of pulses, [log ($F_N N$)]; and the x-axis is the log of the incident number of pulses, [log N]. This plot, figure 1, shows two straight lines for a <110> Al surface. Below N = 10 pulses, the curve has a smaller slope of S = 0.558; and above N = 10, the curve has a steeper slope of S = 0.902. In figure 1, the slope for large N, S = 0.902, approaches the limit of S = 1. A slope of one means that the damage threshold does not change at all with increasing pulse number and that there is no accumulation effect.

From the linear segments of the damage accumulation curve, we can derive the following N-pulse damage threshold equation:

$$F_N = F_{th}\ N^{S-1} \tag{1}$$

For this Al example, when $N \leq 10$, $S = S_m = 0.0558$, and $F_{th} = F_1$ represents single shot damage threshold. When $N \geq 10$, $S = S_p = 0.902$, and F_{th} is replaced with F_{pd} which is the threshold for plastic deformation damage. F_{pd} is obtained from the N = 1 intercept of the $N \geq 10$ line and is given by:

$$F_{pd} = F_{th}\ 10^{(Sm-Sp)\ \log N_t} \tag{2}$$

where N_t is the turning point. Using $N_t = 10$ and the above values for S_m and S_p, $F_{pd} = 0.45F_1 = 0.8 J/cm^2$. This means that the extrapolated single shot damage threshold for plastic deformation is approximately half of single shot damage threshold for this diamond machined Al sample. For the case of Cu, a similar accumulation curve is obtained, but there is just a single straight line as shown in figure 2. In this case $S_m = S_p$ and $F_{pd} = F_{th}$.

For small N, higher fluences are required for damage, and surface defects are damaged easily. Figure 3 shows single shot damage and local melting pits on diamond machined Cu at a fluence of 9.06 J/cm_2. This picture was taken by a 500X optical Nomarski microscope. This morphology near the damage threshold illustrates the form of defect related local melting. However, when the threshold for slip formation is significantly lower than that for defect damage, visible slip lines appear on the surface prior to catastrophic damage or melting. Figure 4 shows slip lines on an Al

surface produced by the thermal stress field induced by 1-on-1 laser tests. The photograph was taken by an optical Nomarski microscope from a single point diamond machined <111> Al sample irradiated at a fluence of 1.5 J/cm^2 with a beam spot diameter of 460 μm. These slip lines are not ripple patterns and are not periodic.

We observed that in the low pulse number regime, defect damage and plastic deformation damage are competitive. If the defect damage threshold is lower than, or of the same order as, the plastic deformation threshold, then defect damage appears first on the surface, and slip is minimal and invisible. If the plastic deformation threshold is significantly lower than that for surface defect damage, then visible slip lines will appear first. In the high pulse number regime where damage fluences are lower, plastic deformation is dominant near threshold. This is strong evidence for the cumulative effect of thermo-mechanical stress induced by repetitive laser pulses on the sample. Prior to catastrophic failure (i.e., before a flash or a spark was observed) [2], the irradiated sites became roughened and the degree of roughness increased with the incident number of pulses. Visible surface roughness was observed after a large number of pulses without the emission of light.

For different materials and polishing methods, the slope of the accumulation curves and single shot threshold data are summarized in table 1. For a single point diamond machined Al sample, the single shot damage threshold was 1.77 J/cm^2, damage onset was 1.62 J/cm^2, and the slope of the accumulation curve was 0.71 for $N \leq 10$ and 0.88 for $N \geq 10$. For Cu samples, the single shot damage threshold was about 10 J/cm^2. Although the damage threshold of Cu surfaces changed with the polishing method, there was only one slope to the accumulation curves.

Table 1. Test Data Summary

SAMPLE	Al		Cu		Ni
	D.T. 8/5/84 Sr.84151	CH.P. 5/22/85	D.T. 8/12/85 Sr.85055	E.P. 6/23/84	D.T. 5/22/85 Sr.84156
1-on-1 50% Prob. (J/cm^2)	1.77±.15	7.66±.9	9.40±.79	10.2	2.72
1-on-1 onset (J/cm^2)	1.62	6.84	8.24		1.81
Slope of 1-on-1 damage Probability Curve	330.3		46.1 (%cm^2/J)		
Slope of Accumulation Curve S	0.709 N<10 0.878 N>10	0.732 N<30	0.980 N<10 0.960 N>10	0.942 1<N<10^4	0.75 N<5 0.880 N>10

Table 2. Theoretical Melt Thresholds vs. 1-on-1 Damage Thresholds

Sample	<A> (average)	Theoretical values Melting threshold (20nsec, 1.06μm) (J/cm²)	Measured values Diamond turned surface 20 nsec (J/cm²) (with spot size as noted)	47 nsec (J/cm²)
Al	0.0704	2.74	1.77±0.15 (200 μm)	3.83±0.6 (68.5 μm)
Cu	0.0253	19.52	9.40±0.79 (208 μm)	-
Ni	0.3175	0.77	0.93±0.2 (68.7 μm)	2.72±0.7 (80.2 μm)

DISCUSSION

When we drew the various damage probability curves, the slope was found to increase with the incident number of pulses and decrease with increasing numbers of defect damage spots in the beam. This is in agreement with Foltyn's findings [1] that the slope is dependent on the beam spot size and surface defect density, and that surface defects can be probed using damage probability curves.

Theoretical melt thresholds and measured 1-on-1 damage thresholds are compared for a pulse width of 20 nsec in table 2. In the second column, <A> is the average optical absorptance which is obtained from the integral equation of Sparks and Loh [3].

$$\langle A \rangle = \frac{\int_{T_0}^{T_m} A_0 (1 + \alpha T)\, dt}{(T_m - T_0)} \qquad (3)$$

where A_o is the surface optical absorptance at room temperature, α is the coefficient of temperature dependent absorption, T_m is the melting temperature, and T_o is the ambient temperature (^oK). When an intense laser beam interacts with a normal metal surface, a fraction of incident energy penetrates the metal to a skin depth and is absorbed by the free carriers in the metal. This absorbed energy is converted to a thermal distribution which generates a thermal stress field. It is the stress field which contributes to the cumulative effect of deformation and slip in multiple pulse damage. If the incident radiation is intense enough, the absorbed energy can raise the surface temperature to melting. The threshold for single shot surface melting is given by [3].

$$F_m = \frac{(T_m - T_o)(\pi K C t_p)^{1/2}}{2\langle A\rangle} \tag{4}$$

where F_m is the fluence (J/cm^2) required to melt the surface, t_p (sec) is the pulse duration, C is the volumetric specific heat capacity in ($J/cm^{3o}K$), and K is the thermal conductivity (W/cm^oK).

In the case of Al and Ni, the theoretical melt threshold and measured single pulse damage threshold values are nearly identical. The agreement is not as good for Cu where the theoretical melt threshold is near 20 J/cm^2, but the measured damage threshold is only 10 J/cm^2.

For the case of N-on-1 damage, we will consider cyclic thermomechanical stress induced by the laser pulse as a possible explanation of the accumulation effect. The thermal expansion of metal surfaces resulting from the transient temperature rise generates compressive stress, followed by tension during the cool-down period. If the temperature rise and the coefficient of thermal expansion are large enough, a permanent irreversible plastic strain will remain due to the compression and tension process. The fluence corresponding to the plastic yield (slip) threshold (F_y) is given by [4]

$$F_Y = \frac{(\pi K C t_p)^{1/2}(1-v)Y}{2\langle A\rangle \beta E} \tag{5}$$

where v is Posson's ration, Y is the yield stress, β is the coefficient of thermal expansion and E is Young's modulus of the metal for an idealized case of strain being linearly dependent on the stress. The experimental threshold for visible plastic deformation, F_{pd}, identified in equation (2) was F_{pd} = 0.8 J/cm^2 for <110> diamond machined Al. The calculated yield threshold at the free surface [4] for the same material is 0.12 J/cm^2. When we compared these two values, the experimental threshold for visible plastic deformation was 6.7 times larger than the theoretically predicted yield threshold. According to Musal's model [4], the predicted free surface elastic displacement is approximately 12 nm per incident J/cm^2 for the case of high quality Al mirror surfaces. If we use the same argument for our diamond machined Al surfaces, the predicted free surface displacement will be approximately 1.4nm at the fluence of 0.12 J/cm^2, and about 6.7 times larger for the experimental case or approximately 9.6 nm. The distinction between these two cases appears consistent with the expected vertical detectivity threshold in Nomarski

microscopy. In other words, the threshold for visibility and for subsequent damage due to plastic deformation might be larger than the threshold for the initiation of plastic deformation. Surface deformation above this threshold is distinguished by an increase in absorptance sufficient to lead to catastrophic surface damage to microscopically visible surface roughening. This cyclic thermomechanical effect can lead to the accumulation observed in N-on-1 damage.

In the previous section, we have shown that the accumulation curves and damage morphologies suggest two damage regimes for low N and high N, where in both cases the N pulse damage threshold, F_N, is in the form of equation (1). The N-on-1 damage threshold decreased with increasing N suggesting an energy storage cycle produced by the thermomechanical stress-strain field of the absorbed laser beam.

For cases such as Cu having a single slope in the accumulative curve, these results may be combined with the equation for the theoretical melt threshold. The result is an equation for N-on-1 damage threshold in terms of material constants, as shown below.

$$F_n = \frac{(T_m - T_o)(\pi K C t_p)}{N^{1-s}\, 2\langle A \rangle} \qquad (6)$$

If S is 0.9 and N is 1000, then the 1000 pulse damage threshold is reduced by a half. Thus the N-pulse damage threshold may be predicted using equation (6) when a typical value of S for the material is known.

CONCLUSIONS

Single and multiple pulse damage threshold measurements have been performed on single crystal Cu, Al, and Ni single point diamond machined, chemically polished, and electro-polished surfaces with a 1.06 μm laser beam in air. Our findings imply that plastic deformation is an important contributor to the nanosecond pulse laser damage of these metal surfaces even at fluences well below their melting or their defect damage thresholds.

The crystal quality of the samples was checked with electron channelling patterns and X-ray diffraction. Diamond machined surfaces had a disordered layer at least 0.1 μm in depth, but the electro-polished and chemically polished surfaces were single crystals. It is well known that the diamond machining process involves high stresses at the surface, so this disorder is not unexpected.

The slope of the damage probability curve is related to the surface damaged defect density and the incident number of pulses. We found that in addition to the expected decrease in slope with increasing defect damage densities, the slope increased with increasing N in N-on-1 experiments.

Accumulation was observed in all samples and the accumulation curves indicated that the damage mechanism had two different regimes -- a low pulse number regime and a high pulse number regime. In the low pulse number regime, the morphology suggests defect dominated local melting; and in the high pulse number regime, the morphology suggests plastic deformation mediated by energy storage cycles from previous pulses. In some cases where the threshold for plastic deformation or yield was extremely low, plastic deformation damage was dominant even for N = 1.

The accumulation effect for all the samples could be described by the experimentally derived equation (1) which indicates decreasing N-pulse damage thresholds with increasing pulse numbers.

The thermal stress field produced by the incident laser pulse appears to drive cyclic thermomechanical behavior involving energy storage by nonconservative circuits around the stress-strain curve. Slip lines form when the absorbed energy exceeds the yield (slip) stress threshold. Under repeated laser irradiation this is manifested in surface roughness, and eventually the surface damages.

C. FOLLOW-UP STATEMENT

This research is substantially complete and JSEP sponsorship has been terminated. Aspects concerning transient laser induced processes in semiconductors will continue under sponsorship of the Texas Advanced Technology Program.

D. REFERENCES:

1. S.R. Foltyn, "Spotsize Effects in Laser Damage Testing." Nat. Bur. Stand. (US) Spec. Publ. #669; 368, 1982.

2. C.S. Lee, N. Koumvakalis, M. Bass, "Spot-size Dependence of Laser-Induced Damage to Diamond Turned Cu Mirrors," Appl. Phys. Lett. 48(7); 625 (1982); "A Theoretical Model for Multiple-pulse Laser Induced Damage to Metal Mirrors." J. Appl. Phys. 54(10); 5727 (1983).

3. M. Sparks, E. Loh, Jr., "Temperature Dependence of Absorptance in Laser Damage of Metallic Mirrors: I. Melting." J. Opt. Soc. Am.; 69(6), 847 (1979).

4. H.M. Musal, Jr., "Thermomechanical Stress Degradation of Metal Surfaces under PULsed Laser Irradiation." Nat. Bur. Stand. (US) Spec. Publ. #568; 159 (1980).

5. J.F. Figueira, S.J. Thomas, "Damage Thresholds at Metal Surfaces for Short Pulse IR Lasers." IEEE J. Quantum Electron.; QE-13, 1381 (1982).

6. S.J. Thomas, R.F. Harrison, J.F. Figueira, "Observations of the Morphology of Laser-induced Damage in Copper Mirrors." Appl. Phys. Lett.; 40(3), 200 (1982).

7. D.C. Cohen, B. Little, F.S. Lueche, "Techniques for Measuring 1-μm Diameter Gaussian Beams." Appl. Opt.; 23(4), 637 (1984).

8. J.I. Goldstein, H. Yakowitz, Practical Scanning Electron Microscopy. Plenum Press, New York; 149-210 (1975).

9. M.F. Becker, Y.-K. Jhee, M. Bordelon and R.M. Walser, "Observations of an Incubation Period for Multi-Pulse Laser Induced Damage," Proceedings of the Conference on Lasers and Electro-Optics (CLEO), Optical Society of America, Washington, D.C. (1983).

10. M.F. Becker, Y.-K. Jhee, M. Bordelon and R.M. Walser, "Charged Particle Exoemission from Silicon During Multi-Pulse Laser Induced Damage," 14th ASTM Laser Damage Symposium, NBS Special Publication (1984).

11. M. Bordelon, R.M. Walser, M.F. Becker and Y.-K. Jhee, "A Study of the PRF Dependence of the Accumulation Effect in Multiple Pulse Laser Damage of Silicon," 14th ASTM Laser Damage Symposium, NBS Special Publication (1984).

12. M.F. Becker, F.E. Domann, A.F. Stewart and A.H. Guenther, "Charge Emission and Related Precursor Events Associated with Laser Damage," 15th ASTM Laser Damage Symposium, NBS Special Publication (1984).

13. M.F. Becker, J.A. Kardach, A.F. Stewart and A.H. Guenther, "Surface Potential as a Laser Damage Diagnostic," 16th ASTM Laser Damage Symposium, NBS Special Publication, Boulder, CO (1985).

14. M.F. Becker, J..A. Kardach, A.F. Stewart and A.H. Guenther, "Surface Potential as a Laser Damage Diagnostic," Proceedings of the Southwest Conference on Optics, SPIE, Bellingham, WA (1985).

15. M.F. Becker, Y.-K. Jhee and R.M. Walser, "Charge Emission and Accumulation in Multiple-Pulse Damage of Silicon," 16th ASTM Laser Damage Symposium, NBS Special Publication, Boulder, CO (1985).

16. Y.K. Jhee, M.F. Becker, and R.M. Walser, "Charge Emission and Precursor Accumulation in the Multiple-Pulse Damage Regime of Silicon," The Journal of The Optical Society of Amercia, Part B, Vol. 2, pages 1626-1633, October 1985.

17. F.E. Domann, M.F. Becker, A.H. Guenther and A.F. Stewart, "Charged Particle Emission Related to Laser Damage," Applied Optics, vol. 25, pages 1371-1373, 1 May 1986.

18. A.L. Huang, M.F. Becker and R.M. Walser, "Laser Induced Damage and Ion Emission of GaAs at 1.06 Microns," submitted to Applied Optics (April 1986).

19. Yong Jee, M.F. Becker and R.M. Walser, "N-on-1 Damage Testing of Single Crystal Metal Surfaces at 1.06 Microns," 17th ASTM Laser Damage Symposium, NBS Special Publication, Boulder, CO, 1986.

20. A.L. Huang, M.F. Becker and R.M. Walser, "Laser Induced Ion Emission and Damage of GaAs at 1.06 Microns," 17th ASTM Laser Damage Symposium, NBS Special Publication, Boulder, CO 1986.

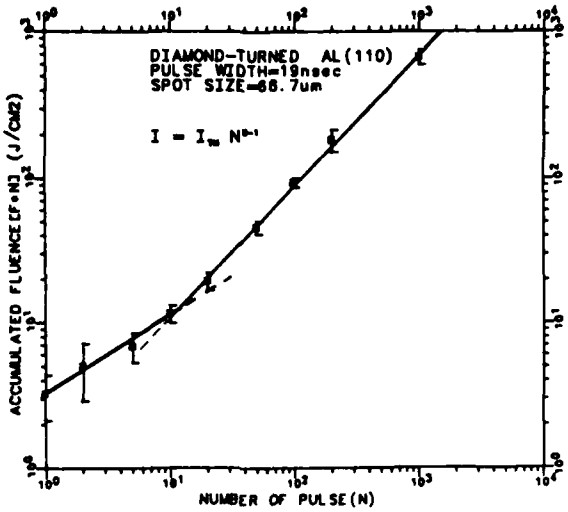


Figure 1. Accumulation curve for diamond turned <110> A1.

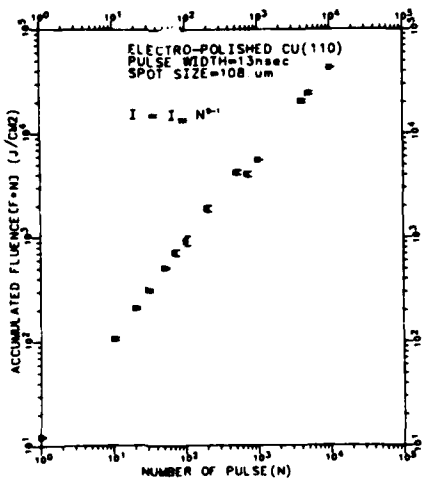


Figure 2. Accumulation curve for electro-polished <110> Cu.

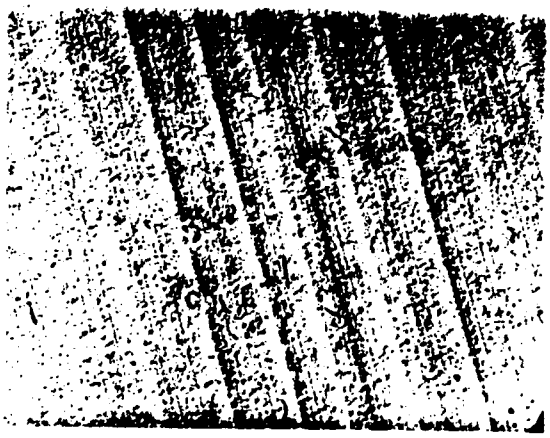


Figure 3. Optical Nomarski micrograph of damage of single point diamond machined <100> Cu which shows defect related local melting pits, N = 1 at 9.06 J/cm^2.

