

AD-A044 207

ROCKWELL INTERNATIONAL ANAHEIM CALIF ELECTRONICS OPE--ETC F/6 20/6  
OPTICAL WAVEGUIDE LENSES. II.(U)

JUN 77 D B ANDERSON, R L DAVIS, J T BOYD

F33615-76-C-1040

UNCLASSIFIED

C76-1187.13/501

AFAL-TR-77-60

NL

1 OF 3  
AD A044207



AD A 044207

AFAL-TR-77-60

2

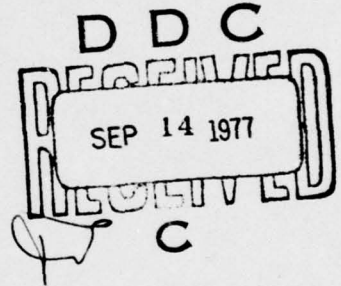
9



# OPTICAL WAVEGUIDE LENSES, II

ROCKWELL INTERNATIONAL CORPORATION  
ELECTRONICS RESEARCH CENTER  
3370 MIRALOMA AVENUE  
ANAHEIM, CALIFORNIA 92803

JUNE 1977



TECHNICAL REPORT AFAL-TR-77-60  
Final Report for Period 1 December 1975 - 1 December 1976

AD NO. \_\_\_\_\_  
DDC FILE COPY

Approved for public release; distribution unlimited.

AIR FORCE AVIONICS LABORATORY  
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES  
AIR FORCE SYSTEMS COMMAND  
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

This report has been reviewed by the Information Office (IO) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

*Michael C. Hamilton*  
MICHAEL C. HAMILTON  
Project Engineer  
Electro-Optics Techniques and  
Applications Group  
Electro-Optics Technology Branch

*Kenneth R. Hutchinson*  
KENNETH R. HUTCHINSON, Chief  
Electro-Optics Techniques and  
Applications Group  
Electro-Optics Technology Branch  
Electronic Technology Division

*William C. Schoover*  
WILLIAM C. SCHOONOVER, Chief  
Electro-Optics Technology Branch  
Electronic Technology Division

ACCESSION for	✓
NTIS	Whole Section <input checked="" type="checkbox"/>
DDC	Brief Section <input type="checkbox"/>
UNANNOUNCED JUSTIFICATION	<input type="checkbox"/>
BY	
DISTRIBUTION/AVAILABILITY CODES	
Dist.	SPECIAL
A	

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

VI A027214

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19 REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 18 AFAL-TR-77-60	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) 6 OPTICAL WAVEGUIDE LENSES, II.		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report 75 Dec 01 - 76 Dec 01
7. AUTHOR(s) 10 D. B./Anderson, R. R./August R. L./Davis, W. H./Southwell J. T./Boyd, C. L. Chen V. G. Kreismanis	14	6. PERFORMING ORG. REPORT NUMBER C76-1187.13/501
9. PERFORMING ORGANIZATION NAME AND ADDRESS Rockwell International Corporation Electronics Group; 3370 Miraloma Avenue Anaheim, CA 92803	15	8. CONTRACT OR GRANT NUMBER(s) F33615-76-C-1040 <i>new</i>
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Avionics Laboratory Air Force Wright Aeronautical Laboratory Air Force Systems Command Wright-Patterson Air Force Base, Dayton, OH 45422	16	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62204F 2001-02-35 12 427
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 9 Final Technical rept. 1 Dec 75 - 1 Dec 76	11	12. REPORT DATE June 1977
		13. NUMBER OF PAGES 276
		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE None
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited. 12 274p.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Thin-Film Waveguide, Generalized Luneburg Lenses, Beam Expansion, Lens Systems, Fourier Transform Lens, Cleaved Reflectors, Waveguide Coupled Photodetector Array with CCD Readout, and Multilayer Thin-Film Waveguide		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The results of an effort to further improve thin-film waveguide lens elements for implementation of the optical Fourier transform as may be employed for real-time RF spectral analysis is delineated. Thin-film waveguide positive inhomogeneous refractors identified as generalized Luneburg lenses were investigated calculating the performance and demonstrating their operation with quantitative measurement of the diffraction patterns. They were assembled as inverting beam expanders and lenses were used with retroreflectors for folding. → next page		

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

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

use 407 114 -

LB

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

The effort included the demonstration of waveguide coupled photodetector arrays for application in the spatial frequency plane of the transform lens. Charge coupled readout mechanization of the detectors was demonstrated. This latter waveguide coupled photodetector array was performed by the Department of Electrical and Computer Engineering at the University of Cincinnati.

The approach emphasized the application of  $Ta_2O_5$  as the high index film, together with Corning 7059 as a waveguide, all of which were deposited upon thermally-grown  $SiO_2$  as an isolation layer on a substrate. This structure permits the integration of the optical components with their electronic counterpart on a single substrate. The problem with scattering and its effect upon the dynamic range and resolution of the Fourier transform received consideration which, in part, led to the choice of this preferred material-structure because the thermally-grown oxide has yielded the smoothest low-scattering surface thus far identified upon which to deposit thin-film optical components.

A numerical procedure was developed to compute the performance of thin-film waveguide generalized Luneburg lenses and lens systems. Using the waveguide lens thickness profile, ray traces through the inhomogeneous lens can be determined together with the ray intercept in the image plane to provide wavefront phase error to determine the resulting intensity diffraction pattern. The procedure allows the introduction of various waveguide thickness profile errors.

Luneburg lenses having F/D extended from 0.5 to 10 have been fabricated. Representative patterns characterizing their performance have been included. Various shapes of deposition masks have been employed to control the radial lens thickness profile. Some measured diffraction spot widths approach  $5\mu$ . The measurements employ a reimaging technique external to the waveguide-lens structure with its prism couplers. Collimated beam expanders of X3 and X90 were demonstrated. Cleaved reflectors utilizing total internal reflection were demonstrated with transform lenses.

Application considerations, comparative lens technology, waveguide coupled photodetector technology, and the computational procedures for inhomogeneous lenses have been delineated for publication elsewhere and are reproduced herein. These preprints, publication and manuscript submissions derived from this program are:

D. B. Anderson, J. T. Boyd, M. C. Hamilton, and R. R. August, "An Integrated Optical Approach to the Fourier Transform"

D. B. Anderson, R. L. Davis, J. T. Boyd, and R. R. August, "Comparison of Optical Waveguide Lens Technologies"

J. T. Boyd and C. L. Chen, "Integrated Optical Waveguide and Charge Coupled Device Image Array"

C. L. Chen and J. T. Boyd, "Linear Charge Coupled Device Detector Array for Imaging Light Propagating in an Integrated Thin-Film Optical Waveguide"

W. H. Southwell, "Inhomogeneous Optical Waveguide Lens Analysis"

W. H. Southwell, "Index and Waveguide Thickness Profiles for Generalized Luneburg Lenses"

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

## FOREWORD

This document is the final technical report by Rockwell International Corporation, Electronics Research Center, Anaheim, California under Air Force Contract No. F33615-76-C-1040 under Project 2001, Task 02. It delineates the effort performed from 1 December 1975 through 1 December 1976. The authors submittal date was February 28, 1977. The Program Manager and Co-Principal Investigator was Mr. D. B. Anderson with Mr. R. L. Davis as Co-Principal Investigator. During this effort Professor J. T. Boyd, University of Cincinnati, served as a consultant.

A part of this effort was performed by the Department of Electrical and Computer Engineering at the University of Cincinnati under a sub-contract carried out under the direction of Professor Boyd and by Mr. C. L. Chen.

Sincere appreciation is expressed here to Mr. R. R. August of the Rockwell Electronics Research Center and to Mr. M. C. Hamilton, Air Force Avionics Laboratory, who jointly recognized and stimulated the application of thermally oxidized silicon as a new substrate for thin-film optical waveguide lenses.

The initial effort under this contract relating to telephoto lens systems, their field of view and field curvature, carried out by Mr. R. E. Eisele by geometric optical ray analysis, was included in Appendix B of the prior contractual final report "Optical Waveguide Lenses, I", AFAL-TR-76-54, and therefore is not included herein.

Stimulating discussions with Capt. W. J. Miceli (AFAL/DHO), Air Force Project Engineer, and Mr. M. C. Hamilton, AFAL, are greatly acknowledged. Capt. Miceli, who served as the Air Force Project Engineer for most of the contract's duration, has been transferred to the Air Force Cambridge Research Laboratory. Mr. Hamilton has fulfilled the Project Engineer responsibilities during the completion phase.

TABLE OF CONTENTS

	<u>PAGE</u>
I. INTRODUCTION . . . . .	1
A. BACKGROUND . . . . .	1
B. PROGRAM OBJECTIVE . . . . .	3
C. TECHNICAL APPROACH . . . . .	4
II. TECHNICAL DISCUSSION . . . . .	9
A. GENERAL . . . . .	9
1. Spectrum Analyzer Theory of Operation . . . . .	9
2. Optical Wavelength . . . . .	16
3. Waveguide Materials Compatible with Silicon Technology . . . . .	16
B. MULTILAYER THIN-FILM WAVEGUIDES . . . . .	25
1. Dielectric Waveguide Modes . . . . .	26
2. Thin-Film Waveguide Dispersion Data . . . . .	28
C. INHOMOGENEOUS REFRACTIVE WAVEGUIDE LENS SYSTEMS . . . . .	37
1. Classical Luneburg Lens . . . . .	37
2. Generalized Luneburg Lenses . . . . .	38
3. Generalized Luneburg Lens Analytical Data . . . . .	42
4. Waveguide Generalized Luneburg Lenses and Lens Systems Experimental Data . . . . .	85
5. Optical Waveguide Lens Characterization . . . . .	108
D. DEFLECTORS FOR THIN-FILM WAVEGUIDE . . . . .	113
E. OPTICAL WAVEGUIDE COUPLED PHOTODETECTOR ARRAYS . . . . .	116
1. Waveguide-Detector Coupling . . . . .	116
2. Photodetector Array . . . . .	117

## TABLE OF CONTENTS (CONTINUED)

	<u>PAGE</u>
3. Integrated Waveguide-Coupled Photodetector Arrays with Charge Coupled Readout . . . . .	119
III. REVIEW . . . . .	123
A. CONCLUSIONS . . . . .	123
B. ACKNOWLEDGMENTS . . . . .	125
APPENDIX A. AN INTEGRATED OPTICAL APPROACH TO THE FOURIER TRANSFORM By D. B. Anderson, J. T. Boyd, M. C. Hamilton, and R. R. August . . . . .	127
Abstract . . . . .	127
I. INTRODUCTION . . . . .	128
II. THEORY OF OPERATION . . . . .	129
III. SPECTRUM ANALYZER DESIGN CONSIDERATIONS . . . . .	135
IV. SPECTRUM ANALYZER IMPLEMENTATION . . . . .	140
V. CONCLUSIONS . . . . .	145
ACKNOWLEDGEMENTS . . . . .	145
REFERENCES . . . . .	146
APPENDIX B. COMPARISON OF OPTICAL WAVEGUIDE LENS TECHNOLOGIES By D. B. Anderson, R. L. Davis, J. T. Boyd and R. R. August . . . . .	157
Abstract . . . . .	157
I. INTRODUCTION . . . . .	158
II. OPTICAL WAVEGUIDE LENSES CONSIDERATIONS . . . . .	159
III. PLANAR LUNEBURG LENS . . . . .	162
IV. GEODESIC LENS . . . . .	165
V. EXPERIMENTAL WAVEGUIDE LENS DIFFRACTION PATTERNS . . . . .	168
VI. REFLECTORS . . . . .	170
VII. CONCLUSIONS . . . . .	172
ACKNOWLEDGEMENT . . . . .	172
REFERENCES . . . . .	173

