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LEVEL II

UNIVERSITY OF SOUTHERN CALIFORNIA

ANNUAL SUMMARY OF RESEARCH PROGRAMS

NO. 25

Covering Research Activity During the Period

1 April 1977 through 31 March 1978

ELECTRONIC SCIENCES LABORATORY

Engineering

ANNUAL SUMMARY OF RESEARCH PROGRAMS

NO. 25

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

This document is an Annual Summary of Research Programs issued by the Electronic Sciences Laboratory, University of Southern California, Los Angeles, California. It summarizes the research activity during the period 1 April 1977 through 31 March 1978. Findings in this report are not to be construed as an official U.S. Government position.

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SUMMARY AND ACKNOWLEDGEMENT

This report presents a summary of the research program in the broad field of electronics conducted during the past year by the Electronic Sciences Laboratory, University of Southern California. The program includes research in solid state materials, semiconductors and devices, low temperature physics, quantum electronics, plasmas, electromagnetics, electric power systems, and electrical information systems to include control, communication and signal processing, and computer systems.

The enclosed summary reports for each research project very briefly describe progress and publications. Readers interested in more detail and publications should contact the principal investigator or author referenced in the summary report.

The overall program is supported by a variety of agencies including the National Science Foundation, the National Aeronautics and Space Administration, the Department of Energy, the University of California, the various agencies of the Department of Defense to include the Joint Services Electronics Program, AVCO Everett Research Laboratories, American Chemical Society, Chevron Oil Field Research Company, Electric Power Research Institute, and Southern California Edison Company. The sponsors are acknowledged in each project summary contained in this report. The contents reflect the views of the authors and do not necessarily reflect the views of the sponsoring agencies.

Since 1964, research programs have been described in Consolidated Semiannual Progress Reports, the last one being Report No. 23, April 1976. Henceforth reports have appeared annually beginning with the April 1977 edition, Report No. 24.

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I. SOLID STATE

1. SEMICONDUCTORS

1.1 Plasmon-Phonon Coupling in Mixed III-V Compound Crystals--$GaAs_{1-x}P_x$ and $Ga_{1-x}Al_xAs$

(The Joint Services Electronics Program)

W. G. Spitzer and O. K. Kim

Objective Summary: The importance of $Ga_{1-x}Al_xAs$ and $GaAs_{1-x}P_x$ pseudo-binary systems as materials for LED (light emitting diode) and solid state laser purposes is well known. They are also systems of considerable intrinsic interest and have been the subject of numerous studies. It is therefore somewhat surprising that some types of phonon-electron studies have not yet been performed since a proper understanding of this subject is of significant importance. To our knowledge there has been no investigation of plasmon-phonon coupling in $GaAs_{1-x}P_x$, $Ga_{1-x}Al_xAs$ or, for that matter, of any mixed III-V crystal system. The coupling effects in a number of partially polar semiconductors such as GaAs, GaP, InSb, CdS, CdTe, etc., have been studied by a number of investigators; however, the only reference to mixed crystals is found in a few lines in a paper by Lucovsky and Chen [1].

Approach Summary: We are studying free carrier effects including plasmon-phonon coupling effects in $GaAs_{1-x}P_x$ and $Ga_{1-x}Al_xAs$ by using primarily optical techniques (infrared spectroscopy and Raman scattering) supplemented by electrical measurements.

Progress:

A. $Ga_{1-x}Al_xAs$

Most of the effort during the first few months of the project was spent on the growth of thick and uniform $Ga_{1-x}Al_xAs$ layers on GaAs substrates by a temperature gradient liquid phase epitaxial growth technique. After growth, substrates were lapped off and the remaining epi-layers were polished chemically on the first grown sides. The composition (x) and its depth profile were evaluated for each layer by using an electron micro-probe. In depth of 120 μm or more compositional variation in a given layer was less than 10%. Each growth run reproduced the x values when the same growth conditions were used.

Infrared reflection spectra were measured in frequency range

1000 cm^{-1} to 50 cm^{-1} for undoped and Te-doped $Ga_{1-x}Al_xAs$. The least square curve fitting of reflection spectra to a classical dielectric function has been done in terms of two resonance oscillators and a plasmon where the complex susceptibilities are assumed to be additive. For samples with $x = 0.14$, measured Hall data agree with n_e obtained from the plasma frequencies (ω_p) to ~ 15% if expected effective mass are used. For sets of samples with higher x ($x = 0.30$ and $x = 0.45$), plasma terms and Hall data have to be analyzed on the basis of contribution of electrons in two different conduction bands, (000) and (100) bands. So far, it seems that due to low mobilities of electrons in $<100>$ band, plasma terms are insensitive to some degree in the curve fitting procedure as well as Hall effect measurements.

Raman scattering measurements have been made for the six undoped samples. Each sample has a different composition from the others and the samples are the same pieces used in the infrared study. The LO modes contribute to the Raman intensity for a (100) surface in the backscattering geometry and the LO frequencies in Raman scattering found to be in good agreement with those obtained from infrared spectra and dispersion analysis. Other probably disorder-induced Raman-active modes were also observed.

B. $GaAs_{1-x}P_x$

Samples of $GaAs_{1-x}P_x$ were grown by vapor phase epitaxy at Epidyne, Inc., in Hawthorne, California. Characterization of the sample was done with a scanning electron microscope (SEM) and Hall effect measurements. No significant variation of composition was observed either in depth or across the surface of epitaxial layers. Infrared reflection spectra were measured, and structures in the spectra were observed similar to that in the early work by Verleur and Barker [2]. The reflectivity has been fitted to a classical dielectric function in terms of three resonance oscillator parameters and a plasmon, instead of using two resonance oscillators. The nature of structure, i.e., the third oscillator terms, is under investigation.

References:

1. G. Lucovsky and M. F. Chen, Solid State Commun. 8, 1397 (1970).

2. H. W. Verleur and A. S. Barker, Jr., Phys. Rev. 149, 715 (1966).

performance of this design

1.2 Effect of Solute-Vacancy Pairs on the Physical Properties of Si-Doped GaAs and Other Compound Semiconductor Systems

(The Air Force Office of Scientific Research)

W. G. Spitzer, S. M. Copley, G. H. Narayanan, and R. L. Chen

Objective Summary: A detailed and quantitative study of the influence of changes in specific defect concentrations on microstructure and electrical, optical and mechanical properties of Si-doped GaAs and a number of other doped semiconductor crystal systems. Preliminary evidence for the GaAs:Si system indicates that defect concentrations and a diverse set of physical properties are indeed observed. The objective of this research is to obtain a more complete understanding of the defect structure of Si-doped GaAs through quantitative correlation of various physical properties and concentrations of Si-related defects and also to track the effect of a single defect species (e.g., solute-vacancy pairs) on several different properties.

Approach Summary: To achieve this goal, it is proposed to systematically investigate the effects of varying concentrations of Si and thermal treatments on the free carrier concentrations, infrared absorption, photoluminescence, critical resolved shear stress and the defect substructure of Si-doped GaAs. All studies will be conducted on samples prepared from adjacent regions of the same crystal ingot. It is further proposed to extend these studies to include GaAs doped with other technologically important impurities such as Ge, Sn, S and Li and also other compound semiconductor systems (e.g., other III-V and II-VI compounds) to determine the generality of the results.

Progress: This research project was initiated in May, 1976. The study involves measurements of electrical, optical, mechanical, and microstructural properties. The first stage required the growth and initial characterization of two large ingots (several hundred grams) of single crystal or large crystallite heavily Si-doped GaAs. Each of these ingots have supplied samples of nearly identical Si concentration for the investigation of the influence of thermal treatments on the various physical properties. Two ingots have been grown, one with a Si concentration of $\sim 2 \times 10^{19}$ cm^{-3} and the other $\sim 1 \times 10^{19}$ cm^{-3}. Samples from each ingot have been prepared for the electrical, optical, TEM, and shear measurements as a function of thermal history (annealing condition). The electrical, mechanical, and most of the optical measurements have been made. Most of the TEM measurements still remain as does the analysis. It is our intent to correlate the changes in these properties with changes in the Si-vacancy pair concentration. To our knowledge, if successful, this will be the first time that the changes in quantities such

as carrier density, infrared absorbtion, vacancy loop size and density, yield stress and luminescence caused by changes in thermodynamic conditions will be correlated and all explained on the basis of a common defect model.

1.3 Growth of Epitaxial Layers of AlN on Sapphire by a Novel Procedure

(National Science Foundation)

F. A. Kroger, U. Chen

Objective Summary: Growing epitaxial films of AlN on a single crystal Al_2O_3 substrate; measurement of properties of the formed films.

Approach Summary: Place a thin dish of Al_2O_3 in a Pt-Rh furnace at $\approx 1600^oC$ with argon or argon + $Al(CH_3)_3$ at one side and NH_3 or $N_2 + H_2$ at the other, and pass a current through the film with the aid of Pt electrodes (NH_3 side negative).

Progress: This project was concluded at the end of 1977 without positive results. Application of a voltage of 1 to 2 kV led to a current of $\approx$ 1 m Amp. The originally clear sapphire discs became milky. While X-ray diffraction of the original sapphire discs showed sharp Laue spots, diffraction of the milky material showed deformed spots of α-Al_2O_3 (and no sign of spots of AlN. IR reflection also is typical of Al_2O_3 rather than of AlN. Although some AlN may have been formed, it was concluded that the method is unsuitable to form clear, even films. Therefore the project was dropped.

1.4 A Transmission Electron Microscope Study of Radiation Damage Induced by Ion-Implantation in GaAs Single Crystals

(The Joint Services Electronics Program)

G. H. Narayanan and B. Hughes

Objective Summary: The objective of this research program is to investigate by using electron microscopy techniques the microstructural characteristics of ion-implantation induced damage in GaAs single crystals and their recovery during post-implantation annealing as a function of implantation parameters such as the energy, fluence and mass of implanted ions, and substrate temperature.

Approach Summary: < 110 >, < 100 > or < 111 > oriented wafers of single crystal GaAs will be implanted at room temperatures and at 400°C with technologically important dopant ions such as Si^+, S^+, Te^+, Be^+, etc., having incident energies of 100, 200, and 300 KeV at total fluences in the range of 10^{13} to 10^{16} ions/cm^2. Implanted samples will be annealed at temperatures in the range of 250° to 900°C using appropriate annealing caps to prevent As loss. The characterization of the radiation damage will be made by thin foil transmission electron microscopy, reflection electron diffraction and scanning electron microscope electron channeling pattern studies.

Progress: During this period, the investigations of the lattice damage introduced by the implantation of 100, 200, and 300 KeV $^{28}Si^+$ and $^{32}S^+$ ions into < 110 > oriented GaAs wafers at total fluences of 10^{13}, 10^{14}, 10^{15} and 10^{16} ions/cm^2 were continued. As was indicated in the previous progress report, the depth distribution of the lattice damage was assessed by electron channeling pattern analysis using a scanning electron microscope combined with the successive removal of surface layers of known thickness by anodic oxidation and stripping technique [1]. The quality of the electron channeling patterns obtained by using the standard detection systems of the SEM proved to be inadequate to quantify the degree of damage. Consequently, considerable effort was spent on developing a solid-state back scattered electron detector which produces channeling patterns with better contrast image intensity and higher resolution. An annular backscattered electron detector was built by using a simple Si solar cell. A suitable amplifier circuit was designed and constructed to interface between the detector and the SEM.

Considerable effort was also spent in developing a consistent method for controlled removal of surface layers of known thicknesses by anodic oxidation and stripping techniques for depth profiling of the damage. The application of the well-established anodic oxidation procedure to our implanted samples was rendered difficult by the fact that the substrate material was semi-insulating.

Consequently, an alternate chemical stripping technique was developed using a solution of H_2SO_4, H_2O_2 and H_2O in the ratio of 1: 1: 100 by volume. An etching rate of ~400 Å/min was established by measuring the step height of masked regions by using interferometry and Dekta stylus. Using this chemical stripping procedure combined with the TEM and SEM techniques, depth-profiling of the damage in Si^+ and S^+ implanted GaAs is being carried out both in the As-implanted and annealed conditions. Some preliminary results of this study were presented at the JSEP Topical Review held at Stanford University during August 1977.

More recently, we also initiated a study of Be-implanted GaAs. This is an interesting system where considerable changes in the dopant distribution profile has been previously reported when heavily implanted (total fluence > 10^{14}/cm^2). Samples are annealed above ~750°C [2].

The profile after annealing shows a sharp build up of Be at the surface, with a monotic decrease in concentration towards the implanted region which is followed by an essentially flat portion extending deep into the bulk and having a sharp step. In order to determine the existence of any possible correlation with the dopant proble and defect distribution profile, we have undertaken a study of GaAs implanted with 280 KeV Be^+ at a total dose of $1 \times 10^{15} cm^2$ following annealing at 800°C and at 600°C. The latter temperature is such that no appreciable delocalization of implanted Be^+ ion profile is expected. Preliminary study of the depth distribution of defects shows that in the 800°C annealed sample, the major defects are interstitial type prismatic dislocation loops. In the 600°C annealed samples in addition to the dislocation loops, the presence of certain unidentified precipitates was observed within the implanted regions. No definite correlation between dopant distribution profile and the defect distribution could be established.

Publications:

1. "The Structural Characteristics of Radiation Damage Produced by High Energy (2.7 MeV) Ion-Implantation in GaAs," (with W. G. Spitzer), accepted for publication in J. Mat. Sci.

2. "On Annealing-Induced Prismatic Dislocation Loops and Electrical Changes in Heavily Te-Doped GaAs," (with B. Hughes), Phys. Stat. Sol. 46 (1978).

3. "Transmission Electron Microscope Study of Implantation-Induced Damage in GaAs," paper presented at the JSEP Topical Review on Semiconductor Integrated Circuits, Devices and Materials, held at Stanford University, August 3 and 4, 1977.

4. "An Investigation of Ion-Implantation Induced Damage in GaAs Single Crystal," paper presented at the 1978 WESTEC Technical Conference held in Los Angeles, March 21, 1978.

1.5 Studies of Interface Electronic Properties of Tetrahedrally Coordinated Semiconductors

(Office of Naval Research)

A. Madhukar, R. N. Nucho, N. V. Dandekar and W. Post

Objective Summary: The objectives of this program are (a) to understand the electronic structure of III-V compound semiconductor interfaces, and (b) to understand the transport characteristics of the inversion layers formed in silicon metal-oxide-semiconductor sandwiches.

Approach Summary: The interface electronic structure is calculated employing the Green's function technique to a tight binding description of the bulk and semi-infinite III-V compound semiconductors. For the study of the transport characteristics of inversion layers we have employed many body techniques as well as the phenomenological Fermi liquid theory.

Progress:

Project (A):

We have succeeded in adapting the Green's function technique for calculations of the interface electronic structure of tetrahedrally bonded semiconductors. Initial attempts have confined their attention to developing the theoretical formalism within the nearest neighbor tight binding model for the bulk electronic structure of the semiconductors of interest. The Green's function technique allows consideration of semi-infinite solids, unlike finite slab calculations forced by the practical limitations of other methods.

Results for the GaAs and AlAs (110) surface electronic structure as well as the interface electronic structure of the GaAs/AlAs (110) interface have been obtained within the nearest neighbor approximation. The GaAs (110) surface shows the presence of surface states, while the AlAs (110) surface does not. Interface states are found to be present at the GaAs/AlAs interface, which can be shown to be remnants of the GaAs surface states. While these results are consistent with previous findings within the nearest-neighbor approximation, the uncertainties of this approximation make these studies of importance only insofar as the development of Green's function method is concerned. We are presently engaged in generalizing the method to include the second nearest neighbor approximation.

Studies of the InAs/GaSb superlattices of thicknesses up to eight atomic layers each were also performed, both within nearest and next nearest neighbor approximation. The superlattice calculations are of course performed using the standard supercell method. These studies in themselves constitute the first attempt to calculate the electronic structure

of InAs/GaSb (001) superlattice and show the change from semiconducting to metallic behavior with increasing thickness, as experimentally observed recently by Esaki and coworkers. While the ability to create superlattices of controlled thicknesses by the use of molecular beam epitaxy methods has made such studies of great importance, we are also in the unique position of calculating the interface electronic structure for semi-infinite InAs against semi-infinite GaSb by using the Green's function technique. This is an important limiting point for a check against the convergence behavior of finite slab calculations.

An important aspect of the interface electronic structure is the issue of charge transfer attendant upon the formation of the interface. Related of course are such questions as band edge discontinuities. To illustrate the importance of self-consistency in determination of charge transfer, we considered a simple two band semiconductor of CsCl structure against a simple cubic metal, a system for which the Green's functions can be calculated analytically. We have obtained a generalization of the Friedel sum rule required for the tetrahedral semiconductors. This sum rule will be exploited in introducing self-consistency via short range Coulomb interactions.

Project (B):

We have investigated the influence of electron-phonon interaction in the effectively two-dimensional carrier gas formed in the inversion layers. The first order vertex correction (Γ_1) in two dimensions was calculated and found to go like $\Gamma_1 \sim \lambda\ (\Omega_o/E_F)^{1/2}$ where λ is the dimensionless electron-phonon coupling constant, Ω_o a characteristic phonon frequency and E_F the Fermi energy. The variation in E_F, attendant to the variation in the carrier concentration (n_s) in the range 10^{11} to $10^{13}/cm^2$ can make the ratio $(\Omega_o/E_F)^{1/2}$ of order unity for the relevant phonons. Consequently, higher order electron phonon interaction effects are of order λ and may not be small, unless λ itself can be shown to be small.

We have exploited the Fermi liquid theory to analyze the Shubnikov de-Haas and Cyclotron resonance effective masses and show that in principle these two are sufficient to provide upper and lower bounds on the relative strengths of the electron-electron and electron-phonon interactions. The uncertain status of the experimental results has not allowed an unambiguous estimate, but taken on face value, these data suggest that the e-e interaction are at best twice as big as the e-ph effects. Attempts at microscopic theories are underway.

We have also investigated some aspects of e-ph interaction at high temperatures viewed as a classical time dependent disorder. Though the one-dimensional tight binding model employed by us is not a good representation of influence of disorder in inversion layers, it nevertheless allowed us to explore the possibilities of the functional derivative technique in problems involving disorder. A side benfit, though of considerable

importance, of the exact solution of the diffusion coefficient obtained by us is its applicability to motion of charge and excitons in molecular solids, and diffusion of light atoms in weak surface potentials. This result has been used by us to suggest for the first time the importance of off-diagonal disorder in giving rise to the observed weak temperature dependence of mobilities in molecular solids. Work towards the role of localization due to static disorder and the electron-phonon interaction is under progress.

Publications:

(A) Electronic Structure Studies

1. D. N. Lowy and A. Madhukar, "Study of the Interface Electronic Structure of a Model Metal-Semiconductor Interface," Phys. Rev. B, May 15, 1978.

2. R. N. Nucho and A. Madhukar, "A Tight Binding Study of the Electronic Structure of InAs/GaSb (001) Superlattice," presented at the V Annual PCSI Conference, January 1978, (proceedings to appear in J. Vac. Sc. Tech.).

3. A. Madhukar, D. N. Lowy, "A Study of the Interface Electronic Structure of Model Schottky Barriers and III-V Compound Semiconductor Heterojunctions," presented at the V Annual PCSI Conference, January 1978 (Proceedings to appear in J. Vac. Sc. Tech.).

4. A. Madhukar and D. N. Lowy, "A Green's Function Theory for the Surface and Interface Electronic Structure of III-V Compound Semiconductors," (in preparation).

5. A. Madhukar, N. V. Dandekar and D. N. Lowy, "Electronic Structure of Some Model III-V Compound Semiconductor Heterojunctions," (in preparation).

6. R. N. Nucho and A. Madhukar, "Electronic Structure of α-Quartz and the Influence of Some Local Disorder: A Tight Binding Study," presented at the International Topical Conference on the Physics of SiO_2 and Its Interfaces, March 1978, (to appear in the Proceedings).

(B) Transport Properties of Inversion Layers

1. A. Madhukar, "Coupled Electron-Phonon System in 2-Dimensions and Its Implications for the Inversion Layers," Solid State Comm. 24, 11 (1977).

2. A. Madhukar, "Electron-Electron and Electron-Phonon Contributions to the Carrier Effective Mass in n-Si (100) Inversion Layers," presented at the Second International Conference on EP2DS, Berchtesgarden, W. Germany (September 1977). (Proceedings to appear in Surface Science.)

3. A. Madhukar and W. Post, "Exact Solution for the Motion of a Particle in a Medium with Site-Diagonal and Off-Diagonal Dynamic Disorder," Physical Review Letters 39, 1424 (1977).

4. A. Madhukar, "A Study of the Electron-Phonon Interaction in 2-Dimensional Systems: Applications to the Inversion Layers," in preparation.

1.6 Transport Characteristics of MOS Inversion Layers

(Air Force Office of Scientific Research)

A. Madhukar

Objective Summary: To investigate the influence of various scattering mechanisms on the carrier mobility in inversion layers.

Approach Summary: We have employed many body techniques, including summation of diagrams and memory function method, to investigate the contributions of electron-phonon and electron-electron interactions to the Shubnikov-de Haas and cylotron resonance effective masses and scattering time.

Progress: Since this work has been underway for only four months, the calculations are not yet complete. We have succeeded, however, in deriving an expression for the cyclotron effective mass in the simultaneous presence of electron-phonon and electron-electron interactions, valid for the metallic regime of the two dimensional electron gas. Calculations of the amplitude of the oscillations in Shubnikov-de Haas measurements are underway. Also underway are investigations of the dielectric screening function for impurity screening in the presence of a magnetic field. All the calculations take full account of the Landau quantization and cover the classical as well as quantum regimes.

1.7 A GaP on Si Integrated Optics Chip

(The Joint Services Electronics Program)

M. Gershenzon, R. Tsui

Objective Summary: Thin epitaxial layers of GaP will be grown on Si (and conversely) in an attempt to develop an alternative system for integrated optics, wherein the GaP would be used for optical processing (wave-guiding, modulation, mixing) and the Si would serve for optical detection and as a base for standard electronic integrated circuitry. The light generator would be a hybrid.

Approach Summary: GaP and Si are chemically incompatible with each other with most common semiconductor crystal growth techniques (liquid phase epitaxy, halide vapor transport). The most promising approach is vapor growth using organometal transport which involves the pyrolysis of $(CH_3)_3Ga$ in a H_2 gas stream containing PH_3.

Progress:

Since the initiation of this new project in June 1977, an RF induction-heated vapor phase reactor has been designed and constructed. The system consists of a flow-control manifold to deliver metered volumes of $(CH_3)_3Ga$, PH_3, and doping and etching gases in a H_2 carrier stream to the reactor, in which the Si substrate is set on a temperature-controlled, graphite susceptor heated by the RF field. The system has been calibrated (flow rates, temperature) and GaP crystals have been deposited. The preparation of thick, pure, defect and strain-free single crystals is currently being optimized with respect to growth temperature, flow rates and substrate orientation and surface cleaning, by studying the early stages of nucleation and growth, using optical and scanning electron microscopy and diffraction techniques.

1.8 LPE Growth of Quarternary Semiconductors on InSb --For Long Wave IR Planar Detectors and for Heterostructure Lasers

(USC Sponsored)

M. Gershenzon and J. K. Abrokwah

Objective Summary: The objective of this program is to grow and electrically and optically characterize metallurgically sound, thin single crystal III-V epi-layers of composition in the region of the bandgap versus lattice constant diagram bounded by GaSb (E_g = 0.72 eV, a_o = 6.0959 Å), InAs (0.35 eV, 6.0584 Å) and InSb (0.18 eV, 6.47937 Å) on InSb substrates.

The applications are for IR detectors and heterostructure lasers between 7.3 u and 12 μ. The bandgap versus lattice constant diagram of the ternary boundary $InAs_xSb$ shows a minimum at composition $x \simeq 0.6$ with a corresponding room temperature energy bandgap of about 0.1 eV. Advantages of these alloy epi-layers would include high purity since the materials are grown at low temperatures (< 525°C, melting point of InSb). Detectors of such materials would have self-filtering capability by tailoring the bandgaps of the layers to obtain desired cut-on and cut-off wavelengths [2].

Progress: We have set up an LPE system consisting of a 20" single zone gold-plated transparent furnace whose profile is flat to within 1°C over most of a region of length 10 1/2", where a horizontal graphite slider, consisting of five melt wells and two bins for a dummy and major substrate, is placed for epi-growth. The temperature of the furnace is controlled to within 0.1°C by conventional electronics and a home made temperature programmer enables us to cool the system down at various cooling rates, typically 0.75°C/min. Growth is carried out below 525°C in an ultra-pure H_2 ambient after pump down and flushing with ultra-pure N_2 for several minutes.

We have in this early stage tried two layer growth of InSb and $In_{1-x}Ga_xSb$ and studied the morphologies using the supercooling growth technique at constant cooling rate with and without dummy substrate for initial melt saturation and also growth at a constant temperature slightly below the melting points of the alloys. The melts are made from high purity (six nines) In, Sb, undoped polycrystalline InSb ($n \sim 10^{14}$/cc), and undoped polycrystalline GaSb ($n \sim 10^{17}$/cc). The material has been selected and carefully preweighed so that we grow as close to InSb as possible. Constant temperature growth without dummy substrate saturation results in regions of island growth that are non-uniform and probably start at defects on the substrate. There are also regions of sharp-edged, triangularly-sided, planar-topped blocks indicating the 3-fold symmetry of the (111) plane. Growth has been on (111)B InSb. There is also evidence of constitutional supercooling. With dummy substrate initial saturation of the melts, the morphologies are improved, but constitutional supercooling is still considerable. Average growth rate under such constant temp conditions is about 0.5 μ/min. The best epi-layer grown has been by the supercooling technique, with initial dummy substrate melt saturation. The melts and the major substrate were brought together within one degree of the melting points while cooling down the furnace at a constant cooling rate of ~0.5°C/min., and cooling continued for typically 2 minutes, before wipe-off. Growth rate for these materials under such conditions is very high ~15 u/min and has yielded a flat morphology with a few non-uniform regions due to constitutional supercooling. The top epi-layer has been analyzed by X-ray diffraction and also by EPMA in the SEM to contain approximately 4 atomic percent Gallium.