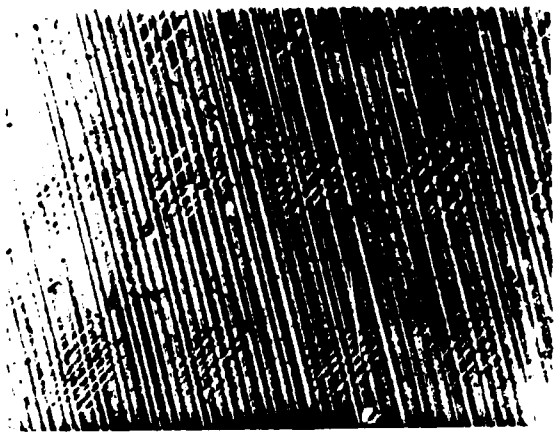


Figure 4. Optical Nomarski micrograph of the damage morphology on a diamond machined <111> Al surface. All the spots have been single shot damage tested at 1.5 J/cm^2.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE85-2 NONLINEAR RAMAN SCATTERING FROM MOLECULAR IONS

Principal Investigator: Professor J.W. Keto (471-4151)

Graduate Students: Mike Bruce, Chong Keem, Winston Layne and Roger Taylor

A. SCIENTIFIC OBJECTIVES: A continuing problem in high pressure discharges is the understanding of the reactions of ions. At high pressures new ions in the form of clusters are formed and reactions of all forms of ions are complicated by the possibility of termolecular reactions. Few accurate experiments investigating ion reactions exist at high densities because of the lack of a suitable probe for studying ions immersed in a high pressure gas. The lack of a suitable diagnostic has effectively prevented an accurate understanding of the ion processes in high-pressure, gas-dynamic lasers such as the rare-gas halogen lasers.

The probes for such studies must have high sensitivity, and good spectral and temporal resolution. Temporal resolution is required so that the decay rates can be used to measure reaction rates. We are interested in reactions such as association, recombination, and charge transfer. Nonlinear optical probes based on coherent Raman scattering processes when used in conjunction with high power pulsed lasers potentially meet all these criteria.

Research on the reactions and structure of ions at pressures near or above atmosphere is new. Such studies are motivated by electron beam driven or preionized lasers [1,2], particle beam weapons [3] and plasma chemistry [4]. In general it is thought that when fundamental two-body interactions are understood, they can be used to model the more complicated systems; however, at higher pressures the interaction of ions is known to become nonlinear. In estimating the formation rates of cluster ions, Smirnov [5] has described several models for estimating three-body (termolecular) reaction rates. Though the importance of termolecular reactions for formation of molecules has long been known, large termolecular reactions rates for molecular ions have only recently been discovered [6].

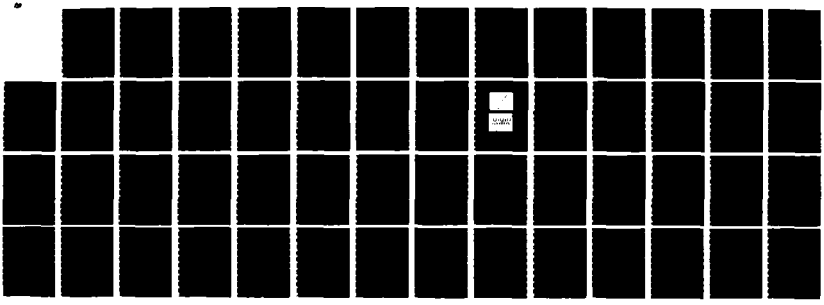
Polyatomic ions of interest include Xe_3^+, Ar_3^+ and Xe_nCl^+ which are relevant to excimer lasers. Other molecular ions for which there exists a need for experimental analysis include those formed in atmospheric discharges; H_3^+, N_3^+, N_4^+, O_3^+ and O_4^+ all fall into this category. The results from such studies will be applicable to the problem of particle beam transport in the atmosphere. Of particular fundamental interest is H_3 which is the simplest nonlinear polyatomic molecule. Data obtained for H_3 may be compared directly to ab initio calculations.

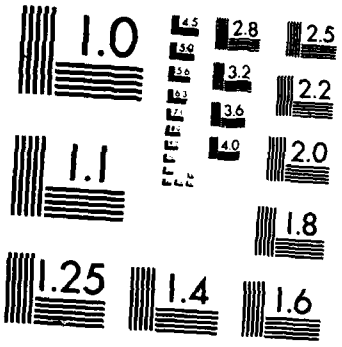
B. PROGRESS: In nonlinear Raman spectroscopy, two lasers - often named the pump and probe laser - are focussed either colinearly or counter propagating onto a gas target. The third order susceptibility induced by the pump laser produces gain of the probe laser. In CARS, two waves from the pump beam combine with the probe to generate gain at the antistokes frequency. Both techniques have sufficient sensitivity to observe scattering from ion densities of 10^{13} cm^{-3}; but experimentally require all aspects to be optimized.

Many of the important developments in the study of high resolution Raman spectra of gases have originated from Owyoung's [7] group at Sandia Research Laboratories. He has developed the most sensitive spectrometer to date. In his experiments, Owyoung used a quasi-c.w. laser as the probe laser. Gain was then induced in the probe laser beam by a 10 nsec, high power dye laser. The quasi-c.w. probe power is limited by the c.w. saturation current of the photodetector to

AD-A174 318 JOINT SERVICES ELECTRONICS PROGRAM(U) TEXAS UNIV AT AUSTIN ELECTRONICS RESEARCH CENTER E J POWERS 30 SEP 86 TR-33 AFOSR-TR-86-0622 F49620-82-C-0033 3/3

UNCLASSIFIED F/G 20/12 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

approximately 100 mW. The signal-to-noise is then limited by fluctuations in the relatively small number of photons incident on the detector during the 10 nsec gain pulse.

The difficulty in Raman gain spectroscopy is trying to measure a small change in the large probe laser intensity. This problem is reminiscent of early experiments in saturation spectroscopy by Hansch; he solved the problem by using polarization techniques [8]. A highly polarized probe laser is crossed with a high power pump laser in the sample and then procedes through a crossed polarizer onto the detector. When the pump and probe lasers are in resonance with the sample, induced birefringence generates a component in the probe of opposite polarization which is transmitted by the polarizer at the detector. The birefringence signal is then observed on a "black" background by the detector.

In the field of Raman gain spectroscopy this technique has been named RIKES (Raman induced Kerr effect spectroscopy) by Levenson [9]. The intensity observed at the detector is

$$I = I_B + (E_{LO} + E_R)^2 = I_B + (E_{LO} + g\,E_o)^2 \tag{1}$$

$$I = I_B + \theta^2 I_o + 2\theta\, g\, I_o + g^2 I_o \tag{2}$$

where $I_B = \beta I_o$ represents the residual background due to birefringence of the probe laser power, I_o in the sample windows, etc., $E_{LO} = \theta\, E_o$ represents a local oscillator field obtaioned by uncrossing the polarizers by an angle θ, and g represents the Raman gain induced by the pump laser

$$g = \alpha\, \ell I(\omega_1)\, |I_m \chi_3| \tag{3}$$

where α summarizes constants of proportionality. Levenson has described the expected signal to noise ratio in detail [9]. Under ideal experimental conditions one can ignore shot noise, thermal detector noise, and electrical noise compared to noise caused by fluctuations in the laser intensities. For an optimum local oscillator intensity

$$\theta\, I_o = (2)^{1/2}\, \beta\, I_o (F_b/F_o) \tag{4}$$

where F_b and F_o are the fractional fluctuations in the intensity for the background and probe laser, we obtain the ratio of signal to noise off resonance

$$S/N = \frac{g}{(F_o F_b \beta)^{1/2}} \tag{5}$$

Levenson subtracted the background signal in Eq. (2), $(\beta + 2\,\theta\, g)I_o$ by using heterodyne detection of modulated c.w. lasers. For the smallest obtainable values of $\beta \cong 10^{-6}$, the optimum local oscillator powers obtained from Eq. 4 againlimits the signal-to-noise by the shot noise in the light incident on the detector, unless very large probe powers I_o can be obtained. For reasonable laboratory c.w. lasers, large values of θ are required. We use a high power pulsed probe lasers in order to obtain the maximum signal-to-noise ratio obtained by Eq. 5 and not be limited by shot noise of the detector [10].

The difficulty is that small changes in the intensity of a short (10 nsec), pulsed probe laser must be measured. The probe power was sampled before and after the target with a FD100 photodiode from EGG, Inc. This diode was selected because of its wide bandwidth and large saturation current. We have found the diode to be linear up to 500 mA peak current. As first done by Nestor [11], the gain was measured by subtracting the diode signals using wideband differential amplifiers. The optimum configuration first integrated the diode signals using low noise charge preamplifiers and then subtracted the signals using a wide band amplifier. The error in subtraction over the full bandwidth was approximately 8% of the pulse height. A gated boxcar integrator was then used to sample the difference at the point best representing the total charge from the integrated signals. This technique reduced the subtraction error to 3% on a single shot basis, and when averaging over 1000 laser shots we could observe a gain or loss of the probe power of about one part in 10^3. The major limitation using the boxcar was our inability to average over the fluctuations in the power of the pump and probe lasers.

We next installed a computerized data acquisition system similar to that used for our two photon experiments [12,13,14]. The function of the boxcar is replaced by a gated, 11 bit, LeCroy charge digitizer. With this facility the signal can be normalized on a shot-to-shot basis to the laser powers sampled with additional diodes. At the same time we experimented with using faster differential amplifiers and then integrating. Several types of amplifiers were used with only slight improvement in the single pulse error over the previous approach.

Both techniques suffer because of the difference in bandwidth of the two diodes. In both of the above experiments we use "matched" diodes and attempted to further match the junction capacitances by varying the reverse bias voltages. We have now devised an elegant technique which uses a single diode to sample the beam before and after gain [15]. This experimental approach is illustrated in Fig. 1. The basic idea is to delay one of the optical signals relative to the other using a low loss optical fiber. The two light signals are then combined onto a single diode to produce an electronic signal as shown at point B. If the second pulse is delayed sufficiently to allow the diode to recover, both light pulses are processed by an identical transfer function. The signal is then split and one half delayed (with cables) so as to bring the two signals into time coincidence again. We have subtracted the signals with amplifiers, or more simply, by using a clipping cable which delays, inverts, and sums the signals at point B. The resulting error is approximately 1% of the optical pulse; and fluctuations in the integrated error is reduced to 1 part in 10^4. With this technique we are able to obtain high quality stimulated Raman gain spectra (SRGS) of liquids with the experimental setup shown in Fig. 1. A typical spectrum of the 459 cm^{-1}

vibrational line of CCl_4 is presented in Fig. 2. The several peaks seen are due to various isotopes of chlorine.

The signal to noise ratio is now improved by about an order of magnitude in comparison to our previous spectra of the 992 cm^{-1} line of benzene, obtained with a differential amplifier. Fluctuations in the integrated error are about one part in 10^4, which seems to be the limit of this technique.

Extensive studies of the propagation of laser pulses in optical fibers have been done to investigate the limitations of this technique. We came to the conclusion that our present technique is limited by fluctuations in the bandwidth of the optical fiber. This can be clearly seen in Fig. 3 where we plot the fractional standard deviation of the pulse at various time intervals during the pulse.

Dramatic improvements in sensitivity are possible by combining our fiber technique with the highly advantageous polarization techniques of coherent Raman spectroscopy which utilize definite input and output polarizations. The main limitation of a traditional polariation experiment is due to stress induced birefringence [9] in the optical components of the system. A schematic illustration of this novel experiment is shown in Fig. 4. Light from a tunable pump laser of frequency ω_2 is linearly polarized 45° with respect to the probe beam. The probe laser has a fixed frequency and is highly linearly polarized to approximately one part in 10^6. The best available Glan - Thompson polarizers are of such quality. In Fig. 4, the sample is indicated by SC and the analyzing polarizer by GT2 which is oriented to reject the probe component $E_y(\omega_1)$ while transmitting the signal $E_x(\omega_1)$. The overall background due to birefringence would normally be the limitation of this experiment. However, this background can be subtracted from the signal with an accuracy 10^{-3} by sampling the probe beam before and after the medium, using our fiber technique. So our overall sensitivity improves more than three orders of magnitude in comparison to the previous result.

As a test of the experimental approach we show in Fig. 5 calculations of the signal-to-noise ratio as a function of the fraction of probe, θ^2, used as the local oscillator. These calculations are for pump and probe powers of 10 kW. It is seen that the highest sensitivity is achieved for a local oscillator power on the order of 10^{-6} I_o, which corresponds to the limit of maintaining minimum birefringence in our system.

Calculated results are in close agreement with our measurements as seen in Fig. 6 where observe the υ_1 band of CH_4 at 2917 cm^{-1} at 1 atm. The calculated signal-to-noise of 50 can be compared with the experimentally observed value of 40.

Theoretical Spectrum of Argon Dimers. The high resolution spontaneous light scattering by argon dimers has been reported by Godfried and Silveira [16]. Such spectra are extremely weak since the dimer fraction is of the order of 1% of the toal gas density which should be low, as otherwise the dimer lines will be unresolvable due to pressure broadening. The limitation of this technique is that only the pure rotational transitions of the lowest vibrational level were measured because of the dominating overlapping spectrum due to the collision induced light scattering from free pairs of atoms, especially at high temperatures. From Fig. 7 is seen that only the pure rotational band below 7 cm^{-1} is visible in Fig. 7. A calculation of the complete rotational-vibrational spectrum of Ar dimers which includes pressure broadening of bound to bound transitions is presented for the first time [17]. We applied Anderson's impact theory extended by Van Kranendonk and Fiutak [18] for linewidth calculation.

Theoretical subtracted OHD-RIKES lineshape is reported on Fig. 7. One can clearly see higher vibrational bands, first appearing at 25 cm^{-1}. The first vibrational band is enhanced

compared to the pure rotational band due to the fact that unlike the spontaneous Raman spectrum, the nonlinear spectrum is proportional to the difference of population between the final and initial state. One can see also that the broad collisional background from unbound molecules is suppressed in comparison to Fig. 7 which is due to the fact that Im χ^3 is proportional to $1/\Gamma$, where Γ is a linewidth. Evaluating Eq. (3) for argon dimers, for Im χ^3 of the order 6×10^{-17} esu at 1 atm pressure, and for a 10 MW pump laser, one expects a gain of 4×10^{-4}. For pump lasers available in our laboratory with powers of 50 kW we expect a gain of 2×10^{-6}.

C. FOLLOW-UP STATEMENT: This work is continuing under Joint Services support. We propose to continue to investigate the use of coherent Raman scattering as a probe of molecular ions in high pressure discharges. As described in the progress section, we have developed technology for measuring small gains in a pulsed probe laser. This technique has been combined with polarization techniques to obtain improved sensitivity for Raman gain spectroscopy. It is now feasible to obtain Raman spectra for particle densities as low as 10^{13} cm^{-3}.

REFERENCES

1. C.A. Brau, Excimer Lasers, C.K. Rhodes, ed., Springer-Verlag, Berlin (1979).

2. C.W. Werner, E.V. George, P.W. Hoff and C.K. Rhodes, IEEE J. Q. Elect. QE-13, 769 (1977).

3. J. Parmentola and K. Tsispis, Sci. Amer. 240, 54-65 (1979).

4. A.T. Bell, "The Interface Between Plasma Physics and Plasma Chemistry," Workshop on Plasma Chemistry and Excited State Reactions, 32nd Annual Gaseous Electronics Conference (1979).

5. B.M. Smirnov, "Cluster Ions in Gases," Sov. Phys. Usp. 20, 119 (1977).

6. Chien-Yu Kuo and J.W. Keto, "Dissociative Recombination of Electrons in Electron Beam Excited Argon at High Densities," J. Chem. Phys. 78, 1851 (1983).

7. Peter Esherick and Adelbert Owyoung, Adv. Infrared and Raman Spectroscopy, vol. 9, 130 (1982); A. Owyoung, IEEE J. Quantum Electron. QE-14, 192 (1978).

8. C. Wieman and T.W. Hansch, Phys. Rev. Lett. 36, 1170 (1976).

9. Marc D. Levenson, "Polarization Techniques in Coherent Raman Spectroscopy," J. Raman Spectrosc. 10, 9 (1981).

10. T.D. Raymond, S.T. Walsh and J.W. Keto, "A Narrowband Dye Laser with a Large Scan Range," Applied Optics 23, 2062 (1984).

11. James R. Nestor, J. Chem. Phys. 69, 1778 (1978).

12. N. Bowering, T.D. Raymond and J.W. Keto, "Enhanced Quenching at Reduced Internuclear Separations of Xenon Collision Pairs," accepted Phys. Rev. Lett.

13. T.D. Raymond, N. Bowering, Chien-Yu Kuo and J.W. Keto, "Two-Photon Laser Spectroscopy of Xenon Collision Pairs," Phys. Rev. A29, 721 (1984).

14. N. Bowering, Chien-Yu Kuo, T.D. Raymond and J.W. Keto, "Spectral Line Shapes from Two Photon Excitation of Xenon," Spectral Line Shapes, vol. 2, Walter de Gruyter & Co., Berlin-New York (1983).

15. J. Borysow, H. Golnabi, and J.W. Keto, "Innovative Technique for Measuring the Gain or Loss of Pulsed Lasers," in preparation.

16. H.P. Godfried and Isaac F. Silvera, Phys. Rev. A27, 3008 (1983).

17. J. Borysow, "Theoretical Nonlinear Raman Spectra of Argon Dimers," submitted to J. Molecular Physics.

18. J. Fiutak and J. Van Kranendonk, Can. J. Phys. 40, 1085 (1962).

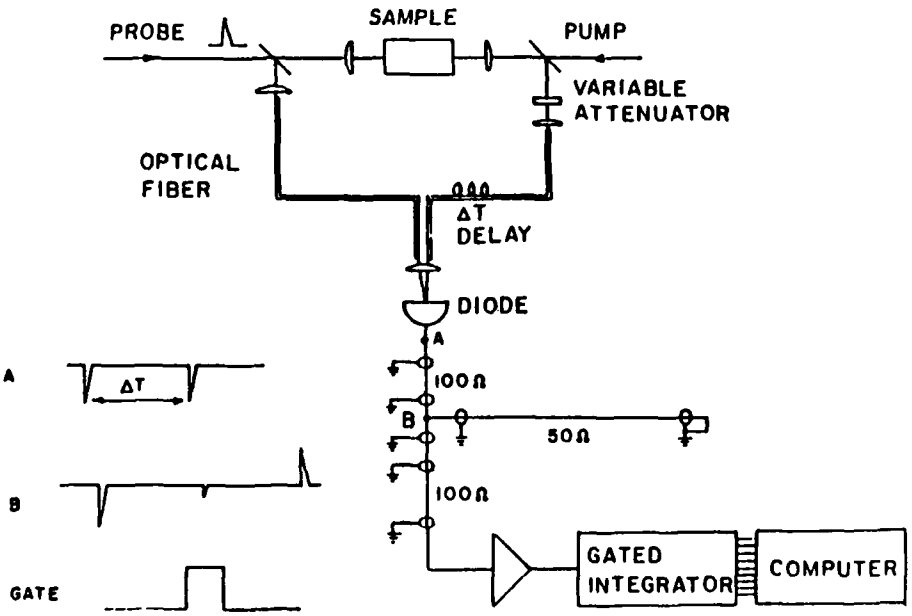


Figure 1. SRGS apparatus using only a single photodetector to measure the probe laser gain.