## TABLE OF CONTENTS (CONTINUED)

	<u>PAGE</u>
APPENDIX C. INTEGRATED OPTICAL WAVEGUIDE AND CHARGE COUPLED DEVICE IMAGE ARRAY By J. T. Boyd and C. L. Chen . . . . .	185
Abstract . . . . .	185
I. INTRODUCTION . . . . .	186
II. DEVICE STRUCTURE . . . . .	188
III. DEVICE OPERATION . . . . .	193
IV. SUMMARY . . . . .	196
REFERENCES . . . . .	197
APPENDIX D. LINEAR CHARGE COUPLED DEVICE DETECTOR ARRAY FOR IMAGING LIGHT PROPAGATING IN AN INTEGRATED THIN-FILM OPTICAL WAVEGUIDE By C. L. Chen and J. T. Boyd . . . . .	203
Abstract . . . . .	203
I. INTRODUCTION . . . . .	208
II. DEVICE STRUCTURE AND OPERATION . . . . .	203
III. APPLICATIONS . . . . .	206
IV. SUMMARY . . . . .	207
REFERENCES . . . . .	208
APPENDIX E. INHOMOGENEOUS OPTICAL WAVEGUIDE LENS ANALYSIS By W. H. Southwell . . . . .	209
Abstract . . . . .	209
INTRODUCTION . . . . .	210
WAVE PROPAGATION IN LAYERED MEDIA . . . . .	211
GRADIENT-INDEX RAY TRACE . . . . .	213
EXIT BOUNDARY LOCATION . . . . .	216
CONVERGENCE AND AN EXTRAPOLATION TECHNIQUE . . . . .	217
WAVEFRONT ERROR . . . . .	220

## TABLE OF CONTENTS (CONCLUDED)

	<u>PAGE</u>
EXAMPLE OF THE GENERAL PROCEDURE ON A WAVEGUIDE PROFILE . . . . .	222
CONCLUSIONS . . . . .	222
REFERENCES . . . . .	223
APPENDIX F. INDEX AND WAVEGUIDE THICKNESS PROFILES FOR GENERALIZED LUNEBURG LENSES By W. H. Southwell . . . . .	231
Abstract . . . . .	231
INTRODUCTION . . . . .	232
NUMERICAL INTEGRATION OF THE INTEGRAL EQUATION FOR GENERALIZED LUNEBURG LENSES . . . . .	233
AN ANALYTICAL APPROXIMATION FOR $\omega(\rho, s)$ . . . . .	235
GENERALIZED LUNEBURG LENS INDEX PROFILES . . . . .	237
WAVEGUIDE LENS THICKNESS PROFILES . . . . .	238
DISCUSSION . . . . .	240
ACKNOWLEDGMENT . . . . .	241
REFERENCES . . . . .	242
IV. REFERENCES . . . . .	251

## LIST OF ILLUSTRATIONS

<u>FIGURE</u>		<u>PAGE</u>
1	Real-Time Spectrum Analyzer Implemented by Coherent Optical Fourier Transform	2
2	Three Cross Sections of Waveguide Luneburg Lens Which Result in Different Degrees and Different Types of Mode Conversion	18
3	Thin-Film Waveguide Attenuation Due to Evanescent Field Absorption in Silicon Substrate for Three Corning 7059 Overlay Waveguide Thicknesses as a Function of the Thermally-Grown SiO <sub>2</sub> Isolation Layer Thickness (After Chen)	20
4	Intensity Distribution of 6328Å Laser Radiation (a) Input Beam to Prism Coupler and (b) Output Beam From Prism Coupler after the Beam Has Traversed Through 9 cm of 7059 Waveguide on Thermally-Grown SiO <sub>2</sub>	21
5	Ray Trace of 6328Å Through Ta <sub>2</sub> O <sub>5</sub> Waveguide on Thermally-Grown SiO <sub>2</sub> on Si, 7 cm Path Length	22
6	Scanning Electron Micrograph of Luneburg Lens Surface (a) Transition Region (Edge), Magnification 270X with Artificial Artifact and Scan Outline, (b) Magnification 27,000X	23
7	Cross Section of Asymmetrical Multilayer Planar Dielectric Waveguide Showing Fourth Order Mode with Evanescent Field	25
8	Effective Refractive Index Versus Normalized Film Thickness for Ta <sub>2</sub> O <sub>5</sub> Film on SiO <sub>2</sub> Substrate	30
9	Effective Refractive Index Versus Normalized Film Thickness for 7059 Glass Film on SiO <sub>2</sub> Substrate	31
10	Effective Refractive Index of Composite Structure as a Function of Normalized Thickness of the Dense Overlay Film (Lens) Where the Overlay Film Normalized Thickness $kt = 2.37\pi$ for TE Modes Only	32
11	Expanded Scale of Figure 10 Showing the Effect of Three Substrates for TE Modes Only	33
12	Effective Refractive Index of Composite Structure as a Function of Normalized Thickness of the Dense Underlay Film (Lens) Where the Underlay Film Normalized Thickness $kt = 2.37\pi$ for TE Modes Only	34
13	Expanded Scale of Figure 12 Showing the Effect of Three Substrates for TE Modes Only	35

## LIST OF ILLUSTRATIONS (CONTINUED)

<u>FIGURE</u>		<u>PAGE</u>
14	Ray Trajectory Through Luneburg Lens Where f-Number = 0.5, S = 1	38
15	Ray Trace Geometry Through Luneburg Lens and Ray Trace Intercept Plot	39
16	Normalized Refractive Index Profile for Generalized Luneburg Lenses for Various S-Parameters Listed by Morgan and Southwell (f-Number = S/2)	41
17	Thin-Film Waveguide Luneburg Lens Design Requirement (the Minimum Ratio of Refractive Indices at Center Perimeter Versus Normalized Focal Length $F/r_0 = S$ )	42
18	Wavefront Phase Error and Corresponding Intensity Dif- fraction Pattern for Classic Geodesic Lens Ray Traced in Figure 14 for Perfect Radial Profile	45
19	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Classic Geodesic Lens Ray Traced in Figure 14 for Perfect Radial Profile Where the Image Plane Has Been Displaced by $.5\mu$ Yielding the Defocus Aberration	46
20	Wavefront Phase Error and Corresponding Intensity Dif- fraction Pattern for Classic Geodesic Lens Ray Traced in Figure 14 for Perfect Radial Profile Where the Image Plane has been Displaced by $10\mu$ Yielding the Defocus Aberration	47
21	Comparison of Computer Ray Traces for Luneburg Lens With f-Number of 2 for Refractive Index Profile $\cos^{0.211}$ Where (a) Thicknesses are Correct, (b) the Lens Thickness Has Been Increased by 10 Percent and (c) Underlying Wave- guide Thickness Has Been Increased by 10 Percent.	49
22	Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (Perfect Luneburg Lens)	52
23	Wavefront Phase Error and Corresponding Intensity Dif- fraction Pattern for Generalized Luneburg Lens Delineated in Figure 22 (Perfect Luneburg Lens)	53

## LIST OF ILLUSTRATIONS (CONTINUED)

<u>FIGURE</u>		<u>PAGE</u>
24	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 22 (Perfect Luneburg Lens) Where Defocusing has been Introduced to Create a $\pi/4$ Phase Error Across the Aperture	54
25	Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (.95 $P_1$ , .7 $P_2$ , 8.4901 $P_5$ )	56
26	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 25	57
27	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 25 (.995 $P_1$ , .997 $P_2$ , -1.0749 $P_5$ )	58
28	Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (1.04 $P_1$ , 10 $P_4$ , -36.2715 $P_5$ )	60
29	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 28	61
30	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 28 (1.0004 $P_1$ , 1.1 $P_4$ , .5752 $P_5$ )	62
31	Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (1.02 $P_1$ , 1.02 $P_2$ , 1.02 $P_3$ , 1.02 $P_4$ , 1.02 $P_5$ )	64
32	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 31	65
33	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 31 (1.0002 $P_1$ , 1.0002 $P_2$ , 1.0002 $P_3$ , 1.0002 $P_4$ , 1.0002 $P_5$ )	66

## LIST OF ILLUSTRATIONS (CONTINUED)

<u>FIGURE</u>		<u>PAGE</u>
34	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 31 (1.0002 P <sub>1</sub> , 1.0002 P <sub>2</sub> , 1.0002 P <sub>3</sub> , 1.0002 P <sub>4</sub> , 1.0002 P <sub>5</sub> ), New Focal Length -4μ.	67
35	Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (.98 P <sub>1</sub> , .98 P <sub>2</sub> , .98 P <sub>3</sub> , .98 P <sub>4</sub> , .98 P <sub>5</sub> )	68
36	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 35	69
37	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 35 (.98 P <sub>1</sub> , .98 P <sub>2</sub> , .98 P <sub>3</sub> , .98 P <sub>4</sub> , .98 P <sub>5</sub> ), New Focal Length +375μ.	70
38	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 35 (.9998 P <sub>1</sub> , .9998 P <sub>2</sub> , .9998 P <sub>3</sub> , .9998 P <sub>4</sub> , .9998 P <sub>5</sub> )	71
39	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 35 (.9998 P <sub>1</sub> , .9998 P <sub>2</sub> , .9998 P <sub>3</sub> , .9998 P <sub>4</sub> , .9998 P <sub>5</sub> ), New Focal Length +4μ.	72
40	Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (1.05 P <sub>1</sub> , 1.35 P <sub>2</sub> , P <sub>3</sub> , P <sub>4</sub> , 10.2680 P <sub>5</sub> ).	74
41	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 40.	75
42	Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (.96 P <sub>1</sub> , P <sub>2</sub> , P <sub>3</sub> , -10 P <sub>4</sub> , 48.6717 P <sub>5</sub> ).	76

## LIST OF ILLUSTRATIONS (CONTINUED)

<u>FIGURE</u>		<u>PAGE</u>
43	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 42.	77
44	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 42 ( $.9996 P_1$ , $P_2$ , $P_3$ , $-1.1 P_4$ , $11.8249 P_5$ ).	78
45	Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (Perfect Luneburg Lens).	80
46	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 45 (Perfect Luneburg Lens).	81
47	Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (Perfect Luneburg Lens).	82
48	Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 47 (Perfect Luneburg Lens).	83
49	Computer-Generated (HP9830) Ray Traces Through Beam Expansion System for (a) Unity Magnification, (b) X2 Magnification, and (c) X4 Magnification.	84
50	Cross Section of Various Deposition Mask Shapes Investigated to Control the Waveguide Luneburg Lens Radial Thickness Profile.	87
51	Operation of Generalized Luneburg Lens Beam Expander (X3) Using $Ta_2O_5$ on 7059 on Thermally-Grown $SiO_2$ on Si (a) Scattering of Individual Ray Traces Through Lenses Using 6328 Å Radiation Extending Over 1 cm Aperture (Output), (b) Scattering of Continuous Wide Aperture Beam Through Same Beam Expander Using Uniform Illumination.	88

## LIST OF ILLUSTRATIONS (CONTINUED)

<u>FIGURE</u>		<u>PAGE</u>
52	Axial Ray of Generalized Luneburg Lens Beam Expander (X3) of Figure 51 Showing Halo Scatter Around Expansion Lens, Scatter From Surface Defect, and Scatter of Objective and Throughput Intensity Output.	89
53	Operation of Generalized Luneburg Lens Beam Expander (X3) Showing Scattering of a Single Ray Where Mode Conversion Occurs in the First Lens Producing Two Refraction Angles and Mode Conversion Occurs Again Showing Two Ray Traces for the $TE_0$ Mode Through the Remainder of the Expander.	89
54	Output Beam Intensity Distribution From Generalized Luneburg Lens Beam Expander (X3) Shown in Figure 51	90
55	Macro Photograph of Luneburg Lens Beam Expansion System (Plan View) Showing Newton Ring of the Objective Thickness Profile. Expansion Ratio 90X.	91
56	Enlargement of the Expansion Luneburg Lens in Figure 55 Showing Newton Rings Depicting the Radial Thickness Profile (radial asymmetry due to offset during deposition).	92
57	Individual Ray Traces Through Generalized Luneburg Lens Beam Expander (X90) With Input Applied to Objective Producing Convergence on Expander Lens Showing Throughput Scattered From Edge of Substrate.	93
58	Individual Ray Traces Through Generalized Luneburg Lens Beam Expander (X90) With Input Applied to Objective Producing Convergence on Expander Lens Showing Throughput Scattered From Edge of Substrate With Two Additional Ray Traces Which Do Not Impinge Upon the Small Expansion Lens.	93
59	Operation of Generalized Luneburg Lens Beam Expander (X90) Shown in Figure 55 Using $Ta_2O_5$ Lens Overlays on Thermally-Grown $SiO_2$ on Si (Same as Figure 51).	94
60	Generalized Luneburg Lens Beam Expander (X90) With Prism Output Coupler Showing Output Beam Collimation.	94