We hope to optimize the growth conditions and expand growth to heterostructures of GaInSb/InAsSb and also InGaAsSb, all close to the InSb corner of the phase diagram.

References:

1. M. B. Parrish and M. Ilegems in "Progress in Solid State Chemistry," Vol. 7, p. 39, H. Reiss and J. D. McCaldin, Editors, Pergamon Press, New York (1972).

2. J. T. Longo, et al., IEEE Trans. on Electron Devices, Vol. ED-25, No. 2, p. 213, Feb. 1978.

1.9 Evaluation of Gallium Nitride for Active Microwave Devices

(The Office of Naval Research)

M. Gershenzon, H. Sankur, L. Anne, D. Wang

Objective/Approach Summary: This contract is aimed primarily at measuring the saturated electron drift velocity in GaN, but incidentally to investigate crystal growth, perfection, purity, doping, electrical properties and device processing parameters of GaN, a direct, wide bandgap (3.3 eV), III-V semiconductor, little explored, primarily because it apparently cannot be doped p-type.

Recent Progress:

1. CVD Grown Crystals

Thick crystals, grown rapidly on R-plane sapphire substrates by chenical vapor deposition at 1050° from GaCl and NH_3 in a H_2 carrier stream (see last report) exhibit cracks if they are greater than 200 μm thick. The cracks are due to differential thermal contraction between the GaN and the substrate on cooldown from the growth temperature and the cracks originate at microvoids present in these thick crystals. GaN grown homoepitaxially on GaN substrates do not crack. The voids are generated during growtn because the surface morphology is non-planar, consisting of both fast and slow-growing planes. One of the latter is a re-entrant surface, which under rapid growth conditions, but with geometrically induced local gas stagnation, sometimes leads to the growing crystal closing imperfectly around such a surface leaving a small void. During continued growth, decomposition inside the void results in the precipitation of Ga. The voids and the resultant cracks can be eliminated by growing at a slower rate. The only defects observed in such crystals by transmission electron microscopy are basal plane stacking faults and some edge dislocations.

2. Defects and Purity

The crystals were characterized by resistivity, Hall effect, emission spectrography, mass spectrometry, electron probe microanalysis and by low temperature (4.2°K) photoluminescence near the band edge. By using ultra-pure starking materials and minimizing contamination during growth (mostly Si, C and O), the crystals are routinely grown with chemical defect densities below 10^{18} cm^{-3}, yet the grown crystals are always n-type with a native shallow donor concentration between 10^{18} and 10^{19} cm^{-3}. This donor is easily monitored because it produces a strong, shallow bound exciton emission line in low temperature photoluminescence. We have attempted to characterize the expected shallow donors and acceptors in GaN and especially to search for a good shallow acceptor to compensate the native donor by ion-implanting GaN with C, S, Mg, Be and S (Ar as a control) with a post-implantation anneal at 900-1100° for 1-3 hrs. in flowing NH_3. Bound exciton and donor-acceptor emission clearly identifies Si as a shallow donor and C and S are relatively deep levels. No shallow acceptors have yet been clearly identified, but our search is continuing.

3. High Pressure-High Temperature Annealing and Growth

It is conjectured that the dominating native shallow donor is due either to the low temperature during growth and/or to the use of NH_3 instead of N_2 to avoid the high pressures needed for growth from N_2. Hence we are attempting to equilibrate previously grown crystals under various pressures of N_2 at high temperatures, and also to grow crystals by liquid phase epitaxy under such conditions. Two high pressure intensifiers (14,000 atm and 3,000 atm capabilities) and three high-pressure high-temperature vessels were installed and surrounded with safety shields. Two of the vessels are internally heated and should be capable of attaining 1400°C at 10,000 atm of N_2, the third is externally heated, with a rating of 1100°C at 3,000 atm. Various time-consuming problems related to shipping damage, operational reliability, gas cleanliness, etc., were solved. Preliminary results indicate that crystals can be grown rapidly from Ga-rich melts.

4. Lasers from Electron-Hole-Liquid Recombination in GaN

Optically pumped lasers were fabricated by cleaving undoped GaN crystals and exciting with a N_2 laser. The GaN emission is in the ultraviolet 0.36 μm and the excitation length and power density dependence of the stimulated emission and the Fabry-Perot mode structure were investigated to obtain the optical gain (as high as $10^5 cm^{-1}$), and the cavity losses (~ 75 cm^{-1}). By analyzing the spectral and temperature dependence of such data, we conclude that the transition is due to electron-hole-liquid recombination, identified here [2] for the first time in GaN, a relatively polar semiconductor. A binding energy of 10 meV, a very high critical temperature of 81°K, and a low temperature liquid density of 4.4×10^{18} cm^{-3} are deduced and provide strong evidence for

the proposed mechanism of this transition.

References:

1. L. Anne and M. Gershenzon, Electronic Materials Conference, TMS-AIME, June 1978.

2. D. Wang and M. Gershenzon, Manuscript in preparation.

1.10 Fundamentals of Sputtered Ion Mass Spectroscopy

(The National Science Foundation)

D. B. Wittry, F. Guo, and S. Yin

Objective Summary: To develop better methods of quantitative secondary ion mass spectrometry starting from existing models based on local thermodynamic equilibrium or existing models based on non-equilibrium processes.

Approach Summary: In this work, we will be using both positive and negative secondary ion spectra from the same specimens under similar conditions of bombardment. We also plan to add a second detection system (for electrons and - ions when + ions are being analyzed). This dual detection system is expected to provide useful information for better quantitative analysis.

Progress:

a) A comprehensive bibliography on quantitative SIMS has been prepared.

b) A new scanning system for the IMMA instrument was designed and constructed. This sytem provides for electronic aperturing for better accuracy in obtaining depth profiles with our instrument. It also provides the possibility of evaluating some of the instrumental parameters in quantitative SIMS.

c) An ion counting system was purchased and installed on our SIMS instrument. The sweep driver for the secondary magnet was modified to provide optimum scanning, i.e., a constant dwell time per peak over the entire range.

d) A new dual polarity secondary ion detector was designed and construction initiated.

e) A secondary ion extraction geometry for dual signal detection has been designed and a computer program is being prepared to evaluate the

performance of this design.

f) Energy distributions were measured for secondary ions of group III and group V from semiconductors, using the quadrupole instrument at Applied Research Laboratories.

Publications:

1. D. B. Wittry, "Optimization of Recording Secondary Ion Mass Spectra," to be presented at the 13th Annual Conference of the Microbeam Analysis Society, Ann Arbor, Michigan, June 19-23, 1978.

2. D. B. Wittry and T. A. Whatley, "Energy Distribution of Positive Ions of Group III and Group V Elements Sputtered from Semiconductors," to be presented at the 13th Annual Conference of the Microbeam Analysis Society, Ann Arbor, Michigan, June 19-23, 1978.

3. J. C. Potosky and D. B. Wittry, "The Secondary Ion Optics of a Quadrupole Ion Microprobe," to be presented at the 13th Annual Conference of the Microbeam Analysis Society, Ann Arbor, Michigan, June 19-23, 1978.

4. F. Guo and D. B. Wittry, "Use of Specimen Current Integration in SIMS," to be presented at the 13th Annual Conference of the Microbeam Analysis Society, Ann Arbor, Michigan, June 19-23, 1978.

1.11 Semiconductor Properties Near Interfaces

(The Air Force Office of Scientific Research)

D. B. Wittry, F. Guo, C. H. Liang, C. J. Wu

Objective Summary: To study the composition of semiconductors near interfaces using cathodoluminescence, electron probe x-ray microanalysis and secondary ion mass spectrometry and to correlate these results with measurements of the electrical properties and the energy levels of impurities in the bandgap.

Approach Summary: In this work we are collaborating with other investigators at the Naval Ocean Systems Center (Dr. Harry Wider), at the University of Colorado (Dr. Russel Hayes), at USC (Dr. James Whelan), at Crystal Specialties (Worth Allred), and at the Air Force Materials Research Laboratory (John Blasingame). In some cases, the electronic properties of the specimens--including heat-treated GaAs, as-grown GaAs, and anodically grown oxides of GaAs, prepared under various conditions are being studied by our collaborators and we are making with the composition and cathodoluminescence measurements. In other cases,

we are evaluating the electronic properties that can be studied by electron beam induced currents and cathodoluminescence. For example, Mr. Wu has recently completed work on evaluation of diffusion lengths in GaAs using electron beam induced currents at Schottky barriers.

Progress:

a) A bibliography on ESI layers (Epitaxial-Semiconductor Interface layers) has been prepared.

b) Preliminary tests of our SIMS instrument were made; spectra of GaAs, Si, Al, and KBr were recorded using negative oxygen primary ions.

c) Our low temperature cathodoluminescence system was put back into operation, a new photomultiplier tube with InAs-GaAs photocathode and a new thermoelectrically cooled housing was ordered and an adapter flange was designed for use with this housing.

d) Depth profiles were obtained by SIMS for oxides anodically grown on GaAs by Dr. Whelan's group.

Publications:

1. C. J. Wu and D. B. Wittry, "Investigation of Minority Carrier Diffusion Lengths by Electron Bombardment of Schottky Barriers," J. Appl. Phys., May 1978, 2827-2837.

1.12 Electrical Techniques for Materials Characterization

(The Joint Services Electronics Program)

C. R. Crowell

Objective Summary: To develop non-destructive electrical techniques which aid in semiconductor materials and device characterization. Of special interest are: (1) a development of the understanding of capacitive evaluation of deep impurity levels from the frequency dependence of junction impedance; (2) to complement (1) with a study of differential deep level transient spectroscopy, DDLTS; (3) an analysis of multiple level systems and sample inhomogeneity by Hall measurements; and (4) charge effects associated with current transport in insulators.

Approach Summary: (1) Investigation of a two-level impurity (Au in n and p type Si) is proposed using high and low barrier Schottky contacts. This will permit a more unequivocal measurement of the deep level parameters than previous investigations using p-n junctions. A theoretical analytic technique that uses an appropriate simplification is also being

developed for the case of majority carrier traps. This is being used to investigate the capture cross-section for holes in In doped p-type Si. A study of thallium in silicon is also proposed.

(2) A study of the limitations of DDLTS will be undertaken from the point of view of the fundamental limits on resolution and sensitivity of the method.

(3) Techniques for meaningful presentation of Hall measurements on multiple level systems will be explored as well as methods for on-line analysis of such data.

(4) A number of features of existing data related to charge transport and storage in silicon nitride will be investigated.

Progress:

1. Capacitive Evaluation of Deep Levels

During this period C. H. Huang [1] has completed an extensive thesis on the Capacitive Evaluation of Deep Levels. Some of the major features of this analysis were presented at the JSEP Topical Review at Stanford, August 4, 1977. Recent data on the more lightly compensated samples of In doped Si have yielded excellent correlation between the experimental data and the theoretical modelling in which the In capture cross section, doping concentration and other species doping concentrations were found. We currently are completing an error analysis of the parameters we deduced. The analysis is an over determined one that is most applicable to cases where the deep level species is of high concentration relative to the shallow dopant. This type of system is not easily amenable to a DLTS approach.

2. DLTS and DDLTS

We have undertaken a study of the modulation techniques that will yield an optimum design of DLTS systems. Our study shows that under many circumstances the differential deep level transient spectroscopy (DDLTS) not only provides spatial as well as energetic profiles of deep levels but for comparable analyses is actually more efficient timewise.

We have also showed that the presence of appreciable concentrations of deep levels relative to the shallow level makes the transient spectroscopy nonlinear in sensitivity and alters the apparent emission time constants of the deep levels.

A measurement system based on guidelines from this work is being planned presently.

3. Due to pressures of time and personnel, the Hall Effect Analysis, Poole-Frenkel Analysis, and Solar Cell Analysis were temporarily set aside.

Publications/References:

1. C. H. Huang, Ph.D. Thesis, January 1978.

2. C. R. Crowell, "Electrical Techniques for Semiconductor Characterization," JSEP Topical Review, Stanford Univ., Aug. 4, 1977.

1.13 Non-Localized Impact Ionization in Semiconductors and Impact Ionization and Hot Carrier Transport in Semiconductors (Continuation)

(U.S. Army Research Office)

C. R. Crowell, C. W. Kao, R. Chwang, T. Griffin

Objective Summary: This work is intended to clarify the theoretical description of the transport process leading to electron or hole initiated electron-hole pair production and to make experimental measurements which can be interpreted in the light of the subsequently improved modeling.

Progress: Basic guidelines as set forth by Chwang and Crowell [1-4] have provided a formulation for quantitative modelling of the ionization process for covalent semiconductors. During the past year we have modified some of the analytic results to provide an extrapolation of the predictions into a more nearly Wolff [5] regime that appears to apply to InP. We have obtained some excellent measurements of multiplication for both hole and electron initiated ionization in Pt on p-type InP Schottky barriers. The results indicate a hole ionization coefficient about an order of magnitude higher than the electron ionization coefficient. We are currently analyzing these data in more detail using guidelines derived from our earlier work [6]. Our earlier attempts to make corresponding measurements on GaAs were partially frustrated by an extraneous mode of carrier injection that appears to be material related.

We have also initiated some theoretical studies of current-voltage characteristics of punch through structures where we give careful attention to the role of the injecting contact. This problem belongs in the category of mathematically stiff systems, but we have attained some preliminary success.

We are constructing guard ring Schottky barriers on 2×10^{16} cm^{-3} doped n-type GaAs with electrolytically grown oxide formation. The barriers exhibit typical n values of 1.03 and nominal bulk breakdown.

The use of the Schottky barrier permits photoinjection of only majority carriers when the light quantum lies between the barrier height and the

band gap. Since the field dependence of the photoinjection determines the base line from which ionization coefficients are measured, we have completed a careful characterization of this process including effects of image force phonon scattering and quantum-mechanical tunneling [5] and applied at very successfully to measurements on the Pt, Si-Si system [6].

Publications/References:

1. R. Chwang and C. R. Crowell, "Normalized Theory of Impact Ionization and Velocity Saturation in Nonpolar Semiconductors via a Markov Chain Approach," Solid State Electron., to be published.

2. R. Chwang and C. R. Crowell, "Effective Threshold Energy for Pair Production in Non-polar Semiconductors," Solid State Comm. 20, 169-172 (1976).

3. R. Chwang and C. R. Crowell, "Interrelationship Between Impact Ionization, Velocity Saturation, and Cascade Process in Nonpolar Semiconductors," Presented at the International Conference on Hot Electrons in Semiconductors, Denton, Texas, July 1977.

4. R. Chwang, Ph.D. Thesis, U.S.C., April 1977.

5. P. Wolff, Phys. Rev. 95, 1415 (1954).

6. C. W. Kao, C. L. Anderson, and C. R. Crowell, "Photoinjection at Metal-Semiconductor Interfaces," invited paper presented at the 4th Annual Conference on Physics of Compound Semiconductor Interfaces, Princeton, New Jersey, February 1977, manuscript in preparation.

7. C. L. Anderson, Ph.D. Thesis, U.S.C., March 1973.

2. DEVICES

2.1 Development of Large Area Solar Cells Based on CdTe

(Subcontract from Monosolar, prime contract from Department of Energy)

F. A. Kroger, M.P.R. Panicker, K. Lehovec,
A. Fedotowsky, R. Assatourian

Objective Summary: To make CdTe photovoltaic solar cells of reasonable energy efficiency by an economic fabrication process (efficiency goal: 10%).

Approach Summary: Deposit cathodically n-type CdTe: In and p-type CdTe: As from aqueous solution of $CdSO_4$ and TeO_2 on a transparent conducting base.

Progress:

A. Technology

Films were deposited on glass covered with a thin film of n-type semiconducting In_2O_3: Sn (so-called ITO) with a resistance of 10 to 20 $\Omega/\square$. Various types of cells were made, viz.,

n ITO / n CdTe: In / p CdTe: As / p Te (1)

n ITO / n CdTe: In / p Te (2)

n ITO / p CdTe: As / p Te (3)

An arrow indicates the expected position of the active junction. The open circuit voltage, V_{OC}, and short circuit current, I_{SC}, of the cells depend sensitively on the ITO surface and the conditions of plating for CdTe and Te.

Sometimes glass as received has an ITO film with a proper surface. In other cases the as received glass gives low efficiency cells. The surface of such oxide films can be improved by an anneal for 1 hour at 300 to 400°C in oxygen-free argon or nitrogen. Wet hydrogen is not a good ambient for the anneal. Current density and pH are important parameters for deposition of both CdTe and Te (as judged from I_{SC} and V_{OC} of the completed cells).

A pH of 3.2 ± 0.2 and current densities $\leq 0.5\ mA/cm^2$ give the best cells. For cell efficiency measurements, cells of limited area are necessary. Such cells can be made on ITO covered glass when part of

the ITO surface is blocked by photoresist or lacquer. They cannot be made by etching away part of the deposited CdTe by acid. Such etching leaves a film of Te at the surface and at the edges of the remaining film which shorts the cells.

B. Physical Properties

Small a.c. signal susceptances and conductances of electroplated CdTe solar cells were measured as functions of frequency and d.c. bias voltage, with and without illumination. It was found necessary to restrict the CdTe film laterally beyond the top electrode to prevent presence of a distributed R-C network resulting from top sheet conductance, junction capacitance, and junction shunt resistance. Presence of this network introduces added variables which make it difficult to interpret the results.

The observed frequency dependencies of the capacitance and of the equivalent parallel conductance over angular frequency, comply in essential features with those calculated for a network comprising a capacitor C shunted by a resistor R_2 and in series with a resistor R_1. In particular, the low frequency capacitance is nearly frequency independent (but not always in illuminated samples) and the low frequency G/ω decreases inversely with ω. The resistance R_2 parallel to the capacitance depends strongly on forward bias voltage, while the series resistance R_1 is rather insensitive to the d.c. bias.

Publications:

1. M.P.R. Panicker, M. Knaster and F. A. Kroger, "Cathodic Deposition of CdTe from Aqueous Electrolytes," J. Electrochem. Soc. 125 [4] 566 (1978).

2. K. Lehovec and A. Fedotowsky, "Degradation of Solar Cell Efficiency by Sheet Resistance," Solid-State Electronics, 70, pp. 725-726 (1977).

3. K. Lehovec and A. Fedotowsky, "Degradation of Solar Cell Efficiency by Sheet Resistance," Solar Energy, in print.

2.2 Investigation of Junction Field Effect Transistors

(The National Science Foundation)

K. Lehovec and S-T. Lin

Objective Summary: To study field effect transistors with emphasis on effects involving the interface between a semiconducting channel and an insulating substrate.

Progress:

A. Electron-Hole Generation at the Silicon-Sapphire Interface

Previously reported experiments on transient currents of silicon MOS-capacitors on sapphire substrate [1] have been augmented by I-V measurements on gated P^+-I-N^+ SOS diodes, and on enhancement mode p-channel and depletion mode n-channel SOS devices. The latter experiments have shown the following:

(i) Electron-hole pair generation at the sapphire interface in deep-depleted MOS capacitors is suppressed by electron build-up at the sapphire interface, i.e., inversion charge build-up arises under the gate rim and spreads from there over the silicon surface under the gate.

(ii) The empirical transient MOS-diode current can be derived from the empirical gated diode steady state I-V characteristics.

(iii) The transient MOS current decay exhibits a hump which is attributed to the fact that electrons emitted from Shockley-Reed-Hall states at the sapphire interface first create only immobile positively charged traps which later promote hole emission to the valence band. The mobile holes thus generated transfer to the silicon/silicon oxide interface causing an added current component responsible for the hump.

B. High-Speed GaAs E-JFET Logic

A theoretical analysis shows the transistor operates during the switching transient in the saturation regime [2] notwithstanding steady state operation in the linear regime. When the transistor is switched off, the transient response is governed by the load resistance and the input capacitance of the subsequent stage.

Publications/References:

1. K. Lehovec and R. Miller, "Investigation of the Sapphire Interface by Transient Current Analysis," Trans. Int. Electron. Device Meeting, Washington, D.C., pp. 283-286 (1976).

2. K. Lehovec in cooperation with R. Zuleeg and J. K. Notthoff of the McDonnell Douglas Astronautics Company, "Femto-Joule, High-Speed Planar GaAs E-JFET Logic," IEEE Trans. Electron. Devices, v. ED-25, N. 6, p. 628, June 1978.

2.3 Charge Motion in Dual Dielectric MNOS Structures

(The Army Research Office)

K. Lehovec, A. Fedotowsky and C-H. Chen

Objective Summary: To study the memory charge distribution in the dual dielectric oxide-nitride, the charge retention and the fatigue effects associated with many alternately write/erase pulses.

Progress: A simple analytical expression was derived [1] for charge retention in MNOS memory devices assuming that retention loss is limited by Frenkel-Poole release from monoenergetic traps. This model shows that charge retention becomes eventually independent of the initial charge distribution. Experimental data obtained at elevated temperatures confirm this model and provide a trap depth of 1.5 eV, Frenkel-Poole coefficient of about 6×10^{-4} $cm^{1/2}V^{-1/2}$ eV, and effective escape attempt rate factor of 1.2×10^{8} sec^{-1}.

A new method for determination of the charge vs. centroid relationship was developed [2]: A sequence of identical voltage pulses is applied, the memory device is returned to flat band condition after each pulse, and the subsequent pulse is superimposed on the flat band voltage corresponding to the accumulated memory charge distribution resulting from the preceding pulses. Staircase patterns of accumulated charge and of device voltage are analyzed, and effects arising from back tunnelling and leakage currents are identified. Comparison of the initial injection current during a voltage pulse with the steady state current indicates that hole injection from the gate does not contribute significantly to the steady state oxide tunnel current.

Publications:

1. K. Lehovec and A. Fedotowsky, "Charge Retention of MNOS Devices Limited by Frenkel-Poole Detrapping," Appl. Phys. Lett. 32, No. 5, March 1, 1978, pp. 335-338.

2. K. Lehovec, C-H. Chen and A. Fedotowsky, "MNOS Charge vs. Centroid Determination by Staircase Charging," IEEE Trans. Electron. Devices, (in print).

2.4 Electrooptic Materials and Optical Image Storage Devices

(The Joint Services Electronics Program)

A. R. Tanguay, Jr.

Objective Summary: (1) To fully characterize the physical processes inherent in the operation of Pockels Effect and Photorefractive Image Storage Devices, and to establish the relationship between the relevant material properties and optimumdevice design parameters. These image storage devices are currently of interest for applications in incoherent-to-coherent conversion and coherent optical processing. (2) To further develop the Czochralski growth technique for the production of large single crystals of optical quality bismuth silicon oxide ($Bi_{12}SiO_{20}$), at present the most promising candidate for the active electrooptic element of both Pockels Effect and Photorefractive Image Storage Devices.

Approach Summary: (1) Continue optimization of Czochralski growth parameters for production of optically and electrically uniform, strain free, highly transparent, non-photochromic bismuth silicon oxide ($Bi_{12}SiO_{20}$) single crystals. (2) Fabricate and evaluate both Pockels Effect and Photorefractive Image Storage Devices based on bismuth silicon oxide and bismuth germanium oxide. (3) Investigate and evaluate alternative materials for the photoconductive electrooptic crystal, dielectric insulating layers, and transparent conducting electrodes to improve device performance.

Progress: This work unit was initiated as an unprogrammed change on 1 September 177. Work effort to date has focused on modification of laboratory facilities and assembly of equipment and apparatus in preparation for initiation of the research program described herein.

We propose to modify both an existing RF induction heated Czochralski puller and a two zone resistance heated Czochralski puller for the growth of bismuth silicon oxide (BSO), bismuth germanium oxide (BGO), and related compounds. Growth parameters necessary for the production of optically uniform, strain free single crystals of intermediate

size (2-3 cm diameter) will be established, including pull rate, rotation rate, radial and axial temperature gradients, and purity of starting material.

Concurrent with the growth parametrization effort, investigations of the impurity-induced photochromic effects in BSO and its isomorphs will be continued. In particular, the hypothesis [3] that the remarkable optical sensitivity of BSO to trace impurities results from incorporation of transition metal ions on Si sites with tetrahedral symmetry will be tested. This will be accomplished by growth and selective doping of all three known phases of the Bi_2O_3-SiO_2 system ($Bi_{12}SiO_{20}$; $Bi_4Si_3O_{12}$; Bi_2SiO_9 [7]). The Si site symmetry is tetrahedral in the 6:1 and 2:3 phases, but not in the 1:3 phase [7], so that measurements of relative photochromic sensitivity to particular dopants can be expected to reveal the effects of incorporation symmetry differences in similar chemical environments. Continued selective doping experiments in concert with thermal annealing/transient optical exposure and optical absorption spectroscopy will be employed to confirm and extend the list of known low-level photochromic-inducing impurities in BSO and BGO. Doping experiments with rare earth ions will be undertaken to evaluate BSO as a prospective solid state laser host.

Measurement of fundamental optical and electrooptical characteristics of BSO and its isomorphs (notably BGO and BTiO) will be extended. The polarization eigenstate technique [4] will be employed to determine the wavelength dispersion of the electrooptic coefficient for BGO and BTiO. This entails accurate determinations of the wavelength dispersions of both the index of refraction and the optical rotatory power.