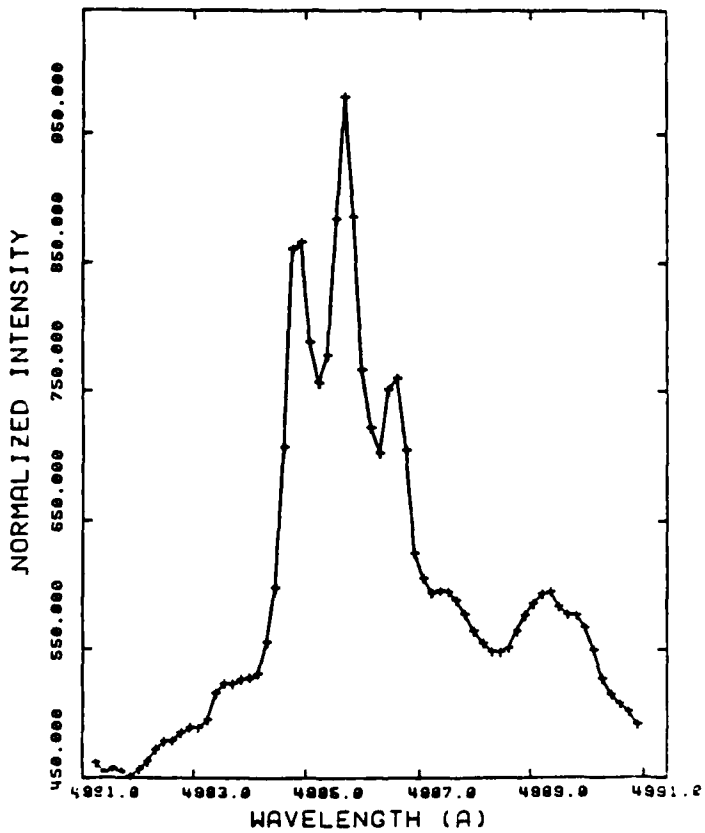


Figure 2. Raman induced gain at 459 cm^{-1} vibrational line of CCl_4.

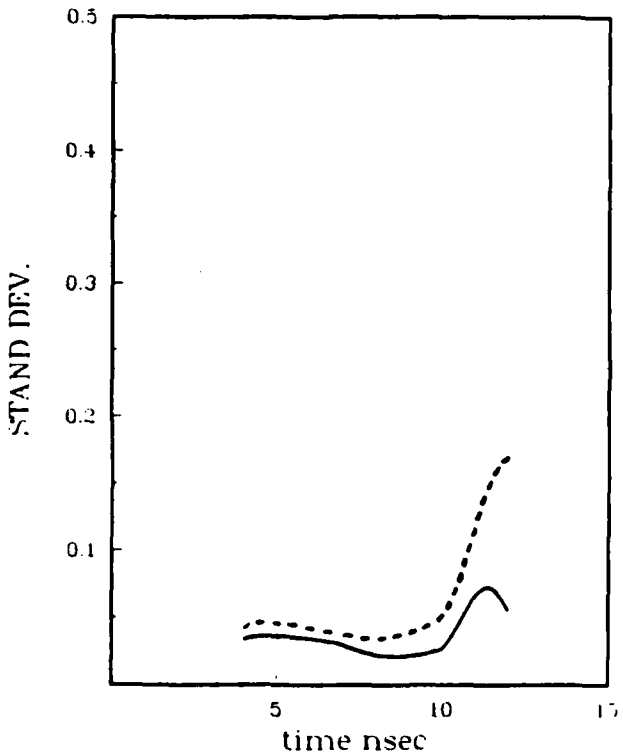


Figure 3. The fluctuations of the laser pulse in time. The solid line corresponds to the pulse after a short fiber, and the dashed line shows the standard deviation for the pulse after passing a long fiber.

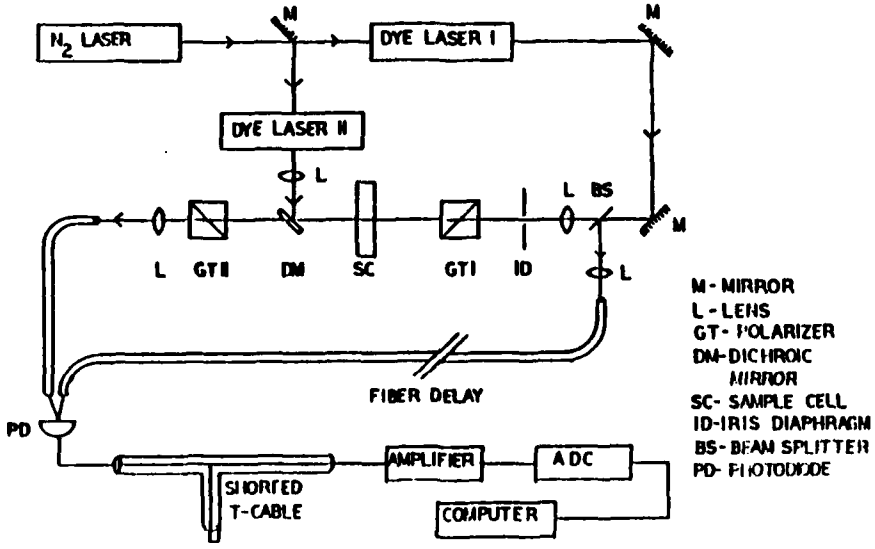


Figure 4. SRGS apparatus with polarizers using a single photodetector to measure depolarized probe laser gain.

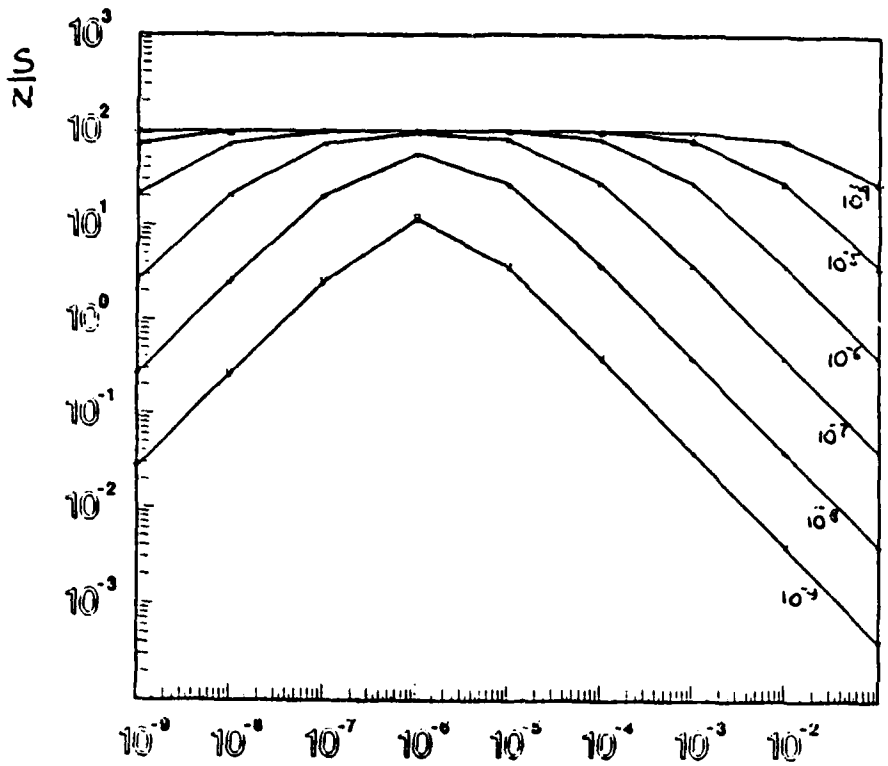


Figure 5. The signal-to-noise ratio as a function of the ratio of the local oscillator power to the probe power for a pump power of 10 kW. Each curve is parameterized by a different conversion coefficient of the probe power.

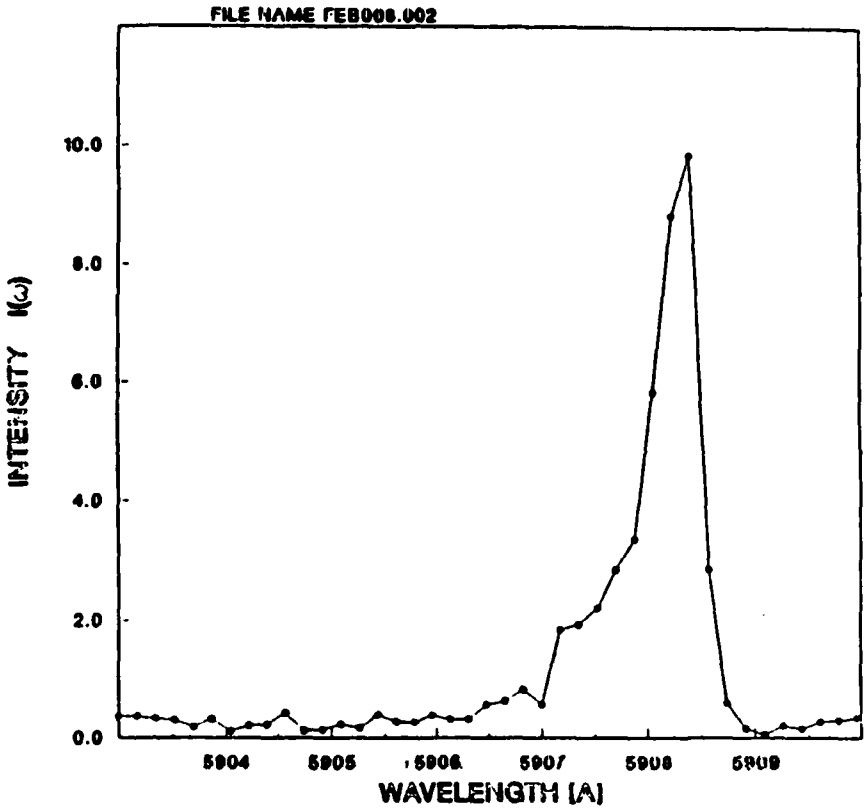


Figure 6. The OHD-RIKES spectrum of the υ^1 2917 cm^{-1} band of CH^4 at a pressure of 1 atm; the pump and probe lasers are elliptically and linearly polarized, respectively.

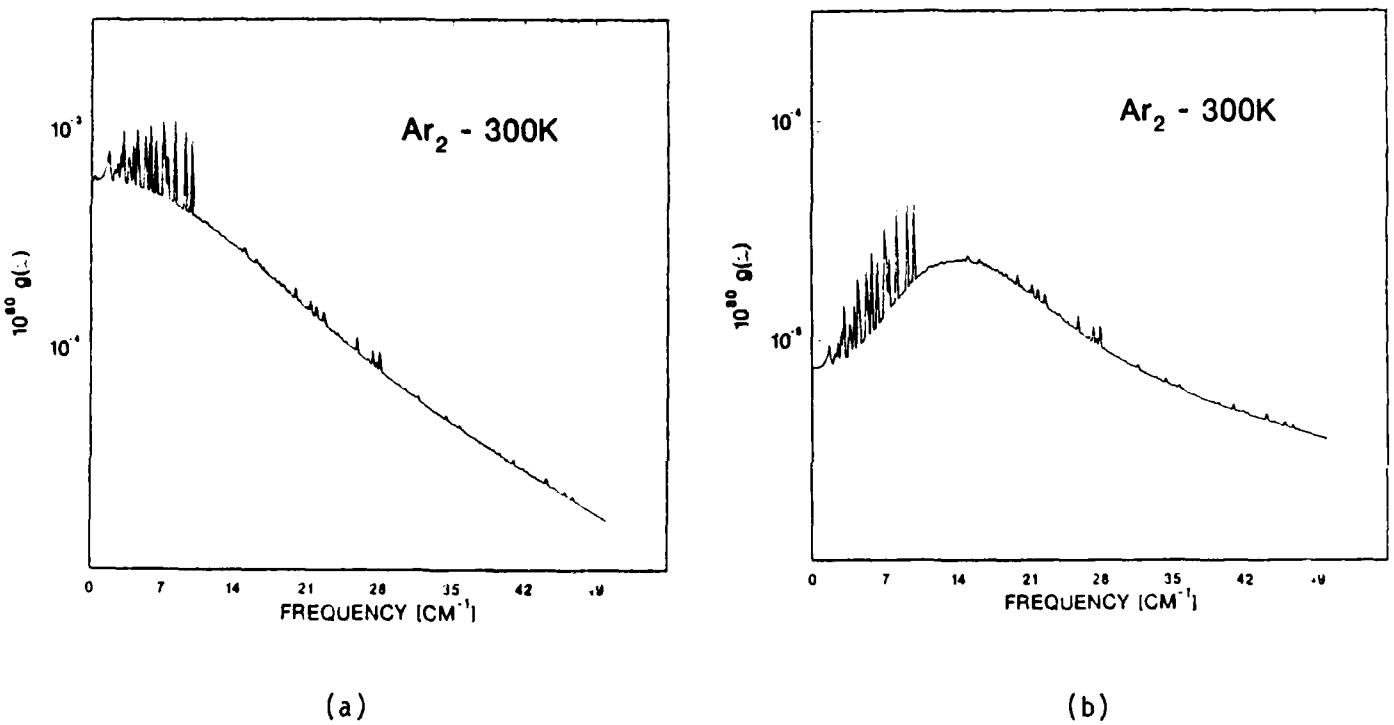


Figure 7. Theoretical spontaneous Raman spectral line shape of argon dimers calculated for MSV III potential at 300K (7a). Theoretical nonlinear Raman spectral line shape for MSV III potential at 300K (7b).

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
QUANTUM ELECTRONICS

Research Unit QE85-3 NONLINEAR OPTICAL INTERACTIONS

Principal Investigators: Professors M.F. Fink (471-5747)
Professor H.J. Kimble (471-1668)

Postdoctoral Associate: Dr. A.T. Rosenberger

Graduate Students: Tim Boyd, Dan Coffman, S. Ketkar, R. Mawhorter, R.J. Brecha and Ling -An Wu

A. SCIENTIFIC OBJECTIVES: This research unit describes work carried out by Drs. Fink and Kimble and deals with the interaction of atoms and molecules with resonant optical fields. The research objectives include a number of fundamental scientific questions relating to the complex behavior exhibited by even very simple optical systems. The principal avenues of investigation involve atomic and molecular beam systems as well as new optical materials for efficient frequency conversion. The general spirit of the work might be termed a study of nonequilibrium phase transitions in optical systems. Just as in their thermodynamic counterparts, optical systems often undergo rather dramatic changes in their operating characteristics for rather minor changes in the set of external control parameters. The laser is of course the best known example in optical physics, but there are a number of other optical systems with similar striking behavior. One example that we are studying is optical bistability which, roughly speaking, provides the optical analogy of a transistor. In addition to the existence of multiple time-independent steady states for a single set of control parameters, there exists a hierarchy of time-dependent self-pulsing states. That is, for constant external excitation, the system spontaneously breaks into an oscillatory state that persists indefinitely. While such nonlinear dynamics are of great scientific interest, there are also a number of potential applications in optical signal processing (due to the potentially extremely high frequencies of oscillation) and in high power output (the self-pulsing state often produces a much greater peak and average power than the corresponding continuous wave output). In addition to an investigation of the dynamical states in optical bistability, another experiment is studying the oscillatory states predicted for one of the simplest possible optical systems, namely intracavity frequency doubling. In this experiment, a cavity containing a nonlinear doubling crystal is pumped at a fundamental frequency ω_1, which builds up inside the cavity. As it does, conversion to the harmonic frequency $\omega_2 = 2\omega_1$ occurs. This second frequency is likewise resonant and increases in amplitude in the cavity. A competition then occurs for the available reserve of excitation leading to a sequence of oscillatory states.

While the work described above relies essentially on classical dynamics for its analysis, optical physics offers the exciting prospect for the investigation of the role of quantum fluctuations. In both the frequency doubling and optical bistability experiments, we are attempting to generate nonclassical states of light that exhibit photon antibunching and squeezing. The objective of the research continues to be an exploration of the role of microscopic quantum processes in producing macroscopic effects. This work is of fundamental scientific interest and has a number of applications in measurement science and optical signal processing.

A third area of research involves the study of optical pumping processes in atomic and molecular vapors. Atomic beams of sodium are employed in the bistability experiments. These beams are optically prepumped to transfer population from one hyperfine component to another

and into a single Zeeman state. This procedure increases the optical absorption coefficient of a given sample of atoms by a factor of three, which is within ten percent of the "best-case" theoretical prediction.

Since much of the research requires extreme stability and precision of the excitation source, one area of activity has been the development of instrumentation for the frequency and intensity stabilization of lasers and of optical cavities. This work has led to impressive improvements in the performance of our laboratory dye lasers and our Nd:YAG laser.

The studies of quantum phenomena of light with atoms dominate the present work in nonlinear optical interactions but in the future molecular systems have to come into play. The knowledge on the molecular quantum levels is far inferior to that of atomic systems, especially when larger molecules have to be considered. With a few exceptions most molecules with chromophoric groups are rather large. Still highly monochromatic lasers are sufficient to resolve all quantum levels. The problem starts when the absorption spectrum has to be interpreted. Our results from electron diffraction are important contributors in the analysis of the spectra.

Until recently electron diffraction results were limited to the structural aspects only. Certainly the geometrical configurations of the atoms constituting the molecules are critical in its quantum behavior but a knowledge of the molecular force fields especially beyond the harmonic approximation is required to calculate spectral functions and line positions. It was our objective to gain new access to the anharmonicities of molecular potential functions and the vibrational spectra through electron diffraction from molecules at high temperatures. This technique is extended to molecules with large extinction coefficients in the visible.