## LIST OF ILLUSTRATIONS (CONTINUED)

<u>FIGURES</u>		<u>PAGE</u>
61	Ray Traces Through Generalized Luneburg Lens Having Focal Length of 7.5cm Using Cleaved Retroreflectors.	95
62	Ray Traces Through Generalized Luneburg Lens Showing Halo Scatter in the Lens Region and Mode Conversion With Equal Power in $TE_0$ and $TE_1$ Modes Providing a Focal Length of 3.4 cm and 10.1 cm, Respectively.	96
63	Collage of Diffraction Patterns for the Same Generalized Luneburg Lens Where the Input Aperture Has Been Varied to Observe the Zonal Effects Upon the Diffraction Pattern, Lens $Ta_2O_5$ -on-7059 on $SiO_2/Si$ , The Focal Length = 4.5 cm, Uniform Illumination.	98
64	Continuation of Collage of Diffraction Patterns for the Same Generalized Luneburg Lens Where the Input Aperture Has Been Varied to Observe the Zonal Effects Upon the Diffraction Pattern, Lens $Ta_2O_5$ -on-7059 on $SiO_2/Si$ , The Focal Length = 4.5 cm.	99
65	Collage of Diffraction Patterns for the Same Generalized Luneburg Lens Where the Mask Edge Shape Has Been Varied to Observe Effects Upon Diffraction Pattern, Lens $Ta_2O_5$ -on-7059 on $SiO_2/Si$ , Focal Length = $\sim 11$ cm, Input Gaussian Beam Width 2.4mm @ 8.6 dB.	101
66	Collage of Diffraction Patterns for the Same Generalized Luneburg Lens Where the Mask Edge Shape Has Been Varied to Observe Effects Upon Diffraction Pattern, Lens $Ta_2O_5$ -on-7059 on $SiO_2/Si$ , Focal Length = $\sim 11$ cm, Input Illumination Uniform $W=6$ mm.	102
67	Collage of Diffraction Patterns for Generalized Luneburg Lens Where the Mask Thickness and Conical Edge Has Been Varied to Observe Effects Upon Diffraction Pattern, Lens $Ta_2O_5$ -on-7059 on $SiO_2/Si$ , Focal Length = 10 cm, Gaussian Beam Width 2.4 mm @ 8.6 dB.	103
68	Generalized Luneburg Lens Diffraction Pattern (Same as Figure 66, Section (b), Except for the Use of Reimaging System), Focal Length $F=10$ cm, Uniform Illumination $W=6$ mm.	104

## LIST OF ILLUSTRATIONS (CONTINUED)

<u>FIGURE</u>		<u>PAGE</u>
69	Generalized Luneburg Lens Diffraction Pattern, Ta <sub>2</sub> O <sub>5</sub> Lens-on-BaO-rich 7059-on-7059, Lens Diameter 11.2 mm, Focal Length 12 mm, Using (a) Cosine Illuminated 5 mm Aperture and (b) 2.5 mm Irised Section of (a) Approximately Uniform).	106
70	Schematic of Reimaging Technique to Characterize Thin Film Waveguide Lenses.	109
71	Photograph of Apparatus for Measurement of Thin-Film Waveguide Lenses Using Fiber Probe of Reimaging Beam.	110
72	Measured Transverse Beam Intensity Profiles in the Region of the Focus for Two Types of Reimaging Lenses on Both Sides of the Focus Using a 1-Micron Diameter Pin Hole and 6328 Å Radiation (a) Spectra-Physics Model 333 Objective, FL=86mm, f=3.5 and (b) Wollensak Oscillo-Raptor FL=75 mm, f=1.9.	112
73	Thin-Film Waveguide Retro-reflector Using Total Internal Reflection Employing 7059 Waveguide on Thermally-Grown SiO <sub>2</sub> on {100} Si with Input Ray Incident on Near Perfect First Cleaved Edge and with Imperfect Reflector at Second Edge.	114
74	Thin-Film Waveguide Reflector Employing 7059 Waveguide on Thermally-Grown SiO <sub>2</sub> on Si Using {110} Cleaved Edge with Aluminization on Edge Only.	114
75	Scanning Electron Micrograph of Cleaved Reflector Through Ta <sub>2</sub> O <sub>5</sub> Overlay Luneburg Lens on Corning 7059 Waveguide on Thermally-Grown SiO <sub>2</sub> Isolation Layer on Si Substrate: (a) Untouched {110} face, (b) Intentionally etched (HF) to delineate each of the oxide layers.	115
76	Photographic Collage of Waveguide Coupled Photodetector Array Showing (a) Plan View of Array With Lead Fan-Out, (b) Array With Luneburg Lens, and (c) Apparatus Employed to Demonstrate Operation of Luneburg Lens Focused on Detector Array.	118

## LIST OF ILLUSTRATIONS (CONTINUED)

<u>FIGURE</u>		<u>PAGE</u>
77	(a) Device Configuration of the Integrated Optical Waveguide-CCD Detector Array (b) Surface Potential Profile During Integration and Transfer Cycles (c) Electrode Waveforms for the Control Gate (CG), the Charge Integration Gate (CIG), the Transfer Gate (TG), and the Phase 1 and Phase 2 Gates ( $\phi_1$ and $\phi_2$ ).	120
78	(a) Circuitry for Generating Two-Phase Clock Voltages ( $\phi_1$ and $\phi_2$ ) (b) Circuitry for Generating the Transfer Gate (TD) and Charge Integration Gate (CIG) Electrode Waveforms (c) Circuitry for Generating Serial Input Gate (IG) Signal for CCD Charge Transfer Efficiency Measurement.	122
1A	Coherent Optical Fourier Transform Spectrum Analyzer Schematic.	149
2A	Integrated Optical Fourier Transform "Chip" Layout for F/D 6 and 7.6 cm Dia. Structure includes Corning 7059 waveguide film on thermally-grown $\text{SiO}_2$ isolation layer on {100} Si substrate with overlays of $\text{Ta}_2\text{O}_5$ , ZnO, and Al.	149
3A	Spectrum Analyzer Time-Bandwidth-Product.	150
4A	Optical Fourier Transform Spatial-Temporal Resolution Limited by Either Detector Period or Aperture Diffraction where Aperture Distribution Ranges from Uniform to Truncated Gaussian.	151
5A	Thin-Film Waveguide Attenuation due to Evanescent Field Absorption in Si Substrate for Corning 7059 Overlay Waveguide Thickness and Thermally-Grown $\text{SiO}_2$ Isolation Layer Thickness [23].	152
6A	Thin-Film Luneburg Lenses Using $\text{Ta}_2\text{O}_5$ on Corning 7059-on-7440 Glass: (a) plan view of beam expansion system showing Newton rings indicating the radial tapered thickness profile, (b) scattering of ray traces through beam expansion system using 6328 Å radiation, and (c) circumferential ray trace around Luneburg lens.	153

## LIST OF ILLUSTRATIONS (CONTINUED)

<u>FIGURE</u>		<u>PAGE</u>
7A	Cleaved Retroreflector Employing Corning 7059 Waveguide on Thermally-Grown SiO <sub>2</sub> -on-Si.	153
8A	Surface Elasto-Optic Bragg-Type Diffraction Efficiency for Waveguide Structures: (a) Ta <sub>2</sub> O <sub>5</sub> -on-Si[3], (b) Nb <sub>2</sub> O <sub>5</sub> -on-LiNbO <sub>3</sub> , and (c) Ti or Ni-indiffused-LiNbO <sub>3</sub> [10], for TM modes at 290 MHz.	154
9A	Calculated Surface Elastic Wave Velocity Dispersion for Thermally-Grown SiO <sub>2</sub> Overlay on Si Substrate {001} Cut, [100] Propagation, [33].	154
10A	Calculated Electronic-Elastic Conversion Loss for Two Wideband, Bragg-Type Interdigital Transducer Arrays after Tsai [14].	155
11A	A Luneburg Lens Integrated with a Linear Array of Photo-detectors Arranged in Groups.	155
12A	Hybrid Coupling of (GaAl)As Laser to Ga <sub>0.3</sub> Al <sub>0.7</sub> As Waveguide Via the Laser Fabry-Perot Side Wall Evanescent Field.	156
1B	Homogeneous Thin-Film Waveguide Refractors Using Ta <sub>2</sub> O <sub>5</sub> on Corning 7059 on 7440 Glass: (a) a plan view of negative refractors showing Newton rings indicating tapered edges, (b) scattering of ray traces through telephoto lens system using 6328 Å radiation, and (c) same as (b) except using 1 cm wide input beam.	175
2B	Thin-Film Waveguide Luneburg Lens: (a) cross-section using high index underlayer with continuous waveguide, and (b) ray traces through generalized Luneburg lens.	176
3B	Normalized Radial Effective Refractive Index Profile as a Ratio ( $n_{\text{lens}}/n_{\text{waveguide}}$ ) for Several Values of f-number (F/D).	177
4B	Thin-Film Waveguide Luneburg Lens Design Requirement (the minimum ratio of refractive indices at center per perimeter versus normalized focal length (F/r <sub>0</sub> )).	177

## LIST OF ILLUSTRATIONS (CONTINUED)

<u>FIGURE</u>		<u>PAGE</u>
5B	Generalized Waveguide Luneburg Lens Using Ta <sub>2</sub> O <sub>5</sub> on 7059 on 7440: (a) plan view showing Newton Rings indicating the radial tapered thickness profile, (b) scattering of individual ray traces through lens using 6328 Å radiation extending over 5mm aperture, (c) same as (b) except increased aperture is showing aberration due to incorrect radial thickness profile, and (d) same as (b) except using continuous 5mm wide beam.	178
6B	Waveguide Luneburg Lens Radial Profiles: (a) radial lens thickness profile derived from Newton rings depicted in Fig. 5B, (b) ideal effective refractive index profile, and (c) calculated effective refractive index profile using data of (a).	179
7B	A Thin-Film Waveguide Geodesic Lens: (a) cross-section, and (b) projected ray trace through geodesic lens.	179
8B	Spherical Waveguide Geodesic Lens f-number as a Function of the Depression Angular Sector.	180
9B	Circumferential Ray Trace of Rinehart-Luneburg Geodesic Lens Using Corning 7059 on 7440.	180
10B	Experimentally Measured Waveguide Lens Diffraction Patterns: (a) planar thin-film Luneburg lens using Ta <sub>2</sub> O <sub>5</sub> on BaO-rich 7059 on 7059 and a uniform illuminated aperture of 5 mm, F=12 mm, and (b) spherical depression waveguide geodesic lens using 7059 on 7440 using 7 mm Gaussian input beam depicted in Fig. 11B, F=20 mm.	181
11B	Waveguide Scattering Using 7059 Waveguide on Thermally-Grown SiO <sub>2</sub> on Si: (a) Gaussian input beam profile, and (b) measured output beam profile after propagating through BK-7 input/output coupling prisms and 5 cm of 7059 waveguide.	182
12B	Thin-Film Waveguide Reflector Using Cleaved Metallized Edge (Al) of 7059 Waveguide on Thermally-Grown SiO <sub>2</sub> on Si.	183