Pockels Readout Optical Memory devices will be fabricated by vapor deposition of parylene insulating layers and electron beam deposition of transparent conductive electrodes on highly polished surfaces of BSO single crystal wafers. The device performance will be evaluated to determine the effects of material parameters on fundamental operational limitations (resolution, cycle time, sensitivity, linearity, etc.). The uniformity of charge storage decay will be examined to investigate possible correlations between the observed characteristic anisotropies in optical density [1,2] and anisotropies in bulk resistivity. Such anisotropies would be expected to incur undesirable time-dependent errors in the optical transfer function. The symmetry of exposure/resolution characteristics under conditions of opposite initial applied bias will be investigated electrically and electrooptically in hopes of understanding the field-induced charge transfer behavior of the device. The effects of optical activity on the device optical transfer function [6] will be studied by careful characterization of devices with widely varying design parameters. The possibilities of extending the optical exposure sensitivity of the device from the blue end of the spectrum further into the visible region, and of providing electrical erasure capability in addition to the present optical illumination method will be examined from the point of view of possible

heterostructures and doping techniques.

Photorefractive image storage devices utilizing BSO and its isomorphs will be fabricated and evaluated. The effects of large natural optical activity on the relationship between diffraction efficiency and space charge modulation will be examined both theoretically and experimentally. The possibility of substituting bismuth titanium oxide (which has a much smaller optical rotatory power than bismuth silicon oxide) as the active element in such a device will be investigated.

References:

1. A. R. Tanguay, Jr., S. Mroczkowski, and R. C. Barker, "The Czochralski Growth of Optical Quality Bismuth Silicon Oxide ($Bi_{12}SiO_{20}$)," Proc. Fifth International Conference on Crystal Growth, Boston (1977).

2. A. R. Tanguay, Jr., S. Mroczkowski, and R. C. Barker, "The Czochralski Growth of Optical Quality Bismuth Silicon Oxide ($Bi_{12}SiO_{20}$," accepted for publication in Journal of Crystal Growth (1978).

3. A. R. Tanguay, Jr., S. Mroczkowski, and R. C. Barker, "Impurity Induced Photochromic Behavior in Bismuth Silicon Oxide ($Bi_{12}SiO_{20}$)," to be published (1978).

4. A. R. Tanguay, Jr., and R. C. Barker, "Polarization Eigenstate Measurement Scheme for the Discrimination of Concurrent Optical Activity and Electric Field Induced Birefringence," to be published, (1978).

5. A. R. Tanguay, Jr., and R. C. Barker, "Electrooptical Properties of Bismuth Silicon Oxide ($Bi_{12}SiO_{20}$)," to be published (1978).

6. A. R. Tanguay, Jr., and R. C. Barker, "Implications of Concurrent Optical Activity and Electric Field Induced Birefringence for Pockels Readout Optical Memory Performance," to be published (1978).

7. B. C. Grabmeier, "A New Compound in the Bismuth-Oxide Germanium-Dioxide System," Fifth International Conference on Crystal Growth, Boston (1977).

2.5 Other Projects

The following projects are not reported in this edition:

1. Surface Acoustic Wave Resonator Fundamental Study (Army Research Office)

2. Grwoth and Characterization of Epitaxial Piezoelectric and Semiconductor Films (The Office of Scientific Research)

3. Piezoelectric Transducers (Rockwell, International).

3. SUPERCONDUCTORS

3.1 High Field Superconductivity

(The National Science Foundation)

Y. B. Kim, H. M. Kim, I-H. Choi

Objective Summary: Experimental investigation of surface loss in the high field superconductors, especially Nb_3Ge ($T_c = 23^oK$). The flux entry field profile are being studied by microwave technique and its correlation with metallurgical treatment of the surface by laser glazing.

Approach Summary: Flux entry profile and their correlation with the sample surface properties metallurgically treated by laser glazing can be studied by a microwave resonator of high dielectric constant which reduces the cavity size considerably and enables one study in local surface properties in the flux entry.

Nb_3Ge foil or thin film is prepared by well-controlled and highly reproducible chemical vapor deposition process.

Progress: Nb_3Ge samples are readily prepared with various parameters under control in the chemical vapor deposition process. Following the strong effect of the height of the surface protrusion [1] in the previous investigation the flat surface of the sample are prepared by laser glazing [2]. Systems of measuring accurate T_c and surface flux entry measurements are established. Various Rutile resonators [3] are designed to optimize its probing function in the flux entry measurement.

References:

1. Y. B. Kim and K. S. Kim, "Reduction of AC Losses in High Temperature Superconductors," Research Report, EPRI TD-136, April 1976.

2. B. H. Kear and C. M. Banas, "Processing Material with Lasers," Physics Today, Nov. 1976.

3. A. Okaya, L. F. Barash, "The Dielectric Microwave Resonator," Proc. IRE, 50, 2081, 1962.

4. ALLOYS, CERAMICS AND METALS

4.1 Deformation Mechanisms in Superplasticity

(The National Science Foundation)

F. Abdi, M.M.I. Ahmed, D. G. Bhat, S. Siperstein,
D. A. Miller, F. A. Mohamed and T. G. Langdon

Objective Summary: This program is designed specifically to contribute toward an understanding of the deformation mechanisms occurring during superplasticity.

Approach Summary: Tests will be carried out to evaluate the mechanical characteristics of materials deforming both within and outside of the superplastic region.

Progress: Mechanical tests were conducted on Zn-22% Al, Pb-62% Sn, and two copper dispersion alloys, using both constant stress and constant strain rate conditions. Density measurements indicate that cavities are nucleated in the materials at very low stress levels. Under optimum conditions, strains of up to 4850% may be achieved in Pb-62% Sn.

Publications (1977/78):

1. H. Ishikawa, D. G. Bhat, F. A. Mohamed and T. G. Langdon, "Evidence for Cavitation in the Superplastic Zn-22 Pct Al Eutectoid," Met. Trans., 8A, 523-525, 1977.

2. T. G. Langdon and F. A. Mohamed, "Ductility and Fracture in a Superplastic Alloy," in Fracture 1977 (D.M.R. Taplin, ed.), University of Waterloo Press, Waterloo, Ontario, 1977, Vol. 2, pp. 525-531.

3. F. A. Mohamed, M.M.I. Ahmed and T. G. Langdon, "Factors Influencing Ductility in the Superplastic Zn-22 Pct Al Eutectoid," Met. Trans., 8A, 933-938, 1977.

4. T. G. Langdon and F. A. Mohamed, "The Activation Energies for Superplasticity," Scripta Met., 11, 575-579, 1977.

5. M.M.I. Ahmed and T. G. Langdon, "Exceptional Ductility in the Superplastic Pb-62 Pct Sn Eutectic," Met. Trans., 8A, 1832-1833, 1977.

6. T. G. Langdon, "The Conditions Required for Superplasticity in Metals," in Proceedings of the Fifth New Zealand Science of Materials Conference, Wellington, New Zealand, 1977, pp. 11-15.

7. T. G. Langdon and D.M.R. Taplin, "Rupture of Strain-Rate Sensitive Alloys," Solid Mechanics Archieves, 2, 329-368, 1977.

8. T. G. Langdon, "The Relationship Between Strain Rate Sensitivity and Ductility in Superplastic Materials," Scripta Met., 11, 997-1000, 1977.

9. S. Siperstein, "An Evaluation of Methods of Determining the Strain Rate Sensitivity in Superplasticity," M. S. Thesis, University of Southern California, 1977.

10. S-A. Shei and T. G. Langdon, "The Mechanical Properties of a Superplastic Quasi-Single Phase Copper Alloy," Acta. Met., 26, 639-646, 1978.

11. S-A. Shei and T. G. Langdon, "The Fracture Characteristics of a Superplastic Single Phase Copper Alloy," J. Mater. Sci. 13, 1084-1092, 1978.

12. S-A. Shei and T. G. Langdon, "The Activation Energies for Plastic Flow in a Superplastic Copper Alloy," Acta. Met. (in press).

13. T. G. Langdon, "A Microscopic Examination of Void Formation in Superplastic Materials," J. Microscopy (submitted for publication).

4.2 Grain Boundary Sliding and Deformation Mechanisms During High Temperature Creep

(Department of Energy)

B. Singh, S. S. Vagarali, R. B. Vastava, P. Yavari, D. A. Miller, F. A. Mohamed and T. G. Langdon

Objective Summary: This research program is designed to investigate the deformation mechanisms in various pure metals, metallic alloys and ceramics under high-temperature creep conditions.

Approach Summary: Creep tests will be carried out under a wide range of temperatures and stress levels, to determine both the magnitude of grain boundary sliding and the precise deformation processes.

Progress: Creep tests were conducted on high-purity aluminum and magnesium, several metallic solid solution alloys, and KBr single crystals. The role of grain boundary sliding during high temperature fatigue of lead was investigated as a function of amplitude and frequency. Deformation mechanism maps were developed for ceramics, incorporating ambipolar diffusion.

Publications (1977/78):

1. P. Yavari and T. G. Langdon, "The Transition from Nabarro-Herring to Harper-Dorn Creep at Low Stress Levels," Scripta Met., 11, 863-866, 1977.

2. F. A. Mohamed and T. G. Langdon, "Recent Developments in Deformation Mechanism Maps for Ceramics," in Ceramic Microstructures '76 (R. M. Fulrath and J. A. Pask, eds.), Westview Press, Boulder, Colorado, 1977, pp. 763-773.

3. T. G. Langdon and F. A. Mohamed, "The Characteristics of Independent and Sequential Creep Processes," J. Australasian Inst. Metals, 22, 189-199, 1977.

4. T. G. Langdon and F. A. Mohamed, "A New Type of Deformation Mechanism Map for High Temperature Creep," Mater. Sci. Eng., 32, 103-112, 1978.

5. T. G. Langdon and F. A. Mohamed, "The Incorporation of Ambipolar Diffusion in Deformation Mechanism Maps for Ceramics," J. Mater. Sci. 13, 473-482, 1978.

6. T. G. Langdon and F. A. Mohamed, "A Simple Method of Constructing an Ashby-Type Deformation Mechanism Map," J. Mater. Sci., 13, 1282-1290, 1978.

7. T. G. Langdon, "Recent Developments in Deformation Mechanism Maps," Metals Forum (in press).

8. T. G. Langdon and R. C. Gifkins, "Observations on the Analysis of Interdependent Creep Processes," J. Mater. Sci. (in press).

9. R. C. Gifkins and T. G. Langdon, "Comments on Theories of Structural Superplasticity," Mater. Sci. Eng. (submitted for publication).

10. D. A. Miller and T. G. Langdon, "Evidence for Cavitation in Superplastic Zn-22 Pct Al of Very High Purity," Met. Trans. (submitted for publication).

4.3 Electrical and Mechanical Properties of Oxide Ceramics

(Department of Energy)

F. A. Kroger, S. K. Tiku, L. D. Ho , H. A. Wang

Objective Summary: Determine the effect of grain boundaries on the properties of oxide ceramics, in particular, Al_2O_3.

Approach Summary: Preparation of dense polycrstalline Al_2O_3 with various dopants and grain sizes and measure in these high temperature ionic and electronic conductivity and compressive creep rate, all as a function of oxygen pressure and temperature.

Progress: Dense material of grain size between 1 and 200 μm were prepared by hot pressing and sintering from oxide powder made from reagent grade Al-sulphate (I) and from Al-propoxide (II). As dopants iron and titanium were used. Undoped samples I were found to be acceptor dominated, with Mg as the probable acceptor; the conductivity is largely by holes at high p_{O_2} and by ions at low p_{O_2}.

The hole conductivity decreases with increasing grain size, indicating considerable grain boundary conduction. The ionic conductivity shows the opposite behavior, indicating conduction by a bulk process, grain boundaries hindering rather than promoting the ionic conduction. Iron-doped samples showed ionic conduction independent of grain size--again eliminating the possibility of considerable ionic grain boundary conduction. Activation energies of ionic conduction are in the range 3.4 to 4.4 eV. Creep is by Nabarro-Herring mechanism at small grain sizes, small stresses, and by a dislocation mechanism at large grain sizes and stresses.

The activation energies for the N-H creep are in the range 4.8 to 6.5, all larger than the activation energies for ionic conduction. A value of 8.8 eV was found for the dislocation mechanism. The activation energies of N-H creep are the same at low and high p_{O_2} when σ_i/σ_h is respectively $>$ and $<$ 1. Yet this does not rule out ambipolar diffusion of ions and holes as a limiting process for creep, because creep rate may be limited by an Al species the conductivity of which, σ_i' may remain $< \sigma_h$ at all p_{O_2}. Thus fast diffusion of O by neutral atoms or molecules is still possible.

A beginning has been made with the preparation of samples of type II (made from propoxide). These samples are found to be purer, but their properties are still acceptor-dominated. For undoped material, again σ_i increases with increasing grain size and the same behavior was found for Ti-doped samples. So also for donor-dominated samples there is no appreciable ionic grain boundary conduction. Model calculations for the variation with grain size of the distribution of dopants and native defects

over grain boundaries, subgrain boundaries (space charge region) and bulk in order to see whether a change in grain size exponent of creep so far attributed to a change from bulk diffusion limitation to grain boundary limitation can be explained on this basis. A paper "Conductivity and Creep of Acceptor-Dominated Polycrystalline Al_2O_3" was written and submitted to J. Materials Science.

4.4 Other Projects

The following projects are not reported in this edition:

1. Optical and Mechanical Properties of IR Materials (The Office of Scientific Research)

2. Physical Metalurgy of Beta Titanium Alloys (The Office of Scientific Research)

3. Hydrogen Effects in Alloys (Hydril Company)

4. Laser Assisted Hot Spot Machining (The Office of Naval Research)

5. Solidification of Melts Produced by Laser Irradiation (The National Science Foundation)

6. Laser Heat Treating (Rockwell, International).

II. QUANTUM ELECTRONCS

1. Low Frequency Dispersion of the Nonlinear Index of Refraction

(The Joint Services Electronics Program)

M. D. Levenson, J. J. Song, J. H. Lee

Objective Summary: To observe and parametrize the contributions to the nonlinear index of refraction due to dynamical processes in ions or molecules interacting with an intense laser field.

Approach Summary: The nonlinear index of refraction can be related to a third order optical nonlinearity:

$$n_2(\omega) = \frac{12R}{n} \chi^{(3)}(-\omega, \omega, \omega, -\omega)$$

and $\chi^{(3)}(-\omega_2, \omega_1, -\omega_1, \omega_2)$ can be studied by frequency mixing techniques. We are studying this quantity using the Raman induced Kerr effect and other polarization spectroscopy techniques. Orientational motion of non-absorbing molecules and the dynamics of absorbing species manifest themselves as a resonant enhancement of the polarization spectroscopy signal near $\omega_1 - \omega_e = 0$. From the observed lineshape, we derive the values of the various relaxation rates.

Progress: Experiments in the past year have focussed on the dynamics of the absorption processes in dyes used as passive Q-switches and mode lockers. The dynamics are best described in the density matrix formalism. We have found that the dominant population relaxation times in these dyes is in the picosecond range, while the coherence decay occurs on a femtosecond time scale. This result justifies the usual rate equation treatment of saturable absorption.

Publications:

1. J. J. Song and M. D. Levenson, "Electronic and Orientational Contributions to the Optical Kerr Constant Determined by Coherent Raman Techniques," J. Appl. Phys. 48, 3496-3501 (1977).

2. G. L. Eesley, M. D. Levenson, W. M. Tolles, "Optical Heterodyne Detection of Coherent Raman Signals," J. Quant. Elect. Q.E.-14, 45-49 (1978).

3. J. J. Song, J. H. Lee, and M. D. Levenson, "Picosecond Relaxation Measurements by Polarization Spectroscopy in Condensed Phases," Phys. Rev. A (April 1978).

2. Development of Bistable Optical Devices

(The Joint Services Electronics Program)

J. H. Marburger, E. Garmire, M. D. Levenson, and H. Winful

Objective Summary: To demonstrate bistable operation of a variety of optical devices employing electronic feedback to enhance the intensity dependence of the index of refraction and to investigate, experimentally and theoretically, ways in which such bistable optical devices can be developed into useful logic elements.

Approach Summary: In many crystals, the Pockels effect causes applied d.c. electric fields to alter the index of refraction. Such crystals are used, for example, in Pockels cell switches. If this d.c. field is controlled by a photodetector, an electronically enhanced nonlinear index of refraction results. Such feedback controlled Pockels cells are capable of bistable operation without the need for a delicately aligned Fabry Perot resonator. A related device employs the electric field dependence of the coherence length of a second harmonic generation crystal.

Progress: Bistable operation has been demonstrated in both proposed devices. Unfortunately, theoretical analysis presently indicates that all such devices operate too slowly when consuming little power and too inefficiently when adjusted for maximum switching speed. A paper describing these results will be presented at the Ninth International Quantum Electronics Conference, May 29, 1978.

3. Nonlinear Mixing Spectroscopy of Solids

(The National Science Foundation)

M. D. Levenson, J. J. Song, G. L. Eesley, and J. H. Lee

Objective Summary: To develop frequency mixing spectroscopy techniques and apply them to fundamental problems in the physics of condensed phases.

Approach Summary: Coherent Raman and other nonlinear spectroscopic techniques have been applied to crystals showing soft phonon modes, excitons, and absorbing impurities. The underlying dynamics is reflected more explicitly in the nonlinear spectra than in conventional optical techniques.

Progress: The Raman induced Kerr effect has been extended to the study of birefringent crystals, and materials at cryogenic temperatures. A narrow spectral feature of the polarization spectrum of filter glass has also been observed.

Resonant RIKES spectra have been detected in diphenyl octatetraene, but most absorbing samples show a strong non-Raman signal due to excited state absorption or saturation of the absorption.

The second order Raman spectrum of diamond has also been resolved by optical heterodyne detected Raman induced Kerr effect spectroscopy. Doing so required suppressing strong background signals from birefringence and the nonlinear background susceptibility. The coherent Raman spectra confirm previous results obtained by spontaneous scattering.

4. High Resolution Multiphon Spectroscopy

(The Office of Naval Research)

M. D. Levenson, I. C. Khoo, G. Chan, G. L. Eesley

Objective Summary: To study multiquantum absorption and multiquantum ionization of alkali atoms using narrowband single mode pulsed lasers.

Approach Summary: A xenon ion laser or Nd: YAG laser second harmonic beam was used to pump a long pulse tuneable dye laser which was then focussed into an atomic beam of sodium or potassium. Ions created as the result of two or three photon absorption were detected, and the ion signals plotted as a function of laser intensity, polarization, and frequency.

Progress: The collapse of the xenon pump laser necessitated the development of a unique long pulse Q-switch YAG system. While that was being debugged, multiquantum ionization experiments were undertaken in sodium and potassium using a nitrogen pumped dye laser capable only of reduced resolution. Nevertheless, two photon resonant three photon ionization was observed in both atoms. In the case of sodium, it was possible to saturate the two photon transition even with this broadband laser source. The phenomenlogy observed and the underlying theory was the subject of one publication. In potassium, the two quantum

transition was much weaker, but the excited level could be ionized with unit probability. This fact resulted in seemingly anomalous values for the ratio of ion signals produced with circular and linear polarization. The phenomenlogy and explanation was the subject of a second paper. More recently, the narrowband laser system has been made operational, and off resonant ionization signals have been sought using much improved resolution.

Publications:

1. P. Agostini, A. T. Georges, S. E. Wheatley, P. Lambropoulos and M. D. Levenson, "Saturation Effects in Resonant Three Photon Ionization of Sodium with a Nonmonochromatic Field," J. Phys. B. (to be published).

2. S. E. Wheatley, P. Agostini, S. N. Dixit, and M. D. Levenson, "Saturation Effects in Resonant Three Photon Ionization of Potassium," Physica Scripta (to be published).

5. Integrated Optics Laser Components

(U.S. Navy - Naval Training Equipment Center)

E. Garmire, M. Chang, and H. Stoll

Objective Summary: To develop a high brightness GaAs laser for use as a training device. The goal is 1 watt, 200 nsec pulses, low duty cycle with 1 mrad beam divergence, using integrated optics.

Approach Summary: An integrated optics circuit has been designed which includes a 45° grating as a beam expander and a grating output coupler. High power is obtained by locking together several lasers to oscillate at the same frequency. This project is a joint effort between USC and the Aerospace Corporation, the latter under subcontract to USC.

Progress: The problem of developing this complex device has been broken down into several manageable chunks which will proceed simultaneously. This includes separate development of the locking of lasers, the output coupler, the beam expander, and the development of fabrication techniques.

Transverse locking between two adjacent lasers has been demonstrated and a theory developed to explain the results. Publication awaits the obtaining of separately contacted lasers.

An output coupler has been demonstrated which has a 1 mrad beam divergence.

The 45^{o} grating beam expander has been demonstrated both theoretically and experimentally, confirming the concept of beam expansion using a 45^{o} grating.

Fabrication techniques have been developed which involve epitaxial growth, ion beam milling and selective chemical etch.

Publications:

1. H. Stoll, Proc. SPIE, Washington D.C., March 1978.

6. Waveguide Beam Expansion for Fibre Optics Sources and Optical Information Processing

(The Air Force Systems Command - RADC)

E. Garmire, S. D. Allen, A. Chen, and H. Stoll

Objective Summary: To develop integrated optics techniques for coupling to and from multimode fibers using grating beam expanders and output couplers. To develop multimode integrated optics switches which are compatible with multimode fiber optics.

Approach Summary: The grating beam expander will be developed in $LiNbO_3$ with careful attention to grating profile to obtain efficient coupling to fibers. The grating will also be used to make a polarization analyzer. This project involves a research subcontract with the Aerospace Corporation.

Progress: Beam expansion has been demonstrated theoretically [1] and experimentally. It has been demonstrated that overlapping with metal increased the coupling efficiency.

Calculations have been performed on alternative means of beam expansion using a negative waveguide lens.

Publications:

1. H. Stoll, Appl. Optics, to be published.

2. E. Garmire, S. D. Allen, J. Marburger, Optics Comm., to be published.

7. Bistable Optical Devices

(This is a USC supported follow-on project related to work performed under the JSEP Project reported in the preceding item #2)

E. Garmire, S. D. Allen, H. Winful, and J. Marburger

Objective Summary: Development of incoherent, mirrorless, bistable optical switch using hybrid electrical/optical feedback.

Approach Summary: By detecting the output of an electro-optic modulator and feeding it back as a voltage onto the modulator, the device can be made bistable, demonstraing an optical memory, differential gain, an optical limiter, and a number of other optical functions.

Progress: We have demonstrated the device in a bulk $LiNbO_3$ modulator and in a waveguide modulator, using a CdS detector as the detector and feeding the signal back onto the modulator. Bistability was observed and good agreement was seen between experiment and theory.

Publications:

1. E. Garmire, S. D. Allen, J. Marburger, Appl. Phys. Lett. 32, 320 (1978).

2. E. Garmire, J. Marburger, S. D. Allen, Proc. SPIE, Washington, D.C., March 1978.

3. E. Garmire, Bistable Optical Device Conference, ARO, Philadelphia, Nov. 1977.

8. Coherent Propagation Effects in Dye Solutions

(The National Science Foundation)

J. C. Diels and E. Van Stryland

Objective Summary: To measure the ultrashort (fraction of a picosecond) phase relaxation time in liquid dye solutions by means of coherent propagation effects. All previous knowledge of this relaxation time results from interpretation of frequency measurements. The first measurement in the time domain of the subpicosecond phase relaxation time will be made. In addition, coherent propagation effects will be used to shape and compress pulses to less than 0.1 ps.

Aporach Summary: The basic experiment involves sending a sequence of two picosecond pulses separated by a fraction of a picosecond through a dye solution, and to measure the energy transmission factor. Since only the energy of the two pulse sequence has to be measured, the new method requires only detection time resolution in the nanosecond range. A transient coherent interaction is seen if the transmission is dependent upon the relative phase of the two-pulse sequence. The phase relaxation time T_2 can be deduced from the anomalously high transmission factor of the 180^o out of phase sequences called "zero area pulse".

Progress:

A source of picosecond pulses has been developed. By modification of the cavity of a CW argon laser pumped dye laser, and inclusion of a passive mode locker pulse duration of 25 ps, 3 ps and 0.2 ps were generated. These pulses were sent through a Michelson type interferometer developed to meet the following characteristics.

1) Creates a pulse sequence with any predetermined time separation between 0 (accuracy of the zero: $\pm$ 0.03 ps) and 150 ps.

2) The phase relationship between the two pulses can be set to any value between 0 and π, or scanned continuously.

3) The intensity ratio of the two pulses is adjustable.

4) The accuracy of the aforementioned settings (1, 2 and 3) is such that complete extinction of the full aperture of the expanded (beam (~ 10 μm) can be maintained even with the shortest pulses.

5) The zero area pulse shaper gives two complementary outputs, providing easy monitoring of the signal being sent through a dye solution.

Publications:

1. J. C. Diels, E. van Stryland, G. Benedict, CLEOS, paper TuIT5, San Diego, February 1978.

2. J. C. Diels, E. van Stryland, D. Gold, Topical Meeting on Picosecond Phenomena, Paper WC9, Hilton Head, S.C., June 1978.

3. J. C. Diels, E. van Stryland, 10th Int. Quantum Electronics Conf., paper J8, Atlanta, June 1978.

4. J. C. Diels, E. van Stryland, G. Benedict, Optics Comm. 25, 93, 1978.

9. Intense Phase Matched Picosecond Third Harmonic Generation, Using Coherent Propagation and Two-Photon Resonance Enhancement

(The Joint Services Electronics Program)

J. C. Diels and A. T. Georges

Objective Summary: To demonstrate a new method of third harmonic generation, which would generate picosecond pulses of GW peak power in the wavelength range between 1800 Å and 2000 Å. Such a source would have applications in:

a) time resolved spectroscopy, measurements of short relaxation times;

b) meteorological and atmospheric studies (remote pressure measurements; remote study of atmospheric constituents by Raman spectroscopy);

c) plasma diagnostics.

Approach Summary: To utilize results of computer simulation of the propagation of picosecond pulses from a mode-locked Rhodamine 6G laser through lithium vapor. These calculations predict a range of pulse frequencies, temporal shapes and intensities for which extremely high conversion efficiency to third harmonic can be expected. This occurs because of a combination of the following factors:

a) a large third order susceptibility resulting from using a fundamental frequency which is at resonance with a two-photon transition;

b) the use of a phase matchable mixture of Mg and Li vapors;

c) low loss propagation for the selected pulse shapes, and the absence of saturation effects for these pulses when their durations are shorter than the collision time in the vapor mixture.