In addition, new insight into the beam formation of molecules from hot ovens with small none-knife-edge openings was gained by measuring the thermodynamics of cluster formations at high temperatures and modest pressures. The presence of solid materials at the oven and the walls of the nozzle system assures that we were dealing with the solid-gas phase equilibirum only. The materials chosen were the alkali halides.

Finally, the laser facilities available were utilized to develop a spectrometer to measure the spontaneous Raman spectra of the gaseous samples present in the electron diffraction. The objective here is to combine spectroscopy and diffraction data to enhance the precision in the final structural analysis and to avoid local minima in the least square search for the data evaluation.

B. PROGRESS: In this section we report the status of the individual research programs that comprise this research unit.

(1) Optical Bistability

An optical system is said to be bistable if two stable operating states exist for a single value of a given set of control parameters. In the case of bistability in passive systems, a medium whose susceptibility is a function of laser intensity is placed within an optical resonator. For a given laser intensity incident upon the medium-plus-resonator combination, the intensity transmitted can be a multivalued function of the input. The actual output state from two or more possibilities is determined from a hysteresis cycle of output versus input. The different segments of the hysteresis cycle correspond not only to distinct operating regimes but as well to transmitted radiation with distinctly different statistical characteristics. Hence, each branch of the cycle corresponds to a different "phase" for the non-equilibrium system. The objective of our research program has been to make a quantitative characterization of these various phases. Specifically, we are studying the critical onset of bistability, the transient or switching behavior in bistability, the intrinsic stability of the various phases, and the role of the quantum nature of the atom-field coupling in bistability.

Our investigation of optical bistability is conducted with a collection of atoms within an extremely stable, high finesse optical resonator. The atoms behave, to a very good approximation, as if they had a single ground state and a single excited state and thus represent the most fundamental spectroscopic entity. The virtue of our experiment is the simplicity of its components (atoms and resonator), and because of this we have been able to generate by far the most detailed quantitative comparison between theory and experiment yet made in this field. We have explored the critical onset and evolution of steady state hysteresis [1-7] as well as the transient or switching behavior of this system [8]. Measurements have been carried out in traveling-wave and standing-wave interferometers, both with and without Doppler broadening, due to the atomic motion. Our experiments have allowed a critical assessment to be made of the validity of existing theories of the steady state regime in optical bistability and represent one of only a few such measurements in optical physics. More importantly, they have mapped the topography of the deterministic regime for use as a guide in our future work. An example of our results is shown in Figure 1, which is an absolute comparison between experiment and theory for the critical onset and growth of the hysteresis cycle in optical bistability.

An exciting recent observation is of dynamical instability in optical bistability [9]. The bistable system transforms continuous-wave light into light of oscillatory intensity. The basic mechanism responsible for the self-pulsing instability is intrinsic to virtually all problems involving the interaction with an intense optical field. What were once the individual constituents of the optical system (A=atoms, B=intracavity field) become so strongly coupled as to form a completely new entity C, the structure of which can be very unlike that of either A or of B or of a simple superposition (A+B). The strong coupling produces optical gain or amplification from an otherwise absorbing medium, so that the system actually becomes unstable to its own radiation. The investigation of the bifurcations associated with these dynamical instabilities draws from a diversity of fields, including atomic physics, quantum optics, non-equilibrium statistical mechanics, and nonlinear dynamics. Figure 2 illustrates both the marked change in the qualitative nature of the steady state input-output characteristic as well as the actual output intensity versus time.

(2) Frequency Doubling Within a Resonant Interferometer

Perhaps the simplest nonlinear interaction between light and matter is that of frequency doubling in which light at a fundamental frequency ω_1 generates its harmonic frequency $\omega_2 = 2\omega_1$ (and vice versa) within a crystal. We are attempting an experiment which adds one element to this process, namely the insertion of the crystal into a resonant optical cavity in which the excitations at frequencies ω_1 and ω_2 must coexist. The cavity is driven by an external source, and the subsequent dynamics investigated. The situation is not unlike that found in the study of predator-prey populations, with ω_1 = prey and ω_2 = predator.

The experimental effort thus far has taken three directions. The first is the construction of a source of excitation. We have built a continuous-wave Nd:YAG laser operated at 1.06 μm with a power output of 1.5 Watts and with a frequency stability of 100kHz (3 parts in 10^9), which represents performance an order of magnitude better than any other previous demonstration for high power Nd:YAG lasers [10]. The second avenue has been the investigation of appropriate nonlinear crystals and the construction of the actual apparatus. We are currently attempting the experiment with a sample of barium sodium niobate, but are studying other new materials as well.

The third direction that we have taken has been rather unexpected. Unlike many optical interactions, frequency doubling within an optical cavity involves a rather stringent phase relation between fundamental and harmonic. This basic phase relationship is often not commensurate with the boundary conditions imposed by the optical cavity. As a result, the coupling efficiency

between ω_1 and ω_2 can exhibit a very sensitive dependence upon cavity geometry. This dependence was overlooked in recent theoretical treatments of this problem, so that a coupling that should be "of order unity" can in fact range between zero and one due to only micrometer changes in cavity length. We have investigated this feature experimentally [11], and our observations have led us to consider new schemes for generating temporal instabilities.

(3) Other Related Experimental Work

An ongoing project in the laboratory is the development of extremely stable lasers for our experiments. We have worked for the past two and a half years to implement a locking scheme for our dye lasers that would produce frequency stability of better than one part in 10^{11}, or a hundredfold improvement over current performance. Intensity servos have been developed that reduce laser intensity fluctuations to the theoretical limit. A large number of smaller projects have been completed, such as the construction of efficient, compact "optical diodes" for optical isolation of various components of a given experiment. In all cases our aim is not technology for its own sake, but rather in each particular case some aspect of the research forces us to go beyond the existing technology.

The simplicity of electronic structures of atoms and the power of Schrodinger's equation make the atomic targets in optical experiments manageable and comprehensible, but also, it limits the choice of targets to a few systems which have strong absorption spectra in the visible (the alkali and some earth alkali). If molecules could be used, the possibilities of exciting experiments would increase significantly. The rotational, vibrational and electronic quantum structure of even modestly large molecules is to a large extent unknown, starting from the molecular structure via the force field of the ground state to the excited states and its force fields. Electron diffraction results are not even close to precise enough to compete with optical spectroscopy, but due to fortuitous averaging of the vibrational wavefunctions, we can determine the force constants along molecular bonds. When the occupation number of the higher vibrational states are altered by elevating the temperatures of the gas sample the anharmonicity of the force field and the mode couplings can be studied. The first molecule investigated was SF_6 and its diffraction pattern could be used to decide amongst potential functions proposed by the analysis of the high resolution spectral data [12,13]. The true success in combining electron diffraction and spectroscopy on the force field level came with the completion of the temperature dependence of the vibrationally averaged structure parameters of CO_2, SO_2, and N_2O and the excellent agreement with theoretical predictions based solely on spectroscopic data [14,15,16]. This success encouraged us to study the first large dye molecule $Cr_2(O_2CCH_3)_4$. This compound is pivotal in the understanding of metal-metal bonds and a strong but unstable, chromophor. After two years of careful nozzle-oven development, the structure and force field could be reported and predictions for the vibrational spectra are made [17]. Preliminary reports from a research group in Germany utilizing matrix isolation Raman spectroscopy agree with our prediction within 10%. This is the first successful optical prediction based on electron diffraction in the literature.

During last year, electron diffraction data were collected from the highly nonvolatile compounds of the alkali halides. Again, the motivation was the force field and ensuing spectra. Because of the high temperatures involved, a systematic study of highly ionic compounds has not been made leaving many questions open, from the production of aluminum to the nucleation of clusters. The alkali halides containing Cl, Br and I have been determined, not only the monomeric species but also all dimers [18,19]. From the ratio of monomer to dimer, new information can be extracted concerning the jet formation in nozzles, the thermodynamics of the expansion and the cluster formation through sublimation.

During the last three years we also made some noteworthy technological advances. We built the first modern electron diffraction unit which can separate elastic and inelastic scattered

electrons with a resolution of ($1/4 \cdot 10^5$) by optimizing the performance of an electrostatic cylinder line system driven far off axis (Moellenstedt analyzer) [20,21]. First, purely elastic data were recorded and analyzed with respect to correlation and binding effects in quantum chemical systems (CO_2) [22].

C. FOLLOW-UP STATEMENT: The research program investigating dynamic instabilities in optical bistability and in intracavity frequency doubling will continue under JSEP sponsorship in the new triennium. The research of quantum fluctuations in these systems has received support from the National Science Foundation and from the Venture Research Unit of British Petroleum International. This work will be continued, but under the new sponsorship.

D. PUBLICATONS:

I. JSEP Sponsored Work

1. D.E. Grant and H.J. Kimble, "Optical Bistability for Two-Level Atoms in a Standing-Wave Cavity," Optics Letters 7, 353 (1982).

2. H.J. Kimble, D.E. Grant, A.T. Rosenberger and P.D. Drummond, "Optical Bistability with Two-Level Atoms," Lecture Notes in Physics, vol. 182, eds. J. Harvey and D. Walls, pp. 14-40 (Springer 1983).

3. A.T. Rosenberger, L.A. Orozco, and H.J. Kimble, "Observation of Absorptive Bistability with Two-Level Atoms in a Ring-Cavity," Physics Review A28, 2569 (1983).

4. A.T. Rosenberger, L.A. Orozco and H.J. Kimble, "Optical Bistability: Steady State and Transient Behavior," in Fluctuations nd Sensitivity in Non-Equilibrium Systems, eds. W. Horsthemke and D.K. Kondepudi, pp. 62-69 (Springer 1984).

5. H.J. Kimble, P.D. Drummond and A.T. Rosenberger, "Optical Bistability with Two-Level Atoms," in Optical Bistability II, eds. C. Bowden, H. Gibbs and S. McCall, p. 1 (Plenum 1984).

6. A.T. Rosenberger, L.A. Orozco and H.J. Kimble, "Intrinsic Dynamical Instability in Optical Bistability with Two-Level Atoms," in Optical Instabilities, eds. R.W. Boyd, M.G. Raymer, and L.M. Narducci, p. 325 (Cambridge University Press 1986).

7. L.A. Orozco, A.T. Rosenberger, M.G. Raizen and H.J. Kimble, "Optical Bistability with Two-State Atoms: Steady States and Dynamical Instabilities," in Optical Bistability III, eds. H.M. Gibbs (Springer-Verlag 1986).

8. D.E. Grant and H.J. Kimble, "Transient Response in Absorptive Bistability," Optics Communications 44, 415 (1983).

9. L.A. Orozco, A.T. Rosenberger and H.J. Kimble, 'Intrinsic Dynamical Instability in Optical Bistability with Two-Level Atoms," Physical Review Letters 53, 2547 (1984).

10. Kun-Chi Peng, Ling-An Wu and H.J. Kimble, "Frequency Stabilized Nd:YAG Laser with High Output Power," Applied Optics 24, 938 (1985).

11. L.A. Wu and H.J. Kimble, "Interference Effects in Second Harmonic Generation Within An Optical Cavity," Journal of the Optical S. . ety of Amercia B2, 697 (1985).

12. M.H. Kelley and M. Fink, "The Temperature Dependence of the Molecular Structure Parameters of SF_6," J. Chem. Phys. 77, 1813-1817 (1982).

13. Peter Pulay, R. Mawhorter, D.A. Kohl and M. Fink, "Ab Initio Hartree-Fock Calculation of the Elastic Electron Scattering Cross Section of Sulpher Hexafluoride," J. Chem. Phys. 79, 185 (1983).

14. R.J. Mawhorter, M. Fink and B.T. Archer, "An Experimental Determination of the Vibrationally-Averaged, Temperature-Dependent Structure of CO_2," J. Chem. Phys. 79, 170 (1983).

15. R.J. Mawhorter and M. Fink, "The Vibrationally Averaged Temperature Dependent Structure of Polyatomic Molecules II SO_2", J. Chem. Phys. 79, 3292 (1983).

16. Bruce R. Miller and M. Fink, "The Vibrationally Averaged, Temperature Dependent Structure of Polyatomic Molecules III. N_2O," J. Chem. Phys. 83, 939-944 (1985).

17. S.N. Ketkar and M. Fink, "The Structure of Dichromium Tetraacetate by Gas Phase Electron Diffraction," J.A.C.S. 107, 338-340 (1985).

18. R.J. Mawhorter, M. Fink and J. Hartley, "An Electron Diffraction Study of Alkali Chloride Vapors," J. Chem. Phys. 83, 4418-4426 (1985).

19. J. Hartley and M. Fink, "An Electron Diffraction Study of the Alkali Bromide Vapors," J. Chem. Phys (submitted.

20. Renhe Tian and M. Fink, "Dispersion and Resolution of a Moellenstedt Analyzer", Rev. Sci. Instr. (submitted).

21. J.J. McClelland and M. Fink, "Electron Correlation and Binding Effects in Measured Electron Scattering Cross Sections of CO_2", Phys. Rev. Lett. 54, 2218-2221 (1985).

II. Other Related Work

22. H.J. Kimble and L. Mandel, "Photoelectric Detection of Polychromatic Light," Physical Review A30, 844 (1984).

23. H.J. Kimble, A. Mezzacappa and P.W. Milonni, "Time Dependence of Photon Correlations in a Three-Level Atomic Decay," Physical Review A31, 3686 (1985).

24. Min Xiao, H.J. Carmichael, and H.J. Kimble, "Quantum Statistical Theory of Optical Bistability with a Spatially Dependent Coupling Coefficient," in preparation.

25. R.J. Cook and H.J. Kimble, "Possibility of Direct Observation of Quantum Jumps," Physical Review Letters 54, 1023 (1985).

26. D.D. Kohl, P. Pulay and M. Fink, "On the Calculations of Scattering Cross-Sections from Molecular Wavefunctions -- CF_4 and CH_4", Theo. Chem. 108, 149-159 (1984).

27. J. Ganz, A. Siegel, W. Bubert, K. Harth, M.W. Ruf, H. Hotop, J. Geiger and M. Fink, "On the Ne($2p^5ns'$,nd') Autoionization Resonances: High Resolution Measurement and Quantum Defect Analysis," J. Physics B16, L569-L576 (1983).

28. Shang-de Xie, M. Fink and D.A. Kohl, "Basis Set Dependence of ab initio SCF Elastic Born Scattering Cross Sections for Electrons on C_2H_4," J. Chem. Phys. 81, 1940-1942 (1984).

29. J.D. Coffman, M. Fink and H. Wellenstein, "Elastic Small-Angle Electron Scattering by He, Ne and Ar at 35keV," Phys. Rev. Lett. 55, 1392-1394 (1985).

30. R.A. Bonham and M. Fink, "Small-Angle Elastic Scattering and Moments of the Molecular Electronic Charge Density," Phys. Rev. A33, 1569-1577 (1986).

31. A.W. Ross and M. Fink, "New Atomic Scattering Factor and Spin Polarization Calculations," J. Chem. Phys. (accepted).

32. M. Fink, Y. Zhang and R.A. Bonham, "Charge Deformation Maps, Molecular Moments and High Energy Electron Scattering," Int. J. Quant. Chem. (accepted).

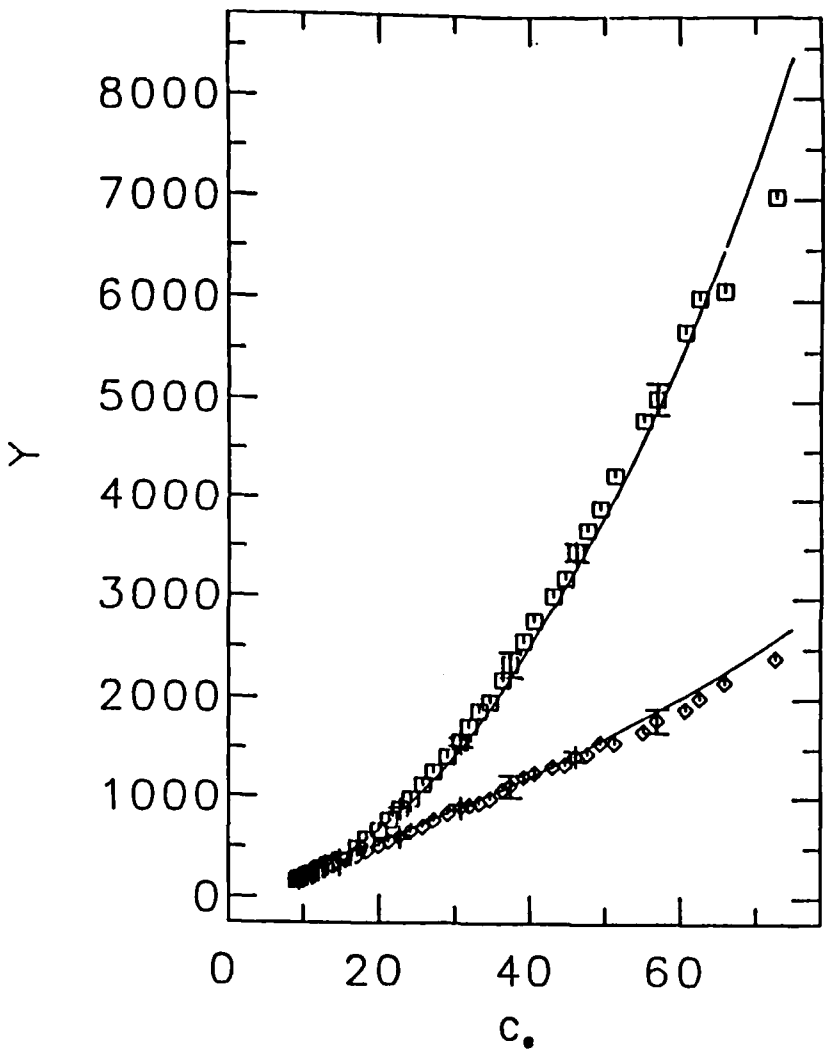
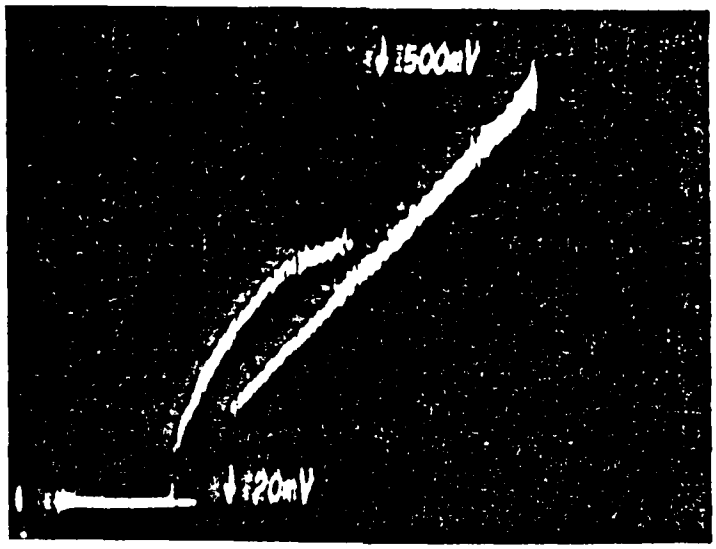
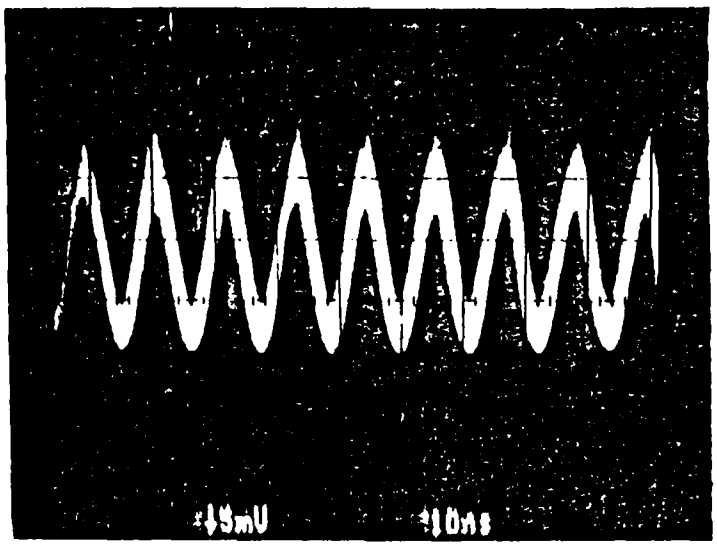


Figure 1: Switching intensities (Y_1,Y_2) versus effective cooperativity parameter Ce. Y_2 (squares) denotes the incident intensity at which switching from the lower to upper branch of the hysteresis cycle occurs while Y_1 (diamonds) denotes that for switching from upper to lower branch. The cooperativity parameter Ce is defined as the ratio of atomic absorption to passive cavity loss and is varied by changing the intracavity atomic density. The full curve is the prediction of the single transverse mode theory with no adjustable parameters.