## LIST OF ILLUSTRATIONS (CONTINUED)

<u>FIGURE</u>		<u>PAGE</u>
1C	Integrated Optical Waveguide and CCD Detector Array.	199
2C	Detector Length for Efficient Coupling of Light from Waveguide to Detector as a Function of Waveguide Thickness for a Waveguide Refractive Index $n = 1.61$ .	200
3C	Linear Photodiode Imaging Array Coupled to a Two-Phase, Overlapping Gate CCD.	201
4C	(a) Light Propagating in an Optical Waveguide from the Prism Coupler to the Integrated CCD Detector Array. (b) CCD Output Signal Corresponding to Illumination Shown in (a).	202
1D	Integrated Optical Waveguide and CCD Detector Array.	204
2D	Detector Length for Efficient Coupling of Light from Waveguide to Detector as a Function of Waveguide Thickness for a Waveguide Refractive Index $n = 1.61$ .	205
3D	Linear Photodiode Imaging Array Coupled to a Two-Phase, Overlapping Gate CCD.	205
4D	(a) Light Propagating in an Optical Waveguide from the Prism Coupler to the Integrated CCD Detector Array. (b) CCD Output Signal Corresponding to Illumination Shown in (a).	206
5D	Integrated Optical Spectrum Analyzer Configuration.	206
6D	Detector Array Center-to-Center Spacing as a Function of Spectrum Analyzer Frequency Resolution.	207
1E	Cross-Section of Multilayer Planar Dielectric Waveguide. Optical Propagation is from Left to Right.	224
2E	Ray Path Geometry Showing Ray Position Vector $r$ and the Ray Vector $s$ . The Scalar $s$ is the Distance Along the Path and the Vector $s$ is a Unit Vector Tangent to the Path.	224
3E	Plot of the Ray Paths Traced Through the Classical Luneburg Lens Described by Eq. (31).	225

## LIST OF ILLUSTRATIONS (CONTINUED)

<u>FIGURE</u>		<u>PAGE</u>
4E	Plot of the Ray Trace Error as a Function of the Step Size $\Delta s$ for a 2 cm Radius Classical Luneburg Lens Shown in Fig. 3E. It is Shown that Extrapolation Techniques can Yield Required Accuracy Without Using Extremely Small Step Size.	225
5E	Wavefront Phase Error in Radians in the Exit Pupil of the Luneburg Lens of Fig. 3E as Derived from the Ray-Trace Technique Using $\lambda=0.633\mu$ . This residual phase error is due to the numerical ray-tracing, but may be made as small as desired at the expense of more computer running time. However, the error shown is within the diffraction limit.	226
6E	Diffraction Pattern Showing the Log of the Intensity in the Image Surface for the Luneburg Lens of Figs. 3E and 5E. This pattern agrees with the sinc function squared.	226
7E	Phase Error of the Luneburg Lens of Fig. 3E Defocused by $0.5\mu$ .	227
8E	Diffraction Pattern Resulting from Defocused Luneburg Lens Shown in Fig. 7E. A 64-point fast Fourier transform algorithm was used to generate this pattern.	227
9E	Waveguide Layer Profile Represented by $\cos^{.18}$ Dependence (upper curve) and $\cos^{.25}$ Dependence (lower curve). Referring to Fig. 1E, the other waveguide parameters used to trace this lens are: $n_1=1$ , $n_2=2$ , $n_3=1.565$ , $n_4=1.47$ , $d=0.75\mu$ , and $\lambda=0.633\mu$ .	228
10E	Ray Plots of Waveguide Lens Described in Fig. 9E: (a) with $\cos^{.18}$ dependence profile; (b) with $\cos^{.25}$ dependence profile; (c) with $\cos^{.211}$ dependence profile.	229
1F	Cross-Section of Multilayer Planar Dielectric Waveguide.	248
2F	Index Profiles for Generalized Luneburg Lenses. From top to bottom, the lenses have full aperture f-numbers of $f/1$ , $f/1.5$ , $f/2.5$ , and $f/4.5$ .	248

## LIST OF ILLUSTRATIONS (CONCLUDED)

<u>FIGURE</u>		<u>PAGE</u>
3F	Waveguide Overlay Thickness Profiles for the Generalized Luneburg Lens Profiles Shown in Fig. 2F for the Waveguide Parameters Listed in Table V.	249
4F	Ray Trace of the $s=2$ Generalized Luneburg Lens Using the Index Profile Derived from Eq. (7).	249
5F	Phase Error Profile in the Pupil Plane of the $s=2$ Generalized Luneburg Lens Using the Approximation Eq. (7) to Derive the Index Profile.	250
6F	Intensity Diffraction Pattern Using Logarithmic Scale in the Image Surface for the Luneburg Lens of Figs. 4F and 5F. (Note that this coincides with a diffraction-limited distribution).	250

## I. INTRODUCTION

### A. BACKGROUND

The development of electronic integrated circuits and their application to our defense systems has led to increased reliability and life; reduced cost, size and weight; and reduced primary power requirements. The example set by this development has provided the justification for a corresponding effort addressed to an integrated optical circuit technology with the expectation of realizing some of the same benefits for optical computers, sensors and communication systems, while simultaneously providing an increased information handling capacity.

One important application of integrated optics is in the field of coherent signal processing employing the Fourier transform.<sup>1,2</sup> Optical signal processing is admirably suited to perform linear analog operations such as matrix products, the Fourier transform integration and related correlation and convolution.<sup>3-5</sup> The process employs a coherent source, modulation function(s) and the detection function to be performed throughout the signal spatial field with one or more Fourier transform lenses between. The optical signal processing function is usually performed for a two-dimensional image, whereas an integrated optics format will limit the processing to a single transverse dimension as a function of time.

For an application such as spectral analysis of microwave signals extending over a broad expanse of the spectrum, this one-dimensional characteristic is not a limitation. The optical Fourier transform applied to spectral analysis of microwave signal is attractive because it provides "wide open" continuous response.<sup>2</sup> The schematic diagram of Figure 1 illustrates the essential components of an optical Fourier transform process applied to spectral analysis. An integrated optics implementation of the spectrum analyzer will contain a coherent source (presumably a (GaAl)As distributed-feedback laser)<sup>6,7</sup> coupled to a thin-film optical waveguide,<sup>8</sup> an assortment of thin-film waveguide lenses performing the beam expansion and the transform functions, together with a spatial modulator<sup>9-14</sup> (presumably a surface elasto-optic interaction within a

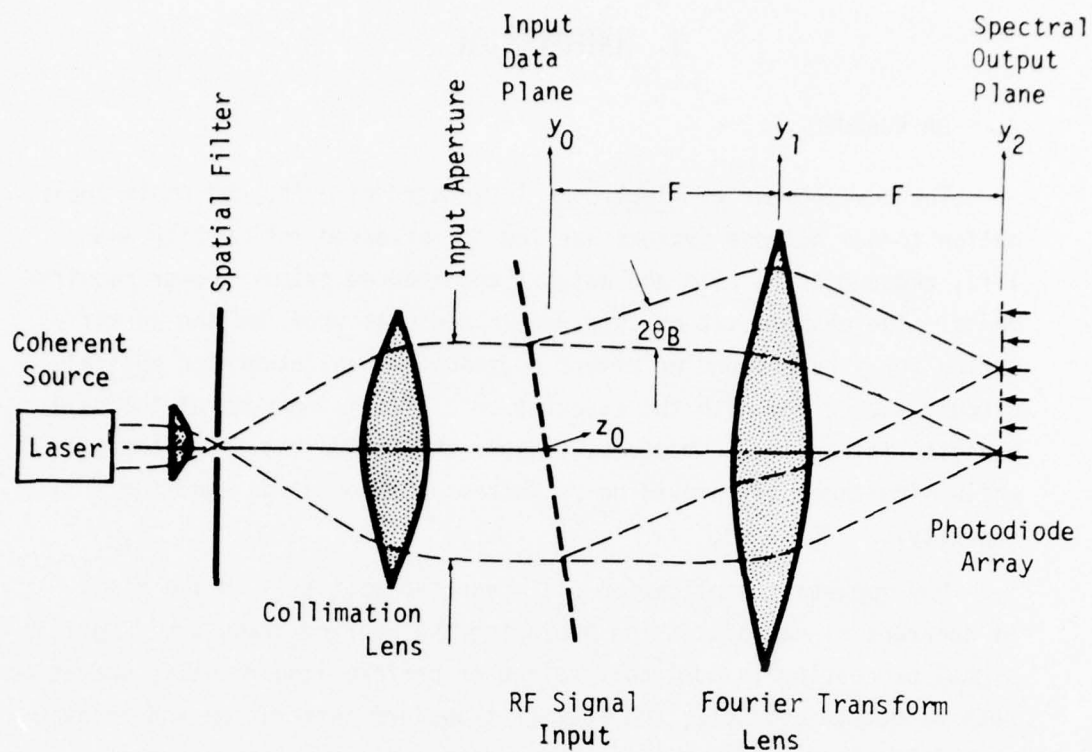


Figure 1. Real-Time Spectrum Analyzer Implemented by Coherent Optical Fourier Transform

common thin-film) and a thin-film detector array<sup>15</sup> responsive to the laser with a temporal bandwidth encompassing the down-converted convolved microwave signal. The microwave signal is temporarily "stored" as a waveform in the spatial modulator which is simultaneously accessed in its entirety by the optical field and transformed into various spectral components spatially separated by the lens and detected in an array. Use of the integrated optics format for the spectrum analyzer on a single substrate provides the necessary mechanical structure to obtain rigidity between the various optical elements. It also provides the potential for a substantial reduction in size and weight of optical signal processing systems.

The optical Fourier transform process requires a series of lenses with sufficient aperture and resolution to encompass the time-spatial-

bandwidth-product system requirements. Near diffraction-limited lens performance and low scattering are necessary to obtain a useful resolution and dynamic range. Lens systems designed to fulfill these requirements using conventional optical elements in three dimensions is a highly developed art.<sup>5</sup> The corresponding implementation of lenses in two-dimensional thin-film waveguides constitutes a developing technology of which this report constitutes a second year's effort sponsored by the Air Force Avionics Laboratory. The first year's effort<sup>16</sup> addressed various approaches to lenses, lens systems and reflectors, as may be required for implementation of the optical Fourier transform function in an integrated optics format, whereas this second effort has addressed a most promising approach and has proceeded towards its optimization.

#### B. PROGRAM OBJECTIVE

Basic to the development of an integrated optics technology are the requirements for (1) a coherent source (2) the general modulation function, both temporal and spatial (3) the detection function and (4) a waveguide technology to appropriately interconnect these components, all of which must be implemented as a planar structure compatible with various thin-film processes used in the semiconductor industry. It is the optimization of thin-film waveguide lenses, lens systems and reflectors for use in a real-time spectrum analyzer to which this program is addressed.

Optical lens elements within a thin-film waveguide media have several additional design freedoms and some restrictions when compared with conventional optical systems. First, the lens system is entirely immersed in the thin-film waveguide which has an effective refractive index determined by the choice of materials and film thickness. The ambient waveguide effective refractive index may be greater than, or less than, the index employed for the lenses. The available range of refractive indices is restricted to values greater than that of the substrate bulk refractive index to preserve wave binding within the thin-film waveguide. Second, the use of nonplanar substrates permits the formation of lenses of uniform refractive index by changes of the path length because the rays traverse geodesics. The maximum refractive index is usually limited by

the thin-film waveguide material except for geodesics where the path length increase synthesizes the larger value. Third, inhomogeneous lens elements are feasible using homogeneous dielectrics and may be produced by graded waveguide film thickness. Consideration of these various ramifications was included in the initial effort, Optical Waveguide Lenses, I.<sup>16</sup> One important conclusion derived from this initial effort suggested that generalized thin-film Luneburg lenses were a favored approach for optimization in integrated optics format.

Referring to Figure 1, the essential lens elements include a beam expansion system and a Fourier transform lens. In addition to the requirement for near diffraction-limited performance and low scattering, the design of these lenses must consider the length of the optical axis because the Fourier transform "chip" substrate area is limited. Reasonable substrate dimensions are comparable to that employed in the electronic circuit industry. Therefore, consideration of the telephoto effect so as to reduce the physical focal length of the Fourier transform lens received attention during the initial program, Optical Waveguide Lenses, I. The required large compression of the physical focal length, field of view and field curvature negated further consideration of the telephoto effect in preference to a folded optical system. It was also necessary to develop *plane refractors for folding* so as to minimize the substrate area employed.