Progress:

A theoretical analysis of the propagation and trippling of Rh6G laser pulses in lithium vapor, under conditions of two photon resonance, was made. The conversion efficiency can exceed 8%. The latter figure pertains to the trippling of a 70 ps duration (FWHM), 80 mJ/cm^2 energy density "90° phase shifted pulse"[+] in a 1 m cell containing lithium vapor at a pressure of 1 torr. An abstract has been submitted to the Multiphoton

[+] A "90° phase shifted pulse" is made of a succession of two pulses with a relative phase difference of 90°.

Rochester Conference [1]. The following effects were taken into account in analyzing the interaction and propagation:

1) a large population redistribution from the ground (2s) to the 4s level of lithium;

2) a Doppler broadening of the same order of magnitude as the pulse Rabi frequency, and slightly different for each of the two isotopes of lithium;

3) a time dependent nonlinear suceptibility at the fundamental frequency associated with population exchanges between the 2s and 4s levels and with the resonant two-photo transition;

4) a time dependent nonlinear susceptibility at the third harmonic frequency due to the same population redistribution;

5) a transient Stark shift which amounts to several Doppler widths;

6) phase and energy relaxation of the "induced dipoles";

7) photoionization.

Computer calculations showed that the third harmonic generated by the "90° phase shifted pulse" is a smooth, unmodulated bell shaped pulse. In contrast, in conditions of "two photon self-induced transparency" [2], a wildly modulated (in phase and amplitude) third harmonic pulse is generated. Although the energy of the input pulse in the latter scheme is 130 mJ as against 50 mJ for the 90° phase shifted pulse, the highest conversion efficiency is only 2%.

The pulse shaper that generates 90° phase shifted pulses [3] provides two complementary outputs. More recent calculations show that the second output can be used for parametric complication of the third harmony created by the first one, yielding still higher conversions than the area reported above. Efficiency of the harmonic generation or 115 nm also occurs in this process and is currently under investigation.

The results of this theory are summarized in a letter [3] and detailed in a manuscript in preparation [5].

The theoretical work has now contoured fairly accurately the physical parameters required for the experimental demonstration. The laser source should include:

1) an oscillator generating pulses shorter than 50 ps;

2) amplifiers stages to reach an energy of at least 10 mj/pulse;

3) a device forming a "phase shifted pulse".

Items (1) and (3) have now been successfully developed. The laser

amplifiers will be built in the coming year.

A heat pipe oven to produce an homogeneous mixture of Mg and Li has been constructed, together with a pump station.

Publications/References:

1. J. C. Diels and A. T. Georges, International Conference on Multiphonon Processes, University of Rochester, June 6-9, 1977.

2. J. C. Diels, Optical and Quantum Electronics 8, 513 (1976).

3. J. C. Diels and A. T. Georges, Optics Letters, 1, 158 (1977).

4. J. C. Diels and A. T. Georges, 10th Int. Quantum Electr. Conf., paper L5, Atlanta, June 1978.

5. J. C. Diels and A. T. Georges, manuscript in preparation.

10. Laser Devices and Applications

(The Joint Services Electronics Program)

C. P. Christensen and W. H. Steier

Objective Summary: To investigate techniques for improving transverse mode quality and increasing the lasing pulse width of rare gas halide excimer lasers.

Approach Summary: Small bore capillary discharges have been shown to be much more stable than conventional, unconfined discharges at high gas pressures. They also typically exhibit a cylindrical symmetry that is conducive to formation of low-order optical modes. We have investigated the application of this type of discharge to excitation of rare gas halide laser systems.

Progress:

The majority of the experiments have utilized capillary bores in the range 0.5 mm to 2.0 mm. These devices require about 10 kV/cm to achieve breakdown of a one atmosphere mixture of He, Xe, and a halide compound. Since 20 to 50 centimeters of active length are desirable for laser operation it is necessary to divide the discharge into one to three centimeter segments in order to avoid extremely high operating voltages. Using transmission line techniques we have developed a method for uniformly and simultaneously exiciting a large number of discharge segments and have achieved laser operation in XeF and XeCl in a 25 cm

x 1 mm capillary device. Diffraction limited output was obtained from this device with only a minimal amount of intracavity aperturing, indicating a tendency toward low-transverse-mode operation in this device.

Discharge stability was investigated in several capillary configurations by applying a current pulse of long duration and observing the temporal behavior of the excimer fluorescence. Although a slightly extended fluorescence duration was observed in the smaller bore devices, every discharge studied degenerated into an arc mode within 100 nanoseconds after initiation. Theoretical estimates suggest that bore diameters of less than 0.1 mm are necessary for effective stabilization and we plan an extension of our fluorescence studies to capillaries of extremely small bore.

11. Feasibility Study of Device Synthesis of Non-Linear Filters

(The Air Force Office of Scientific Research)

W. H. Steier, R. S. Bucy, C. P. Christensen,
A. Sawchuk, and R. Joiner

Objective Summary: This contract is concerned with device synthesis of an optimal phase demodulator. On the basis of extensive digital computer studies [1,2] it has become clear that non-standard methods are necessary to implement the convolution task section of the loop that realizes the nonlinear filter in order to obtain fast and inexpensive synthesis.

Approach Summary: Our research has been two-pronged; analog and digital methods for convolution. On the analog side incoherent optical methods have been selected and on the digital side a special purpose array processor has been selected for study.

Progress:

The real time realization of the non-linear filter has progressed in two areas: all digital realization and hybrid optical-digital realization. The all digital filter is now ready for real time on-line use for 2-D problems and has met all of the initial objectives. The key development has been the inclusion of the AP-120B Array Processor in the system. Work is now underway on the 3-D problem. The hybrid system uses an incoherent LED-CCD optical convolver interfaced with a digital system. Initial measurements of the optical system impulse response and the overall system linearity are included and show the system working up to expectations. The design of the data acquisition system for accuracy measurements on the convolution is underway.

Publications:

1. Feasibility Study of Device Synthesis of Non-Linear Filters, Annual Report 3/1/77 - 2/28/78.

2. W. H. Steier, D. Drake, C. P. Christensen, R. Joiner, H. Barr, "A High Accuracy 2-D Optical Signal Processor, 1978 IEEE/OSA Conference on Laser and Electro-Optical Systems, San Diego, February 7-9, 1978.

References:

1. R. S. Bucy, K. D. Senne, "Digital Synthesis of Nonlinear Filters," Automatica, 7, No. 3, 1971, pp. 287-289.

2. R. S. Bucy, "Nonlinear Filtering with Pipeline and Array Processors," Proceedings IEEE Conference on Decision and Control, New Orleans, 1977.

3. R. S. Bucy, "Nonlinear Filtering with Pipeline and Array Processors," Proceedings IEEE Conference on Decision and Control, New Orleans, 1977.

12. Mode Locked High Energy Ultraviolet Lasers

(The National Science Foundation)

C. P. Christensen and W. H. Steier

Research Objective: To investigate techniques for short pulse generation in the near ultraviolet using rare gas halide lasers.

Approach Summary: Although the rare gas halide systems are capable of efficient, high-power operation in the near UV short pulse generation using conventional active modelocking techniques is complicated by the extremely short duration of optical gain (~20 ns). Passive modelocking techniques are expected to be more suitable but have not been explored due to the lack of well-characterized saturable absorbers. We have therefore initiated a program for identification and characterization of saturable absorbers for use in the ultraviolet. In addition, we are studying short pulse amplification in rare gas halide systems and are investigating a new type of discharge which shows promise for extending the gain duration in rare gas halide discharge devices.

Progress:

Absorber Characterization. The primary parameters of interest in the

characterization of saturable absorbers are the absorption cross-section and the recovery rate. It is desirable for modelocking applications that the cross-section be large and the recovery rapid. We have identified several organic dyes which absorb in the 300-350 nm range, which exhibit large cross-sections, and which are expected to have relatively short recovery lifetimes. We have constructed a modelocked, frequency-tripled Nd: $YAlO_3$ laser which provides high-power pulses of 10 psec duration at 355 nm. This devices is being used to accurately measure the recovery time of the selected dyes using an excite and probe technique.

Short Pulse Amplification. Linear amplification of sub-nanosecond pulses in a rare gas halide system has been demonstrated, but to date there have been no studies of short pulse energy extraction in these media. We have constructed a rare gas halide oscillator-amplifier system which will be used to study nonlinear effects in short pulse amplification. Experimentally the oscillator output is passed through a fast electro-optic shutter of variable aperture time. Gain saturation effects are then studied as a function of pulse duration. The results of these experiments should provide some insight into the kinetic processes in the amplifying medium.

Extension of Gain Duration. The temporal duration of optical gain in the rare gas halide systems is intimately related to the stability of the discharge. We have investigated transverse electrodeless discharges as a means for obtaining increased gain duration in excimer lasers, and we find that discharges which are stable for periods of microseconds can be obtained with this configuration. To date observations have been confined to a bell jar apparatus, but a laser based on these principles is under construction.

13. Engineering Design of Repetitively Q-Switched Solid State Lasers for Precision Ranging

(National Aeronautics and Space Administration)

L. G. DeShazer, J. G. Sliney, Jr., and T. S. Lomheim

Objective Summary: Laser engineering design of Nd in YAG and BeL will be studied by spectroscopy and argon-laser pumping of Nd lasers.

Approach Summary: Determining the spectroscopic parameters necessary to analyze the laser performance, such as lifetime and quantum efficiency. Operation of a Nd laser by argon-laser pumping to check the spectroscopic predictions.

Progress:

The repetitively Q-switched performance of x-axis Nd:BeL was compared to that of Nd:YAG. In identical test arrangements, Q-switched outputs of Nd:BeL were observed to be 3 times that obtained from Nd:YAG. This results from the higher energy storage of Nd:BeL and is an intrinsic property of this laser crystal. Substantially higher flash lamp pump energy was required for Nd:BeL compared to Nd:YAG to obtain the greater Q-switched output. The Q-switched performance exhibited good correlation with the stimulated emission cross-sections. Determination of the cross-sections for x-axis and y-axis Nd:BeL yielded $0.9 \times 10^{-19} cm^2$ and $1.4 \times 10^{-19} cm^2$ respectively.

Bulk damage thresholds were measured for Nd:BeL, Nd:YAG, Nd:YLF, Nd:YVO_4 and Nd:GGG; surface damage thresholds were determined for Nd:BeL, Nd:YAG and Nd:YVO_4. The bulk and surface damage thresholds for Nd:BeL (approximately 10 GW/cm^2 and 9 GW/cm^2 respectively) were very close to those of Nd:YAG. This result can be considered favorable for Nd:BeL in high peak power applications since large diameter boules can be readily grown.

Publications:

1. J. G. Sliney, Jr. and L. G. DeShazer, "Temperature and Concentration Dependence of Laser Bulk Damage to Neodymium Glass," in Laser Induced Damage in Optical Materials: 1977, edited by A. J. Glass and A. H. Guenther (NBS Special Publication).

2. T. S. Lomheim and L. G. DeShazer, "New Procedure of Determining Neodymium Fluorescence Branching Ratios as Applied to 25 Crystal and Glass Hosts," Opt. Comm. 24, 89 (1978).

3. T. S. Lomheim and L. G. DeShazer, "Optical Absorption Intensities of Trivalent Neodymium in the Uniaxial Crystal Yttrium Orthovanadate," to be published in J. Appl. Phys., Aug. 1978.

4. T. S. Lomheim and L. G. DeShazer, "Determination of Optical Cross-Sections by the Measurement of Saturation Flux Using Laser-Pumped Laser Oscillators," submitted to J. Opt. Soc. Am.

14. Theory of Electromagnetic Scattering Processes at Resonance and with Intense Fields

(The Joint Services Electronics Program)

R. W. Hellwarth

Objective Summary: To be able to interpret and predict the nature of the electromagnetic radiation that is scattered by matter from a strong incident monochromatic wave whose frequency is at or near a resonance of the scattering medium. The problems to be attacked include those that arise in mode-locking, saturable absorption, saturation spectroscopy, high-energy optical amplifiers, infrared-laser window failure, and optical image and frequency converters.

Approach Summary: Our approach will be mainly theoretical and directed toward the nees of experimenters currently utilizing resonant laser-matter interactions (tunable and high-power laser sources, detectors, etc.).

Progress:

Task A: Two-Photon Amplifiers and Two-Photon Interactions

In order to evaluate the third order non-linear susceptibility for hydrogen-like atoms, we sought an analytical form for a triple sum over continuum and discrete states of a product of hydrogenic matrix elements and energy denominators. We have proceeded along lines suggested by Schwartz and Tiemann [Annals of Physics: 2, 178-187, 1959] where a part of the sum is removed by the introduction of a function defined by a separate differential equation. By use of a Laplace transform technique, we obtained a closed form integral solution to this equation which may be solved numerically. However, results of this method were found to be inconsistent with previously published limiting values, and in some cases do not seem to be physically realistic. We have begun a different approach to this calculation, using instead a Green's function method following that of Karule (J. Phys. B 4, 267, 1971), which, however, appears to require more lengthy numerical evaluations.

We obtained preliminary experimental verification (using borrowed apparatus) of the concept of an energy-reservoir level to supply population to a level from which stimulated two-photon emission is possible. Experiments monitored the non-exponential fluorescent decay from the 13s level of potassium vapor excited by 2-photon absorption from a tunable dye laser.

Task B: Theory of Ultra-High Optical Field Interactions

1. Nonlinear Counter-Propagating Pulses (NCP). The first portion of our proposed project studying chirp compensation with counter-propagating pulses has been completed. A report of the work has been accepted for publication as an Applied Physics Letter [2]. In this study, only plane wave situations were analyzed. The result of our study is that forward chirp developed by pulse propagation in a nonlinear medium can be removed near the pulse peak by allowing the pulse to overlap with a backward pulse at the exit of the medium. Details of the calculation are reported in ref. [2].

Beams of finite aperture tend to self-focus in non-linear medium, and this alters the self-phase modulation process. We have developed approximate equations to describe counter-propagating pulses of finite aperture and are designing a computer code for their numerical solution. Some analysis is possible for steady state counterpropagating beams, but even in this case complete solutions require numerical analysis.

2. Self-Trapped Propagation Excitations. The nonlinear Maxwell equations which govern propagation of electromagnetic waves at high intensities in plasma were examined for solutions which are self-trapped balls of energy in three dimensions. Such solutions were found to exist, but at field strengths beyond those presently obtainable in laser beams. A computational algorithm for their differential equation has been found for monochromatic stationary excitations of spherical symmetry. By computer analyses we have established that the number of such solutions (in the classical regime) is a function of the difference between the plasma frequency and e-m wave frequency. It remains to determine if these solutions are stable to center-of-mass motion and angular variations.

3. Polarization Spectroscopy. A study of the relative merits of several laser-spectroscopy techniques for plasma diagnostics was continued. The first results have shown that the Raman-induced Kerr effect (discovered previously in this project) has unique advantages [1]. The results are being used by experimentalists elsewhere.

4. Phase-Conjunction and Beam Restoration by Stimulated Scattering. From recent experiments by Nosach et al. [4] and Zl'lovich et al. [5] it is apparent that both stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) in the backward direction can produce waves that are remarkably close to being "phase-conjugate" to the pump beam, and therefore to being a time-reversed replica of it. Such a replica can back-track through a distorting medium to emerge restored to the condition of the entering pump beam. We completed the first theory of the degree to which stimulated waves are phase-conjugates under various experimental conditions, and the powers required for efficient generation of replica waves by this process [6]. The conditions under which stimulated scattering can

usefully produce a phase-conjugate wave are found to be very wide.

Publications/References:

1. R. W. Hellwarth, "Nonlinear Optical Effects for Plasma Diagnostics," Appl. Phys. 11, 147 (1976).

2. J. Marburger, R. Shockley, "Nonresonant Chirp Compensation with Counterpropagating Optical Pulses," Appl. Phys. Letters 30, 441 (1977).

3. A. T. Georges, P. Lambropoulos, J. Marburger, "Theory of Third Harmonic Generation in Metal Vapors Under Two-Photon Resonance Conditions," Phys. Rev. A15, 300 (1977).

4. O. Nosach, V. Popovichev, V. Ragul'skii, and F. Faisullov, "Cancellation of Phase Distortions in an Amplifying Medium with a 'Brillouin Mirror'," Sov. Phys. JETP Lett. 15, 109 (1972).

5. B. Ya. Zel'lovich, N. Mel'nikov, N. Pilipetskii, and V. Tagul'skii, "Observation of Wavefront Inversion in Stimulated Raman Scattering of Light," Sov. Phys. JETP Lett. 25, 36 (1977).

6. R. Hellwarth, "Theory of Phase Conjugation by Stimulated Scattering in a Waveguide," to be published in July 1978, in Journ. Opt. Soc. Am.

15. Studies of Optical-Beam Phase Conjunction by Nonlinear Refraction

(The Air Force Office of Scientific Research)

R. W. Hellwarth, J. Feinberg and S. M. Jensen

Objective Summary: This project aims to explore the nature of the process of the generation of time-reversed replicas, or "phase-conjugates" of image bearing optical beams. Applications to beam restoration will be explored.

Approach Summary: The approach will be both theoretical and experimental.

Progress: We have seen the first generation of the time reversed replica of an optical beam by coupling it into a waveguide where it interacts with counter-propagating pump waves in a nonlinear medium (liquid CS_2). This configuration requires lower pump powers and is much

less sensitive to beam alignment than is the corresponding process with unguided waves.

Publications:

1. S. M. Jensen and R. W. Hellwarth, "Generation of Time Reversed Waves by Nonlinear Refraction in a Waveguide," to be published in Appl. Phys. Letters.

16. Raman-Induced Kerr Effect Studies

(U.S. Army Research Office)

R. W. Hellwarth, D. Heiman, G. Martin and C. Harper

Objective Summary: To extend and exhibit spectroscopic applications of the Raman-induced Kerr effect (RIKE), which was conceived [1,2], and recently demonstrated in this laboratory.

Approach Summary: To use tunable lasers to observe RIKE spectra in various media, and to make theoretical estimates of these and other spectra.

Progress: A repetitively pulsed, Q-switched, and frequency-doubled Nd: YAG laser-and-amplifier was constructed to serve as pump source for tunable dye lasers. Tunable dye lasers were constructed. Preliminary experiments were performed. The theory of RIKE in plasma was completed [4].

References/Publications:

1. R. W. Hellwarth, "Third-Order Optical Susceptibilities of Liquids and Solids," (Pergamon Press, Oxford, to be published).

2. R. W. Hellwarth, "Raman-Induced Kerr Effect, A Nonlinear Spectroscopic Tool," in Proc. of II International Conference on Interaction of Electrons with Strong Electromagnetic Field, Budapest, 1975.

3. D. Heiman, R. Hellwarth, M. Levenson, and G. Martin, "Raman-Induced Kerr Effect," Phys. Rev. Lett. 36, 189 (1976).

4. R. W. Hellwarth, "Nonlinear Optical Effects for Plasma Diagnostics," Appl. Phys. 11, 147 (1976).

17. Infrared Microscopy Employing Nonlinear Optical Techniques

(The National Science Foundation)

R. W. Hellwarth, P. Christensen, and S. Jensen

Objective Summary: To be able to see and study microstructure of materials that is invisible to, or difficult to examine by, conventional microscopes.

Approach Summary: Our approach is to generate optical images, for magnification and viewing, using the inhomogeneities in the nonlinear refractive indices of a material.

Progress: The contract was awarded in November 1975 for research intended to expand the preliminary observations made with a novel nonlinear optical microscope and reported in references [1] and [2].

During this period we assembled a ruby laser to use as a nonlinear microscope illuminator, we completed the theory of a new nonlinear effect which yields microscopic images of nonlinear index variations in media of any symmetry [3], and achieved the first experimental verification of this effect by observing the time-reversed waves that it can produce.

References/Publications:

1. R. Hellwarth and P. Christensen, "Nonlinear Optical Microscope Examination of Structure in Polycrystalline ZnSe," Optics Communications 12, 318 (1974).

2. R. Hellwarth and P. Christensen, "Nonlinear Optical Microscope Using Second Harmonic Generation," Appl. Optics 14, 247 (1975).

3. R. W. Hellwarth, "Generation of Time-Reversed Wave Fronts by Nonlinear Refraction," J. Opt. Soc. Am. 67, 1 (1977).

18. Characterization of Self-Focusing Mechanisms in Laser Materials

(Lawrence Livermore Laboratory)

R. W. Hellwarth, J. Cherlow, and D. Heiman

Objective Summary: To determine certain parameters relevant to predicting beam distortions in high-energy laser-pulse amplifier chains.

Approach/Progress: We are pursuing theoretical and experimental studies to determine and predict the nonlinear refractive indices of laser materials. In this period, nonlinear indices, Pockels' coefficients, and elasto-optic coefficients were measured for a wide spectrum of glasses [1]. A new triple-pass Fabry-Perot interferometer facility was assembled for studying low frequency excitations.

Publications:

1. R. W. Hellwarth and D. Heiman, "Characterization of Self-Focusing Mechanisms in Laser Materials," Progress Report, Lawrence Livermore Laboratory, subcontract 7509105, October 1976; and to be published.

2. J. M. Cherlow, T. T. Yang, and R. W. Hellwarth, "Nonlinear Optical Susceptibilities of Solvents," IEEE Journ. Quant. Elect. 12, 644 (1976).

19. Studies of Pyroelectricity in Extremely Thin Samples for Improved High Speed Infrared Detectors

(The U.S. Army Research Office)

M. Simhouy, M. Bass, and E. Tenescu

Objective Summary: The objectives of this program are to understand the phenomenon of pyroelectricity in extremely thin samples and to identify means to prepare long lived high speed infrared detectors.

Approach Summary: The approach is to examine new materials, electrode configurations and poling techniques to obtain maximum signal with minimum rise time. The detectors will be tested using a pulsed CO_2 TEA laser.

Progress: A new means for stacking ultrathin detector elements to add

their electrical outputs with minimum additional capacitance has been developed. Studies of PLZT pyroelectric devices have been initiated.

20. Flexible Waveguides for Infrared Energy Transmission

(The National Science Foundation)

E. Garmire, M. Bass and T. McMahon

Objective Summary: We are developing a flexible waveguide for use at 10.6 μm as a convenient means of delivering power from a CO_2 laser to a target in such applications as welding and surgery.

Approach Summary: In view of the linear polarization available from CO_2 lasers we have confined our waveguide designs to those of rectangular cross-sections with metallic walls. Our analysis of waveguide losses treats the metal walls as imperfect conductors with a complex conductivity. Furthermore, in arriving at the overall dimensions of our present designs, we have considered the balance that must be maintained between inherent straight guide losses and additional losses brought about by bending the waveguides.

Progress:

1. Transmission of 200 W with 80% transmissivity has been demonstrated in a FIT waveguide having aluminum walls. The sample was 1.2 m long and contained a 90° bend during this test. The input light was focused into the guide with a cylindrical lens.

2. Studies of multimode propagation in FIT waveguides were initiated using a rigid guide with nearly perfect walls. These studies were begun using both HeNe and CO_2 lasers. Theoretical analyses are also in progress.

3. Twist losses were measured. A 90° twist over 80 cm introduces only 15% additional loss. In addition, the twisted waveguide was demonstrated to be an excellent infrared polarization rotator.

Publications:

1. E. Garmire, T. McMahon, M. Bass, "Los Loss Optical Transmission Through Bent Hollow Metal Waveguides," submitted to Applied Physics Letters.

2. T. McMahon, E. Garmire, M. Bass, "Flexible Infrared Transmissive Waveguides at 10.6 μm," Abstract, Meeting of the Optical Society of America, October 1976, J. Opt. Soc. Am. 66, 1102 (1977).

21. IR Molecular Lasers Pumped by Electronic-Vibrational Energy Transfer

(The Army Research Office)

C. Wittig, C. P. Christensen, A. Hariri and H. Reisler

Objective Summary: The objectives of this research are two-fold. First, we have as a goal the development of IR molecular lasers that are excited by electronic to vibrational ($E \rightarrow V$) energy transfer. Second, we are engaged in a study of the fundamental processes involved in $E \rightarrow V$ energy transfer.

Approach Summary: The approach is experimental. Laser experiments are performed using flash photolysis excitation in order to produce electronically excited Br atoms in the $4^2 P_{1/2}$ state. These atoms, hereafter referred to as Br^*, then excite small molecules, via $E \rightarrow V$ transfer, in a mode selective manner. The molecules then undergo stimulated emission. Diagnostic experiments are of the laser induced fluorescence type. A dye laser is used to create an instantenous population of Br^* at $t = 0$. The subsequent molecular excitation via $E \rightarrow V$ transfer is monitored by the IR emission of the molecular species and/or Br^*. The time record of this fluorescence then allows a direct determination of the rates of the fundamental processes involved.

Progress: The progress to date is considerable, and is described in detail in a number of publications. Briefly, in the laser experiments, we have obtained stimulated emission from CO_2, N_2O, NO, H_2O, C_2H_2, and HCN when these species are excited by transfer from Br^* [1-3]. The wavelength range covered is 3.85 - 17 μm. These lasers are all pulsed, but we have also demonstrated cw gain in the case of CO_2. As an example of the utility of such a pumping scheme we have recently constructed a Br^* pumped CO_2 laser operating at a pressure of 14 atm. Because of the flashlamp pumping of the laser, it is straightforward to operate such a device at these high pressures, where the rotational band components overlap giving a bandwidth of 10's of cm^{-1}. In the diagnostic experiments, we have measured many relevant energy transfer rates and these data are available in preprint and reprint form [4-6].