(a)



(b)

Figure 2: (a) Input-output trace in a region of self-pulsing. Shown is the time-averaged transmitted versus incident power. The region of dynamical instability corresponds to the arched segment of the trace.

(b) Transmitted intensity versus time at one point in the region of self-pulsing as in (a). All external control parameters are held fixed. The oscillation is spontaneous and persists indefinitely.

IV. ELECTROMAGNETICS

THE UNIVERSITY OF TEXAS AT AUSTIN ELECTRONICS RESEARCH CENTER
ELECTROMAGNETICS

Research Unit EM82-1 GUIDED-WAVE DEVICES FOR THE FAR-INFRARED -MM WAVE SPECTRUM

Principal Investigators: Professor A.B. Buckman (471-4893)
Professor T. Itoh (471-1072)

Graduate Students: Yoshiro Fukuoka and Lingtao Wang

A. SCIENTIFIC OBJECTIVES: This work has as its overall objective the identification, analysis and, finally, the prototype demonstration of useful semiconductor waveguide devices for production and control of radiation in the frequency range from ten to a few hundred gigahertz. This part of the spectrum is uniquely suited to a number of DoD needs, but its exploitation will require a mix of designs, some using concepts first developed in interated optics, and others adapting microwave techniques. This research will focus on use of the Gunn and IMPATT mechanisms for radiation sources and on use of carrier injection and the field effect for electronic active guided wave devices such as modulators, active filters and beam deflectors. For the most part, the device concepts to be studied are compatible with planar waveguide integrated circuit technology.

B. PROGRESS:

(a) Gain Devices

In the area of distributed gain devices, two additional works have been initiated in addition to development of Gunn devices.

(a.1) Distributed Gunn Devices

This work is the continuation of the previous effort in realizing distributed Gunn devices made of a subcritically doped GaAs layer. Based on the theoretical study on characteristics of distributed gain mechanism [1], we built several test devices during the previous period. Although we found that gain mechanism certainly exists, the overall gain was still too small to compensate the insertion loss of the structure.

During the present period, we continued fabrication using several GaAs wafers. To date the best performance was obtained in one of the devices. As shown in Fig. 1, we need one more dB to generate a device gain in this device. Assuming that a substantial insertion loss comes from the series resistance in coplanar electrodes, we are fabricating another device with thick electrodes by the plating technique at Hughes Aircraft Company.

(a.2) Distributed IMPATT Devices

A new effort in characterizing distributed IMPATT devices of either single-drift or double-drift types has been initiated. Since IMPATT structures require PN junctions, precise control with fabrication process is needed if a distributed structure is considered. Due to recent advances in MBE technology, this problem is now solved. From points of view of gain and frequency limit, the IMPATT is more attractive than Gunn. In our analysis program the effects of several semiconductor layers, lossy electrodes and transverse size can be incorporated.

(a.3) Distributed Heterostructure

A recent prediction of negative differential gain based on the real-space transfer mechanism [2] can be used for distributed gain devices. As a first step, we analyzed a structure consisting of several alternating layers of GaAs and GaAℓAs. The former is using a negative conductivity and the latter positive conductivity. This is a model to study the minimum requirement on the negative conductivity in order to generate a net gain out of this distributed device. The numerical results have been obtained.

A more realistic approach has also been initiated in which we obtain a distributed impedance (per unit length) obtained from the calculation of negative differential gain in the lumped device model. Our effort is concentrated in obtaining a circuit model from the device theory [2]. Once this impedance information is available, we can model a distributed structure as a transmission line with this impedance distributed through the line. The propagation constant and the characteristic impedance then provide gain information.

(b) Control Devices

(b.1) Schottky Coplanar Waveguide

It is known experimentally that there exist slow waves in a coplanar or microstrip transmission line created on a lossy semiconductor substrate if one of the electrodes is Schottky contacted. The size of the depletion layer beneath the Schottky contact can be controlled by a DC bias, resulting in electronic control of the phase delay of the slow wave (variable distributed phase shifter). In the previous period, two algorithms were developed to analyze these slow wave phenomena [3,4].

One of the problems associated with the Schottky slow wave structure is its inherent loss. During this period, we have made an attempt to reduce this loss by using a periodically doped semiconductor substrate. A calculation of such a periodic Schottky coplanar waveguide clearly indicates a substantial reduction of the attenuation constant. However, an even more interesting feature of this periodic

structure with an appropriate doping level is that at higher frequencies, the slow-wave ratio is improved which decreases in a uniform line as the frequency is increased (Fig. 2). These two phenomena, namely reduced attenuation and enhanced slow-wave factor at higher frequencies, make this structure more attractive [5]. An experimental study has recently been conducted using graphite powder that simulates doped semiconductor. The results confirm validity of our theoretical procedure that resulted in the prediction [6].

(b.2) Polarization and Mode Control

It has been theoretically shown that a dielectric waveguide structure may be constructed to discriminate a particular mode out of several modes with identical and orthogonal polarizations [7,8]. This structure is all dielectric, all isotropic and promises to greatly relax the constraints of extinction ratio versus insertion loss trade-off which limit the usefulness of other mode filters. During this period, this concept was tested using a dielectric waveguide structure designed for 60 GHz operations. The experimental results indicate basic soundness of the theoretical prediction.

C. FUTURE DIRECTIONS:

(1) In the area of distributed Gunn devices, we first wait for the results of a new thick-electrode device presently being fabricated. Depending on the results, new geometries will be studied such as the rib structure. The majority of the work will be transformed to an existing ARO contract.

(2) The distributed IMPATT work initiated toward the end of this contract period requires several more weeks' investigation before we find out a preferred approach.

(3) Heterostructure Devices

This work is considered very important and is well correlated with other JSEP units. In the coming year, we will concentrate on analysis of this structure under JSEP support.

(4) Studies on Schottky contact planar waveguides will be investigated in two important areas. The first is the discontinuity at the junction between planar waveguides such as the one appearing in a periodic structure. The second is an experimental study of periodically doped Schottky coplanar waveguides. Two possible fabrication techniques seem to be available. One is to create periodic mesa in the substrate and another is periodic ion planting. we evaluate these two techniques more carefully before selecting the preferred approach.

D. REFERENCES

1. I. Awai and T. Itoh, "Analysis of Distributed Gain Devices with Subcritical Doping," Int. J. Infrared and Millimeter Waves, Vol. 2, pp. 883-904, 1981.

2. H. Shichijo, K. Hess and B.G. Streetman, "Real-Space Electron Transfer by Thermionic Emission in GaAs-$Al_x Ga_{1-x}$ As Heterostructures: Analytical Model for Large Layer Widths," Solid-State Electronics, Vol. 23, pp. 817-822, 1980.

3. Y.C. Shih and T. Itoh, "Analysis of Printed Transmission Lines for Monolithic Integrated Circuits," Electronics Lett., Vol. 18, pp. 585-586, 1982.

4. Y. Fukuoka and T. Itoh, "Analysis of Slow-Wave Phenomena in Coplanar Waveguide on a Semiconductor Substrate," Electronics Lett., Vol. 18, pp. 589-590, 1982.

5. Y. Fukuoka and T. Itoh, "Slow-Wave Propagation on MIS Periodic Coplanar Waveguide," Electronics Lett., Vol. 19, pp. 37-38, 1983.

6. Y. Fukuoka and T. Itoh, "Slow-Wave Coplanar Waveguide on periodically Doped Semiconductor Substrate," to be presented at the 1983 IEEE MTT-S International Microwave Symposium, Boston, MA., June 1983.

7. A.B. Buckman, "Polarization-Selective Lateral Waveguiding in Layered Dielectric Structures," J. Opt. Soc. Am., Vol. 72, pp. 688-691, 1982.

8. A. B. Buckman, "Mode Selection with a Three-Layer Dielectric Waveguide," J. Opt. Soc. Am., Vol. 73, pp. 33-36, 1983.

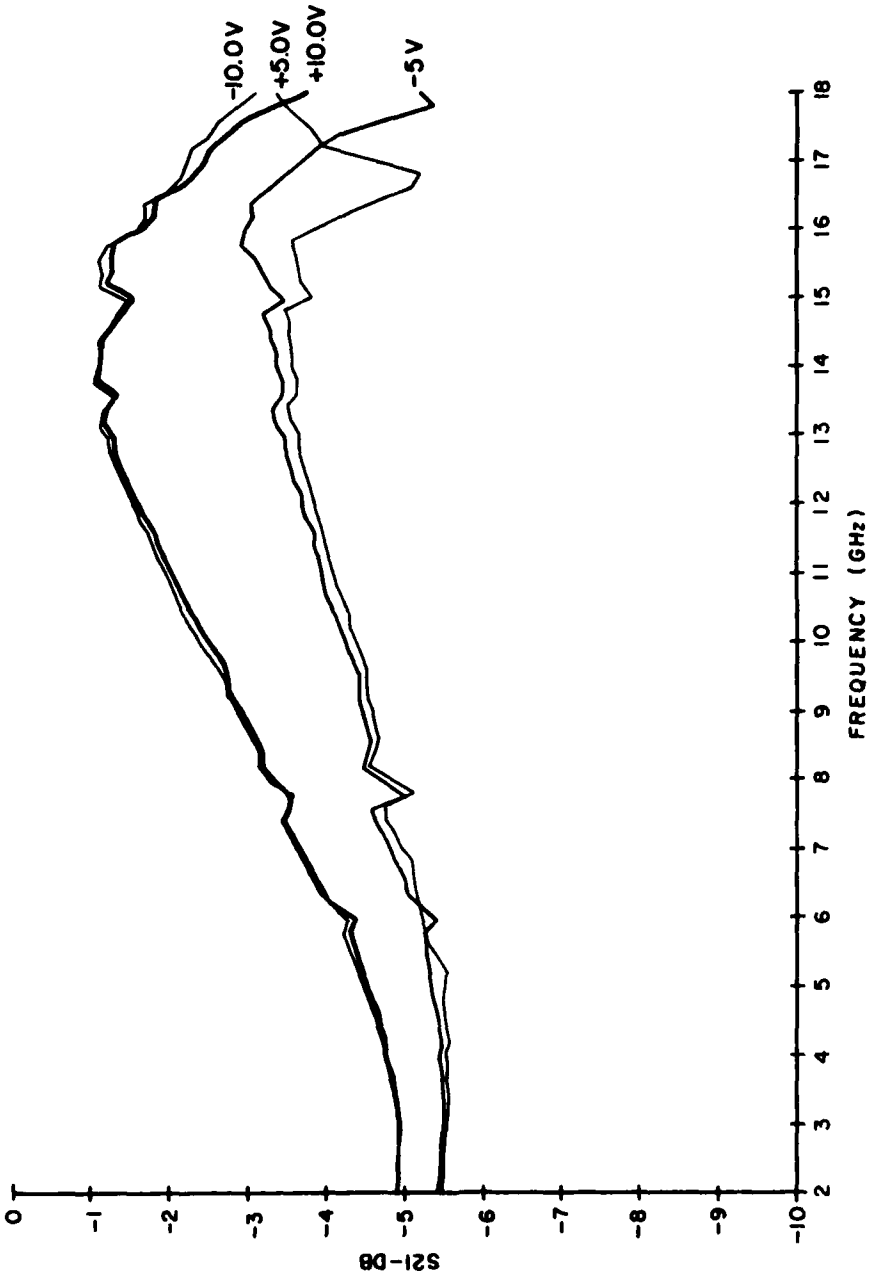


Fig. 1 Transfer characteristic of a distributed Gunn device $n = 3 \times 10^{14}$ cm^{-3}, Device length 5000 μm.

THE UNIVERSITY OF TEXAS AT AUSTIN

ELECTRONICS RESEARCH CENTER
ELECTROMAGNETICS

Research Unit EM85-1 GUIDED WAVES IN COMPOSITE STRUCTURES

Principal Investigator: Professor T. Itoh (471-1072)

Research Associate: Yoshiro Fukuoka

Graduate Students: Nag Un Song and C.-K. Clive Tzuang

A. SCIENTIFIC OBJECTIVES: Several guided wave structures will be studied for potential applications in millimeter-wave configurations. Analysis procedures will be developed and design data obtained for structures that contain semiconductor materials. Some experimental verifications will be performed. The primary objective is to identify and characterize structures which may lead to new functional device in monolithic form. The second objective is to provide analytical foundations for several guided wave structures being used in millimeter-wave circuits that have not been extensively analyzed.

B. PROGRESS:

(a) Finline Discontinuities

In the area of millimeter-wave integrated circuits, particularly in a monolithic form, characterization of discontinuities in a transmission line is important, because it is almost impossible and very expensive to adjust the monolithic circuit after fabrication. In millimeter-wave monolithic circuits, guided wave structures other than microstrip lines are frequently used. To date only a few analyses have been performed on the discontinuities in slot lines, coplanar waveguides and finlines.

An efficient numerical method for analyzing finline discontinuities has been developed. The method consists of computing the resonant frequencies of a resonator obtained by short circuiting a finline section containing the discontinuities to be analyzed. The computation of the resonant frequencies is based on a transverse resonance technique. The field is expanded in terms of TE and TM modes of the waveguide housing. After the slot field is expressed in terms of a suitable set of functions, we obtain a set of homogeneous equations, the solution to which provides the resonant frequency. From an appropriate number of numerical experiments based on this algorithm, the parameters of the equivalent circuit of the discontinuities are extracted as a function of frequency and geometry. The step discontinuity has been studied [1].

In addition to an isolated step discontinuity, cascaded finline step discontinuities have been analyzed. Although the transverse resonance method described above can be directly applied to these structures, certain simplifications can be done if the structure is longitudinally symmetric such as the cascaded step discontinuities that form capacitive strips or inductive notches. It is possible to introduce a magnetic wall at the midpoint between the two steps and consider only one-half of the structure. Once the structure is analyzed electromagnetically, it is described in terms of network parameters. Figure 1 shows the results of a capacitive step consisting of two cascaded step discontinuities in a finline. The characteristics are given in terms of the element values of an equivalent T-junction at 26 GHz [2].

(b) Distributed Phase Shifters

The slow wave phenomenon was originally intended for delay line applications [3]. However, a slow wave structure has good potentials for applications in distributed electronic phase shifters suitable in monolithic circuit configurations. The major problem in using such a structure is the insertion loss inherently associated with the lossy semiconductor included in the structure. This slow wave phenomenon can be observed both in MIS and Schottky-contacted microstrip and coplanar waveguides. Only the Schottky structure is suited for phase shifter applications.

Two analytical methods have been developed for analyzing these structures. Results by both methods correlate very well with each other as well as with measured data [4]. Since the analysis methods have been developed, they can be used for various purposes such as design and optimization.

An attempt has been made to reduce the insertion loss and at the same time to enhance the slow wave factor [5]. We studied a coplanar waveguide on a periodically doped semiconductor substrate. Reduction of the loss and enhanced slow wave factor at higher frequencies have been predicted. The latter is caused by the existence of the surface wave stopband created by the periodicity.

The most interesting application of the slow wave effect in the foreseeable future is the development of an electronically variable distributed phase shifter. The electronic phase variation can be effected by changing the DC bias applied between the center and outer conductors of a coplanar waveguide with a Schottky-contacted center strip as shown in Figure 2. This is because the size of the depletion layer can be adjusted by the DC bias, resulting in electronic control of the phase delay. For high frequency operation of such a device, it is important to reduce the attenuation caused by the semiconductor substrate. The method developed in the course of work described above has been applied to find the optimum conditions for both uniform and periodic Schottky contact coplanar waveguides as variable phase shifters. First, the optimum conductivity and depletion layer thickness have been found for the electrode structures that do not cause breakdown for an appropriate bias and also do not increase the conductor loss excessively.

In many applications, it is more important to reduce the bias dependence of the insertion loss rather than the minimum insertion loss. The latter can be compensated for by an amplifier. The bias dependence, on the other hand, can only be compensated for by an elaborate digital control scheme. For example, in the structure with a half micron center electrode and one micron gaps on a 3 μm doped region to be operated at 60GHz, the conductivity should be chosen at 10^5 s/m to minimize the bias dependence. The minimum insertion loss is obtained at a somewhat smaller value of conductivity.

For higher frequency operations, the conductor thickness cannot be neglected. An analysis method has been developed for a slow-wave coplanar waveguide with finite conductor thickness. The method is based on the mode matching technique. By an appropriate elimination process of the unknown coefficients, a coupled matrix equation corresponding to the Fredholm integral equation of the second kind has been derived. This formulation makes the numerical solutions stable and fast converging [6].