Characterization of optical element performance is essential for design and applications requiring near diffraction-limited performance. Various techniques are available to characterize conventional three-dimensional lens systems. However, new techniques were necessary to characterize the performance of thin-film optical elements because they are imbedded within the film and, therefore, their development has been included and applied.

#### C. TECHNICAL APPROACH

Based upon the result of the preceding program, Optical Waveguide Lenses, I, this current effort, Optical Waveguide Lenses, II, reported herein, addresses inhomogeneous thin-film waveguide lenses, lens systems and reflectors which are apposite to the optical Fourier transform function continuing the emphasis upon waveguide material-structures with compatible

planar processes. The basic refractive element considered is the positive generalized Luneburg lens (with arbitrary axial foci equal to, or greater than, the lens diameter). Two of these lenses with comparatively short focal length are employed for the beam expansion while a single lens with a longer focal length is employed for the Fourier transform function using reflectors for folding.

Specific considerations during the current effort have included (1) optimization of inhomogeneous lens radial refractive index profile to more closely approach the diffraction-limited performance, (2) reduction of scattering losses due to the waveguide films, substrate isolation layers and optical element boundaries, (3) establishment of lens reproducibility, alignment and positioning without regard to the specific profiles and (4) suppression of mode conversion within optical elements. As a result, the capability to fabricate generalized Luneburg lenses with specific parameters has been established, together with the means to characterize and predict their performance.

Motivated by the potential advantages of integration of both optical and electronic components, a new waveguide material-structure was identified, developed and used to create the deliverable lens systems. The new waveguide material-structure exploits thermally-oxidized silicon as an isolation layer between the waveguide and the supporting silicon substrate. Typical Luneburg lenses employ  $Ta_2O_5$  as an overlayer or underlayer in conjunction with Corning 7059 glass employed as the waveguide. The thermally-oxidized substrate with appropriate careful processing has proven to yield the lowest scattering substrate thus far identified. All of the effort reported herein has utilized this waveguide material-structure. It should be noted this structure is also compatible with the waveguide coupled detector array and spatial modulator requirements for the optical Fourier transform "chip" using an overlayer of ZnO as the piezoelectric!<sup>17-22</sup>

A part of this program has been directed to the waveguide coupled photodetector array for use in the spatial frequency plane of the optical Fourier transform "chip." Lenses and waveguide have been formed and characterized using the thermally-grown  $SiO_2$  on Si substrate where the

SiO<sub>2</sub> isolation layer has been removed for coupling of the waveguide to the photodetector using the evanescent field. This waveguide photodetector array investigation has been carried out by the Department of Electrical and Computer Engineering at the University of Cincinnati under a subcontract under the direction of Professor J. T. Boyd.

The following Technical Discussion is organized by subdivisions into the reporting of specific results complemented by a series of appendices constituting scientific papers in the process of publication in the open literature. The appendices include:

- (A) D. B. Anderson, J. T. Boyd, M. C. Hamilton, and R. R. August, "An Integrated Optical Approach to the Fourier Transform," to be published, IEEE Journal of Quantum Electronics Special Issue, Integrated Optics, April, 1977.
- (B) D. B. Anderson, R. L. Davis, J. T. Boyd, and R. R. August, "Comparison of Optical Waveguide Lens Technologies," to be published, IEEE Journal of Quantum Electronics Special Issue, Integrated Optics, April, 1977.
- (C) J. T. Boyd and C. L. Chen, "Integrated Optical Waveguide and Charge Coupled Device Image Array," to be published, IEEE Journal of Quantum Electronics Special Issue, Integrated Optics, April, 1977.
- (D) C. L. Chen and J. T. Boyd, "Linear Charge Coupled Device Detector Array for Imaging Light Propagating in an Integrated Thin-Film Optical Waveguide," Proceedings Conference on Charge Coupled Device Technology and Applications, sponsored by the National Aeronautics and Space Administration, November 30 - December 2, 1976, Washington, D. C.
- (E) W. H. Southwell, "Inhomogeneous Optical Waveguide Lens Analysis," to be published, Journal of Optical Society of America, Aug. 1977.
- (F) W. H. Southwell, "Index and Waveguide Thickness Profiles for Generalized Luneburg Lenses," to be published, Journal of Optical Society of America, Aug. 1977.

An effort has been made to avoid duplication between the Technical Discussion and the various appendices. Therefore, reading of the appendices is

suggested prior to delving into the technical discussion section in depth. Appendix (A) introduces the optical Fourier transform design considerations with supplementary details provided in the following section. Appendix (B) compares various thin-film waveguide lens technologies largely encompassing the work of the prior effort, Optical Waveguide Lenses I. Appendices (C) and (D) are the result of this effort which has been performed at the University of Cincinnati. Appendices (E) and (F) are also the result of this effort directed to the computation of lens performance to provide a tolerance analysis, more fully developed in the following section.

## II. TECHNICAL DISCUSSION

### A. GENERAL

Some general properties of optical Fourier transform signal processing are delineated herein prior to detailed discussion of thin-film optical waveguide lenses, reflectors and lens systems. The following analyses should be considered simultaneously with Appendix A, "An Integrated Optical Approach to the Fourier Transform." Both of these analyses consider various aspects of the spectrum analyzer theory of operation which is essential background for the development of thin-film optical waveguide lenses, reflectors and lens systems delineated herein because the optical performance of these elements has direct impact upon spectrum analysis.

The optical Fourier transform as an electronic spectrum analyzer is illustrated in Figure 1. Coherent laser light propagating in a thin-film waveguide is expanded and collimated prior to being incident on a surface elastic wave which has been excited by the incoming electrical signal. Diffraction of light by the surface elastic wave occurs in such a way that light is diffracted at different angles corresponding to different electrical signal frequency components. For a range of signal frequencies and surface elastic wave intensities, the deflection angle is linearly proportional to the signal frequency, and the diffracted light amplitude is linearly proportional to the signal surface elastic wave amplitude. A waveguide lens is then positioned so as to perform a one-dimensional Fourier transform. Signal spectral information which is represented by the angular composition of light emerging from the surface elastic wave region then becomes represented by the transverse spatial variation of light in the Fourier transform plane. The intensity of the light spatial distribution in the transform plane corresponds to the signal power density spectrum and can then be converted to an electrical signal by means of a detector array.

#### 1. Spectrum Analyzer Theory of Operation

Considering the optical waveguide geometry shown in Figure 1, the field amplitude  $E(y_2)$  in the transform plane is related to the field amplitude in the input plane  $E(y_1)$  according to<sup>23</sup>

$$E(y_2) = b \int_{-\infty}^{\infty} E(y_0) e^{i \frac{kN_e(m)y_2}{F} y_0} dy_0, \quad (1)$$

where  $y$  is oriented along the waveguide surface perpendicular to the axis of wave propagation ( $z$  axis) and the  $x$  axis is normal to the waveguide surface. The  $x$  dependence of the field contains the form of the waveguide modes and will generally be suppressed for conciseness in the present development. However, its effect on Bragg diffraction is incorporated.<sup>10</sup> In (1),  $F$  is the lens focal length,  $N_e(m)$  is the thin-film waveguide mode effective refractive index for the  $m$ th order mode,  $k = 2\pi/\lambda$  where  $\lambda$  is the optical wavelength, and  $b$  is a complex constant. As use of the optical Fourier transform for spectral analysis in an integrated optical format dictates minimizing substrate area, the separation of the lens and the input plane should approach zero. The resulting phase quadrature term in the Fourier transform<sup>23</sup> is of no consequence since only the signal power density spectrum is detected. If a uniform plane wave over an aperture  $D$  is present at the input, the output has the familiar form:

$$E_0(y_2) = bD \operatorname{Sinc} \left( \frac{kN_e(m)Dy_2}{2F} \right), \quad (2)$$

where  $\operatorname{sinc} x = \sin x/x$ . The  $1/2$  width between nulls of this diffraction pattern is

$$\Delta y_2 = \frac{\lambda F}{N_e(m)D} \quad \cdot \quad (\text{Plane Wave}) \quad (3a)$$

For the more realistic situation of a Gaussian transverse dependence truncated to the  $1/e$  value, the corresponding diffraction pattern width is given as:<sup>24</sup>

$$\Delta y_2 = 1.41 \frac{\lambda F}{N_e(m)D} \quad \cdot \quad (\text{Truncated Gaussian}) \quad (3b)$$

Similar expressions can be obtained for other transverse field distributions. For a given transverse field distribution, expressions of the form given in (3) determine the smallest resolvable distance in the Fourier transform.

The optical axis in Figure 1 and the surface elastic wave propagation axis are oriented so as to satisfy the Bragg condition at the signal center frequency. The z axis in Figure 1 is thus at an angle  $2\theta_B$  with respect to the optical axis of the incident wave which we denote as  $z_i$ , where  $\theta_B$  is the Bragg angle defined as

$$\text{Sin}\theta_B = \frac{\lambda f_{so}}{2N_e(m)v_r} \quad , \quad (4)$$

where  $f_{so}$  is the signal center frequency and  $v_r$  is the Rayleigh wave velocity. We now consider both the optical wave incident on the surface elastic wave and the diffracted optical wave to have the form:

$$E_i(y_i, z_i, t) = \iint A_i(\omega_i, \bar{k}_i) e^{i(\omega_i t - \bar{k}_i \cdot \bar{r}_i)} d\omega_i d\bar{k}_i \quad (5a)$$

$$E_d(y, z, t) = \iint A_d(\omega_d, \bar{k}_d) e^{i(\omega_d t - \bar{k}_d \cdot \bar{r}_d)} d\omega_d d\bar{k}_d \quad , \quad (5b)$$

where the subscript i refers to the incident wave and the subscript d refers to the diffracted wave and  $k_{i,d} = \omega_{i,d} N_e/c$ . The coordinates (y, z) without subscripts apply to the diffracted wave. The surface elastic wave field has the form:

$$g(y, z) = \iint G(f_s, \bar{k}_s) e^{i(2\pi f_s t - \bar{k}_s \cdot \bar{r})} df_s d\bar{k}_s \quad , \quad (6)$$

where

$$k_s = 2\pi f_s / v_r \quad \text{and} \quad \omega_d = 2\pi f_s + \omega_l \quad .$$

The variation of the elastic wave amplitude along the propagation axis of the elastic wave  $g(y, z)$  represents the time variation of the applied electronic signal so that we can write

$$g(y, z) \Big|_{\substack{\text{Propagation} \\ \text{axis}}} \equiv g(t) \quad (7)$$

where  $g(t)$  is the signal function for spectral analysis. By following the procedure described by a number of authors,<sup>11,25,26</sup> substituting the above field expansions into the electromagnetic wave equation and making the usual assumption of neglecting the spatial second derivatives of the optical field amplitudes  $A_{i, d}$ , the following equation can be derived for  $A_d$ :

$$\frac{dA_d}{dz} = i n_d \iiint e^{i \bar{\Delta} \bar{k} \cdot \bar{r}} G(f_s, \bar{k}_s) A_i(\omega_i, \bar{k}_i) d\bar{k}_s d\bar{k}_i \quad (8)$$

where

$$\bar{\Delta} \bar{k} = \bar{k}_d - \bar{k}_s - \bar{k}_i \quad (9)$$

$$n_d = \frac{\omega_d N_e^3 p S_0}{4c} Q \quad (10)$$

In (10),  $p$  is the photoelastic constant and  $N_e$  the refractive index of the waveguide,  $S_0$  is the maximum value of the elastic strain,  $G(f_s, \bar{k}_s)$  is normalized so that its maximum value is unity,  $c$  is the velocity of light, and  $Q$  is an overlap integral given elsewhere<sup>10</sup> which is a measure of the strength due to coupling for the suppressed  $x$  dependence of the fields.