References:

1. A. B. Petersen, C. Wittig, and S. R. Leone, Appl. Phys. Lett. 27, 305 (1975).

2. A. B. Petersen, C. Wittig, and S. R. Leone, J. Appl. Phys. 47, 1051 (1976).

3. A. B. Petersen, L.W. Braverman, and C. Wittig, J. Appl. Phys. 48, 230 (1977).

4. A. Hariri, A. B. Peteresen, and C. Wittig, J. Chem. Phys. 65, 1872 (1976).

5. A. Hariri and C. Wittig, "Electronic to Vibrational Energy Transfer from Br($4^2 P_{1/2}$) to CO_2, COS, and CS_2," J. Chem. Phys., submitted.

6. A. Hariri and C. Wittig, "Electronic to Vibrational Energy Transfer from Br ($4^2 P_{1/2}$) to H_2O and Deactivation of H_2O (001)," in preparation.

22. Basic Studies of Gas Phase E-V Energy Transfer

(American Chemical Society)

C. Wittig, J. Campbell, A. Hariri, and H. Reisler

Objective Summary: To study and understand the physics of E-V energy transfer.

Approach Summary: A pulsed dye laser is used to produce excited atoms or molecules on a time scale which is short compared to that of the subsequent kinetic processes. The time evolution of the excited species is detected by kinetic spectroscopy. The results of ab initio calculations using simple potentials are compared to experimental results.

Progress: The progress during the past year is best summarized in the following:

Abstract

In this paper, we report a study of the quenching of Br($4^2 P_{1/2}$) by CO_2, COS, and CS_2. Laser photolysis of gas samples containing Br_2 and the molecular species of interest produces Br($4^2 P_{1/2}$), and the subsequent quenching of this species results in vibrational excitation of the molecule of interest. By monitoring the time resolved IR fluorescence from Br($4^2 P_{1/2}$) and the (001) states of CO_2, COS, and CS_2, we are able to measure the quenching rate coefficients for these species as well as rate coefficients for these species as well as rate coefficients for a number of V-V, T, R processes. By comparing the intensities of the Br($4^2 P_{1/2}$) and (001) state fluorescences, we measure directly the rate coefficients for electronic to vibrational (E → V) energy transfer into the product states that contain at least one quantum of ν_3 vibration.

Publications:

1. A. Hariri, A. B. Petersen, and C. Wittig, J. Chem. Phys. 65, 1872 (1976).

2. A. Hariri and C. Wittig, "Electronic to Vibrational Energy Transfer from $Br(4^2 P_{1/2})$ to CO_2, COS, and CS_2," J. Chem. Phys., submitted.

3. A. Hariri and C. Wittig, "Electronic to Vibrational Energy Transfer from $Br(4^2 P_{1/2})$ and Deactivation of H_2O (001)," in preparation.

23. Infrared Molecular Lasers Suitable for Photochemical Applications

(The Department of Energy)

C. Wittig, J. Campbell, J. Tiee, and M. Yu

Objective Summary: This research is concerned with the development and use of molecular lasers which are suitable for doing photochemical experiments. The experiments include isotope separation, laser induced chemical reactions, and also the selective excitation of specific energy states for the purpose of studying subsequent kinetic processes.

Approach Summary: The research is experimental in nature. FIR lasers are pumped by optical pumping techniques using conventional CO_2 and HF lasers. Kinetic processes are monitored by time resolved kinetic spectroscopy using IR and dye lasers as the sources of excitation. A wide range of IR and visible detectors are used in order to monitor the kinetics of the various internal energy states of the atoms and molecules under consideration.

Progress: During the past year, we have made very respectable progress along the directions mentioned above. Several papers have been submitted for publication and several others are in preparation. Abstracts from three such representative papers are listed here, and details can be obtained from the references cited below.

Abstract

A large number of laser transitions in the 11-17 μm region have been obtained by optically pumping CF_4, NOCl, CF_3I, and NH_3 with a single, line-tunable CO_2 TEA laser. These lasers have respectable conversion efficiency, and can be scaled to high energies in a spectral region where the selective excitation of molecules is prerequisite to

performing selective photodissociation and laser induced chemistry experiments. With the observation of laser oscillation in the CF_4 Q-branch at 631 cm^{-1}, the CF_4 laser offers considerable potential as a source for the laser isotope separation of uranium via UF_6 photodissociation.

Abstract

Time resolved measurements of HF spontaneous emission, following the irradiation of SF_6/H_2 mixtures with the focused output from a CO_2 TEA laser, are reported. Our results indicate that F atoms are produced directly by the photodissociation process, and that these atoms have a recoil energy which is $\leq$ 500 cm^{-1}, and varies only slightly with the radiation intensity. Further, our results show a linear dependence of fluorescence intensity with laser energy, indicating that processes other than direct photodissociation may play a significant role in the ultimate fate of species excited by IR collisionless multiple photon absorption.

Abstract

We have obtained stimulated emission in the 16 μm region from CF_4 and NOCl with an optical pumping scheme which uses a single CO_2 TEA laser as the excitation source. Measured laser energies from CF_4 and NOCl are 4 and 3 mJ respectively, which represents an order of magnitude improvement over existing molecular lasers oscillating in this region. There appear to be no fundamental limitations to scaling these lasers to energies $\geq$ 1 J. These lasers offer considerable promise for the laser isotope separation of uranium.

Publications:

1. J. J. Tiee and C. Wittig, "CF_4 and NOCl Molecular Lasers Operating in 16 μm Region," Appl. Phys. Lett. 30, 420 (1977).

2. J. J. Tiee and C. Wittig, "Optically Pumped Molecular Lasers in the 11-17 μm Region," J. Appl. Phys., submitted.

3. A. B. Petersen, Ph.D. Thesis, U.S.C., Nov. 1976.

4. C. R. Quick, Jr., and C. Wittig, "Time Resolved HF Vibrational Fluorescence from the IR Photodissociation of SF_6/H_2 Mixtures," Chem. Phys. Lett., in press.

5. A. B. Petersen, J. Tiee, and C. Wittig, "Transient Molecular Absorptions Induced by the Absorption of CO_2 Laser Radiation," Opt. Commun. 17, 259 (1976).

24. Diagnostic Techniques for Molecular Multiple Photon Absorption

(The National Science Foundation)

C. Wittig, J. Campbell, C.R. Quick, Jr., and M.H. Yu

Objective Summary: The objectives of this research are to: (1) study the physics of collisionless multiple photon absorption (CMPA), (2) develop diagnostic techniques toward the end of applying these techniques to the study of CMPA, and (3) study and develop applications in areas of applied physics and chemistry using the CMPA excitation of molecules.

Approach Summary: The experimental approach is based on the interaction of radiation with matter. Collisionless processes are studied using one and two laser techniques. In the one laser technique, molecules are photodissociated with the output from a high energy pulsed IR laser, and the vibrationally excited products are monitored by IR kinetic spectorscopy, with discrete vibrational states monitored by thin fluorescences. In the two laser experiments, photofragments are monitored via laser induced fluorescence using a tunable dye laser. Many free radicals which are m products of CMPA have absorptions in the visible and near UV and can therefore be conveniently detected using this technique. Examples of such photofragments are C_2, CN, NH_2, CH, and NO_2. The power of the two laser techniques lies in the use of separate laser beams to excite and probe the medium with the high sensitivity of PMT detection. For example, we can obtain very respectable signals with only 1 μm Hg of parent species present in the sample chamber. For a pump laser pulse duration of 100 nsec, this situation corresponds to approximately one collision every 100 μsec, and for a pump laser duration of 500 nsec, we are clearly able to probe the unimolecular dynamics under collisionless conditions.

Progress: We have applied the one laser technique to a number of problems, and our preliminary results are summarized below:

1. By using $F + H_2 \rightarrow HF^+ + H$ as a sensitive time resolved diagnostic of CMPA, we are able to photdissociate species for which no data exist due to the difficulty of using standard analyses (NF_3, CF_4, SeF_6, ...).

2. In the case of SF_6 photodissociation, we were able to extract considerable information concerning the dynamics of $SF_6^{\neq} \rightarrow SF_5 + F$. Information about this system is available as per the references.

3. Unimolecular decay has been studied by monitoring the vibrationally excited products of decomposition. We have

applied this technique to the detection of products from the unimolecular decay of CF_3NO, C_2H_3F, C_2H_3Cl, and $C_2H_2F_2$ (1,1). We were able to estimate the initial vibrational distribution and compare this to models invoking statistical and dynamic (trajectories) arguments.

The two-laser technique is a bit more involved experimentally, and this experiment is just now nearing completion. The dye and CO_2 lasers are complete and it remains to synchronize these sources in time and space and to iron out a few difficulties in the detection dectronics.

Publications:

1. C. R. Quick, Jr., and C. Wittig, "Time Resolved HF Vibrational Fluorescence from the IR Photodissociation of SF_6/H_2 Mixtures," Chem. Phys. Lett., in press.

2. C. R. Quick, Jr., and C. Wittig, "An IR Kinetic Spectroscopy Study of CMPA," presented at the Intl. Conf. on Multiphoton Processes, Rochester, N.Y., June 1977; available in the proceedings of this meeting.

3. C. R. Quick, Jr., and C. Wittig, "Product Vibrational State Distribution from the CO_2 Laser CMPA Photodissociation of Vinyl Fluoride," in preparation.

25. Dynamic Processes in Chemically and Collisionally Pumped Lasers

(The Joint Services Electronics Program)

C. Wittig

Objective Summary: To develop and study molecular lasers which may be useful in technologically important applications. These lasers may be excited directly by a chemical reaction or by some energy transfer process following a chemical reaction. The roles of the various fundamental processes in these systems will be evaluated and the potential of these lasers as useful devices will be assessed. The laser systems under consideration have the potential for high power and efficient operation at wavelengths that are useful for many applications.

Approach Summary: The proposed research is experimental in nature. A non-equilibrium distribution of gas phase species will be prepared by optical pumping, chemical reaction, energy transfer, etc. The return to equilibrium will be monitored as per the diagnostic techniques described

below, thereby allowing the rate coefficient(s) for the process under consideration to be obtained in a straightforward manner. These diagnostics are absolutely necessary in order to monitor the fundamental processes of interest after initiation. Diagnostics are mainly resonance processes of interest after initiation. Diagnostics are mainly resonance absorption spectroscopy and laser excited fluorescence. Laser devices are usually constructed at the earliest convenience and relevant data from these devices goes into an overall appraisal of the laser system.

Progress: During this period, progress was made along two fronts. First, research was completed on the transfer of energy from HF^+ to HCN. Rate coefficients were measured for the fundamental processes that would be important to the operation of an HF/HCN chemically pumped transfer laser [1,2]. Calculations carried out in parallel with the experimental effort confirmed that long range forces are responsible for the energy exchange [1,2]. The results of this work leads us to believe that an HF/HCN transfer laser is indeed possible, but that such a device would suffer severely from fundamental constraints and would not be a serious competitor to other chemically pumped laser devices. Further research on this problem is not recommended.

At the same time, we have been in the process of redirecting the kinetics experiments toward the study of visible and UV molecular lasers [3]. Toward this end, we have made the following progress:

(1) We have singled out HgCl as our first candidate for these experiments. This species lases under electron beam excitation [4, 5] and the emission wavelengths lie in the visible portion of the spectrum. The system appears promising on the basis of a few simple considerations, but there exist no kinetic data concerning the various states involved in the general laser scheme.

(2) An N_2 pumped dye laser has been constructed, which will serve as a pump source in the laser induced fluorescence measurements. This device will be described in detail elsewhere.

(3) Several schemes for generating HgCl have been pursued (on paper) and we will begin construction of the flow apparatus shortly.

Publications/References:

1. D. Shim, "Vibrational Energy Transfer in the HF/HCN System," Ph.D. Thesis, University of Southern California, Fall 1977.

2. D. Shim and C. Wittig, manuscript in preparation.

3. C. P. Christensen, L. W. Braverman, W. H. Steier, and C. Wittig, Appl. Phys. Lett. 29, 424 (1976).

4. J. H. Parks, Appl. Phys. Lett. 31, 192 (1977).

5. In the future, it is expected that other mercury monohalides and other excitation procedures will become available, as has been the case with other excimer laser systems.

III. INFORMATION SYSTEMS

1. COMPUTERS

1.1 Design of Easily Maintainable Digital Systems

(The Joint Services Electronics Program)

J. P. Hayes, A. Goundan

Objective Summary: To develop methods for designing digital systems in which faults can be easily detected and located. To develop design techniques for cost-effective fault-tolerant systems.

Approach Summary: Various logic models are used to represent the structure and failure modes of digital systems. The use of special control circuits to improve diagnosability is considered, as well as unconventional techniques for processing test response data.

Progress:

The usual concept of fault equivalence has been extended to combinational logic modules of arbitrary complexity [1,2,3]. We have developed systematic methods for designing totally fault locatable (TFL) networks in which equivalent faults can be confined to a small portion of the network. These design methods use at most one control input line. Relationships between the path structure of a logic network and its test requirements were also obtained [4].

An investigation of check sum testing methods [7,8] was completed with the development of optimal algorithms for generating transition count test sequences [5].

Many digital system design problems involve increasing the size or number of the operands processed by system components. We have shown that systematic operand expansion algorithms exist for almost all standard design components at all complexity levels [6]. A classification method for expansion algorithms has been developed, and the properties of some basic algorithms have been studied [6].

Publications:

1. A. Goundan, "Fault Equivalence in Logic Networks," Ph.D. Dissertation, Dept. of Electrical Engineering, University of Southern California, Feb. 1978.

2. A. Goundan and J. P. Hayes, "Design of Totally Fault Locatable Logic Networks," in preparation.

3. A. Goundan and J. P. Hayes, "Identification of Equivalent Faults in Logic Networks," in preparation.

4. J. P. Hayes, "Path Complexity of Logic Networks," IEEE Trans. Computers, vol. C-27, May 1978, to appear.

5. J. P. Hayes, "Generation of Optimal Transition Count Tests," IEEE Trans. Computers, vol. C-27, pp. 36-48, Jan. 1978.

6. J. P. Hayes, "Component Expansion Techniques in Computer Design," March 1978, submitted for publication.

References:

7. J. P. Hayes, "Transition Count Testing of Combinational Logic Networks," IEEE Trans. Computers, vol. C-25, pp. 613-620, June 1976.

8. J. P. Hayes, "Check Sum Methods for Test Data Compression," Journ. of Design Automation and Fault Tolerant Computing, vol. 1, pp. 3-17, Oct. 1976.

1.2 Analysis and Design of Fault Tolerant Computer Systems

(The Air Force Office of Scientific Research)

J. P. Hayes, J. Shen, T. Sridhar

Objective Summary: To study the design of fault tolerant systems, with emphasis on their reconfiguration and recovery mechanisms. To develop efficient methods for designing and testing systems containing large numbers of microprocessors.

Approach Summary: Fault-tolerant systems are modeled by facility graphs. Dynamic methods are used to implement fault diagnosis, reconfiguration and recovery in the event of failures.

Progress:

The facility graph model introduced in [4] has been extended to include the concept to multistep recovery in distributed systems. Necessary and sufficient conditions for a system to be optimally t-step recoverable were obtained [1]. A survey of interconnection structures

for multi-microprocessor systems was carried out [2] and some properties of the n-cube interconnection structure [5] were obtained. Several problems related to the design and testing of bit-sliced microprocessors were investigated [3].

Publications:

1. J. P. Hayes and R. Yanney, "Fault Recovery in Multiprocessor Networks," Proc. 1978 Intnl. Symp. on Fault-Tolerant Computing (FTCS-8), Toulouse, France, June 1978, to appear.

2. J. Shen, "Fault-Tolerant Multi-Microcomputer Systems," Ph.D. Dissertation Proposal, University of Southern California, January 1978.

3. J. P. Hayes, "Component Expansion Techniques in Computer Design," March 1978, submitted for publication.

Other References:

4. J. P. Hayes, "A Graph Model for Fault Tolerant Computing Systems," IEEE Trans. Computers, vol. C-25, pp. 875-884, Sept. 1976.

5. M. C. Pease, "The Indirect Binary n-Cube Microprocessor Array," IEEE Trans. Computers, vol. C-26, pp. 458-473, May 1977.

1.3 Design Automation of Digital Systems

(The National Science Foundation)

M. A. Breuer, P. Argawal, H. Carter

Objective Summary: We are developing new algorithmic tools for design automation problems, such as placement and routing, by investigating the use of the concept of incremental processing.

Approach Summary: The basic concept behind incremental processing is to solve an already solved problem for a new set of data by using the previous solution and the "difference" in data between the two problems.

Progress: We have applied the concept of incremental processing to several design automation problems. In the area of simulation, the new data is the next input, and an event-directed simulator is naturally an incremental process. We have also successfully applied this concept to placement and routing problems. In the area of placement, we have

been able to achieve a significant speed up in the Steinberg placement algorithm by proper ordering the unconnected sets. We have modified the Munkres' assignment algorithm so that it can process a new problem which varies from the previous one by a change in only one row or column in the assignment matrix.

We have also developed several new procedures for routing nets on a unidirectional line. We employ a graph model, and are able to solve problems related to fix densities as well as allow new wires to "shove" aside old wires.

Publications:

1. P. Agrawal, "Routing of Printed Circuit Cards: Density Analysis and Routing Algorithms," USC-ESL-EE Report #495, June 1977.

2. M. Breuer, "Min-Cut Placement," Journal Design Automation and Fault Tolerant Computing, November 1977, pp. 343-362.

1.4 Automata, Formal Languages, and Grammar Theory

(The National Science Foundation)

R. Fleming, S. Ginsburg, R. Hoffman, G. Milles, and J. Polajnar

Objective Summary: To develop suitable models of computer devices and software languages, and to use the mathematical models to answer questions of interest to computer science.

Approach Summary: The method consists of studying various families of devices, families of languages, and forms for describing families of grammars.

Progress: During the report period, three papers [1-3] were published and three [4-6] written. The new reports concern the following: In [4], a study is made of conflic-freeness in grammar forms. Characterizations on a form are presented in order for all its interpretations of particular kinds to be conflict free. Characterizations on a form are then given in order for it to have a strongly equivalent (of particular kinds) conflict-free form. In [5], strict interpretations of grammar forms are studied with respect to parsing, ambiguity, and decidability for intersection and containmemt. In [6], subset-strict interpretations of grammar forms are considered. Subsets of terminals of a grammar G for which subset-strict interpretation inherit structural properties of G related to unambiguity are characterized. These characterizations provide a

unified means of: (i) studying the effect of markers or puctuation upon unambiguity, and (ii) producing large classes of unambiguous languages and grammars.

Publications:

1. S. Ginsburg and H. Maurer, "On Quasi-Interpretations of Grammar Forms," Computing, Vol. 19, (1977), pp. 141-147.

2. A. B. Cremers, S. Ginsburg, and E. H. Spanier, "The Structure of Context-Free Grammatical Families," Journal of Computer and System Sciences, Vol. 15, (1977), pp. 262-279.

3. S. Ginsburg and E. Rounds, "Dynamic Syntax Specification Using Grammar Forms," IEEE Transactions on Software Engineering, Vol. SE-4, (1978), pp. 44-45.

4. S. Ginsburg and D. Wood, "Simple Precidence Relations in Grammar Forms".

5. S. Ginsburg, B. Leong, O. Mayer, and D. Wotschke, "Strict Interpretations of Grammar Forms".

6. G. Miles, "Subset Strict Interpretations and Unambiguity," Ph.D. Dissertation.

1.5 A Programming Language for the Design of Highly Reliable Concurrent Processing Systems

(The National Science Foundation)

P. Brinch-Hansen and W. Franzen

Objective Summary: To adapt the programming language Concurrent Pascal to the PDP 11/55 mini-computer at USC.

Approach Summary: The complexity and unreliability of present computer programs seriously limits our ability to use computer technology for industrial process control, communication networks, and terminal systems. These are all real-time applications in which a computer must perform several activities simultaneously.

The investigator has developed the first secure programming language for real-time applications. The new language Concurrent Pascal makes it possible to build a large concurrent program out of small modules that can be programmed and tested one at a time. Some of these modules are

concurrent processes that are executed simultaneously; others are monitors that synchronize processes and transmit data between them.

When concurrent programs are written inexisting programming languages, the slightest mistake can cause obscure programming errors that are impossible to find by testing. This can make a real-time computer system extremely unreliable. Most of these obscure programming errors are detected automatically by the Concurrent Pascal compiler before a concurrent program is even tested.

Progress: A new system kernel has been written in a readable assembly language. A compiler for this language is now being implemented.

1.6 Verification of Operating Systems Written in Concurrent Pascal

(The National Science Foundation)

P. Brinch-Hansen and J. Staunstrup

Objective Summary: To develop verification rules for the programming language Concurrent Pascal and verify parts of the Solo operating system written in the language.

Approach Summary: It is now possible to prove mathematically that small computer programs are correct. This verification can either be done manually or semi-automatically on a computer. Formal verification is still limited to programs of about one page or less.

Since a Concurrent Pascal program can be divided into modules of one page each, there is reason to believe that the verification techniques for sequential programs can be extended to concurrent programs as well.

The verification techniques developed should be useful to both programmers and theoreticians.

Progress: We have invented a new specification language for concurrent programs and have used it to specify the properties of major parts of the solo operating system.

Publications:

1. P. Brinch-Hansen and J. Staunstrup, "Specification and Implementation of Mutual Exclusion," to appear in IEEE Transactions on Software Engineering.

2. J. Staunstrup, "Specification, Verification, and Implementation of Concurrent Programs," Ph.D. dissertation, Computer Science Department, University of Southern California, Los Angeles, Ca., May 1978.

1.7 Modular Design of Operating Systems Using Abstract Data Types

(The Army Research Office)

P. Brinch-Hansen and J. Fellows

Objective Summary: To use the programming language Concurrent Pascal to design a multiterminal operating system for the PDP 11/55 computer. The main goal will be to establish standards for the specification, design, and documentation of nontrivial concurrent programs.

Approach Summary: The new programming language Concurrent Pascal has been used to write three model operating systems for the PDP 11/55 minicomputer:

A single-user operating system, called Solo, supports the development of Pascal and Concurrent Pascal programs on the minicomputer using a disk filing system and a single terminal. Solo is the first major example of a hierarchical concurrent program made of processes and monitors.

A job-stream system compiles and executes a stream of short Pascal programs input from a card reader and output on a line printer. Input, execution, and output take place simultaneously using large buffers stored on disk.

A real-time scheduler controls industrial applications in which a fixed number of concurrent tasks are carried out periodically with frequencies chosen by an operator.

These concurrent programs were developed at a fraction of the cost of writing them in machine language and have been used daily for more than a year without program failure.

Progress: The major decisions concerning the system functions and the structure of the filing system have been made. Parts of the system are now being programmed.

Publications:

1. P. Brinch-Hansen, "Reproducible Testing of Monitors," submitted for publication.

1.8 Design of Programming Languages and Machine Architectures for Reliable Microprocessor Networks

(The Office of Naval Research, following project initiation under the Joint Services Electronics Program)

P. Brinch-Hansen and C. Hayden

Objective Summary: Microprocessor technology has now reduced hardware costs to the point where all future computer applications soon will be dominated by software costs. Based on the software experience with larger computer during the last two decades it is safe to predict that a comparable reduction of programming costs only can be achieved by using machine-independent programming languages which hide the details of microprocessor components and by designing microprocessor architectures which make the compilation and execution of these languages straightforward and efficient.

Since the hardware technology makes multiprocessing very economic, one should look for concurrent programming languages which support simultaneous execution of many subtasks. The programming languages and architectures of present microprocessors seem very inadequate for the job (being more than a decade behind the state of the art).

We feel that some of the necessary programming methodology already exists on some minicomputers and can be transferred to microprocessor networks if the architecture of microprocessors is designed to support the best existing programming languages. Of particular interest are the languages Pascal and Concurrent Pascal which already have reduced the software costs of some compilers and operating systems for minicomputers by an order of magnitude and have made them more reliable than the hardware on which they run.

Approach Summary:

(1) Review existing microprocessors and networks of them from the point of view of making language implementation and concurrent programming simple.

(2) Make the programming languages Pascal and Concurrent Pascal available on single microprocessors and microprocessor networks.

(3) Write and test real-time programs in Concurrent Pascal on a PDP 11/55 minicomputer and transfer them to a network of commercially available microprocessors.

(4) Design and build new microprocessor architectures and networks of them that will support a concurrent programming language directly.

Progress: We have invented a new language concept, called Distributed Processes, for microprocessor networks and have proposed a multiprocessor architecture for the programming language Concurrent Pascal. In addition, we have compared the efficiency of existing 16-bit microcomputers.

Publications:

1. P. Brinch-Hansen, "Network - A Multiprocessor Program," IEEE Transactions on Software Engineering, May 1978.

2. P. Brinch-Hansen, "Distributed Processes - A Concurrent Programming Concept," to appear in Communications of the ACM.

3. P. Brinch-Hansen and C. Hayden, "Microcomputer Comparison," submitted to the IEEE CompSac 78 Conference.

4. P. Brinch-Hansen, "Multiprocessor Architectures for Concurrent Programs," submitted to the ACM 78 Conference.

1.9 Checkpoint Recovery in Computer Systems

(The Joint Services Electronics Program)

D. L. Russell

Objective Summary: Investigate checkpoint recovery in single-processor and distributed systems. Develop flexible recovery methodologies that minimize overhead.

Approach Summary: Recent work by Chandy will be extended to the case of multiple-part data bases. Language approaches to process backup will be investigated.

Background: When a data base system or an operating system is in operation for a long period of time, it is almost inevitable that errors occur. These errors may be either of hardware or software origin. When these errors are found, it must be possible to return to a state of execution that existed before the error occurred. This is normally done by taking a checkpoint of the system data at regular intervals. When a system error is detected, the system can be restored to the most recent checkpoint. If the error is detected immediately after its occurrence, a "latency difference" (time of detection-time of occurrence) of zero is said to occur. If the latency difference is positive, then the error may have occurred before the most recent checkpoint was taken. In this case,

restoring the system to the most recent checkpoint will not allow the system to recover from the error; it is necessary to restore the system to an even earlier checkpointed state.