(c) Traveling Wave IMPATT

Although IMPATT diodes are the best obtainable sources for a class of millimeter-wave circuits, their performance deteriorates as the frequency of operation increases. A traveling wave IMPATT is an alternative and is particularly suited for monolithic circuit applications. Fabrication of such a large area device became a reality only recently with the advent of molecular beam epitaxy (MBE). These devices have been recently developed at Texas Instruments Central Research

Laboratory. Although there exist a number of analytical works on the traveling wave IMPATT, none of them is capable of analyzing a realistic structure without introduction of debatable simplifications.

In the present work [7], a complete set of differential equations governing both the wave propagation and avalanche multiplication is solved with boundary conditions including the finite conductivities of the metal contacts and the material losses. Small signal assumption has been made and the results have been obtained for a GaAs double-drift as well as single-drift IMPATT diode under a traveling wave mode of operation. The cross section of the double-drift device is shown in Figure 3. Numerical results for the oscillation frequency versus device length are shown in Figure 4 for the device used as an oscillator with one end open and another short-circuited. The results are compared with the experimental results obtained at Texas Instruments [8]. They are in good agreement except for a few instances in which higher order resonance ($3\lambda/4$) takes place and the actual terminating condition might be more complicated.

(d) Periodic IMPATT Oscillator

Instead of a traveling wave IMPATT described above, several lumped IMPATT diodes placed periodically in a transmission line can be used as a distributed oscillator if the structure is appropriately terminated. Figure 5 shows a schematic of the structure designed for an integrated format with printed transmission line. The diodes are made on the ground plane. Metal posts connect the diode anodes to the microstrip. We calculated the RF admittance of the diodes, characterized the metal posts, and found the propagation constants and the characteristic impedance of the transmission line. From these results, the structure is modeled by a transmission line loaded periodically with impedances with negative real parts. Due to the periodicity only at a certain frequency for which the imaginary part of the signal impedance is zero does the structure oscillate. An example is worked out assuming that four diodes are placed at each 10 mils in a microstrip line with 10 mil wide and 50 mil long strip. The structure oscillates at 50 GHz. The results explain well the experimental findings [9].

(e) Finite Element Analysis of 3-Terminal Devices

A two-dimensional finite element (FEM) characterization has been applied to a realistic three terminal device such as GaAs FET's. For the first time, very stable solutins have been obtained with the FEM for GaAs FET's with carrier concentration higher than 10^{17}1/cm^3. The V-I characteristics have been obtained that compare reasonably well with experimental data. In the program, a temperature model is included so that the effect of the energy transport phenomena is better represented [10]. Additionally, rectangular elements have been used for discretization instead of usual triangular elements. This feature significantly simplifies the block generation in the simulation of non-planar device structures.

The method has been applied to FET's with a recessed gate [10], ion-implanted MESFET's [11] and self-aligned gate FET's [12]. Figure 6 presents the cross section of a typical recessed gate MESFET being simulated. Some results of the V-I characteristics are presented in Figure 7. The method can predict the behavior of the MESFET's. For instance, in the case of ion-implanted recessed gate device, the results predict correctly that the cutoff frequency $f_T = g_m/(2\pi C_{gs})$ increases with gate recess depth. Throughout the simulation study, it was found that the developed computer program is efficient requiring less than 2 sec of execution time per iteration on a CDC Dual Cyber 170/750 with less than 500 nodes in the finite element algorithm.

C. FOLLOW-UP STATEMENT: Several projects reported above are being extended under non-JSEP supports. For the distibuted phase shifter, a modified structure controlled optically has been under investigation with the support from AFOSR both theoretically and experimentally. For the traveling wave devices, a new approach incorporating a large signal analysis is being initiated. The structure is not limited to the IMPATT but a Gunn device may be studied as well. Initial investigations along this line are underway.

D. REFERENCES

1. R. Sorrentino and T. Itoh, "Transverse Resonance Analysis of Finline Discontinuities," 1984 IEEE MTT-S International Symposium, San Francisco, CA (May 30-June 1, 1984).

2. R. Sorrention and T. Itoh, "Transverse Resonance Analysis of Finline Discontinuities," IEEE Trans. Microwave Theory and Techniques, vol. MTT-30, no. 12, pp. 1633-1638 (December 1984).

3. H. Hasegawa, "Properties of Microstrip Line on Si-SiO_2 System," IEEE Trans. Microwave Theory and Techniques, vol. MTT-19, pp. 869-881 (November 1971).

4. Y. Fukuoka, Y.C. Shih and T. Itoh, "Analysis of Slow-Wave Coplanar Waveguide for Monolithic Integrated Circuits," IEEE Trans. Microwave Theory and Techniques, vol. MTT-31, no. 7, pp. 567-573 (July 1983).

5. Y. Fukuoka and T. Itoh, "Coplanar Schottky Variable Phase Shifter Constructed on GaAs Substrate for Millimeter-Wave Applications," Int. J. Infrared and Millimeter Waves, vol. 5, no. 6, pp. 793-801 (June 1984).

6. C. Tzuang and T. Itoh, "Analysis of Coplanar Waveguide with Finite Conductor Thickness and a Substrate with a Lossy Layer," 1985 North American Radio Science/IEEE AP-S Symposium Digest, Vancouver, British Columbia (June 17-21, 1985).

7. Y. Fukuoka and T. Itoh, "Field Analysis of a Millimeter-Wave GaAs Double-Drift IMPATT Diode in the Traveling-Wave Mode," IEEE Trans. Microwave Theory and Techniques, vol. MTT-33, no. 3, pp. 216-22 (March 1985).

8. B. Bayraktarogulu and H.D. Shih, "Millimeter-Wave GaAs Distributed IMPATT Diodes," IEEE Electron Devices Lett., vol. EDL-4, no. 11, pp. 393-395 (November 1983).

9. B. Bayraktarogulu and H. Shih, "Monolithic IMPATT Diodes for Millimeter-Wave Application," 10th International Conf. Infrared and Millimeter Waves, Lake Buena Vista, FL (Dec. 9-13, 1985).

10. N.U. Song and T. Itoh, "Accurate Simulation of MESFET by Finite Element Method Including Energy Transport and Substrate Effects," 15th European Microwave Conference, Paris, France (September 1985).

11. N.U. Song, D.P. Neikirk and T. Itoh, "Modeling of Ion-Implanted GaAs MESFET's by the Finite-Element Method," IEEE Electron Devices Letters, vol. EDL-7, no. 4, pp. 208-210 (April 1986).

12. N.U. Song, D.P. Neikirk and T. Itoh, "Analysis of a Self-Aligned Gate GaAs MESFET Structure Using the Finite Element Method", submitted to ICCAD-86.

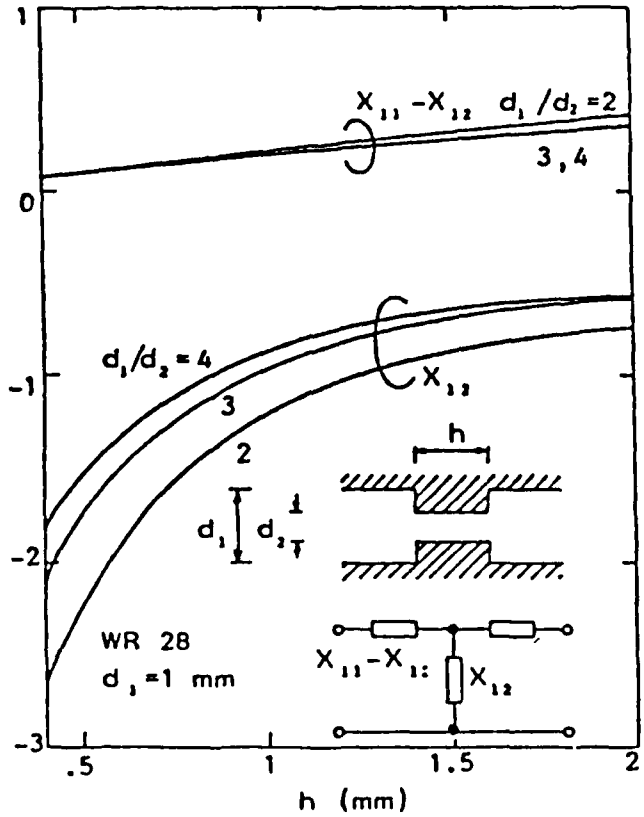


Figure 1. Characteristics of a Capacitive Step in a Finline.

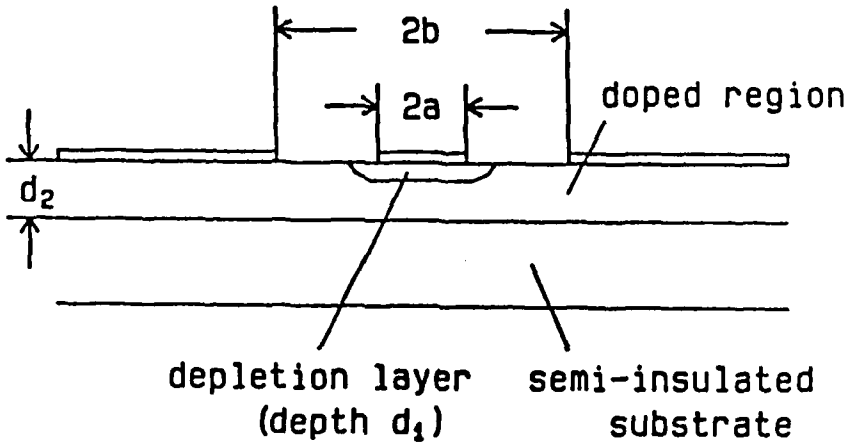


Figure 2. Distributed Phase Shifter

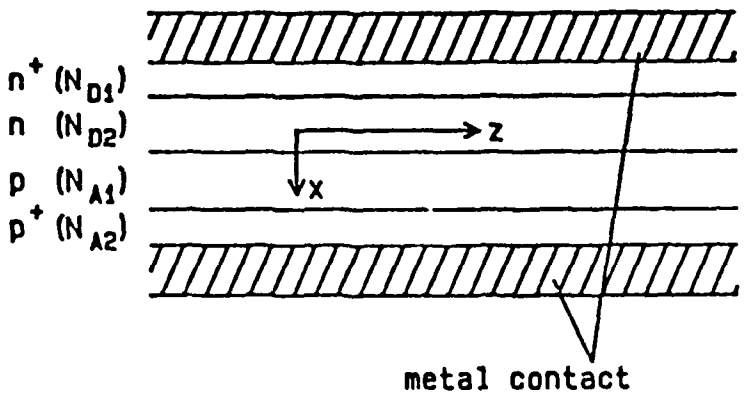


Figure 3. Side View of a Travelling Wave IMPATT.

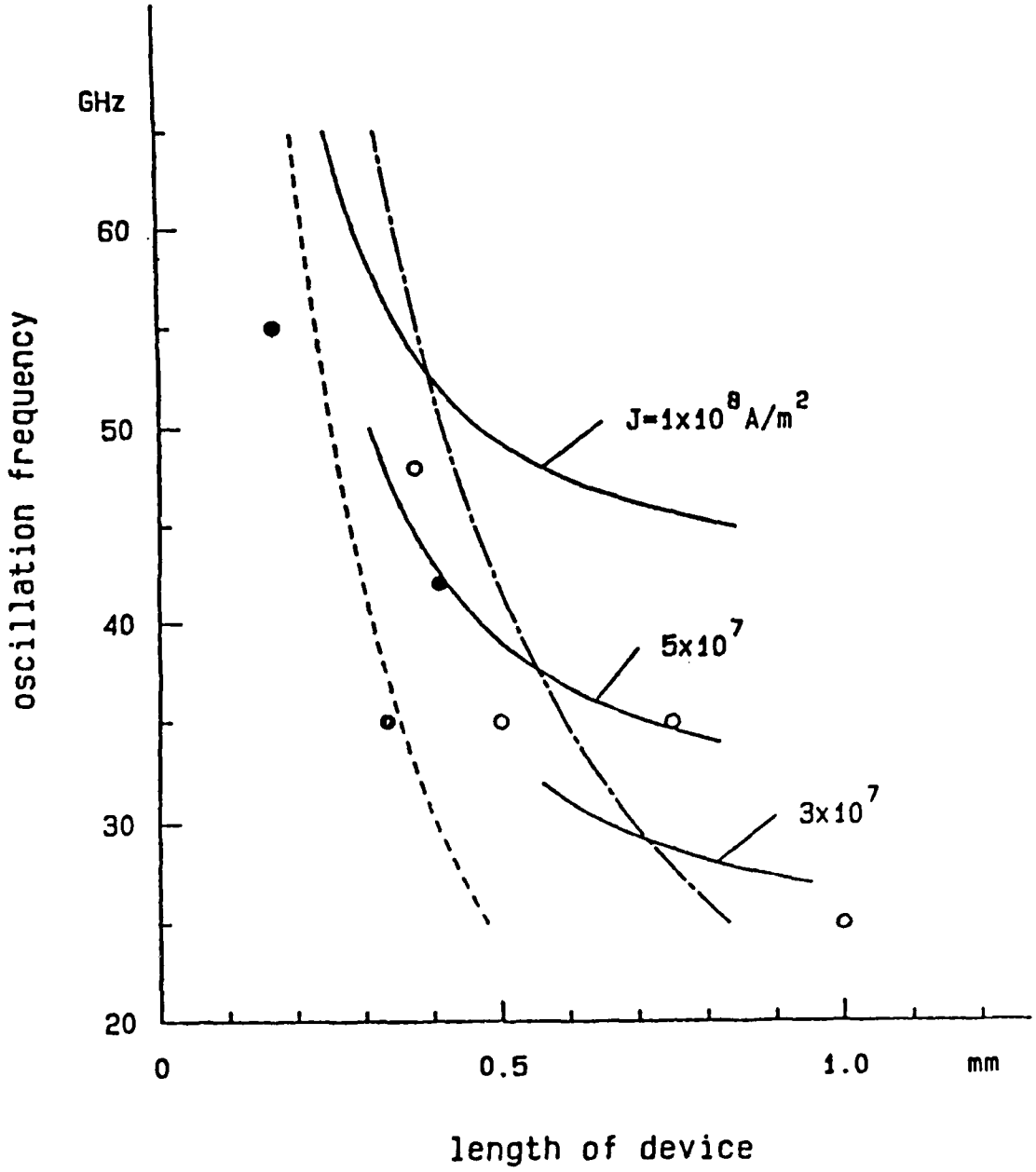
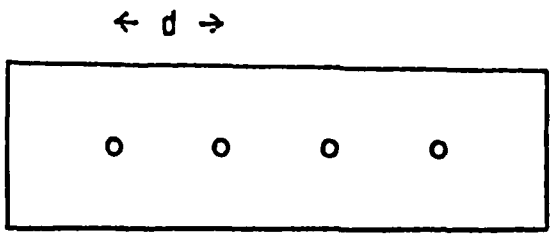
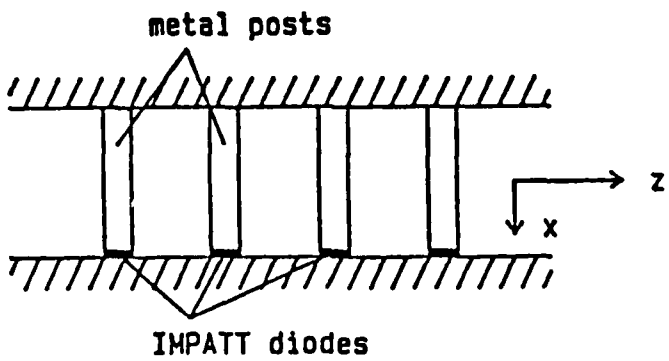


Figure 4. Oscillation characteristics of a traveling wave IMPATT.



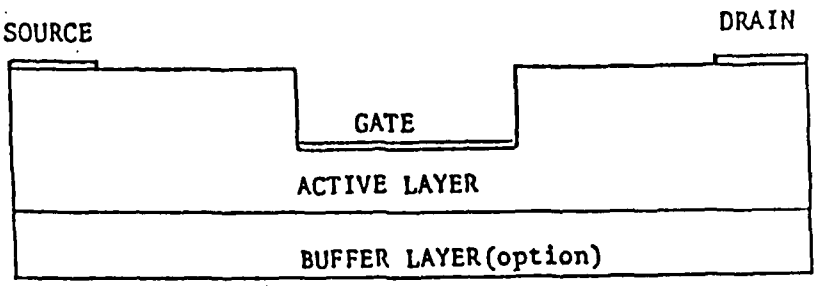
a



b

Figure 5. (a) Top view of the periodic IMPATT oscillator

(b) Side view.



electron concentration in active layer	$1.5 \times 10^{17}/cm^3$
electron concentration in buffer layer	0.
drain and source length	.25 µm
gate length	.7 µm
gate width	300 µm
drain to gate, source to gate distance	1.15 µm
active layer depth	.2 µm
recessed gate depth	.03 µm
buffer layer depth	.05 µm
gate built-in voltage	.7 V
node number with buffer	694
node number without buffer	536
time step	.01 psec

Figure 6. Two-dimensional MESFET model.

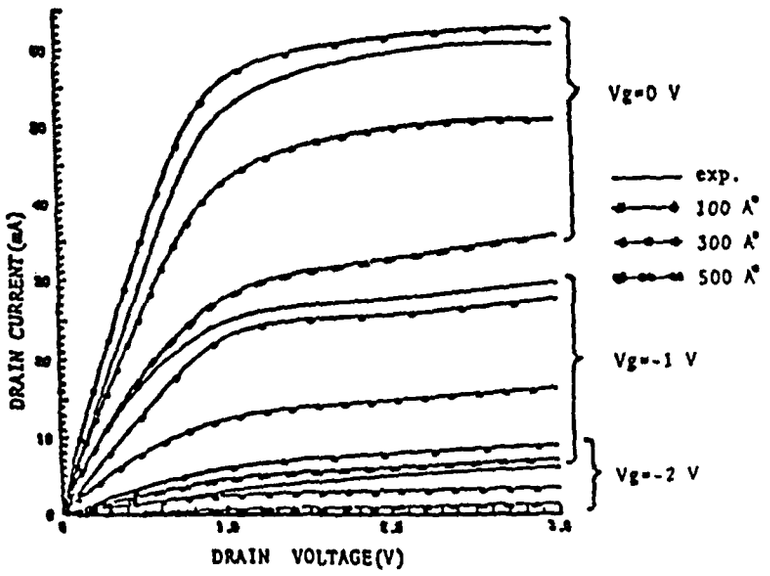


Figure 7. Simulated I-V characteristics by varying gate recess.

RESEARCH GRANTS AND CONTRACTS

RESEARCH GRANTS

FEDERAL FUNDS

Defense Advanced Research Projects Agency, Contract F33657-84-C-2058, "Research on Advanced Thin Film Magnetodielectrics," Professor R.M. Walser, Principal Investigator, October 31, 1983-November 1, 1986.