We now assume that the input optical wave is composed of only a single plane wave component. Furthermore, the surface elastic wave consists of uniformly-weighted plane wave components within diffraction angle  $\delta\phi$  and no components beyond  $\delta\phi$ , i.e.,

$$A(\omega_i, \bar{k}_i) = A_{i0} \delta(\bar{k}_i - \bar{k}_{i0}) \quad (11a)$$

$$G(f_s, \bar{k}_s) = \begin{cases} G(f_s) & k_s \text{ within } \delta\phi, \\ 0 & \text{otherwise} \end{cases} \quad (11b)$$

where  $\delta\phi$  is assumed sufficiently large so that the elasto-optic bandwidth is limited by the transducer bandwidth<sup>10</sup>. In (11b),  $G(f_s)$  is the Fourier transform of the input electric signal  $g(t)$ . The assumption (11b) concerning the angular spectrum of the surface elastic wave can be closely approximated over large signal bandwidths through the use of tilted transducer arrays.<sup>12,27</sup> The assumptions (11) correspond to the case in which the optical beam spread is much less than the surface elastic beam spread. For this case, the optical beam spread will not be significantly altered by the elasto-optic interaction.<sup>13,28,29</sup> We further restrict our attention to the Bragg regime so as to eliminate the possibility of ambiguities caused by multiple scattering. Furthermore, as noted by Giallorenzi and Milton,<sup>13</sup> second-order multiple scattering is avoided if  $k_{s \text{ max}} < 2 k_{s \text{ min}}$ , where  $k_{s \text{ min}}$  and  $k_{s \text{ max}}$  are the minimum and maximum values of  $k_s$  over the range of the signal band. Using (11), the equation governing the amplitude, (8) reduces to

$$\frac{dA_d}{dz} = i \eta_d A_{i0} G(f_s) \int_{\bar{k}_s \subset \delta\phi} e^{i\Delta\bar{k}\cdot\bar{r}} d\bar{k}_s \quad (12)$$

If we restrict our attention to the region of operation in which the incident wave is not depleted, then the diffracted amplitude is readily obtained by a simple integration. Operation of the spectrum analyzer requires a linear relationship between the diffracted field amplitude and the signal amplitude spectrum, which is achieved by limiting the surface elastic wave intensity. Cumulative and thus efficient energy transfer from the signal input to the diffracted optical beam only occurs when momentum conservation is satisfied, i.e.,  $\Delta\bar{k} = 0$ .<sup>14</sup> Restricting our attention to only the surface elastic wave angular component which causes  $\Delta\bar{k} = 0$  and using the solution of (12) for a nondepleted incident wave, we obtain from (5b):

$$E_d(y, z, t) = a e^{i(\omega_d t - k_{do} z)} \int_{-\infty}^{\infty} G(f_s) e^{-i \frac{2\pi}{v_r} (f_s - f_{so}) \cos \theta_B y} e^{i \frac{2\pi}{v_r} |f_s - f_{so}| \sin \theta_B z} df_s \quad (13)$$

where

$$k_{do} = |\bar{k}_{i0} + \bar{k}_{s0}| \quad (14)$$

and  $a$  is a collection of constants and  $k_{s0} = 2\pi f_{s0}/v_r$ .

The transverse portion of the spatial field distribution (13) emerging from the surface elastic wave propagation region is then Fourier transformed by the optical waveguide lens according to (1). Letting  $z = 0$  be the transform input plane and substituting the spatial portion of (13) into (1) gives

$$E(y_2) = ab \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(f_s) w(y_0) e^{-i \frac{2\pi}{v_r} (f_s - f_{so}) \cos \theta_B y_0} e^{i \frac{kN_e y_2}{f} y_0} dy_0 df_s \quad (15)$$

where  $w(y_1)$  is a window function defined such that

$$w(y_1) \begin{cases} \neq 0, & |y_0| < D/2 \\ = 0, & |y_0| > D/2 \end{cases} \quad (16)$$

The Fourier transform result (15) corresponds to the starting point, i.e., Equation (5A) in the paper "An Integrated Optical Approach to the Fourier Transform" reproduced in Appendix A of this report. In that paper, we show that (5A) above reduces to the usual truncated Fourier transform relation; that is, the convolution of the signal spectrum with

the Fourier transform of the window function (7A). The above paper then proceeds to point out that this convolution will yield an accurate mapping of the Fourier transform of the input signal in the output optical transverse plane if the time-bandwidth product of that portion of the surface elastic wave delay line traversing the input optical aperture is much greater than one. Thus, as in other Fourier transform techniques, the appropriate time-bandwidth product serves as a figure of merit for measuring the fidelity of the spectrum analysis process.

The paper, "An Integrated Optical Approach to the Fourier Transform," then proceeds to develop various design considerations of the spectrum analyzer indicating how the lens aperture and focal length determine the time-bandwidth-product and the spectrum analyzer resolution where a surface elasto-optic Bragg type spatial modulator is employed and where a discrete set of photodetectors are employed in an array. The center frequency of the spatial modulator and the photodetector array spatial resolution are determined by the lithographic art employed which determines the minimum practical dimensions realizable with reasonable yield. Figures 3A and 4A of Appendix A indicate these functional relationships which have served as the base for this effort, "Optical Waveguide Lenses II."

The spectrum analyzer requires a beam expansion lens system with a large expansion ratio ( $\sim 90$ ) confined to a minimum of substrate area ( $\sim 2$  cm). The Fourier transform lens requires a field of view on the order of 3 degrees and an f-number in the range of .5-10. The original intent to employ a telephoto system was abandoned because of the difficulty of realizing the field of view without excessive field curvature. Thus, a single Luneburg lens with a retroreflector was substituted to minimize the substrate area required and to obtain a comparatively flat field with a long folded focal length. The spectrum analyzer also requires a detector array coupled to the thin-film waveguide containing the Fourier transform lens. The results of the investigation relating to these optical elements for the spectrum analyzer follow.

## 2. Optical Wavelength

Several considerations dictate the preference for an optical wavelength in the far red or near infrared for use in the integrated optical Fourier transform "chip." The emission wavelength of the electron injection laser is in the vicinity of 0.9 microns. Its characteristics of small size, efficiency, and adaptability for hybrid coupling to thin-film waveguide optics are compatible with the integration concept. Incorporation of distributed feedback will provide the requisite narrow emission linewidth and emission wavelength stability.

Another important consideration is the waveguide materials, structures and associated processes that must yield low-loss waveguide because scattering can degrade the Fourier transform's dynamic range and degrade its resolution. Some oxide thin films have been demonstrated to exhibit comparatively low loss in the far red and near infrared. Because Rayleigh scattering is inversely proportional to the fourth power of wavelength, it becomes essential to emphasize the near infrared to minimize scattering. Use of the longer wavelength relaxes the tolerances required for thin films to obtain reproducible controlled waveguide effective refractive indices. Waveguide lens aberrations are also wavelength dependent.

Although  $0.9\mu$  is recognized as the preferred wavelength, most experiments reported herein have employed  $0.633\mu$  radiation from a He/Ne gas laser for experimental convenience.

## 3. Waveguide Materials Compatible with Silicon Technology

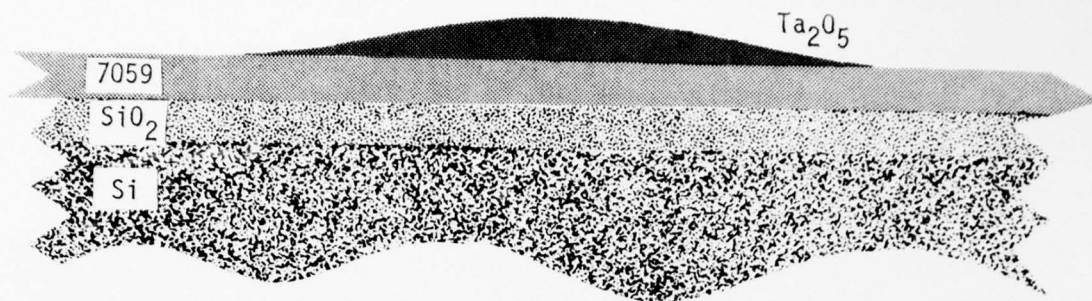
During the preceding program, Optical Waveguide Lenses I,<sup>16</sup> various types of homogeneous and inhomogeneous refractors were investigated using a variety of thin films and substrates. Planar and geodesic lenses were included. As a result and recognizing the requirements for the optical Fourier transform function, this current effort, Optical Waveguide Lenses II, has emphasized a single lens-waveguide structure formed by processes which yield relatively low losses. All refractors considered herein have employed multilayer thin films to form generalized Luneburg lenses. The waveguide-lens material-structure universally employed

consists of  $Ta_2O_5$  on Corning 7059 waveguide on thermally-grown  $SiO_2$  on a single crystal silicon substrate.

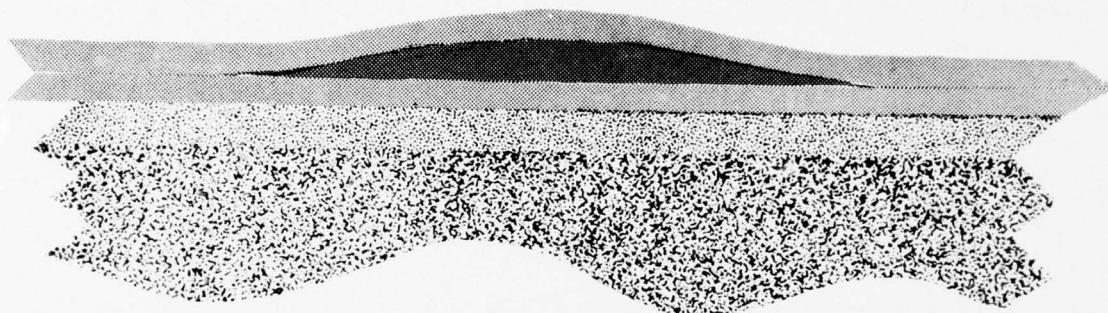
Several factors have led to placement of emphasis upon the use of  $Ta_2O_5$  on 7059 on thermally-grown  $SiO_2$  on Si. First, thermally-grown  $SiO_2$  has proven to yield the lowest loss, low-scattering substrate surface as an isolation layer between the waveguide and the substrate. The thermal growth process and resulting film resemble that of ultra low-loss fibers implying that it is reasonable to expect comparable results due to this substrate structure for integrated optical circuits. Second, single-crystal wafers of silicon have sufficient dimensions to encompass all optical elements for integration on a single "chip." They are available at reasonable cost, and its associated processing is a mature technology. Third, an integrated optical circuit may be formed on the oxide isolation layer while integrated electronic circuits may be formed under the layer with coupling between established by removal of the oxide.<sup>15</sup> Some optical circuits will require the presence of a piezoelectric to initiate a surface elasto-optic or electro-optic interaction. RF-sputter-deposited ZnO on the  $SiO_2$  can fulfill this requirement.<sup>17</sup> An optical circuit may be integrated with the electronic counterpart providing for its simultaneous exploitation.