Chandy et al. [3] and Young [4] both discuss the case of immediate detection (i.e., zero latency difference) and find optimum checkpoint intervals when restoration to the most recent checkpoint is successful. Preliminary results extending this work to latency distributions for systems where detection is not immediate have been obtained by Russell and Babu [5]. Similar work has been reported by Gelenbe [6]. Other authors have found optimal strategies for the placement of checkpoints under different assumptions [7,8,9]. Lohman and Muckstadt have shown that many checkpointing and data base reorganization schemes have similar formulations as inventory control problems [10].

Progress: Optimum checkpoint intervals for systems with non-zero error latencies and where errors may be detected during checkpoint or recovery have been obtained [1], extending the preliminary results of [5]. Delayed detection of errors drastically increases the optimum checkpoint interval and the run-time overhead. In particular, when error latencies are very large, a "repeated retrial" approach to recovery becomes impractical and better diagnosis is necessary. It has proved very difficult to obtain closed form solutions, particularly with more realistic extensions of the model of [1,5]. Alternate models have therefore been examined with the hope of realizing more tractable analyses. Some success has been obtained with a language-directed model of state restoration and backup [2]. The model describes recovery in multiprogramming systems; the recovery activity undergone by the system is shown to be directly related to the system interconnections and internal process structures.

Publications:

1. D. L. Russell and K. R. Babu, "Optimum Checkpoint Intervals with Delayed Error Detection," in preparation.

2. D. L. Russell, "Process Backup in Producer-Consumer Systems," Proc. Sixth Symposium on Operating Systems Principles, Purdue, November 16-18, 1977, pp. 151-157.

Other References:

3. K. M. Chandy, J. C. Browne, C. W. Dissly and W. R. Uhrig, "Analytic Models for Rollback and Recovery Strategies in Data Base Systems," IEEE Trans. on Software Engineering SE-1 (March 1975), 100-110.

4. J. W. Young, "A First-Order Approximation to the Optimum Checkpoint Interval," Comm. ACM 17, 9 (Sept. 1974), 530-531.

5. D. L. Russell and K. R. Babu, "Optimum Inter-Checkpoint Intervals," (unpublished notes), August 1976.

6. E. Gelenbe, "A Model of Rollback Recovery with Multiple Checkpoints," Proc. Second International Conference on Software Engineering, San Francisco, Oct. 13-15, 1976, pp. 251-255.

7. K. M. Chandy and C. V. Ramamoorthy, "Rollback and Recovery Strategies for Computer Programs," IEEE Trans. Comput. C-21, 6 (June 1972), 546-556.

8. K. M. Chandy, "A Survey of Analytic Models of Rollback and Recovery Strategies," Computer 8, 5 (May 1975), 40-47.

9. W. Warren-Angelucci, "The Optimal Placement of Dynamic Recovery Checkpoints in Recoverable Computer Systems," Ph.D. Thesis, TR 126, Digital Systems Laboratory, Stanford University, December 1976.

10. G. M. Lohman and J. A. Muckstadt, "Optimal Policy for Batch Operations Backup, Checkpointing, Reorganization, and Updating," Proc. International Conference on the Management of Data, Toronto, Ontario, Canada, Aug. 3-5, 1977.

1.10 Enhancement of Computing System Reliability through Fault-Tolerant Programming and Multiprocessor System Architecture

(The Joint Services Electronics Program)

K. H. Kim

Objective Summary: The objective of this project is to find effective methods of using program redundancy for the purpose of tolerating both residual program errors and hardware faults in real-time applications. It specifically aims at the development of computing system architectures capable of efficiently executing programs containing redundancy and at the development of software tools aiding structured incorporation of redundancy into a program.

Approach Summary: The basic approach of this project to the efficient execution of programs containing redundancy, here called fault-tolerant

programs, is to maximally overlap the main stream computation with the redundant computation (related to error detection and recovery). Exploitation of this parallelism can be made transparent to the programmer and automatically handled by a multiprocessor system. An approach adopted in this project to the efficient design of fault-tolerant programs is to develop and use high-level language constructs which simplify structured incorporation of program redundancy into a program.

Progress:

1. Among the results obtained during the last reporting period were (1) a parallel (dual processor) system structure containing a novel memory organization, termed a duplex memory, for efficient execution of fault-tolerant programs, and (2) the evaluation of the performance gain by a parallel system over a sequential system (that performs the main-stream computation and the validation in non-overlapped mode). These results were slightly refined and presented during the period covered in this report [1,2].

2. An application of the parallel execution approach to the systems which establish checkpoints at regular intervals in a manner transparent to the program designer, was studied. This study produced a new rollback and retry scheme, termed a two-level rollback, which establishes two types of checkpoints for reduction of both time overhead and rollback distance. The scheme establishes one type of checkpoints with high frequency but with negligible time overhead by utilizing the parallel execution concept and establishes the other type of checkpoints less frequently (and thus with less time overhead) than checkpoints in existing systems. It thus leads to both a reduced rollback distance and a reduced time overhead. Sometimes a multi-step rollback, i.e., backing up past the most recent checkpoint, is executed to recover from a long latent error. An analytic model of this scheme was also developed to facilitate the determination of an optimal checkpoint interval and an optimal multi-step rollback strategy. These results are summarized in [3].

3. Efficient rollback and retry in real-time multiprogrammed systems was studied. This study aimed at optimal checkpointing, i.e., minimization of the time overhead incurred by checkpoint establishment, under the constraint that once an error is detected, the subsequent rollback and retry must be done within a given time limit. We attempted to extend the approach developed by Chandy and Ramamoorthy [IEEE Trans. on Computers, June 1972] for uniprogrammed situations so that it may be applicable to multiprogrammed situations. This required the development of a new inter-process communication protocol. It was then learned that truly optimal checkpointing in general multiprogrammed situations is not feasible. Various classes of systems in which optimal checkpointing becomes feasible, have been identified. These results will be summarized in [4].

4. A survey of recent developments in the area of fault-tolerant software was carried out and its results are summarized in [5].

Publications:

1. K. H. Kim and C. V. Ramamoorthy, "Structure of an Efficient Duplex Memory for Processing Fault-Tolerant Programs," Proc. the 5th Annual Symposium on Computer Architecture, April 1978, pp. 131-138.

2. K. H. Kim and M. J. Jenson, "Performance Evaluation of a Parallel System Processing Fault-Tolerant Program," Proc. 1977 International Conference on Parallel Processing, August 1977, pp. 131-138.

3. K. H. Kim, "A Two-Level Rollback Scheme and Its Optimization," to be submitted for publication.

4. N. Daouk, "Error Recovery Among Communicating Processes," Ph.D. dissertation, in preparation.

5. K. H. Kim, D. L. Russell, and C. V. Ramamoorthy, "Software Fault Tolerance Through Program Redundancy," to be submitted for publication.

1.11 Methodologies and Tools for Developing Robust FTSC Software

(The Air Force Systems Command - SAMSO)

K. H. Kim

Objective Summary: The objectives of this project are (1) to identify good structures and design strategies for the software that controls recovery from hardware faults and (2) to find effective ways of using design/program redundancy in development and maintenance of real-time software.

Approach Summary: As a means of identifying problem areas and experimenting with various potential solutions, the design of a recovery program of the FTSC (Fault-Tolerant Spaceborne Computer, developed by U.S. Air Force - SAMSO) was chosen. A recovery program is entered after hardwired fault detectors report detection of faults and is responsible for recovering an operational system configuration and resurrecting the interrupted computation. A recovery program was considered to be an

ideal subject of a fault-tolerant programming experiment due to its relatively small program size and unusual input, i.e., a faulty machine whose behavior is difficult to analyze. The experimental design was organized as a four-step process: (1) modeling of the FTSC, (2) identification of feasible recovery strategies, (3) specification of a recovery program in PASCAL, and (4) coding of selected sections of a recovery program in an assembly language.

Progress:

1. Several basic design rules that have been found to be useful in obtaining an easily understandable recovery program of the FTSC but may also be useful in development of recovery programs of other computers, were obtained. A systematic recovery strategy has resulted from the application of those rules and has been incorporated in an FTSC recovery program. Recognizing the difficulty of obtaining a single perfect recovery strategy, a provision was made in the recovery program for using an alternate recovery strategy when the primary strategy is not effective and for determining the acceptability of the results of a strategy. These results are summarized in [1].

2. The recovery block is a language construct developed by Horning et al. [Lecture Notes in Computer Science, vol. 16, Springer-Verlag] to support structured incorporation of program redundancy. In order to facilitate the study on the use of design/program redundancy, often called fault-tolerant programming, a software that translates a program written in PASCAL augmented with the recovery block into an equivalent program in ordinary PASCAL, has been developed. The translator itself is written in PASCAL and documented in [2].

3. Rollback and retry in distributed systems (or systems of cooperating parallel processes) was studied. Each of the cooperating processes may be capable of error detection, rollback, and retry, and the recovery points of the processes must be properly coordinated to prevent a disastrous avalanche of process rollbacks. In contrast to the previously studied approaches that require the program designer to coordinate the recovery point specifications of processes, an approach of relieving the program designer of that burden was developed. The new approach relies upon an intelligent processor system (that runs processes) capable of establishing and discarding recovery points of cooperating processes in a well-coordinated manner such that (1) a process never makes two consecutive rollbacks without making a retry between the two, and (2) every process rollback becomes a minimum-distance rollback. Three basic rules of reducing storage and time overhead in such a processor system were also developed. These results were reported in [3,4].

Publications:

1. K. H. Kim, H. Hecht, J. Huang, and M. Naghibzadeh, "Structured Design of a Fault-Tolerant Recovery Program of the FTSC," to be presented at COMPSAC 78, Nov. 1970.

2. K. H. Kim and T. Arshi, "A Translator of PASCAL Augmented with Recovery Block," in preparation.

3. K. H. Kim, "Programmer-Transparent Coordination of Recovering Parallel Processes," Tech. Memo. PETP-5, Electronics Sciences Lab., USC, March 1978. (Also IEEE Computer Society Repository R78-59).

4. K. H. Kim, "Programmer-Transparent Coordination of Recovering Parallel Processes: Philosophy and Rules for Efficient Implementation," submitted to IEEE Trans. on Software Engineering. (A short version to be presented at the 1978 Int'l Conf. on Parallel Processing).

1.12 Software Reliability and the Application of Axiomatic Data Structure Specifications

(The Joint Services Electronics Program and
The National Science Foundation)

J. Guttag and E. Horowitz

Objective Summary: To investigate the application of the axiomatic specification of data structures to enhance software reliability. We hope to demonstrate that formal program verification techniques can be effectively combined with testing procedures in the development of reliable software.

Approach Summary: Our approach is to extend in a practical direction some recent work on the axiomatic specification of abstract data types. The emphasis will be on the implementation and application of techniques that have been described and discussed but never tested.

Progress: A primary goal was to study the mathematical foundations of this formalism with respect to determining completeness and consistency. This work was begun earlier and was further expanded during the grant period in (4). Based upon this work a completeness "checker" for algebraic axioms has been implemented by D. Baker, a graduate student supported by the current grant. This piece of software will be used in conjunction with the Data Type Verification System (DTVS) which we are building jointly with Drs. Ralph London and David Musser at USC's Information

Sciences Institute (ISI).

Another research goal was to investigate how one might use an algebraic axiomatization of a data type to participate in the verification of its implementation. This was the major thrust of (2). In that work it is shown how to take (i) an algebraically axiomatized data type; (ii) an implementation of the data type; and (iii) an equality interpretation, and to use these to construct a proof of the validity of the implementation. The proof proceeds as a series of substitutions. Though the redunctions can become tedious they are simple in nature and are readily susceptible to machine aids.

This led us to an automated data type verification system which we have now implemented in INTERLISP on a PDP/10. This system serves dual purposes: testing and verification. The input to DTVS is a collection of algebraically axiomatized data types and an arbitrary LISP-like program which makes use of any subset of these data types. DTVS will permit the program to be executed despite the fact that these data types have not been implemented. An implementation is automatically devised which uses the axioms as the semantics of the operations. Though the automatic implementation may be inefficient, its virtue is that testing of a very high level design of a software system is possible without the effort of implementing possibly complex data types. Once the testing phase has been completed an implementation of one or more data types can be supplied to DTVS. The system will then automatically generate the verification conditions which need to be established for correctness. It will then attempt to prove each one in turn, using the reduction process explained in (2).

The development of DTVS and its underlying theory led to other questions of more practical significance. One such question was how to specify error conditions. This was dealt with in (3). A final area of investigation was the question of how to combine the use of algebraic axioms with the use of Floyd-Hoare like specifications of programs.

Publications:

1. J. V. Guttag, "Abstract Data Types and the Development of Data Structures," Communications of the ACM (June 1977).

2. J. V. Guttag, E. Horowitz, and D. R. Musser, "Abstract Data Types and Software Validation," (to appear Communications of the ACM).

3. J. V. Guttag, E. Horowitz, and D. R. Musser, "Some Extensions to Algebraic Axioms," Proceedings of an ACM Conference on Language Design for Reliable Software (March 1977).

4. J. V. Guttag and J. J. Horning, "The Algebraic Specification of Abstract Data Types," (to appear Acta Informatica).

2. COMMUNICATIONS AND SIGNAL PROCESSING

2.1 Development of Optimal Coherent Receivers and Their Performance for QPSK, Staggered QPSK and MSK Signal Foremats

(USC Sponsored)

C. L. Weber

Objective Summary: The objective of this research is to determine receiver block diagrams of optimal coherent receivers for QPSK, staggered QPSK (SQPSK), and MSK signal foremats based on different optimality criteria. The performance of these receivers is then determined so that a system comparison can be made.

Approach Summary: The first approach is to use the same guidelines which were used to develop optimal coherent receivers for the PSK signal foremat, and extend the results to QPSK, SQPSK, and MSK. This approach leads to the 4th power loop and the 4-phase Costas loops.

The criterion of forcing all available signal power to be despread and employed to generate the track error signal results in the "Demod-Remod" tracking loop concept.

A final criterion is to employ the general theory of nonlinear estimation theory, from which better performance is expected than those previously considered.

Progress: A demod-remod coherent tracking loop for QPSK, and SQPSK has been analyzed and its performance determined. This type receiver is very attractive since all of the available signal power is developed and used to generate the tracking loop error signal. All system parameters pertinent to system performance have been enumerated. The effects of the IF as well as the arm filters on the statistics of the noise and QPSK signal have been determined. The results of performance of computations have been evaluated.

Publications:

1. C. L. Weber, "Design of a Quadriphase Receiver Operation in a Burst Data SSTDMA Environment," AIAA 6th Communication Satellite Systems Conference, Montreal, Canada.

2. C. L. Weber, "Candidate Receivers for Unbalanced QPSK," Proceedings of the International Telemetry Conference, Vol. XII, pp. 455-464.

3. C. L. Weber, Satellite Communications Future Systems, Chapters entitled, "Design of a Demod/Remod Receiver Operation on Burst QPSK Data," American Institute of Aeronautics and Astronautics, New York, 1977.

4. C. L. Weber and W. K. Alem, "Demod-Remod Coherent Tracking Receiver for QPSK and SQPSK," IEEE Transactions on Communications (submitted).

2.2 Network Synchronization and Digital Signal Processing in Advanced Communication Receivers

(USC Sponsored)

W. C. Lindsey

Objective Summary: To develop models for studying the problem of network synchronization and perform analysis to study performance of such networks. To develop math models/computer simulations of digitally implemented control algorithms for advanced communication receivers. The research output is directly applicable to defining satellite communication systems architecture and their interconnections to form networks.

Approach Summary: The statistical behavior of a set of interconnected communication nodes to be mutually synchronized in a timing network can be modeled mathematically. For various configurations these models will be analyzed and performance developed so that engineering tradeoffs can be made. Design and development of optimal signal processing algorithms required in the implementation of an all digital communications receiver are to be postulated and optimized.

Progress:

Mathematical models for studying mutual and/or master slave synchronization of N phase controlled oscillators connected to form a Time Transfer Network ([1], [2], and [3]), have been developed. Network models are presented in the form of nonlinear, stochastic, integro-differential matrix equations in which network interconnection matrices are manifested. Using these matrices the topological structure of the time transfer network is manifested from which graph theory can be applied to study connectivity, reliability and survivability. Two equivalent mathematical models for the network have been developed, viz., (1) the Total Phase Model in which the total phases of the output of nodal oscillators characterize the dynamic behavior of the network, and

(2) the Phase Error Model which uses the nodal phase errors as network error variables.

Each model is useful in characterizing performance measures of a Time Transfer Network prior to and after the network of oscillators (clocks) begins to function in unison as a single unit. The phase error model is more useful when one wants to characterize nodal performance. Some results on steady state network frequency are presented along with a method for compensation of mean "path delay" components.

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2.3 Image Understanding Research

(The Advanced Research Projects Agency, monitored by The Air Force Systems Command, ASD/WPAFB)

H. C. Andrews (Director), N. E. Nahi, R. Nevatia, W. K. Pratt, K. E. Price, A. A. Sawchuk, and T. C. Strand

Objective Summary: Research in the USC Image Processing Institute (USCIPI) is conducted in three areas: Image Understanding Projects, Image Processing Projects, and Smart Sensor Projects. The details of progress and results are reported to ARPA semiannually, the most recently being USCIPI Report 800, March 31, 1978. These and other USCIPI reports should be available through the DDC or NTIS. The following project area summaries are taken from the recent report (as well as the list of publications).

Progress:

A. Image Understanding Projects

The projects reported herein describe progress on a variety of fronts in our image understanding efforts. Segment matching is discussed

in some detail followed by symbolic matching of images with substantial changes in orientation. Results in both these areas are encouraging as the reader will see in reading these contributions. A technique is next presented for locating structures in aerial images followed by the presentation of a new edge fitting algorithm. A quantitative analysis tool is developed to more accurately define what and where an edge is. These contributions are followed by a discussion on stochastic texture analysis in which some previously accepted perceptual moment assumptions are challenged. Finally the section closes with a discussion on singular value decomposition image feature extraction as a useful tool for obtaining features in an image understanding scenario.

B. Image Processing Projects

The image processing projects represent a broad variety of research topics in which more fundamental signal processing principles are utilized. The first contribution presents a new way of generating binary phase holograms via the digital computer. Such holograms are then recorded on hardcopy devices (see Section 5) and after film development are played back in the Institute optical laboratories. The second contribution in this section presents rather encouraging results on the blind deconvolution process of a posteriori restoration. This project is currently coming to fuition with quite improved results for arbitrary space invariant distortions. A radar imaging task is next presented in which multi-frequency radar returns are coherently processed to form images of aircraft mounted on a turntable. Previous reports included the analysis associated with this theory and this report presents the images resulting from such processing. This section closes with a brief summary of perceptual model color image coding. Results are presented in which 24:1, 48:1, and 96:1 compressions are obtained with good visual color quality maintained.

C. Smart Sensor Projects

This section reports on the successes of the smart sensor CCD chip development under contract at the Hughes Research Laboratories. Earlier reports presented descriptions of two circuits under development, the Sobel circuit and Circuit II which included considerably more complex processes. Both circuits have been demonstrated to produce proper processing results. These past six months have seen the implementation of Circuit II in real time TV (2 MHz reduced horizontal bandwidth) with successful results. It is anticipated that minor redesign will achieve the nominal 10 MHz real time TV bandwidth. In addition, progress is being made on other fronts. New circuit designs are in process and a two-year plan is presented in the last contribution to this section.

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2. J. Bescos and T. C. Strand, "Optical Pseudocolor Encoding of Spatial Frequency Information," to appear in Applied Optics, August 15, 1978.

3. C. C. Chen and H. C. Andrews, "Numeric-Structural Models of Imaging Systems," submitted for publication in IEEE Transactions on Acoustics, Speech, and Signal Processing.

4. C. C. Chen and W. Frei, "Fast Boundary Detection: A Generalization and a New Algorithm," IEEE Transactions on Computers, Vol. C-26, October 1977.

5. G. B. Coleman and H. C. Andrews, "Image Segmentation by Clustering," submitted for publication in IEEE Proceedings.

6. H. S. Hou and H. C. Andrews, "Cubic Splines for Image Interpolation and Digital Filtering," submitted for publication in IEEE Transactions on Acoustics, Speech, and Signal Processing.

7. D. G. McCaughey and H. C. Andrews, "Image Approximation by Variable Knot Bicubic Splines," accepted for publication in IEEE Transactions on Computers.

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9. F. Naderi and A. A. Sawchuk, "Estimation of Images Degraded by Film-Grain Noise," to appear in Applied Optics, Vol. 17, 1978.

10. F. Naderi and A. A. Sawchuk, "Detection of Low Contrast Images in Film-Grain Noise," to appear in Applied Optics, Vol. 17, 1978.

11. R. Nevatia and K. Price, "Locating Structures in Aerial Images," Proceedings of ARPA Image Understanding Workshop, Palo Alto, October 1977.

12. R. Nevatia and K. Price, "A Color Edge Detector and Its Use in Scene Segmentation," IEEE Transactions on Systems, Man, and Cybernetics, November 1977, pp. 820-826.

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17. M. J. Peyrovian and A. A. Sawchuk, "Discrete Representation of Image Degradation Using Monospline Quadrature Formulae," submitted to IEEE Transactions on Acoustics, Speech, and Signal Processing.

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21. T. C. Strand and A. F. Turner, "Hybrid Optical-Electronic Processing Applied to Chest Radiographs," to appear in Journal of Applied Photographic Engineering.

2.4 Image Processing Error Criterion

(U.S. Air Force - AFSC/ASD)

H. C. Andrews

Objective Summary: The purpose of this project is to develop computer methods for Cosine transform coding algorithms which are currently being implemented to compress image data in the nonlinear perceptual space, utilizing the human visual perceptual system in defining quantitative image quality measures for digital image bandwidth compression.

Approach Summary: The method consists of utilizing a nonlinear color model of the human perceptual system to transform imagery to a nonlinear space which is both spatially and perceptually more appropriate for efficient image coding. Rate distortion measures will be utilized in evaluating the efficiency of this approach to the source coding of color imagery.

Progress: Simple mathematical models are developed from the physiological and psychophysical traits of the human visual system. Expressions for the statistical characterization of these models are obtained. When used as a preprocessor, the models are shown to produce images which are statistically compatible with the underlying assumptions necessary to solve the parametric rate distortion equations. The derived power spectrum equations were used to code black and white and color images with a quality superior to previous results. In addition, it is shown that the preprocessor produces a "perceptual space" in which normalized mean square error is an effective image quality measure.

2.5 Practical Applications of Numbered Graphs

(The Army Research Office)

S. W. Golomb

Objective Summary: By a numbered graph we mean a graph for which non-negative integers are assigned to the nodes, and for which each edge is then assigned the number which is the absolute value of the difference of the node numbers at its end points. Graphs which are numbered in this sense have been the subject of several recent theoretical papers and many interesting mathematical results have been obtained. Moreover, this viewpoint has been useful in identifying a wide variety of seemingly unrelated practical applications for which the notion of a numbered graph provides the underlying mathematical model.

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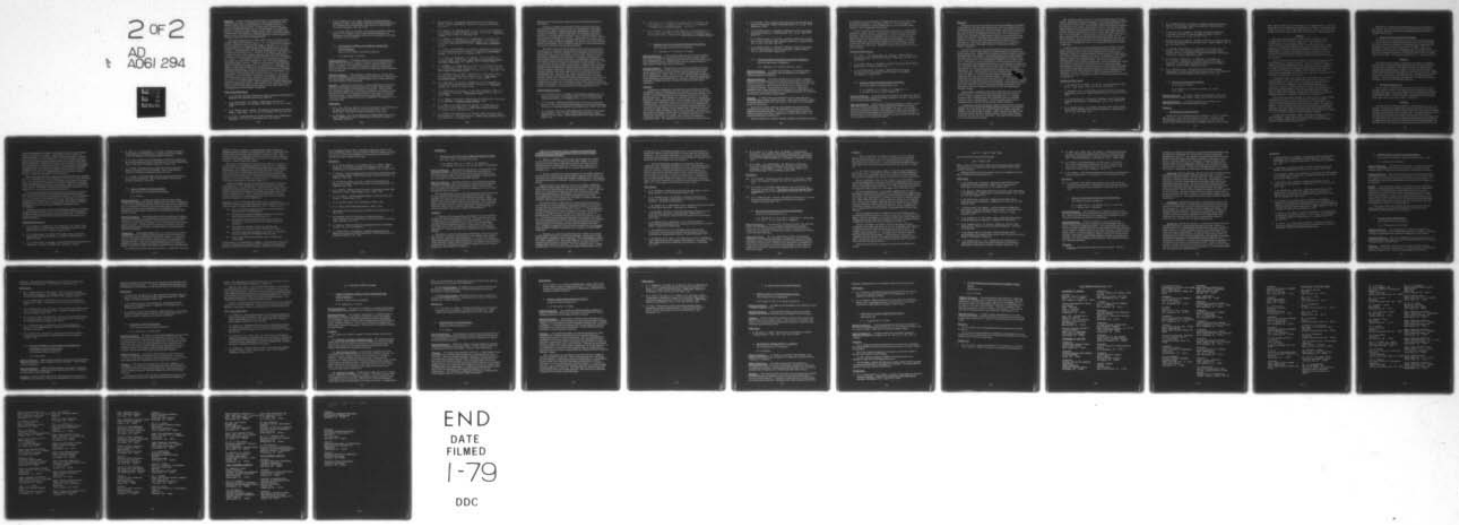

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Progress: In radar and sonar signal design, one recognizes that the distance to the target corresponds to an a priori unknown time delay, and the velocity of the target produces (by the Doppler effect) an a priori unknown frequency shift. In many noise environments, the maximum likelihood detector for the returning signal is a correlation detector; and thus the signal design problem reduces to finding transmitted patterns with optimum "ambiguity functions," where the ambiguity function is the correlation between transmitted and received signal as a function of both time shift and frequency shift.