Department of Defense/University Research Instrumentation Program, "Molecular Beam Epitaxy," Professor Ben G. Streetman, Principal Investigator, 1984-1985.

Department of Defense Joint Services Electronics Program Research Contract F49620-82-C-0033, "Basic Research in Electronics," Professor E.J. Powers, Principal Investigator on behalf of the Faculty Affiliates of the Electronics Research Center, April 1, 1983-March 31, 1986.

Department of Energy, "Kinetics of Excited Molecules Following State Selective Laser Excitation," Professor J.W. Keto, Principal Investigator, March 15, 1981-March 14, 1987.

NASA, Langley Research Center, "Determination of Fuel Optimal Flight Paths for Atmospheric Vehicles," Professor J.L. Speyer, Principal Investigator, May 1, 1983-July 31, 1984.

National Science Foundation, "Chemisorption and Catalysis on Well-Characterized Metal Surfaces," Professor J.M. White, Principal Investigator, June 1, 1982-May 31, 1983.

National Science Foundation ECS-7918246 (Amendment No. 1), Extension; "Periodic Optimal Control Theory," Jason L. Speyer, Principal Investigator, Extension from December 1, 1981-May 31, 1983.

National Science Foundation, DMR 8113088, "Research Grade Ion Implantation Instrument," Professors R.M. Walser and H.L. Marcus, Co-Principal Investigators, March 15, 1981-January 31, 1983.

National Science Foundation, MEA 78-00719, "Experiments on Nonlinear Interactions During the Transition to Turbulence," Professors R.W. Miksad and E.J. Powers, Co-Principal Investigators, November 1, 1978-October 31, 1982.

National Science Foundation, MEA 8211205, "Experiments on Spectral Energy Redistribution Due To Nonlinear Interactions and Phase and Amplitude Modulations During Transition to Turbulence," Professors E.J. Powers and R.W. Miksad, Co-Principal Investigators, February 15, 1983-February 15, 1986.

National Science Foundation, DMR-83-04368, "Experimental Studies of Intrinsic Surface Electronic Properties - Metal and Semiconductor Surfaces," Professor J.L. Erskine, Principal Investigator, July 1, 1983-June 30, 1986.

National Science Foundation, DMR-8312013, "Texas/Cornell Synchrotron Beam Line Project," Professor J.L. Erskine, Principal Investigator, May 15, 1983-May 14, 1985.

RESEARCH GRANTS

National Science Foundation, ECS-8111616, "Investigation of Excess ("1/f") Noise and Dielectric Response of Non-Crystalline Structures Preceeding First Nucleation in Thin Film Systems," Professor R.W. Bene, Principal Investigator, November 15, 1981-April 30, 1985.

National Science Foundation, CHE 83-07174, "Experimental Determinations of Charge Densities by Electron Diffraction," Professor M. Fink, Principal Investigator, July 1, 1983-June 30, 1986.

National Science Foundation, ECS-8022033, "Lie Algebraic Methods in Nonlinear Estimation," Professor S.I. Marcus, Principal Investigator, March 15, 1981-August 31, 1984.

National Science Foundation, ECS-8412100, "Stochastic Adaptive Estimation and Control," Professor S.I. Marcus, Principal Investigator, October 1, 1984-March 31, 1986.

National Science Foundation, ECS 8 802-1511, "Computational Models for Processing Sequences of Bioengineering Images," Professor J.K. Aggarwal, Principal Investigator, May 1, 1981-October 31, 1984.

National Science Foundation, ECS-830-5340, Equipment for Digital Analysis in Stereo-scopic Light Microscopy, Professors J.K. Aggarwal and Ken Diller, Co-Principal Investigators, August 1, 1983-January 31, 1985.

National Science Foundation, "Optimal Periodic Control Processes," Professor J.L. Speyer, Principal Investigator, January 15, 1985-June 30, 1988.

National Science Foundation, PHY-8211194, "Cooperant Atomic Activity in Optical Bistability (Physics)," Professor H.J. Kimble, Principal Investigator, January 1, 1983-June 30, 1986.

National Science Foundation, PHY-8351074, "Quantum Dynamics of a Bistable Absorber," Professor H.J. Kimble, Principal Investigator, August 1, 1985, continuing.

National Science Foundation, ECS-8420002, "Studies of Ion Implanted Multilayer Heterojunctions," Professor B.G. Streetman, Principal Investigator, April 15, 1985-April 15, 1988.

Office of Naval Research, Contract N000014-79-C-0533, "Studies of Non-Reciprocal Effects in Planar Submillimeter to Optical Waveguiding Structures," Professor T. Itoh, Principal Investigator, June 1, 1980-August 31, 1984.

Office of Naval Research, Contract N00014-79-C-0533, Mod P00007, "MMW Transmission Lines," Professor T. Itoh, Principal Investigator, September 1, 1984-September 30, 1988.

Office of Naval Research, Contract N000114-84-K-0453, "Study of Electromagnetic Interactions in Microstructural TFM Particles and Ensembles," Professor R.M. Walser, Principal Investigator, June 1, 1984-March 31, 1985.

U.S. Air Force Armament Lab, Eglin AFB, Florida, "Investigation of Information Enhancement, Estimation, and Guidance Algorithms for Homing Missiles," Professor J.L. Speyer, Principal Investigator, October 1, 1981-September 30, 1984.

RESEARCH GRANTS

U.S. Air Force Office of Scientific Research AFOSR 79-0025, "Optimal and Suboptimal Estimation for Nonlinear Stochastic Systems," Professor S.I. Marcus, Principal Investigator, December 1, 1978-November 30, 1983.

U.S. Air Force Office of Scientific Research Grant No. AFOSR 84-0089, "Research in Adaptive and Decentralized Stochastic Control," Professor S.I. Marcus, Principal Investigator, March 15, 1984-November 14, 1985.

U.S. Air Force Office of Scientific Research, AFOSR-86-0036, "Monolithic Phase Shifter Study," Professors D.P. Neikirk and T. Itoh, Principal Investigators, November 1, 1985-October 31, 1986.

U.S. Air Force Office of Scientific Research AFOSR 80-0154, "High Resolution Electron Energy Loss Studies of Chemisorbtion Species of Aluminum and Titanium," Professors J.L. Erskine and J.M. White, Principal Investigators, April 1, 1982-March 31, 1983.

U.S. Air Force Office of Scientific Research, AFOSR 83-0131, "High Resolution Electron Energy Loss Studies," Professor J.L. Erskine, April 1, 1983-March 31, 1986.

U.S. Air Force Office of Scientific Research, 82-0064, "Automatic Recognition and Tracking of Objects," Professor J.K. Aggarwal, Principal Investigator, December 1, 1981-November 30, 1982.

U.S. Air Force Office of Scientific Research, F49620-83-K-0013, "Automatic Recognition and Tracking of Objects," Professor J.K. Aggarwal, Principal Investigator, December 1, 1982-December 31, 1984.

U.S. Air Force Office of Scientific Research, F49620-85-K-0007, "Automatic Recognition and Tracking of Objects," Professor J.K. Aggarwal, Principal Investigator, January 1, 1985-December 31, 1985.

U.S. Air Force Office of Scientific Research/SCEEE, Professor M.F. Becker, Principal Investigator, May 1, 1983-August 31, 1983.

U.S. Air Force Office of Scientific Research/SCEEE, Professor M.F. Becker, Principal Investigator, February 1, 1984-December 1, 1984.

U.S. Air Force Office of Scientific Research/RADC, "Studies of Electrical Activation and Impurity Migration in Ion-Implanted Indium Phosphide," Professor B.G. Streetman, Principal Investigator, February 1984-March 1985.

U.S. Air Force Office of Scientific Research, "Guidance Algorithms for Homing Missiles with Bearings-Only Measurement," Professor J.L. Speyer, Principal Investigator, September 30, 1984, September 29, 1985.

U.S. Air Force School of Aerospace Medicine, Contract F33615-83-K-0610, "Solid State Electronic Gas Sensors," Professors J.W. Barlow, D.W. Lloyd and R.M. Walser, Co-Principal Investigators, September 1, 1982-October 31, 1984.

RESEARCH GRANTS

U.S. Army Research Office, DAAG29-81-K-0053, "Interface Structures for Millimeter-Wave Circuits," Professor T. Itoh, Principal Investigator, March 1, 1981-August 31, 1984.

U.S. Army Research Office, DAAG29-81-K-0053, "Interface Structures for Millimeter-Wave Circuits," (additional funding), Professor T. Itoh, Principal Investigator, March 1, 1981-August 31, 1984.

U.S. Army Research Office, DAAG29-84-K-0076, "Guided Wave Interactions in Millimeterwave Integrated Circuits," Professor T. Itoh, Principal Investigator, September 1, 1984-August 31, 1987.

OTHER THAN FEDERAL FUNDS

Ardex, Inc., "Image Processing Techniques for Kerr Magneto-Optic Microscopy," Professors M.F. Becker and R.M. Walser, Co-Principal Investigators, March 1986-September 1986.

General Dynamics Corporation, Fort Worth Division, "Development of Synthesis Techniques for Fault Tolerant Digital Flight Control Systems," Professor Jason Speyer, Principal Investigator, February 17, 1984-June 1, 1985.

Hughes Aircraft Company, P.O. #P3-100001-U24, "Printed Line Structures for Monolithic Millimeter-Wave Circuits," Professor T. Itoh, Principal Investigator, May 15, 1984-September 30, 1986.

Hughes Aircraft Company, "Millimeter Wave Planar Circuits," Professor T. Itoh, Principal Investigator, August 1, 1985-July 31, 1986.

Martin Marietta Corporation, "Millimeter Wave Research," Professor T. Itoh, Principal Investigator, September 1, 1985-August 31, 1986.

NTT Electrical Communication Laboratories, "Millimeter Wave Monolithic Circuits," Professor T. Itoh, Principal Investigator, October 11, 1985-May 31, 1986.

Petroleum Research Fund, "The Interaction of Vibrationally Excited Ammonia and Methanol with Well-Characterized Surfaces," Professor J.M. White, Principal Investigator, September 1, 1982-August 31, 1983.

Robert A. Welch Foundation, F-788, "Coherent Raman Spectroscopy of Molecular Ions," Professor J.W. Keto, Principal Investigator, June 1, 1980-May 31, 1985.

Robert A. Welch Foundation, F-789, "Momentum Redistribution by Resonant Radiation," Professor H.J. Kimble, Principal Investigator, June 1, 1980-May 31, 1983.

Robert A. Welch Foundation, "Interactions of Reactive Species with Surfaces," Professor J.M. White, Principal Investigator, June 1, 1982-May 31, 1983.

RESEARCH GRANTS

Robert A. Welch Foundation, F534, "Electron Scattering from Alkali Halide Vapors," Professor M. Fink, Principal Investigator, June 1, 1980-May 31, 1985.

Robert A. Welch Foundation, F-720, "Experimental Studies of Metal Surface Absorbates," Professor J.L. Erskine, Principal Investigator, June 1, 1981-May 31, 1984.

Texas Advanced Technology Program, "Transient Microelectronic Device and Material Processing," Professors M.F. Becker, D.L. Kwong, H.L. Marcus and R.M. Walser, Co-Principal Investigators, November 1985-August 1987.

Texas Advanced Technology Program, "Multilayer Heterojunctions in III-V Semiconductors," Professor B.G. Streetman, Principal Investigator, November 6, 1985-August 31, 1987.

Texas Atomic Energy Research Foundation Grant," Analysis and Interruption of Plasma Fluctuation Data Utilizing Digital Time Series Analysis," Professor Edward J. Powers, Principal Investigator, May 1, 1976-April 30, 1986.

Texas Instruments, "Millimeter-Wave Transmission Lines Study," Professor T. Itoh, Principal Investigator, June 1, 1976-December 31, 1984.

University of Texas Research Instrumentation Grant, Professor R.M. Walser, Principal Investigator, January 18, 1982-August 1, 1982.

University of Texas Research Institute, "Investigations of Optical Bistability," H.J. Kimble, Principal Investigator, November 19, 1981-November 18, 1982.

University of Texas Research Institute, "Investigations of Optical Bistability," H.J. Kimble, Principal Investigator, February 1, 1982-January 31, 1983.

Venture Research Unit of British Petroleum, Int., "Nonequilibrium Phase Transitions in Optical Systems," Professor H.J. Kimble, Principal Investigator, February 1, 1983-January 31, 1986.

CONSULTATIVE AND ADVISORY FUNCTIONS

J.K. Aggarwal attended and participated in the NATO-Advanced Study Institute in Braunlage, West Germany, June 1982.

Edward J. Powers visited Dr. Jim Smith of the Office of Naval Research and Dr. Sevick of the David Taylor Model Basin, Washington, D.C., to discuss research possibilities on June 30, 1982.

On July 1-2, 1982, Edward J. Powers met with Dr. William Von Winkle and colleagues of the Naval Underwater Systems Center, New London, Connecticut to discuss research possibilities.

On July 13, 1982 Dr. Donald Ball, Director of Chemical and Atmospheric Sciences AFOSR visited with Dr. James Erskine in his lab.

Dr. Erskine attended an ONR contractors meeting being held at The University of Texas at Austin, September 9-10, 1982, and then later met with ONR representatives.

T. Itoh visited Dr. H. Jacobs of Army ERDACOM at Fort Monmouth on September 10, 1982, to answer questions on distributed gain and control devices as well as dielectric waveguides.

T. Itoh was on an Advisory Panel for Graduate Fellowship Program of the Army Research Office on November 8-9, 1982.

T. Itoh serves on the National Research Council panel for evaluation of proposals submitted to the Army Research Office.

On December 1-3, 1982, Dr. James Erskine participated in an AFOSR molecular dynamics seminar at the Air Force Academy, Colorado Springs, Colorado.

Professor R.M. Walser visited DARPA in Arlington, Virginia on January 11, 1983 to consult with Dr. Robert Stovall on magnetic thin films.

Professor R.M. Walser visited NRL in Washington, D.C. on January 10, 1983 to consult with Drs. Bruce Faraday, Carmen Carasella, Gary Prinz and others on the subject of magnetic thin films. He also presented a seminar on "Thin Film Magnetodielectrics."

On January 17-21, 1983, T. Itoh met Dr. C. Krowne of the Naval Research Laboratory on the occasion of IEEE Committee Meetings in Boston and Houston and discussed the future directions of slow-wave and other monolithic transmission line problems conducted at the University of Texas and at the Naval Research Laboratory.

In June 1983, Professor E.J. Powers visited Dr. Ed Strickland at the United States Air Force Armament Technology Lab (Eglin) and Dr. V.B. Venkayya at the United States Air Force Avionics Lab (Wright Patterson) to discuss potential research involving applications of digital signal processing to important nonlinear aerodynamic phenomena.

Professor E.J. Powers visited Dr. Bill Von Winkle at the Naval Underwater Systems Center, New London, Connecticut in July 1983 and presented a seminar entitled "Applications of Digital Bispectral Analysis to Nonlinear Signal Processes," and discussed possible joint research programs.

CONSULTATIVE AND ADVISORY FUNCTIONS

Professor M.F. Becker has had a long term interaction with the Air Force Weapons Laboratory (AFWL) on the subject of laser induced damage. He received a SCEEE Fellowship to spend the summer of 1983 doing research at AFWL and will spend the summer of 1984 there also under SCEEE sponsorship. Shorter meetings between Prof. Becker and AFWL personnel have been held in order to plan this research and a conference presentation. The AFWL individuals involved are Dr. A.H. Guenther and Dr. A.F. Stewart.

On October 20, 1983, Profs. S.I. Marcus and J.L. Speyer met with Mr. Jarroll Elliott, branch chief for controls technology at the NASA Langley Research Center, for an initiation meeting for their grant on periodic optimal aircraft cruise.

Dr. J.W. Mink of the Army Research Office visited T. Itoh on November 17, 1983 to discuss a number of subjects on millimeter-wave circuits.

On December 8-9, 1983, Dr. Jon Burns, Director of the Control Theory Progress at AFOSR met with Profs. J.L. Speyer and S.I. Marcus at U.T. for a briefing on stochastic control and estimation theory.

Professors J.L. Speyer and S.I. Marcus visited Dr. Lambert, chief scientist, on March 12, 1984 at the U.S.A.F. Armament Lab, Eglin AFB, to report on their progress over the last three year contractual effort on advanced homing missile guidance and to brief him on the ideas for their next three year effort.

Edward J. Powers visited Dr. Robert Whitehead and Dr. Michael Reischmann of ONR on April 4-5, 1984 to discuss research on turbulence and turbulence modification.

T. Itoh visited the Army Electronics Technology and Devices Laboratory, Fort Monmouth to discuss millimeter-wave structures with Drs. Wandinger, Babit and Stern on May 3, 1984.

In June 1984, Dr. Vernon Schlie of A.F. Weapons Lab visited Prof. Keto's laboratory to discuss techniques for electron bombardment of cryogenic liquids.

T. Itoh visited Dr. G. Simmons and gave a seminar on millimeter-wave transmission lines at Army Harry Diamond Laboratory on June 29, 1984.

In September 1984, Prof. J.W. Keto served on an expert panel convened by AFOSR to review research on metastable helium for the Air Force Rocket Propulsion Labs.

In November 1984, Dr. John Keto visited the Laser Division at Sandia National Laboratories upon invitation by Dr. Adelbert Owyoung who has developed high precision CW Raman gain spectroscopy.

T. Itoh participated and gave a keynote speech at ARO Workshop on Near Millimeter Wave Communication technology organized by Drs. J.W. Mink and F. Schwering, December 5-8, 1984, at New York Institute of Technology, Glenn Cove, N.Y.

In February 1985, E.J. Powers presented the seminar "Applications of Digital Time Series Analysis Techniques" at the U.S. Air Force Rocket Propulsion Laboratory, Edwards A.F.B. He also discussed with Dr. T. Park and J. Levine digital signal processing problems relating to the analysis and interpretation of fluctuation data associated with instabilities which occur in solid

propellant rocket engines. E.J. Powers also provided Dr. Park a copy of a bispectral analysis program.

Professor Ben Streetman serves on the National Research Council panel for evaluation of proposals submitted to the Army Research Office. He also serves on the Engineering Research Council Panel on Materials Systems Research. His technical interactions with DoD laboratories include sharing of InP samples and data with Eirug Davies of RADC (Hanscom AFB) and Harry Dietrich of NRL.

Professor M.F. Becker has consulted several times (at the Boulder Laser Damage Conference, at the Southwest Conference on Optics, and by telephone) with Dr. Hugh Hurt of the Naval Weapons Laboratory about metal surface finishing methods.