The formation of a generalized Luneburg lens is a simple process. Three different cross sections of waveguide Luneburg lens structures are illustrated in Figure 2. The lenses are circular symmetric and are formed by deposition through a suitably shaped mask. The transverse electric mode of the lowest order ( $TE_0$ ) is normally employed in the waveguide. The overlay lens structure (a) has been employed for most experiments for expedience whereas the overlay structure (c) is better because it suppresses scattering at the feathered edge of the  $Ta_2O_5$ . Cross sections (a) and (c) are asymmetrical and, therefore, can potentially excite the next higher order mode,  $TE_1$  or  $TM_1$ . The waveguide lens (b) is the preferred structure because it is nearly symmetrical and because the feathered edge is immersed. This structure only minimally excites the  $TE_1$  mode but may excite the  $TE_2$  and higher orders if sufficiently thick, a condition to be avoided. Because the Luneburg lens derives its inhomogeneity by

(a) Lens Overlay - Asymmetrical Waveguide



(b) Lens Interleave - Symmetrical Waveguide



(c) Lens Underlay - Asymmetrical Waveguide

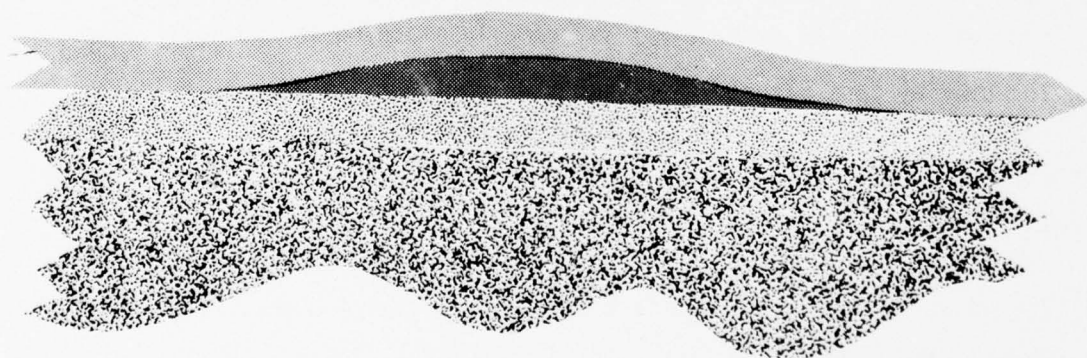


Figure 2. Three Cross Sections of Waveguide Luneburg Lens Which Result in Different Degrees and Different Types of Mode Conversion.

changes of waveguide thickness, it will exhibit an inherent chromatic aberration.

The losses encountered in optical waveguide propagation are due to absorption and scattering, the latter of which is important because it may limit the spectrum analyzer dynamic range and resolution. Aside from the waveguide material absorption, a structure employing an isolation layer may also exhibit additional losses due to the penetration of the evanescent field through the isolation layer into the substrate. The calculated<sup>30</sup> waveguide attenuation due to evanescent field absorption in a silicon substrate for three waveguide thicknesses of 7059 as a function of the thermally-grown SiO<sub>2</sub> isolation layer thickness is depicted in Figure 3. Observe that a waveguide with a thickness comparable to the wavelength or less with an isolation layer, more than a wavelength thick, suppresses the absorption due to the evanescent field to a trivially small value.

During this program, considerable effort was devoted to the suppression of Mie and Rayleigh scattering because it constitutes the one major factor that may compromise the exploitation of a thermally-oxidized silicon substrate. Sufficient evidence has now been obtained to show that the scattering may be suppressed, although its consistent realization is sometimes elusive. The transmission of He/Ne radiation at 6328Å through Corning 7059 waveguide is depicted in Figure 11B, Appendix B, and in Figure 4. In each case, a collimated beam resembling a Gaussian was employed. The measured input beam profile is included in the figures. The observed output transverse profile, after propagation through 9 cm of 7059 waveguide using input and output prism couplers (Ti<sub>2</sub>O), is shown in Figure 4. The beam width and profile are essentially the same except for fine-grain, spatial noise. The residual scattering level of both the input and output beam distributions at approximately -28 dB is an electronic instrumentation limit of the beam profile probe and recording system. Relatively long sections of 7059 waveguide have been produced on thermally-grown SiO<sub>2</sub> for which the scattering trace is not apparent to the eye. Typical Corning 7059 waveguide absorption and scattering loss is on the order of 1 dB/cm. While some specimens are in the 0.3 dB/cm regime, these depositions degrade with time with the attachment of atmospheric particulates, which

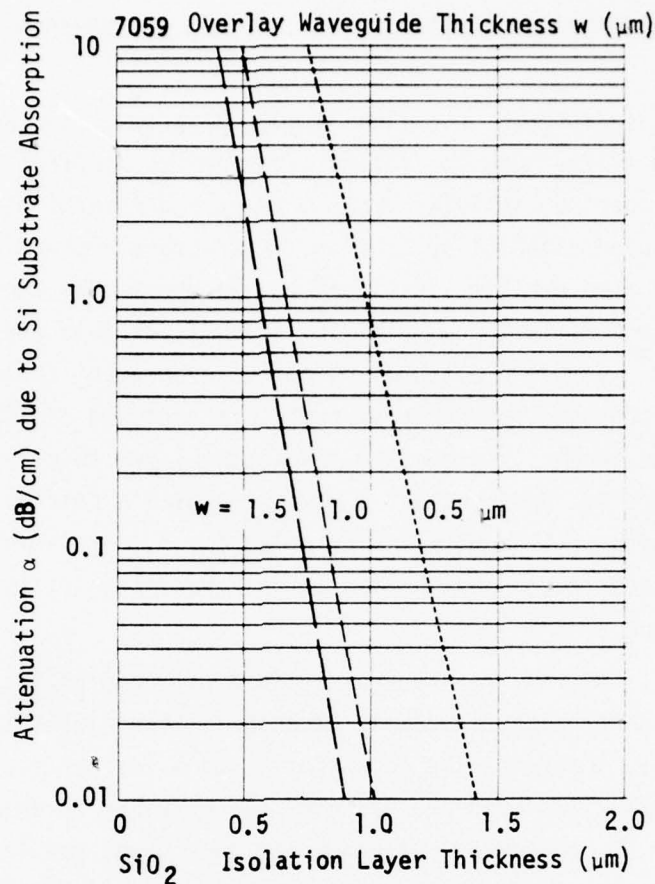


Figure 3. Thin-Film Waveguide Attenuation Due to Evanescent Field Absorption in Silicon Substrate for Three Corning 7059 Overlay Waveguide Thicknesses as a Function of the Thermally-Grown SiO<sub>2</sub> Isolation Layer Thickness (After Chen).<sup>30</sup>

suggests the use of a superstrate isolation layer, possibly an organic deposited from solution.

Tantalum pentoxide<sup>31-33</sup> and Nb<sub>2</sub>O<sub>5</sub> have been employed to form homogeneous and inhomogeneous thin-film lenses.<sup>35</sup> Their losses are in the 0.5-3 dB/cm range depending upon the deposition process. The larger value is usually obtained for very thin layers on Corning 7059 and a lower value may be obtained when immersed or in thicker cross sections. All of the experimental results, depicting lens performance photographically, have employed the overlay structure and thus exhibit the larger loss. The photograph

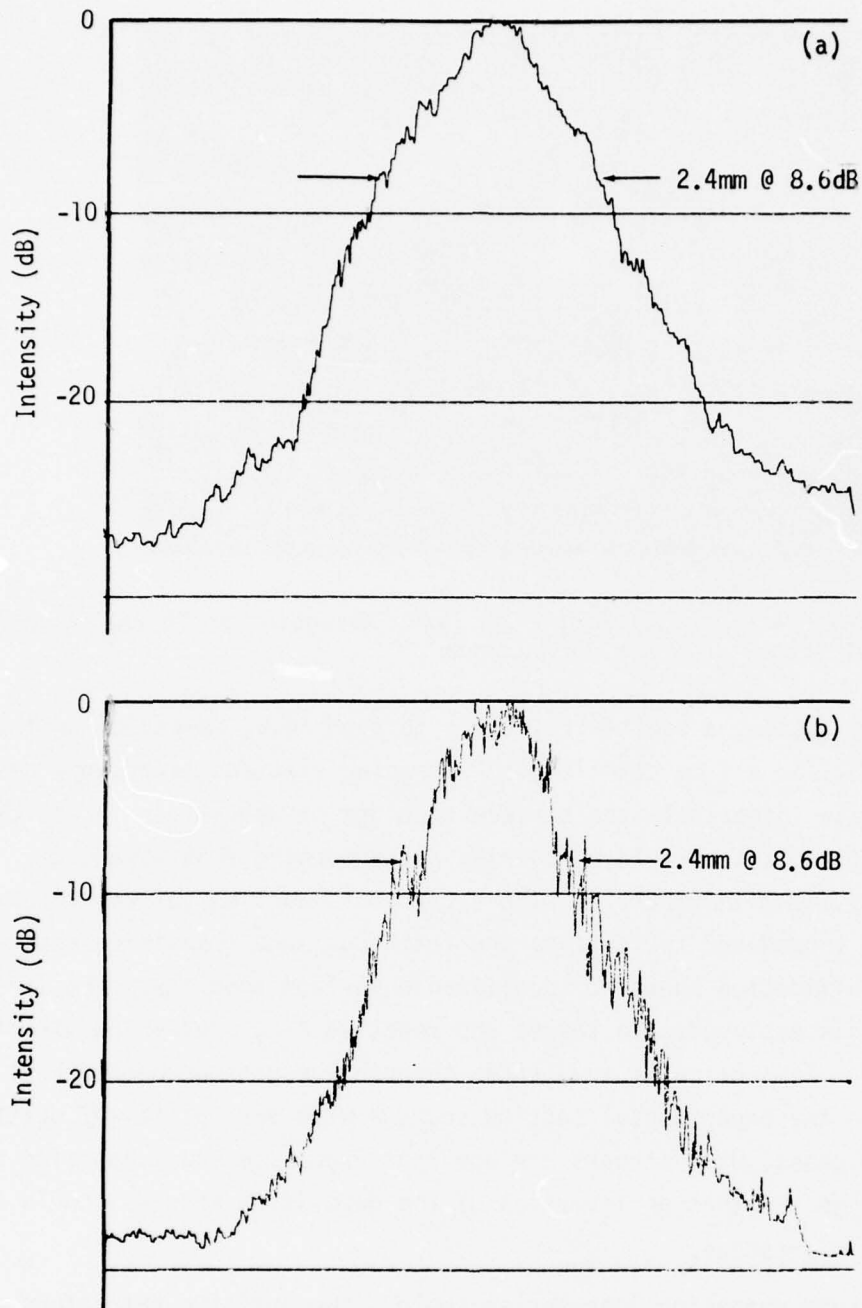


Figure 4. Intensity Distribution of 6328 Å Laser Radiation (a) Input Beam to Prism Coupler and (b) Output Beam From Prism Coupler After the Beam Has Traversed Through 9 cm of 7059 Waveguide on Thermally-Grown SiO<sub>2</sub>.

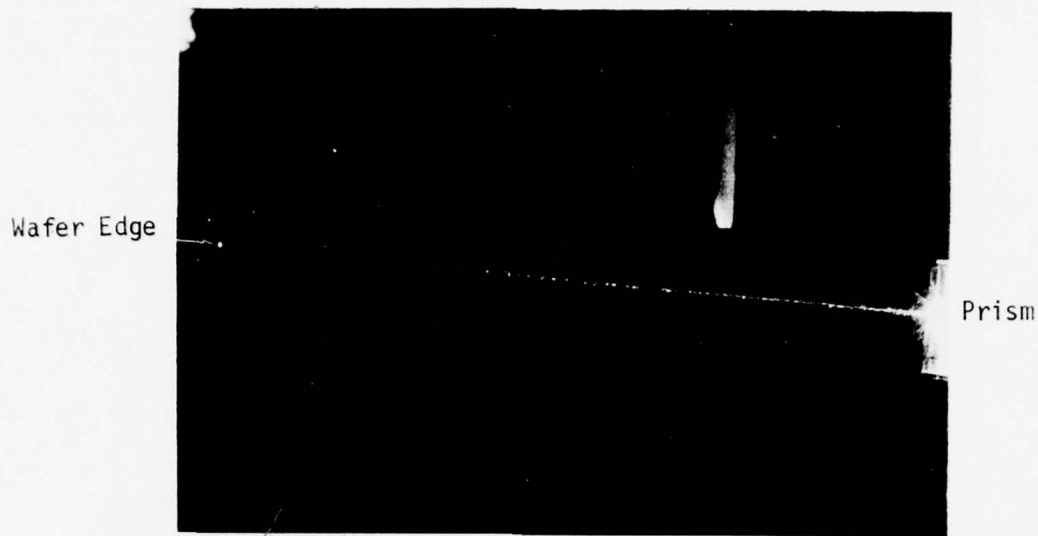


Figure 5. Ray Trace of 6328 Å Through  $Ta_2O_5$  Waveguide on Thermally-Grown  $SiO_2$  on Si, 7 cm Path Length

of Figure 5 shows a scatter ray trace through  $Ta_2O_5$  waveguide on thermally-grown  $SiO_2$  for a 7 cm path length. Scanning electron microscopy has been employed to investigate the surface topology of waveguides in the transition region between a  $Ta_2O_5$  overlay and a Corning 7059 waveguide. A result is shown in Figure 6. The artifact in Section (a) was intentionally introduced to identify the feathered edge transition region. High magnification shows no identifiable surface topology. The lens overlay has employed a Ta target and reactive  $A-O_2$  sputtering directed downward. Inspection of ray traces through the various photographs contained in the experimental section shows a wide variability of scattering. In a few cases, dark streaks are apparent from some Mie scattering centers. It is suggested that an inversion of the deposition process should minimize their presence.