One signal design which has been proposed (see [1]) involves transmitting n adjacent frequencies, $f_1, f_2, \ldots, f_n$, in some permuted order, during n consecutive time intervals, $t_1, t_2, \ldots, t_n$, where the permutation is to be picked so as to optimize the ambiguity function, i.e., so as to minimize the autocorrelation against all phase shifts in both time and frequency. Combinatorially, the optimum configurations correspond to n×n permutation matrices (i.e., matrices of 1's and 0's, with exactly one 1 in each row and in each column), with the added constraint that any translation of the matrix against itself produces at most one coincidence of a 1 with a 1. Equivalently, if the $\binom{n}{2}$ line segments are drawn between the centers of all the cells containing 1's, then all of these segments represent distinct "vectors". (That is, no two agree in both length and slope.) No method was known to Dr. J. Costas in [1], other than trial and error (inherently limited to very small values of n) for finding such optimum configurations. We have succeeded in finding several constructions which work for infinite classes of values of n. In particular, if p is any prime, then constructions are known for all n = p-1, all n = p-2, and those n = p-3 such that 2 is a primitive root modulo p. Moreover, if q is any power of any prime, then there is an optimum construction for n = q-2. All of these constructions are based on the properties of primitive roots in finite fields. These problems are a natural generalization to two dimensions of the one-dimensional "ruler problems" described in [2], which were discussed in the context of pulse radar patterns for resolving time but not frequency ambiguities.

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2.6 Fast Digital Correlation and Transforms Using Finite Field Techniques

(The Air Force Office of Scientific Research)

I. S. Reed and S. W. Golomb

Objective Summary: Techniques using the structure and properties of finite fields can be used in a variety of ways for the computation of fast digital correlations and convolutions, and for a number of other fast digital transforms. In particular studies are made of an appropriate choice of finite fields in which fast transforms involving complex numbers can be performed.

Approach Summary: The properties of finite fields are studied, with particular emphasis on real and complex fast transforms over finite fields. Now fast decoding algorithms of Reed-Solomon codes, using transforms over finite fields are also developed.

Progress: During the current study, we have undertaken to develop the detailed relationships between the properties of finite fields and their utilization in fast digital correlations and transforms. These results have immediate application to the design of hardware and software for the fast optimum detection of communication and radar signals in practical military systems, to two dimensional image processing, to recursive realization of finite impulse filters and for syndrome calculations of error correcting codes.

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halftone screen used and the selection of various diffraction orders in the system.

Particular nonlinearities that have been achieved include both smooth and discontinuous function such as exponentiation, logarithms, level slicing, analog-to-digital conversion, quantization, and pseudo-coloring of brightness. Most significantly, the technique shows the promise of real-time application with the use of an optical input transducer having a threshold characteristic. Many types of real-time devices with linear characteristics are now available (such as the liquid crystal or Pockels readout modulator (PROM)); now that there is a demonstrated need for thresholding, there should be motivation to continue development of the devices with the required characteristics.

The entire process has been studied in some detail from practical and theoretical viewpoints, and the effects of non-ideal input media have been considered. It is also possible to precompensate for some of these deficiencies and improve the overall accuracy of the nonlinear function. A number of refinements and extensions of nonlinear processing have been considered in the most recent work. A mathematical technique has been found to predict performance degradation for input media (e.g., film or a real-time optical transducer) with any given characteristic curve, rather than for an approximate characteristic. Following from this work should be improvements in precompensation and finally, a determination of all the ultimate limitations. Recent work has also been performed to examine nonlinear processing without the use of a halftone screen or intermediate step. Obviously, the range of functions achievable will strongly depend on the input medium characteristics and on the optical filtering system, but it appears that many useful functions can be achieved. Of particular interest are electro-optic effects in certain crystals and variable phase grating effects in liquid crystals which might be utilized for nonlinear processing. The results of this project, especially those involving halftone processing, are summarized in several publications [1-7].

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2.7 Nonlinear Operations in Optical Information Processing

(The Joint Services Electronics Program)

A. A. Sawchuk, T. C. Strand, A. Armand

Objective Summary: To accurately synthesize wide classes of general non-monotonic nonlinear multi-dimensional functions in optical signal processing systems. To extend and determine the limits of dynamic range, space-bandwidth product, flexibility and real-time implementation for applications in signal filtering and estimation.

Approach Summary: Monotonic and nonmonotonic nonlinear functions are achieved by a pulse width modulation preprocessing step involving special optical filters and a high contrast (thresholding) optical input device (halftoning). Another filter in a simple optical system produces the multidimensional output instantaneously. The flexibility and gnerality of the technique includes application in real-time signal processing when used with a suitable coherent or incoherent optical real-time input transducer.

Progress:

A number of refinements and extensions to the halftone technique of nonlinear optical processing have been considered in this period. The nonlinear processing method studied in detail in this project achieves very general types of two-dimensional point nonlinear functions in an optical parallel processor. The technique is extremely general in concept and application. The method involves a preprocessing of the two-dimensional continuous level input data to convert it to an ideally binary pulse-width modulated input. The pulse-width modulation step is accomplished by a variation of the halftone process used in ordinary photoreproduction. An ideally binary input medium is used together with a halftone screen filter to produce an input composed of dots or linear gratings. This input is then used in a standard coherent optical processing system, where simple spatial filtering produces the output. The system output also is a desampled, continuous level signal, and it can then be displayed or processed further. The nonlinearities achieved depend on the particular

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5. S. R. Dashiell and A. A. Sawchuk, "Nonlinear Optical Processing: Analysis and Synthesis," Applied Optics, Vol. 16, pp. 1009-1025, April 1977.

6. S. R. Dashiell and A. A. Sawchuk, "Nonlinear Optical Processing: Non-monotonic Halftone Cells and Phase Halftones," Applied Optics, Vol. 16, pp. 1936-1943, July 1977.

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2.8 Incoherent Optical Computing with Synthetic Holograms

(The National Science Foundation)

A. A. Sawchuk, T. C. Strand, and C-K. Hsueh

Objective Summary: To extend the advantages of incoherent optical signal processing by combining it with the flexibility of synthetic or computer-generated holograms.

Approach Summary: This work includes the use of existing synthetic holograms in incoherent processors and the development of new types of synthetic holograms. Problems of hologram phase coding, dynamic range and quantization have been considered via theoretical analysis and computer simulation. Several types of high-accuracy, high space-bandwidth filters using existing and new techniques are being fabricated. The theoretical and experimental use of synthetic holograms for incoherent interpolation and filtering is being studied.

Progress: A study of several techniques for fabricating high space-bandwidth optical spatial filters has begun. Both a high resolution plotting microdensitometer and a CRT film recorder with 4096 x 4096 resolvable points are being used.

Some work on phase coding for interpolating incoherent impulse responses has been underway. The objective is to synthesize a good polynomial interpolating function such as a B-spline using a phase-only spatial frequency plane filter. Preliminary results indicate that a very good approximation is possible [3].

Several methods for encoding complex amplitude and phase information

in a hologram have been studied. Complex functions on color film using the ROACH technique [1] are being considered for certain types of incoherent processors. These devides operate on axis and thus reduce spatial frequency bandwidth requirements.

A major effort has been devoted to the development of "Double Phase Holograms" (DPH). This is a new method of computer generating binary holograms based on the decomposition of a complex value into two phase quantities. Each Fourier transform cell is divided into subcells and phase quantities are encoded by the detour phase technique. A complete analysis with many experimental examples is being published [2], and an analysis of the noise due to the displacement of the subcells and the phase coding has been made. Methods of suppressing this noise have also been developed.

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2.9 Nonlinear Real-Time Optical Signal Processing

(Air Force Office of Scientific Research)

A. A. Sawchuk, T. C. Strand, A. R. Tanguay, Jr., A. Armand, D. Drake, and J. Michaelson

Objective Summary: To perform general nonlinear operations in coherent and incoherent optical signal processing systems in real-time using various types of optical input transducers.

Approach Summary: Three major techniques applicable to liquid-crystal light valves (LCLV's) Pockels readout modulators (PROM's) and other types of real-time devices have been studied. They are: (a) real-time extensions of halftone nonlinear processing with a binary input transducer; (b) use of the inherent nonlinear characteristics of real-time devices to directly achieve certain functions; and (c) use of the variable grating mode of LCLV devices in a coherent processor.

Progress:

Because of the recent emergence of the two technologies of nonlinear processing and real-time input transducers, there is no single method or combination of methods that is clearly superior, and several alternatives have been explored during the first year's work. Some short term goals have been to work with existing LCLV devices [1-2] or with devices having very elementary modifications in order to demonstrate the feasibility of the concept. The longer term aspects are those involving new methods of achieving optical nonlinearities and extensive device development. The parts of this project involving LCLV devices have been pursued jointly with Hughes Research Laboratories (HRL) of Malibu, California.

To effectively use the well-developed halftone method of nonlinear processing, a binary hand-clipping recording medium is needed for the preprocessing step. Although most existing real-time devices do not have this threshold characteristic, simulations showed that smooth nonlinear functions such as logarithms and exponentials might be achieved with a non-threshold device if a precompensated halftone screen could be used [3-5]. Detailed device measurements on a 45° twisted nematic LCLV were made and a precompensated screen for a log function was fabricated. The resulting transfer function of the screen-LCLV real-time system was logarithmic over two decades with less than 10% error. In another experiment, two crossed multiplicatively combined Ronchi ceilings were used as the input. The difference in Fourier spectra betw[illegible] multiplicatively and additively combined rulings could be distinguishe[illegible] In connection with real-time halftone processing, a new study of [illegible]g effects and precompensation has been made [8-10]. The degradi[illegible]ects of real-time devices with arbitrary characteristic curves can be predicted simply and accurately by means of this technique. The prediction results have been used with computer models and iterative solutions of some differential-difference equations to design the best precompensated halftone screens.

New methods of halftone screen fabrication have been reasonably successful [10]. A Dicomed image recorder has been used to make 4" x 4" screens on Kodak SO-115 film with good accuracy. Another technique uses a shifted grating with a low duty cycle to repeatedly exposure a high resolution plate. A desired screen profile can be approximated by repeated translation and variable exposure.

A technique of incoherent optical feedback around a LCLV has been explored for achieving threshold (high gamma) operation in the halftone method. The control side of a LCLV is used as a positive summing junction to provide positive feedback. When a small input signal is fed to the LCLV input, the large readout signal is fed back and summed to quickly drive the LCLV to saturation. Very high effective gammas have been noted by this method.

The technique of direct nonlinear processing with halftones has been studied. This method has the advantage that it could be performed without coherent light and the problems of speckle, phase nonuniformities, and the need for a laser source. It should also require less spatial resolution than halftoning since sharp edges of binary dots are not involved. Many existing types of real-time devices have a periodic sinusoidal output as a function of applied input light due to their electro-optic effect operation. Based on this principle, a parallel optical analog-to-digital converter has been conceived which can simultaneously extract bit planes from an incoherent input. The system uses the electro-optic effect of a real-time device along with simple parallel electronic thresholding and electronic readout with a photodetector array. An experimental test of the system is underway.

A third method of real-time nonlinear optical processing currently under study involves the conversion of different input levels to a local phase-modulated input whose spatial frequency is a function of the brightness. When the variable grating is placed in the front focal plane of a coherent Fourier transform processor, the difference in local spatial frequency should cause different input levels to be effectively placed at different points in the transform plane. By selective filtering and recombination of the transform components, various nonlinearities should be possible. Although this method has not yet been experimentally demonstrated, the liquid crystal component of certain liquid crystal light valve (LCLV) real-time devices has shown the variable grating mode in experiments [8-10]. Some theoretical analysis of this technique has been undertaken, and an overall effort to compare fundamental limits of resolution, accuracy, and dynamic ranges of these three major techniques is in progress.

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2.10 Research in Communication Theory

(Army Research Office)

R. A. Scholtz, L. R. Welch, N. Bekir, K. Leung and J. Olsen

Objective Summary: To study communication problems in the areas of synchronization, signal design, coding, and channels with memory.

Approach Summary: Five basic problems are currently under investigation and are described separately below.

Progress:

1. Spread Spectrum Signal Design

Spread spectrum techniques basically provide a method for reducing the effects of certain types of interference in radio communications. Well-designed spread spectrum signal sets thus are a basis for the design of code-division multiple-access (CDMA) communication systems

which operate with several users in the same frequency band. J. D. Olsen dissertation [6] develops the best known direct-sequence spread-spectrum signal set design (at least in the open literature). We expect that this new design will find immediate application in the military communication field.

Abstract

This dissertation develops a class of binary sequences which asymptotically achieve Welch's lower bound on simultaneous cross-correlation and autocorrelation magnitudes. The sequences are constructed by applying nonlinear feed-forward functions on an n stage maximum-length linear-feedback shift register generator in the Galois configuration. This technique has an additional attribute for many applications because the resulting sequences are nonlinear in that the order of the linear difference equation satisfied by the sequence can be orders of magnitude larger than the number of memory elements in the generator.

A novel approach is taken to sequence design by analyzing correlation properties in a transform domain. The form of the transform domain correlation bounds leads to two separate problems; finding size $2^{n/2}$ subsets of the GF(2^n) which have minimum intersection under a "rotation" permutation, and finding functions such that the transform coefficients have uniform magnitude. The analytical techniques employed are applicable for all n, however, algebraic code constructions can only be given for the case n even.

The optimum codes are obtained when n=0 (mod 4) and are called affine subspace codes. The period of the codes is 2^n-1, they are balanced and have 3 valued cross-correlation functions and 3 value out of phase auto-correlation. The correlation magnitudes are $\leq 2^{n/2}+1$, a factor of $\sqrt{2}$ better than Gold codes. The hardware complexity of these nonlinear generators is approximately the same as that of a Gold code generator. One of these generators can easily produce many nearly orthogonal sequences simultaneously, with little additional hardware. The size of this class is at least $2^{n/4}$.

The feed-forward logic consists of a rank n/2 linear transformation providing the inputs to a "bent" function of n/2 binary variables. Finally, using a shift theorem of the transform, a phase shift on the output of the bent function shifts the Fourier spectrum in the transform domain. A bent function is the characteristic function of a Hadamard difference set, and results in the nonzero Fourier coefficients having uniform magnitudes. In this case the Fourier coefficients of the sequence are zero except for those on a specified affine subspace.

A large class of nonlinear codes, called linear subspace codes, is also developed. These codes are also best when n=0 (mod 4) b have correlation magnitudes off by a factor of 4 from Welch's bound. The size of this class is at least $2^{3n/4}$.

Experimental results are included which agree with the theory in every detail. A partial period correlation function was computed for one example sequence and found to be slightly better than that of a randomly chosen code.

2. Partial-Period Correlation Distributions

One of the major obstacles to the accurate performance analysis of a spread spectrum communication system is the lack of knowledge about the correlation properties of spread spectrum signals when the correlation time is less than the period of the signal. We have developed a method for determining upper and lower bounds on the distribution of partial-period correlations and have applied it to several signals, including PN sequences of lengths up to $2^{23}-1$ for correlation times up to 100 bits. The work is reported in N. E. Bekir's thesis [5].

Abstract

This dissertation presents a systematic procedure for obtaining bounds on the distribution F(z) of partial-period correlation values of sets of periodic sequences. The ability to carry out the procedure depends on the development of a linear code $\mathcal{B}$ from the sequence set. Using the MacWilliams-Pless identities, moments of F(z) can be related to the weight distribution of the dual code $\mathcal{B}^{\perp}$. Bounds on F(z) are then calculated using the theory developed to solve the classical moment problem. The above techniques are applied to two well-known classes of sequences, namely PN and Gold sequences.

3. Generalized Interleaving

When codes are interleaved to counteract error bursts, a loss in effective channel capacity occur when each of the interleaved codes is decoded separately. Our recent research has developed two techniques for mutual decoding of interleaved codes, one for convolutional codes based on the work of J. R. B. de Marca, reported in 1977, and one for block codes based on the work of K. S. Leung [7].

Abstract

This thesis deals with the problem of communicating in burst-error channels. Burst-error channels are used to represent a large class of modern communication media; and the problem of communicating reliably through such media has received much study. Existing techniques include two-way communication scheme that involve error-detection and retransmission, and one-way scheme that utilizes error correcting codes in code interleaving. The error-detection and retransmission scheme is simple but its applicability is restricted to limited environments. On the other hand, the concept of code interleaving has proved to be a very

versatile and effective technique for dealing with burst-error channels. In the code interleaving scheme, code symbols from a number of component codes are interleaved before being sent through the channel. This method effectively distributes the error detection and correction burden amongst the component codes and thus lowers the overall redundancy requirement. However, the memory characteristics of the burst-error channel have not been made use of. This prompts the investigation presented in this thesis to take advantage of such inherent information embedded in the code interleaving scheme when used with burst-error channels. Two ideas to accomplish this goal are explored, namely, mutual decoding and generalized code interleaving.

Mutual decoding is aimed at utilizing information obtained in decoding the first component code to aid in locating errors for the second component code. It is found that the average burst length of the channel, the depth of interleaving, the symbol depths and the word lengths of the component codes are determining parameters contributing to improved performance of the channel. The proper relationships between these parameters also suggest some useful coding and decoding strategies.

In the generalized code interleaving scheme, attempts are made to alter error characteristics of the channel by incorporating matched pre- and post-processing of the channel bit sequence. By re-distributing the error locations, it was hoped that the first component code can be designed to be principally an error-correcting code with the subsequent codes basically erasure codes. Unfortunately, this method is found to be ineffective for the class of code-channel combinations under investigation.

Performance criteria are set up to facilitate performance evaluation. Theoretical formulations are also devised to predict code performance and their validity is verified using computer simulations. Performance is also compared with the theoretically achievable capacities of the channels involved.

Publications/References:

1. I. S. Reed, R. A. Scholtz, T. K. Truong and L. R. Welch, "The Fast Decoding of Reed-Solomon Codes Using Continued Fractions," IEEE Trans. on Inform. Theory, January 1978.

2. R. A. Scholtz and L. R. Welch, "Group Characters: Sequences with Good Correlation Properties," to appear in IEEE Trans. on Inform. Theory.

3. L. R. Welch and R. A. Scholtz, "Continued Fractions and Berlekamp's Algorithm," to appear in IEEE Trans. on Inform. Theory.

4. N. Bekir, R. A. Scholtz and L. R. Welch, "Partial Correlation Computations for PN Sequences," to appear in the Proceedings of the 1978 National Telecommunications Conference.

5. N. E. Bekir, "Bounds on the Distribution of Partial Correlation for PN and Gold Sequences," Ph.D. Dissertation, Electrical Engineering Dept., University of Southern California, January 1978.

6. J. D. Olsen, "Nonlinear Binary Sequences with Asymptotically Optimum Periodic Cross-Correlation," Ph.D. Dissertation, University of Southern California, December 1977.

7. K. S. Leung, "Mutual Decoding and Generalized Code Interleaving in Burst-Error Channels," Ph.D. Dissertation, University of Southern California, June 1978.

2.11 Coherent Multiple-Frequency Systems

(The Joint Services Electronics Program)

R. A. Scholtz

Objective Summary: To develop a digital communication system configuration using constant energy signals which are linear combinations of several free-running oscillators, having the property that (a) performance is comparable to coherent communications using the same data rate, and (b) spread-spectrum processing gain is developed to provide immunity to various types of interference including signals from other similar systems.

Approach Summary: Develop decision-directed techniques for locking a receiver oscillator to an intermittently observed transmitter oscillator which may be bi-phase modulated. If this can be done for each of the transmitter's free-running oscillators, coherent detection of the received signal is possible. By increasing the number of oscillators used and lowering each oscillator's usage, a spread-spectrum processing gain should be achievable.

Background: When digital signals which are constructed from linear combinations of free-running oscillators (tones) are detected with no a priori information concerning the oscillators' phases, a considerable loss [1] in communication system capacity occurs in comparison to coherent detection. This loss grows exponentially with the number of oscillators which are linearly combined simultaneously to generate the signals, and makes multiple-tone signals unattractive for communication.

In an effort to overcome this type of problem, considerable research

effort [2-4] has been spent on continuous-phase phase-shift-keyed (CPFSK) systems in which the transmitted waveform is continuous at the instant when a switch from one frequency to another is made. Such systems, however, transmit only one tone at any given time, and hence the potential savings in CPFSK are not as large as the potential savings in systems using multiple tone signals.

The approach proposed here is to generate synchronous replicas of the transmitter's free-running oscillators at the receiver. This will require some type of phase-locked loop operating only on unpredictably intermittent observations of the tone to which the loop is to be locked. A large literature including well-referenced books [5,6] on phase-locked loops exists, but no discussion of the intermittent observation problem is known to this author. Decision-directed techniques, which should help solve this problem, have been used to overcome the effects of bi-phase modulation on continuous signals [5].

Frequency-hopping spread spectrum systems have been discussed in the literature [7-9], though not in conjunction with the multitone modulation under consideration here. Good frequency hopping codes for multiple-user spread-spectrum systems have been found [10,11] and would undoubtedly be considered for multiple user applications of the system considered here. These codes provide distinctive frequency patterns, which may be superimposed on the data multi-tone signals, to provide distinctive receiver addresses.

Progress: (April 1977 through April 1978) After arranging for a research assistant and familiarizing him with the problem, our research program began in earnest about mid-June, 1977. To date we have:

(a) characterized the statistical properties of an intermittent tone observed in Gaussian noise,

(b) developed the maximum likelihood estimator of the tone's phase during a fixed observation interval,

(c) configured the decision-directed loop which effectively mechanizes a serial search for the maximum likelihood estimator,

(d) generalized the results to allow tone duration and probability of occurrence to be variables in the design,

(e) created an open loop simulation of the system to determine statistical properties of the phase detector, and

(f) made comparisons with continuous-tone-tracking phase-locked loops.

At this point we are attempting to configure a coherent spread-spectrum frequency-hopping system using several such phase tracking devices. Efforts were hampered by the fact that Dr. Scholtz was on sabbatical

leave beginning February 1978. Continued funding after March 1978 was not available and the research assistant returned to Hughes Aircraft Co. to work. Work on the problem may proceed in the fall of 1978 if alternate sources of funds can be found.

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9. Proceedings of the 1973 Symposium on Spread Spectrum Communications, Naval Electronics Laboratory Center, San Diego, Calif., March 13-16, 1973.

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3. CONTROLS

3.1 Estimation and Identification for Modeling Dynamic Systems

(Air Force Office of Scientific Research)

J. M. Mendel (P.I.), N. E. Nahi, H. D. Washburn,
F. A. Habibi, J. S. Lee, A. M. Yu, M. Chan, F. Aminzadeh

Objective Summary: This study has been aimed at two problem areas: multistage modeling, estimation, and identification algorithms for dynamical systems, and state estimation and parameter identification for a new class of models--causal functional equations--which describe wave propagation in lossless layered media systems.

Approach Summary: The first problem is concerned with developing estimation algorithms both for parameter and state estimation that are recursive in the dimension of the parameter vector or state vector. Such algorithms will find utility in system modeling work, where model dimension is often a variable.

The second problem is concerned with developing whole new theories of state estimation and parameter identification for a new class of equations which we refer to as causal functional equations. These equations are continuous-time linear, time-invariant with multiple time delays. They do not contain derivatives or integrals, and no literature apparently exists for them. Causal functional equations are applicable to diverse areas such as reflection seismology, transmission lines, speech processing, optical thin coatings and EM problems.

Progress:

1. Washburn [2] has generalized Firedland's [A] bias estimation technique to partitioned dynamical systems. In the general case, the calculations are of the dimension of the overall system, so that, except for some special but important cases, there are no computational advantages to the multistage approach. Those special cases, where there does appear to be computational advantages for the multistage approach are: colored noise and weak coupling between the partitioned systems.

The general results are important in themselves, since they provide the theory for a particular decomposition of the optimal state estimator for a system of possibly large dimension (i.e., a large scale system). This decomposition gives added insight into the structure and performance of the minimum variance unbiased estimator. In addition, the methodology of proof for this multistage decomposition provides a means for investigating other decompositions of interest.

Under the present grant we have completed our study into the development of multistage Kalman/Bucy filters for linear lumped parameter dynamical systems.

2. We have continued to develop state space models for lossless layered media systems [3] and have proven the validity of our interconnection of state space models which result in a Bremmer Series decomposition of a seismogram [4]. We have made connections [5] between our state space models and the integral equations given by Bremmer [B].

3. We have developed [6] a general theory for describing reinforced events between multiple reflections in lossless layered media, which are described by the wave equation and boundary conditions (e.g., horizontally stratified nonabsorptive earth with vertically traveling plane compressional waves).

Reinforcements occur whenever two or more multiple reflections from different paths inside the media arrive at the surface at the same time so that they add (positively or negatively) together. Those reinforcements occur regardless of what the travel time is in each layer, and distort the appearance of a seismogram; for, they lead one to believe that a significant event has occurred by the appearance of a large amplitude segment of the seismogram, whereas, in reality, that large event is a sum of (many) smaller events.

Our general theory is applicable to a K-layer media system with non-uniform travel times and gives information about the exact location in time, number, and amplitude of reinforced events for n-aries (i.e., secondaries, tertiaries, etc.), where n = 1,2,3,... . The starting point for the development of this theory is Mendel's Bremmer series decomposition [4] and the operator description of state space models of layered media [7] by means of which n-ary reflections (where n = 1,2, 3,...) are generated and analyzed separately and related to each other. The two most significant multiple reflections, secondaries, and tertiaries, have been studied extensively. We have demonstrated that not only do reinforcements occur between the same kind of multiple reflections (e.g., between secondaries), but that reinforcements also occur across different kinds of multiple reflections (e.g., between secondaries and tertiaries).