M.F. Becker visited Dr. Alan Stewart at the Air Force Weapons Laboratory in March 1986 to discuss research results.

DISTRIBUTION LIST*

Chief, Electronic Research Branch
AFWAL/AADR
Wright-Patterson AFB, OH 45433

R.S. Allgaier, R-45
Naval Surface Weapons Center
Silver Spring, MD 20910

Commander
U.S. Army Armament R&D Center
ATTN: DRSMC-TSS (D) #59
Dover, NJ 07801

Commander
U.S. Army Atmospheric Sciences
Laboratory
ATTN: DELAS-AD-PD
White Sands Missile Range, NM 88002

Commander
U.S. Army Communications Command
ATTN: CC-OPS-PM
Fort Huachuca, AZ 85613

U.S. Army Research, Development
and Standardization Group - CA
National Defense Headquarters
Ottawa, Ontario
CANADA KIA OK2

U.S. Army Research Office
ATTN: Library
P.O. Box 122211
Research Triangle Park, NC 27709

Director
U.S. Army Ballistics Research
Laboratory
ATTN: DRDAR-BL
Aberdeen Proving Ground
Aberdeen, MD 21005

Director
Night Vision & Electro-Optics
Labs
ATTN: DELNV-RM-FM (M. Betz)
Fort Belvoir, VA 22060

Director
U.S. Army Electroncis Technology
and Devices Laboratory
ATTN: DELET-I (Mr. Harold Borkan)
Fort Monmout, NJ 07703

Office of Naval Research
800 North Quincy Street
ATTN: Code 411MA (Dr. Stuart L. Brodsky)
Arlington, VA 22217

Director
National Security Agency
ATTN: Dr. G. Burdge, R-54
Fort George G. Meade, MD 20755

Dr. Rudolf G. Buser
Night Vision & Electro-Optics Labs
ATTN: DELNL-L
Fort Belvoir, VA 22060

Director
Electronics Research Laboratory
University of California
Berkeley, CA 94720

Director
Columbia Radiation Laboratory
Columbia Unversity
538 West 120th Street
New York, NY 10027

Director
School of Electrical Engineering
Cornell University
224 Phillips Hall
Ithaca, NY 14853

* The Joint Services Technical Coordinating Committee has established this list for the regular distribution of reports on the electronics research program of The University of Texas at Austin. Additional addresses may be included upon written request to:

Ms. Veronica Williams
Executive Secretary, TCC/JSEP
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709

An appropriate endorsement by a Department of Defense sponsor is required, except on a request from a federal agency.

Mrs. Renate D'Arcangelo
Editorial Office
130 Pierce Hall
Division of Applied Sciences
31 Oxford Street
Cambridge, MA 02138

Commanding Officer
Naval Research Laboratory
ATTN: Mr. J.E. Davey, Code 6810
Washington, DC 20375

Defense Technical Information
Center
ATTN: DDC-DDA
Cameron Station
Alexandria, VA 22314

Naval Ocean Systems Center
ATTN: Mr. W.J. Dejka, Code 831
San Diego, CA 92152

Dr. D.F. Dence, Code 34
Naval Underwater Systems Center
New London Laboratory
New London, CT 06320

G.C. Dilworth, Jr.
Technical Director
Naval Coastal Systems Center
Panama City, FL 32407

Dr. W. Ealy
Night Vision & Electro-Optics
Labs
ATTN: DELNV-AC
Fort Belvori, VA 22060

Dr. Lester Eastman
School of Electrical Engineering
Cornell University
316 Phillips Hall
Ithaca, NY 14850

Naval Underwater Systems Center
New London Laboratory
ATTN: 101E (Dr. Edward S. Eby)
New London, CT 06320

Naval Ocean Systems Center
ATTN: Dr. P.C. Fletcher, Code 55
San Diego, CA 92152

Commanding Officer
Naval Research Laboratory
ATTN: Mrs. D. Folen, Code 2627
Washington, DC 20375

Professor R.E. Fontana
Head, Depart. of Electrical Engineering
AFIT/ENG
Wright Patterson AFB, OH 45433

Judson C. French, Director
Center for Electronics and
Electrical Engineering
B 358 Metrology Building
National Bureau of Standards
Washington, DC 20234

Dr. William F. Gabriel
Antenna Systems Staff
Code 5342
Naval Research Laboratory
Washington, DC 20375

Director
U.S. Army Electronics Technology
and Devices Laboratory
ATTN: DELET-M (Mr. V. Gelnovatch)
Fort Monmouth, NJ 07703

Director
School of Electrical Engineering
Georgia Institute of Technology
Atlanta, GA 30332

David Taylor Naval Ship Research
and Development Center
ATTN: Mr. G.H. Gleissner, Code 18
Bethesda, MD 20084

Dr. J. Hall
Night Vision & Electro-Optics Labs
ATTN: DELNV-AC
Fort Belvoir, VA 22060

Commander
Harry Diamond Laboratories
ATTN: Technical Information Branch
2800 Powder Mill Road
Adelphi, MD 20783

Associate Director of Materials and
Electronics Research
Division of Applied Sciences
McKay Laboratory 107
Harvard University
Cambridge, MA 02138

HQDA (DAMA-ARZ-A)
Washington, DC 20310

Director
Coordinated Science Laboratory
University of Illinois
1101 West Springfield Avenue
Urbana, IL 61801

Director
TRI-TAC
ATTN: TT-AD (K. Lape')
Fort Monmouth, NJ 07703

COL Lawrence E. Larsen, M.D.
Chief, Department of Microwave
Research
Division of Neuropsychiatry-BLD 6 #40
Walter Reed Army Institute of Research
Washington, DC 20307

Mr. Martin Mandelberg
Coast Guard R&D Center
Avery Point
Groton, CT 06340

Director
Research Laboratory of Electronics
Massachusetts Institute of Technology
Bldg. 36-413
Cambridge, MA 02139

Commander
U.S. Army Electronics R&D Command
ATTN: DRDEL-SA (Dr. W.S. McAfee)
Fort Monmouth, NJ 07703

Commander
U.S. Army Missile Command
Redstone Scientific Information Center
ATTN: DRSMI-RPRD (Documents)
Redstone Arsenal, AL 35898

Mr. John Mott-Smith (ESD/ECE)
HQ ESD (AFSC), Stop 36
Hanscom AFB, MA 01731

Director
Division of Electrical, Computer
and Systems Engineering
National Science Foundation
Washington, DC 20550

Director
Division of Materials Research
National Science Foundation
1800 G Street, N.W.
Washington, DC 20550

Naval Air Development Center
ATTN: Code - 301 A. Witt
Technical Library
Warminster, PA 18974

Naval Electroncis Systems Comand
NC#1
ATTN: Code 61R
2511 Jefferson Davis Highway
Arlington, VA 20360

Naval Ocean Systems Center
ATTN: Dr. Alfred K. Nedoluha
Code 552
San Diego, CA 92152

Naval Research Laboratory
Underwater Sound reference Detachment
Technical Library
P.O. Box 8337
Orlando, FL 32856

Naval Surface Weapons Center
ATTN: Technical Library
Code DX-21
Dahlgren, VA 22448

Technical Director
Naval Underwater Systems Center
New London, CT 06320

Director, Technology Assessment
Division (OP-987)
Office of the Chief of Naval Operations
Navy Department
Washington, DC 20350

Office of Naval Research
800 North Quincy Street
ATTN: Code 252
Arlington, VAa 22217

Office of Naval Research
800 North Quincy Street
ATTN: Code 414
Arlington, VA 22217

Director
Electro-Science Laboratory
The Ohio State University
Columbus, OH 43212

Dr. Leon Peters
Electro Science Laboratory
The Ohio State University
1320 Kinnear Road
Columbus, OH 43212

Director
U.S. Army Electronics Technology
and Devices Laboratory
ATTN: DELET-ED (Dr. E.H. Poindexter)
Fort Monmouth, NJ 07703

Director
U.S. Army Electronics R&D Command
Night Vision and Electro-Optics Labs
ATTN: DELNV-IRTD (Dr. John Pollard)
Fort Belvoir, VA 22060

Director
Microwave Research Institute
Polytechnic Institute of New York
333 Jay Street
Brooklyn, NY 11201

Defense Advanced Research Projects Agency
ATTN: Dr. R. Reynolds
1400 Wilson Boulevard
Arlington, VA 22209

Dr. John W. Rockway
Communications Technology Program
Office
Code 8105 Naval Ocean Systems Center
San Diego, CA 92152

Commander
U.S. Army Research & Standardization
Group (Europe)
ATTN: (Dr. F. Rothwarf)
Box 65
FPO NY 09510

Dr. J. Ryles
Chief Scientist
AFWAL/AS
Wright-Patterson AFB, OH 45433

Commander
Harry Diamond Laboratories
ATTN: DELHD-RT (Mr. J. Salerno)
2800 Powder Mill Road
Adelphi, MD 20783

Commander
U.S. Army Satellite Communications
Agency
Fort Monmouth, NJ 07703

Dr. Barry P. Shay
Systems Integration and
Instrumentation Branch
Code 7522
Naval Research Laboratory
Washington, DC 20375

Professor A. Sherngold (62)
Professor and Chairman
Electrical Engineering
SP-304
Naval Postgraduate School
Monterey, CA 93940

Director
U.S. Army Signals Warfare Lab
ATTN: DELSW-D-OS
Vint Hill Farms Station
Warrenton, VA 22186

Director
Edward L. Ginzton Laboratory
Stanford University
Stanford, CA 94305

Director
Stanford Electronics Laboratory
Stanford University
Stanford, CA 94305

Department of the Navy
Naval Sea Systems Command
ATTN: T. Tasaka (SEA-62R1)
Washington, DC 20362

Director
U.S. Army Electronics Technology
and Devices Laboratory
ATTN: DELET-ES (Dr. A. Tauber)
Fort Monmouth, NJ 07703

Director
Electronics Research Center
University of Texas
ENS 132
Austin, Texas 78712

Director
Electronics Sciences Laboratory
University of Southern California
Los Angeles, CA 90007

Dr. John F. Walkup
Dept. of Electrical Engineering
and Computer Science
Texas Tech University
Lubbock, TX 79409

Director
Division of Neuropsychiatry
Walter Reed Army Institute of
Research
Washington, DC 20012

Mr. J.W. Willis
Naval Air Systems Command
AIR-330R
Washington, DC 20361

Dr. Gernot M.R. Winkler
Director, Time Service
U.S. Naval Observatory
Massachusetts Ave. at 24th St., NW
Washington, DC 20390

Dr. Larry Cooper
Office of Naval Research
Code 414
Arlington, VA 22217

Dr. Kenneth Davis
Office of Naval Research
Code 414
Arlington, VA 22217

Ms. Veronica Williams
Executive Secretary, TCC/JSEP
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

Dr. Jimmie R. Suttle
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

Dr. Horst R. Wittmann
Air Force Office of Scientific Research/NE
Building 410
Bolling AFB, D.D. 20332

Dr. Gerald Witt
Air Force Office of Scientific Research
Buildling 410
Bolling AFB, DC 20332

Dr. James Mink
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

Dr. Leo Young
Office of the Deputy Under Secretary
of Defense for Research and
Engineering (R&AT)
Room 3E114
The Pentagon
Washington, DC 20301

Dr. Norm Berg
Harry Diamond Laboratories
ATTN: DELHD-RT-RB
2800 Powder Mill Road
Adelphi, MD 20783-1197

Dr. Stephen G. Bishop, Head
Semiconductor Branch
Code 6870
Naval Research Laboratory
Washington, DC 20375

Dr. Gerald Borsuk
Naval Research Laboratory
Code 6800
Washington, DC 20375

Commander
U.S. Army Missile Command
Research Directorate
ATTN: AMSMI-RRD (Dr. Charles Bowden)
Redstone Arsenal, AL 35898-5248

Dr. J. Bram
AFOSR/NM
Bolling AFB, DC 20332

Dr. Richard G. Brandt
Office of Naval Research
Detachment-Pasadena
Code 414
800 N. Quincy Street
Arlington, VA 22217-5000

Mr. Jerry Brookshire
U.S. Army Missile Command
ATTN: AMSMI-RG
Redstone Arsenal, AL 35898-5248

Dr. Donn V. Campbell
U.S. Army Communications-Electornics
Command
ATTN: AMSEL-COM-RN-4
Fort Monmouth, NJ 07703-9990

LTC Robert W. Carter, Jr.
AFOSR/NE
Bolling AFB, DC 20332

Dr. E. Champagne, Senior Scientist
AFWAL/AAD
Wright-Patterson AFB, OH 45433

Mr. Ball Chin
White Sands Missile Range
ATTN: STEWS-ID-E
White Sands Missile Range, NM 88002

U.S. Army AMCCOM
ATTN: SMCAR-SCF-RD (O) (Dr. T.N. Chin)
Bldg. 95
Dover, NJ 07801-5001

Mr. Samuel A. DiNitto
RADC/COE
Griffiss AFB, NY 13411

Mr. W. Edwards, Chief
AFWAL/AAD
Wright-Patterson AFB OH 45433

Dr. Michael Fahey
Advanced Sensors Directorate
U.S. Army Missile Command
ATTN: DRDMI-RER
Redstone Arsenal, AL 35898-5248

Commanding Officer
Naval Research Laboratory
ATTN: Mr. W.L. Faust
Code 6504
Washington, DC 20375

Mr. Charles Freeman
Night Vision and Electro-Optics
Lab
ATTN: DELNV-D
Fort Belvoir, VA 22060-5677

Dr. Alan Garscadden
AFWAL/POOC-3
Air Force Aeronautical Labs
Wright-Patterson AFB, OH 45433

Mr. Charles Graff
U.S. Army Communications-Electronics
Command
ATTN: AMSEL-COM-RF-2
Fort Monmouth, NJ 07703-5202

Dr. Gerhardt Heiche
NAVAIR
Code 03D
Room 424-J.P.1
1411 Jefferson Davis Highway
Washington, DC 20361

Mr. Edward Herr
U.S. Army Communications-Electronics
Command
CENCOMS
ATTN: AMSEL-COM-RX
Fort Monmouth, NJ 07703-5202

Commander
U.S. Army Missile Command
ATTN: AMSMI-REG (Mr. Edward M. Holliday)
Redstone Arsenal, AL 35898-5253

Dr. Gerald Iafrate
Electronics Technology and
Devices Lab
ATTN: DELET-E
Fort Monmouth, NJ 07703-5302

Mr. Alfred Kahan
RADC/ESE
Hanscom AFB, MA 01731

Commander
U.S. Army Communications-
Electronics Command
CENCOMS
ATTN: AMSEL-COM-RF (Dr. T. Klein)
Fort Monmouth, NJ 07703-5202

Director
U.S. Army Electronics Technology
and Devices Laboratory
ATTN: DELET-E (Dr. Jack A. Kohn)
Fort Monmouth, NJ 07703-5302

Commander
U.S. Army Communications R&D Command
ATTN: AMSEL-TEX-CR (Dr. Leon Kotin)
Fort Monmouth, NJ 07703-5204

Dr. Marlan Kvigne
Naval Ocean Systems Center
Communications Technology Program
Office
San Diego, CA 92152

Dr. Clifford Lau
Office of Naval Research
Detachment-Pasadena
Code 414
800 N. Quincy Street
Arlington, VA 22217-5000

Dr. Robert Leighty
Research Institute
U.S. Army Engineer Topographic
Laboratories
ATTN: ETL-RI
Fort Belvoir, VA 22060-5546

Mr. W.D. Long
Naval Research Laboratory
Information Technology Division
Code 7501
Washington, DC 20375

Director
U.S. Army Electronics R&D Command
Night Vision and Electro-Optics Labs
ATTN: DELNV-IR (Dr. Randy Longshore)
Fort Belvoir, VA 22060-5677

Dr. R.N. Madan
Office of Naval Research
Code 414
Arlington, VA 22217

Dr. John Malamas
Night Vision & Electro-Optics
Labs
ATTN: DELNV-IRT
Fort Belvoir, VA 22060-5677

Mr. Thomas J. Manuccia, Head
Laser Physics Branch
Code 6543
Naval Research Laboratory
Washington, DC 20375

Dr. James McGarrity
Harry Diamond Laboratories
ATTN: DELHD-NW-RC
2800 Powder Mill Road
Adelphi, MD 20783-1197

Dr. Michael Morgan
Naval Postgraduate School
Dept. of Electrical Engineering
Monterey, CA 93943

Dr. Sydney R. Parker
Professor, Electrical Engineering
Code 62PX
Naval Postgraduate School
Monterey, CA 93940

Dr. Robert Rohde
Night Vision & Electro-Optics Labs
ATTN: DELNV-L
Fort Belvoir, VA 22060-5677

Dr. Stephen Sacks
Office of Research and Technology
NAVELEX
Code 61R
Washington, DC 20363

Commander
U.S. Army Research Office
ATTN: AMXRO-EL (Dr. William A. Sander)
P.O. Box 12211
Research Triangle Park, NC 27709-2211

Mr. Joseph Sattler
Harry Diamond Laboratories
ATTN: DELHD-PO
2800 Powder Mill Road
Adelphi, MD 20783-1197

Dr. Howard Schlossberg
Air Force Office of Scientific Research
AFOSR/NP
Bolling AFB, DC 20332

Commander
U.S. Army Communications-Electronics
Command
ATTN: AMSEL-COM-RM-4
(Dr. Felix Schwering)
Fort Monmouth, NJ 07703-5202

Dr. Arthus R. Sindoris
Harry Diamond Laboratories
ATTN: DELHD-NW-EA
2800 Powder Mill Road
Adelphi, MD 20783-1197

Commanding Officer
Naval Research Laboratory
ATTN: Dr. S. Teitler
Code 6801
Washington, DC 20375

Dr. Guenter Winkler
Naval Weapons Center
Code 381
China Lake, CA 93555

Dr. Martin Wolfe
U.S. Army Communications-Electronics
Command
CENTACS
ATTN: AMSEL-TCS-CR
Fort Monmouth, NJ 07703-5204

Dr. George B. Wright
Office of Naval Research
Code 414
Arlington, VA 22217

Mr. Roland Wright
Night Vision & Electro-Optics Labs
ATTN: DELNV-AC
Fort Belvoir, VA 22060-5677

Director U.S. Army Research Office
ATTN: AMXRC-EL (Dr. J. Zavada)
P.O. Box 12211
Research Triangle Park, NC 27709-2211

Dr. M.L. Minges
AFWAL/MLP
Wright-Patterson AFB, OH 45423

Mr. John Mullis
AFWL/NTCA
Kirtland AFB, NM 87117

Col. Hugo Weichel
AFOSR/NP
Bolling AFB, DC 20332

END

1-87

DTIC