4. Because our causal functional state space models for a layered media system represent a new class of equations, we have had to study the computer simulation of these equations. Two computational methods have been considered [8]. In the first approach, we discretized the time axis and inserted states of intermediate delays, to arrive at a set of standard finite-difference equations. For our particular system, matrix multiplications can be reduced to simple scalar multiplications. In the

second approach, we defined mapping rules for the transformation of states at an interface, and kept a state reference table for look-up and branching. The procedure is similar to ray-tracing. Several experiments have been performed to show the trade-off between storage requirement and CPU time-spent for the two methods.

5. We have developed a procedure for extracting reflection coefficients from noise data [9] which we feel is a substantial generalization of similar procedures which have been reported in the literature ([C] for example). Associated with these earlier procedures are Standard Assumptions and Steps which include requirements that the data be noise free and that the observed seismic data be deconvolved. Our procedure avoids these restrictive requirements. Furthermore, our procedure totally avoids the concepts of z-transforms, minimum phase, spectral factorization, forward and reverse polynomial manipulations, etc., which appear in the literature on this subject.

Publications:

1. H. D. Washburn, "Multistage Estimation and State Space Layered Media Models," Ph.D. Dissertation, March 1977.

2. H. D. Washburn and J. M. Mendel, "Multistage Estimation of Dynamical and Weakly Coupled States in Continuous-Time Linear Systems," submitted for publication.

3. J. M. Mendel, N. E. Nahi and M. Chan, "Synthetic Seismogram Using the State Space Approach," submitted for publication.

4. J. M. Mendel, "Bremmer Series Decomposition of Solutions to the Lossless Wave Equation in Layered Media," IEEE Trans. on Geoscience Electronics, Special Issue on Seismic Data Processing, April 1978.

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8. W. M. Chan, N. E. Nahi, and J. M. Mendel, "Computational Solutions to a Non-Uniform Time-Delay Linear System," presented at Symposium on Applications of Computer Methods in Engineering, University of Southern California, Los Angeles, California, August 1977.

9. N. E. Nahi, J. M. Mendel and L. M. Silverman, "Recursive Derivation of Reflection Coefficients from Noisy Seismic Data," presented at 1978 IEEE Int'l. Conf. on Acoustics, Speech, and Signal Processing, Tulsa, Oklahoma, April 1978.

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[C] E. A. Robinson and S. Treitel, "The Spectral Function of a Layered System and the Determination of the Waveforms at Depth," Geophysical Prospecting, 1977.

3.2 Information Processing for Oil and Gas Exploration

(Chevron Oil Field Research Co.)

J. M. Mendel (P.I.), N. E. Nahi, J. Kormylo, F. Aminzadeh, J. S. Lee, A. Yu, M. Chan, H. D. Washburn

Objective Summary: Our research activities have been in the following areas: deconvolution by means of Kalman filtering and smoothing technology, one-dimensional state space models of lossless layered media, inverse problems, and minimum-variance estimation for uniform causal functional equations.

Approach Summary: We have applied Kalman filter and smoothing technology to an important nonstationary geophysical signal processing procedure in which we simultaneously correct for spherical divergence and perform deconvolution. We have also continued our development of a new class of state space models for layered media systems and have studied state estimation and parameter identification in the context of these new models.

Progress:

1. We have shown that our optimal smoother [1,2,3], which is based on Kalman filtering, can handle the nonstationarity associated with spherical divergence easily. It combines gain correction and deconvolution into one process, to produce optimally smoothed estimates of the plane wave reflection coefficient sequence directly from raw data [4].

2. Our work on state space models of lossless layered media has been in five areas: (a) extensions of basic model, (b) understanding the basic model, (c) computation, (d) inverse problems, and (e) minimum-variance state estimation for uniform causal functional equations (UCFE).

We have extended our basic model, which is for a horizontally stratified nonabsorptive earth with vertically traveling plane compressional waves, where both source and sensor are located at the surface to the case of source and sensor in the first layer [5]. This is important for marine seismograms wherein both source and sensor are in the water layer.

We have established the correct initial conditions for our causal functional state space models, both for the uniform and non-uniform travel time cases. We have developed a closed-form solution of a UCFE [6] and have made many connections [7] between our Bremmer series decomposition, which uses state space models to generate primaries, secondaries, etc., and recursive integral equations given by Bremmer [A]. Finally, we have studied the reinforcement phenomenon, which can cause a large component to appear in a seismogram that is due to the superposition (i.e., reinforcement) of many smaller components that are time coincident [8].

We have studied a number of different ways of simulating causal functional equations both for non-uniform travel times and uniform travel times. We have developed a ray tracing technique and a finite-difference technique for the non-uniform travel time case [5,9]. A special parallel computation procedure has been developed for UCFE's [6].

We have developed a procedure [10] for extracting reflection coefficients from noisy data which we feel is a substantial generalization of similar procedures that have been reported in the literature. We considered a K-layer system with uniform travel times and normal incident compressional waves. An equation was derived for the wave that goes down into the basement. "Least squares" values of the coefficients of this equation were obtained in terms of seismic surface data. Our solution led to a set of normal equations which were then solved via the Levinson procedure.

We have derived [6] the minimum-variance state estimator for UCFE

$$\underline{x}(t+\tau) = A\,\underline{x}(t) + B\,\underline{m}(t) + \underline{w}(t)$$

and its associated measurement equation

$$\underline{y}(t) = H\,\underline{x}(t) + \underline{n}(t)$$

When a grid is overlayed on the time axis with grid size equal to data sampling rate, T, we obtain a finite number of Kalman filters which operate in parallel.

Additional details on eleven projects that were completed and seven that are underway can be found in [11].

Publications:

1. J. M. Mendel and J. Kormylo, "New Fast Optimal White-Noise Estimators for Deconvolution," IEEE Trans. on Geoscience Electronics, Vol. GE-15, pp. 32-41, January 1977.

2. J. M. Mendel, "White Noise Estimator for Seismic Data Processing in Oil Exploration," IEEE Trans. on Automatic Control, Vol. AC-22, pp. 694-706, October 1977.

3. J. M. Mendel and J. Kormylo, "Single-Channel White Noise Estimators for Deconvolution," Geophysics, Vol. 43, pp. 102-124, February 1978.

4. J. Kormylo and J. M. Mendel, "On the Treatment of Spherical Divergence for Kalman Filtering Deconvolution," presented at the 47th Annual Meeting of the SEG, Calgary, Alberta, Canada, September 1977.

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3.3 Problems in Parameter Estimation and Identification

(The National Science Foundation)

G. A. Bekey (P.I.), J. M. Mendel (P.I.), J. MacCalla, S. Y. Chang, and A. Andronikou

Objective Summary: Our attention in this continuing study has been directed at both theoretical and practical problems of parameter estimation, with the overall objective of providing a firm foundation for the solution of identification problems in engineering.

Approach Summary: The first problem is concerned with the identification of discrete time systems with state dependent noise by means of maximum-likelihood methods. A second problem has been to develop a Kalman filtering approach to obtain optimal smoothed estimates of the reflection coefficient sequence that characterizes a lossless layered media system. A third problem is concerned with identification of large numbers of parameters in nonlinear dynamic systems by random search methods. The fourth problem applies sensitivity analysis techniques to the study of errors in parameter identification. Some application papers have also been published.

Progress:

Problem I. (Identification of discrete-time systems). We have

developed a technique for maximum a posteriori likelihood (MAPL) state and parameter estimation for a scalar discrete-time system with multiplicative noise [1]. Our approach was to develop a MAPL function and show that its maximization leads to parameter estimation equations which are coupled together with a nonlinear two-point boundary value problem from which we obtain state estimates. We developed an iterative procedure for obtaining MAPL estimates which decouples the state and parameter estimates. Results have been demonstrated via computer simulations. Extensions have been made to multivariable systems [2].

Problem II. (Kalman filtering). We have developed a Kalman filtering approach to obtaining optimal smoothed estimates of the so-called reflection coefficient sequence ([3] through [5]). This sequence contains important information about subsurface geometry, and appears in a traditional convolution summation model associated with seismic data processing in oil exploration. We have shown that estimation of the reflection coefficient sequence is equivalent to estimation of white plant noise in an equivalent state space representation of the convolution simulation model. We have derived optimal smoothers ([3], [4], and [5]) for the reflection coefficient sequence and have compared them with an ad hoc prediction error filter, which has recently been reported on in the geophysics literature. Our estimators perform better than the prediction error filter.

Problem III. (Identification algorithms using random search). We have developed an adaptive random search algorithm which periodically performs an exploratory search to determine the locally optimum step-size variance [6]. The algorithm has been applied successfully to the identification of 25 parameters in a model of a nonlinear, 5 degree of freedom mechanical system. Attempts to repeat the results using a classical gradient procedure (Davidon-Fletcher-Powell) have been prohibitive in computer costs, but lead to an estimated saving of a factor of 100 in computer time by using random search.

Problem IV. (Sensitivity analysis). A systematic analysis of errors arising in parameter identification algorithms and their relation to experimental errors, identifiability and sensitivity has been completed. While applied to a specific biological system, the methodology in the study is of general applicability. A unique feature of the study was the separation of the parameters into two groups: those whose values are assumed known a priori and those estimated by the algorithm in question. The results showed that it was possible to form a hierarchy of the sensitivity coefficients of a system, thus demonstrating the dependence of the parameter estimates on measurement errors, errors in assumed values of "known" parameters, structural errors, and numerical errors. The first results were presented at a symposium [7] and a detailed paper has been submitted for publication [8].

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6. S. F. Masri, G. A. Bekey and F. B. Safford, "An Adaptive Random Search Method for Identification of Large Scale Nonlinear Systems," presented at the 4th IFAC Symposium on Identification and Process Parameter Estimation (Tbilisi, USSR, September 1976) and accepted for publication in Automatica, 1978.

7. T. Grove, G. A. Bekey, "Sensitivity Problems in the Identification of Biological System Parameters," Proc. Symp. on Applications of Computer Methods in Engineering, Los Angeles (Aug. 1977), pp. 625-634.

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3.4 Synthetic Sensory Feedback and Human Balance

(The National Aeronautics and Space Administration - JPL)

G. A. Bekey and M. Momirov

Objective Summary: The purpose of this study is to determine whether electrical stimulation of the skin can be used as an artificial sensory feedback signal to enhance the postural balance of paraplegic persons.

Approach Summary: We propose to measure the deviation of the body axis from the local vertical, process the signals, and use them to control the amplitude of electrical stimulation on the skin above the waist. A mathematical model will be developed so that control system design can be optimized.

Results: The experimental portion of this study is being conducted at Rancho Los Amigos Hospital with the cooperation of the Jet Propulsion Laboratory. An existing floor-mounted force plate has now been instrumented by JPL to provide a direct measurement of the reaction forces F_x, F_y and F_z, as well as the ratios F_x/F_z and F_y/F_z. The force ratios provide the targets of the angle of deviation from the local vertical in two axis. Two canes are currently being instrumented with strain gauges to enable us to measure the corrective forces to be used by the patient to restore the vertical position.

A first stage mathematical model has been constructed, using an inverse pendulum to represented the patient in long rigid braces. Preliminary stability anslyes are encouraging.

3.5 Recursive Image Enhancement

(The National Science Foundation)

L. M. Silverman and N. E. Nahi

Objective Summary: The development of recursive algorithms for solution to a variety of image enhancement problems including restoration of images with unknown blur and object boundaries in noisy images.

Approach Summary: State space modeling of image statistics, blur and noise processes. Development of two-dimensional Kalman-Bucy filtering techniques based on these models.

Progress: Extensions of previously developed techniques for blur effect removal have been carried out [1-3] and work on blur identification has been initiated [4, 5]. Work on image boundary estimation is

continuing. Successful experimentation was performed on natural (not computer generated) pictures. The results are reported in [6].

Publications:

1. M. S. Murphy and L. M. Silverman, "Overview of Recent Image Processing Techniques," Proceedings of the 20th Midwest Symposium on Circuits and Supplies, pp. 179-187, 1977, Lubbock, Texas.

2. A. O. Aboutalib and L. M. Silverman, "Recursive Restoration of Astigmatism," Proc. 11th Asilomar Conf. on Circuits and Systems, 1977.

3. M. S. Murphy and L. M. Silverman, "Image Model Representation and Line-by-Line Recursive Restoration," to appear in IEEE Trans. on Automatic Control, Oct. 1978.

4. M. S. Murphy and L. M. Silverman, "Maximum Likelihood Parameter Estimation Identifying a Class of Unknown Image Blurs," submitted to 1978 IEEE Conf. on Decision and Control.

5. E. J. Dragavon and L. M. Silverman, "A Pattern Recognition Approach to Blur Identification," submitted to 1978 IEEE Conf. on Decision and Control.

6. N. E. Nahi and S. Lopez-Mora, "Estimation-Detection of Object Boundaries in Noisy Images," IEEE Transactions on Automatic Control, 1978.

3.6 Structural Problems in Linear Systems with Application to Modeling, Control and Estimation

(The National Science Foundation)

L. M. Silverman

Objective Summary: Input-output realization and identification algorithms. Geometric structure and its relation to Riccati equations. General theory of Riccati equations.

Approach Summary: Study and apply algebraic and geometric structure of linear systems to various control and estimation problems. Emphasis on numerically robust algorithms.

Progress: Progress has been made on relating geometric structure to transfer function structure. Several new algorithms have emerged [1,2].

Significant headway has been made on the study of non-sign definite linear quadratic control problems [ ]. Precise conditions and algorithms for establishing the non-existence of finite escape times have been developed.

Publications:

1. E. Eme and L. M. Silverman, "New Criterion and System Theoretic Interpretations for Relatively Prime Polynomial Matrices," IEEE Trans. on Automatic Control, April 1977.

2. L. M. Silverman and P. M. Van Dooren, "A System Theoretic Approach for GCD Extraction," submitted to 1978 IEEE Conf. on Decision and Control.

3. E. Jonckheere and L. M. Silverman, "Spectral Theory of the Linear-Quadratic Control Problem: Discrete-Time Single-Input Case," to appear in IEEE Transactions on Circuits and Systems.

3.7 Properties of Structured Systems

(The Joint Services Electronics Program)

N. E. Nahi and L. M. Silverman

Objective Summary: To achieve a better understanding of the structural properties of systems that can be decomposed, in some sense, into several modules with a specified interconnection structure. Successful development of this area of research should lead to new design concepts which will allow a more thorough exploitation of the underlying interconnected structure for control, filtering, and identification purposes. Physical systems to which the results would be applicable are, for example, deformation satellites and compartmental systems.

Approach Summary: To set up an analytic theory for the design of control, filtering and identification schemes having good "robustness" properties. When this is applied to intercoupled systems, the structure of the underlying interconnection becomes particularly relevant.

Progress: This research was initiated in [1] by E. Jonkheere, an RA supported by JSEP, where it was shown that weak observability of the flexible modes of a deformable satellite was related to the structure of the coupling between the rigid body dynamics and the flexible body dynamics.

Progress has been made in [2] where robustness is defined in the filtering content and where its connection with weak observability is

shown. The underlying interconnected structure of the system becomes particularly relevant when robustness is conderned.

Along the same lines, we have studied the problem of concentrating almost all the energy of the motion into one preassigned module of an interconnected structure. This has led to procedures for synthesizing an input signal which makes the behavior of an interconnected analog system very sensitive to the parameter of the preassigned module [3]. This is the analog counterpart of "path sensitization" in digital systems. It is useful for the detections of faults in analog systems.

Consider progress has been made in the study of the Riccati equations which arise in control problems. In particular several long outstanding questions concerning a class of such equations have been resolved [4].

Publications/References:

1. E. Jonckheere, "On the Observability of the Deformable Modes in a Class of Non-Rigid Satellites," Proc. Symp. Dynamics and Control of Non-Rigid Spacecrafts, Frascati, Italy, May 1976, European Space Agency, ESA SP-117, pp. 251-262.

2. E. Jonckheere, "Robustness of Observers for Estimating the State of a Deformable Satellite," Conf. on Altitude and Orbit Control, Noordwyk, The Netherlands, October 1977, European Space Agency, ESA SP-128.

3. E. Jonckheere, N. E. Nahi and L. M. Silverman, "A Geometric Approach to Subspace Energizability in Linear Systems; Application to Fault Detection and Parameter Identification in Analog Systems," Technical Report, Department of Electrical Engineering - Systems, University of Southern California, to appear.

4. E. Jonckheere, "Spectral Theory of the Linear-Quadratic Optimal Control Problem," Ph.D. Dissertation, University of Southern California, January 1978.

IV. ELECTRIC POWER SYSTEMS

1. A Study of Insulator Flashover Under Contaminated and HVDC Conditions

(Electric Power Research Institute)

T. C. Cheng and Y. B. Kim

Objective Summary: The goal is to facilitate a reduction in the number of contamination-caused flashovers on overhead DC transmission lines.

Approach Summary: The program will involve a coordinated plan of field testing, laboratory simulation and flashover theory formulation. The mechanisms of DC contamination flashover must be determined. On-line testing at Sylmar will be used to establish and isolate the salient factors leading to flashover. These factors will then be studied intensively under laboratory conditions. Theories will be developed to explain the observations.

Progress:

The project was started in August 1976 and consists of five major parts:

(1) Collection of weather and flashover data. An automatic weather station was set up at the Sylmar Converter Station to record on magnetic tapes all the relevant weather information at 15-minute intervals. The weather data will then be correlated with the field operating data at Sylmar to determine the important parameters.

(2) Field Testing at Sylmar. A test station consisting of 9 poles of insulators and 2 control poles was built at the Converter Station. The poles are directly connected onto the Pacific Intertie at a voltage of ± 400 KV. Instrumentation was built to monitor continuously the performance of these insulators and their leakage currents, peak currents and surges are all being recorded. Monthly washing of the insulators makes possible the determination of the chemical nature of the contaminants. The rate of accumulation of these different ions have been correlated with weather parameters.

(3) Laboratory Testing. A HVDC power supply was built on campus with the capability of reaching up to 40 KVDC. The power bus line feeds a test chamber which is capable of generating a foggy condition closely resembling that of a natural fog. Intensive and accelerated flashover tests under artificial contamination are being carried out. Through these

tests, a new mechanism in a flashover process was discovered, namely, the formation of clean zones by scintillations.

(4) Scintillation Studies. A separate test set-up was built to study the initiation of discharges and to record on high speed movies the progression of those discharges.

(5) Theory Formulation. Theoretical work has been completed on the initiation of discharges from contaminated water drops resting on or hanging from insulator surfaces.

Publications:

1. C. T. Wu and T. C. Cheng, "Formation Mechanism of Clean Zones During the Surface Flashover of Contaminated Insulators," IEEE Transactions on Electrical Insulation, pp. 149-156, June 1978.

2. Cable Dielectric Breakdown Studies

(Southern California Edison Co.)

T. C. Cheng

Objective Summary: To determine the separate and combined effects of electric field and elevated temperature upon the aging/deterioration rate of extruded dielectrics and to attempt to provide a physical description of deterioration mechanisms.

Approach Summary: Dielectric samples of known quality are tested at various field intensities and temperatures. Electro-optical effects will be utilized to aid in the observation. A theory will be formulated.

Progress: The project was initiated in July 1976. A high voltage testing laboratory was completed with facilities for energizing samples up to 100 KVAC. Samples of known qualities of dielectrics were prepared and the preparation technique was perfected. Discharge experiments were then performed on these samples. Electro-optical effects were also measured as a tool to aid in the observation of the behavior of the samples. Significant discovery was made in the detection of an electro-optical effect in PMMA under room temperature. Further work indicated that the same effect could be detected in cross-linked polyethylene at elevated temperatures. The usefulness of using this technique for nondestructive field mapping purposes is presently being investigated.

Publications:

1. R. E. Cooper, T. C. Cheng, K. Kantak and A. Rein, "Kerr Type Electro Optical Effects in Solid Dielectrics," 1977 Annual Report on Electrical Insulation and Dielectric Phenomena, published by the National Academy of Science.

3. Insulator Contamination Research at U.S.C.

(Southern California Edison Co.)

Y. B. Kim and T. C. Cheng

Objective Summary: For maximum expected wetting conditions in Southern California, optimize the utilization of semiconductive glazed suspension insulators in the Edison service territory.

Approach Summary: The minimum required power dissipation for a suspension insulator to prevent flashover and/or determining an optimum design for the semiconductive glazed suspension insulator will be studied. In addition, a materials test program will be incorporated to develop a methodology for evaluating the performance of high voltage insulating materials in contaminated environments.

Progress: The withstand strength of contaminated insulators under practical field conditions depends on the type and distribution of contaminants as well as their conductivity. We have investigated the dependence of flashover voltage on the chemical composition of multi-component contaminants and have proposed a unique method to relate the flashover voltage to the types of salts present. Although the distribution of contaminants on the surface plays a significant role in the flashover, it was found that no one portion of the insulator tends to predominate in importance and the uniform contamination distribution yields the minimum flashover voltage.

Dew condensation can significantly lower the flashover voltage of outdoor suspension insulators. Since semiconducting glaze insulators have the potential of eliminating moisture condensation, a comprehensive thermal model describing their operating characteristics is being completed. A semiconducting glaze flat-plate insulator is chosen as a test case. The resultant energy exchange equations are solved by Finite Element Method on a computer. The importance of radiative heat loss in facilitating flashovers is demonstrated. The theoretical predictions compare favorably with experimental data.

Publications:

1. L. J. Williams, J. H. Kim, Y. B. Kim, N. Arai, O. Shimoda and K. C. Holte, "Contaminated Insulators-Chemical Dependence of Flashover Voltages and Salt Migration," IEEE Power Apparatus and Systems, Vol. 93, #5, pp. 1572-1580, 1974.

2. K. C. Holte, J. H. Kim, T. C. Cheng, Y. B. Kim and Y. Nitta, "Dependence of Flashover Voltage on the Chemical Composition of the Multicomponent Insulator Surface Contaminants," IEEE Power Apparatus and Systems," Vol. 95, #2, pp. 603-609, 1976.

3. T. Tong, "A Thermal Analysis of the Semiconducting Glaze Suspension Insulator Operating Under a Polluted Enviornment," Ph.D. Thesis, Department of Electrical Engineering, USC, September 1977.

V. PLASMAS AND ELECTROMAGNETICS

1. Nonlinear Effects on Plasma Resonance Cones

(The National Science Foundation)

H. H. Kuehl, K. Ko, W. S. Wang, M. Shoucri

Objective Summary: To obtain an understanding of the nonlinear effects on plasma resonance cones.

Approach Summary: This theoretical study is based on the fluid equations for the plasma with thermal and nonlinear effects included.

Progress: We have derived the nonlinear equation which governs the electric field of the resonance cones. For the case of a circular ring exciter, we are numerically integrating this equation to obtain the cone trajectory and the electric field.

Publication:

1. K. Ko and H. H. Kuehl, "Korteweg-de Vries Soliton in a Slowly-Varying Medium," Phys. Rev. Lett. 40,233 (1978).

2. Ion Resonance Heating Studies in a Tokamak

(The National Science Foundation)

D. G. Swanson

Objective Summary: To obtain more specific understanding of the heating mechanisms in the resonances occurring near the ion cyclotron frequency in a tokamak.

Approach Summary: Theoretical approaches are based on the inhomogeneous mode conversion and tunneling equation with a sink term to represent absorption. Experimental measurements are to be made on both Microtor and Macrotor in collaboration with staff at UCLA.

Progress: The Green's function for mode conversion tunneling equation has been obtained and applied to cyclotron harmonic heating and the two-ion hybrid resonance. Preliminary measurements on cavity modes have been made in Microtor, obtaining cavity mode number and cavity Q.

Diagnostic equipment for more detailed studies have been prepared.

Publications:

1. D. G. Swanson, "Cyclotron Harmonic Absorption Via the Green's Function for the Mode Conversion-Tunneling Equation," to be published in Physics of Fluids.

2. D. G. Swanson, "Mode Conversion and Absorption in a Denterium Plasma with a Hydrogen Impurity," Proceedings of 3rd Topical Conference on RF Heating, Pasadena, Calif. (1978).

3. Gregorian Corrected Toroidal Scanning Antenna

(USC Sponsored)

F. A. Young and W.V.T. Rusch

Objective Summary: To develop appropriate analytical techniques for the analysis of the generalized Gregorian corrected toroidal antennas, and to carry out studies of this class of scanning antenna system.

Approach Summary: To apply integral and asymptotic techniques (physical and geometrical optics) for the analysis of this type of antenna.

Progress:

(a) A complete and coherent derivation of formulas for calculating the caustic distances of the reflected wavefront from an arbitrary surface is developed.

(b) A test computer program is developed to check the results of the objective software called TORUS.

(c) The computer program TORUS is tested and proven to be adequate to take care of all design objectives.

(d) Parabolic, elliptic and spherical toroidal antennas with Gregorian correcting subreflectors are designed and evaluated. It is shown that the parabolic torus has superior performance.

Publications:

1. F. A. Young and W.V.T. Rusch, "Analysis of Toroidal Dual-Reflector Scanning Antennas," IEEE/AP-S Symposium USNC/URSI Spring Meeting, Washington, D.C., May 15-19, 1978.

4. Forward-Scattering from Cylinders of Triangular Cross-Section

(USC Sponsored)

W.V.T. Rusch

Objective Summary: The induced-field-ratios (IFR's) of conducting cylinders of triangular cross-section have been calculated. When the width of the cross-section is in the range of 1-2 wavelengths, the E-polarization IFR's are substantially less than the corresponding values for square or circular cross-sections. From the standpoint of RF aperture blocking of a reflector antenna, the triangular cross-section thus offers an advantageous cross-section for feed-support struts.

Approach Summary: To apply moment-method theory to calculate currents on triangular cylinders induced by incident E-polarization and H-polarization plane waves. These currents then directly yield the IFR values.

Progress:

(a) A complete set of computational data has been generated using the 360/44.

(b) A document describing the calculation, presenting the data, and commenting on the significance of the results has been prepared, reviewed, revised, and accepted for publication.

Publications:

1. W.V.T. Rusch, "Forward-Scattering from Cylinders of Triangular Cross-Section," IEEE Transactions on Antennas and Propagation.

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