The beam expansion lens system employs two positive refractors producing inversion and, therefore, the source radiation comes to a focus in the waveguide. Thus far, no optical damage has been observed in Corning 7059 waveguide on thermally-oxidized silicon. This waveguide safely handles at least  $0.4 \times 10^6$  watts/cm<sup>2</sup> continuously with no apparent photo-induced refraction effects such as appear in  $LiNbO_3$ .

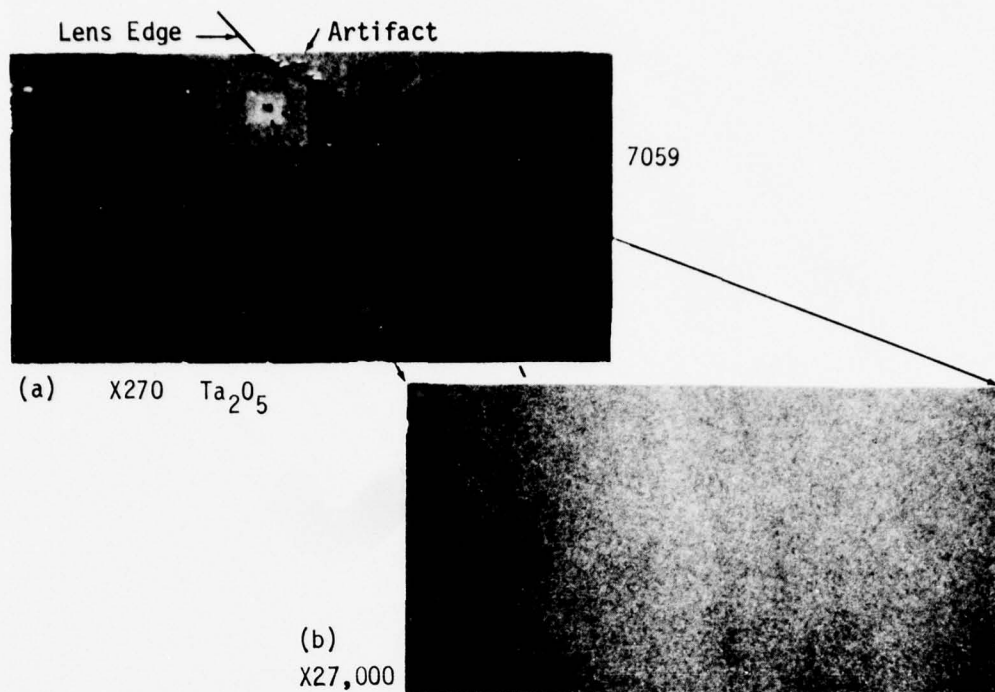


Figure 6. Scanning Electron Micrograph of Luneburg Lens Surface: (a) Transition Region (Edge), Magnification 270X with Artificial Artifact and Scan Outline, (b) Magnification 27,000X.

In conclusion, scattering, particularly Mie, is an important characteristic which must be suppressed for Ta<sub>2</sub>O<sub>5</sub> and Corning 7059 waveguides to be a viable competitive structure applicable to an integrated optical Fourier transform "chip". Experimental evidence shows that it is possible to realize low-scattering-loss waveguides competitive with other thin film approaches. The problem remaining is of consistent reproducibility over large areas.

### B. MULTILAYER THIN-FILM WAVEGUIDES

To provide a basis for direction of optical lenses formed in thin-film waveguide, we will briefly summarize some of the more important properties of bound modes in dielectric waveguide.<sup>34</sup> In particular, we will consider the four-layer structure illustrated in Figure 7. It consists of a substrate having a refractive index of  $n_4$  and superstrate having a refractive index of  $n_1$ , each with an infinite extent with one or two thin films between which serve as the optical waveguides or as a waveguide with isolation layer. The planar structure considered also has infinite extent in  $y$  with

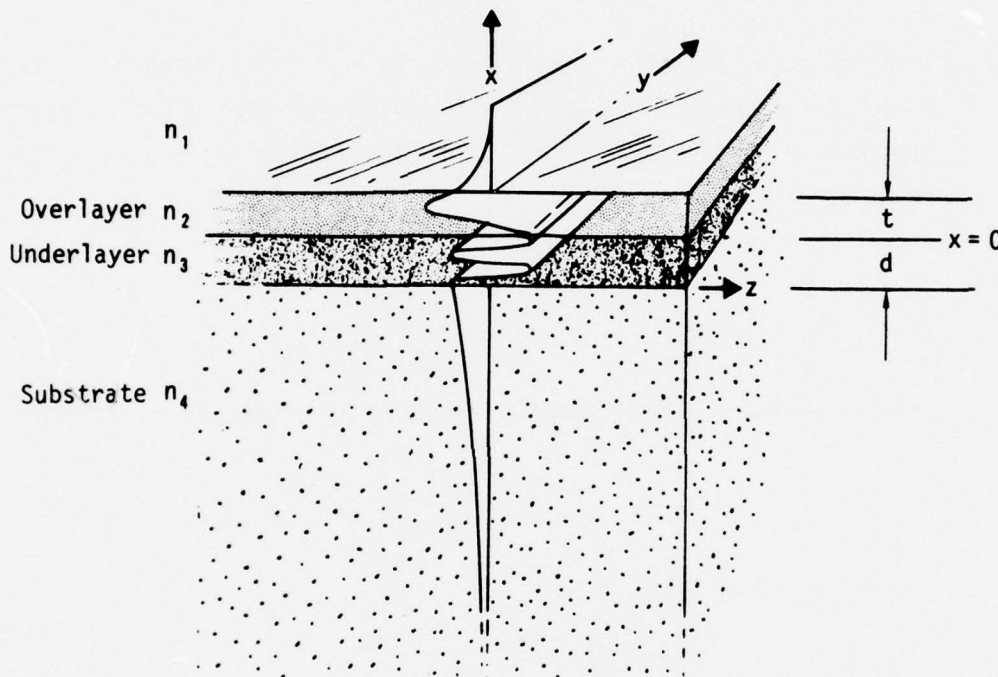


Figure 7. Cross Section of Asymmetrical Multilayer Planar Dielectric Waveguide Showing Fourth Order Mode With Evanescent Field

optical propagation in the  $z$ -direction. For wave binding, it is necessary that  $(n_2$  and/or  $n_3)$  be greater than  $(n_1$  and  $n_4)$ . We will not consider the modes bound to the substrate when it is of limited extent. The modes bound to this type of structure may be either transverse electric ( $TE_m$ ) or transverse magnetic ( $TM_m$ ) of order  $m$ . A transverse field component bounded to both layers (overlayer and underlayer) is illustrated in Figure 7, showing the fourth order with the evanescent field extending into the superstrate and substrate. It is possible that the refractive index and the film thickness of these layers

be such that wave binding occurs only in that region which has the highest index with an evanescent component in the other layers.

### 1. Dielectric Waveguide Modes

The transverse electric modes (TE) are the eigensolutions of the field equation where the time variation  $e^{i\omega t}$  has been suppressed

$$\left[ \frac{\partial^2}{2x^2} + \frac{\partial^2}{2z^2} + \omega^2 \epsilon(x) \mu_0 \right] E_y(x,z) = 0 \quad (17)$$

subject to the following boundary conditions:  $E_y \rightarrow 0$  as  $x$  approaches  $\pm \infty$ , and the tangential components of  $E$  and  $H$  are continuous across the boundaries. The  $z$  dependence will be the same in all four regions for a given mode and can be written as

$$e^{-i\beta_m z} \quad (18)$$

where  $m$  is the mode order. Additionally  $\epsilon(x)$  can be expressed as follows

$$\epsilon(x) = \left\{ \begin{array}{ll} n_1^2 \epsilon_0 & x > t \\ n_2^2 \epsilon_0 & t > x > 0 \\ n_3^2 \epsilon_0 & 0 > x > -d \\ n_4^2 \epsilon_0 & -d \geq x \end{array} \right\} \quad (19)$$

Applying the boundary conditions on  $E$  to the solutions of (17) the fields in the four regions can be written as

$$E_{m1} = A_m e^{-P_m(x-t)} \sin(h_m t + \phi_m) \sin \gamma_m e^{-i\beta_m z} \quad (20a)$$

$$E_{m2} = A_m \sin(h_m x + \phi_m) \sin \gamma_m e^{-i\beta_m z} \quad (20b)$$

$$E_{m3} = A_m \sin(l_m x + \gamma_m) \sin \phi_m e^{-i\beta_m z} \quad (20c)$$

$$E_{m4} = A_m e^{q_m(x+d)} \sin(-\ell_m d + \gamma_m) \sin \phi_m e^{-i\beta_m Z} \quad (20d)$$

where  $A_m$  is a normalization constant, and  $P_m$ ,  $h_m$ ,  $\ell_m$  and  $q_m$  are the transverse components of the propagation vector in regions 1, 2, 3, 4 respectively.  $P_m$ ,  $h_m$ ,  $\ell_m$ ,  $q_m$  and  $\beta_m$  are related by the following dispersion equations

$$P_m = (\beta_m^2 - k^2 n_1^2)^{1/2} \quad (21a)$$

$$h_m = (k^2 n_2^2 - \beta_m^2)^{1/2} \quad (21b)$$

$$\ell_m = (k^2 n_3^2 - \beta_m^2)^{1/2} \quad (21c)$$

$$q_m = (\beta_m^2 - k^2 n_4^2)^{1/2} \quad (21d)$$

Application of the boundary conditions on H yields

$$\tan(h_m t + \phi_m) = -h_m/P_m \quad (22)$$

$$\tan \phi_m = (h_m/\ell_m) \tan \gamma_m \quad (23)$$

$$\tan(-\ell_m d + \gamma_m) = \ell_m/q_m \quad (24)$$

These equations when combined lead to the following transcendental equation

$$\frac{1}{\ell_m} \tan\left(\ell_m d + \tan^{-1} \frac{\ell_m}{q_m}\right) + \frac{1}{h_m} \tan\left(h_m t + \tan^{-1} \frac{h_m}{P_m}\right) = 0 \quad (25)$$

The roots of this equation are the allowed values of the propagation constants.

The transverse magnetic modes (TM) are the eigensolutions of the field equation

$$\left[ \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} + \omega^2 \epsilon(x) \mu_0 \right] H_y(x,z) = 0 \quad (26)$$

The development of the TM modes is identical to that for the TE modes and again the allowed values of the propagation constants are roots of a transcendental equation, which is

$$\frac{n_3^2}{\ell_m} \tan\left(\ell_m d + \tan^{-1} \left[ \frac{n_4^2}{n_3^2} \frac{\ell_m}{q_m} \right]\right) + \frac{n_2^2}{h_m} \tan\left(h_m t + \tan^{-1} \left[ \frac{n_1^2}{n_2^2} \frac{h_m}{p_m} \right]\right) = 0 \quad (27)$$

## 2. Thin-Film Waveguide Dispersion Data

Tantalum pentoxide and Corning 7059 glass have been universally employed to form waveguides and lenses on thermally-grown  $\text{SiO}_2$  substrates because they exhibit comparatively low scattering loss and may be deposited with reproducible properties and thickness profiles. Therefore, the dispersion for each has been calculated and the dispersion when combined to form refractive lens elements has also been calculated. Dispersion data is also presented for the multi-layer structure when the field is trapped in only the dense layer and when it is trapped in both layers.

The single layer thin-film waveguide dispersion of  $\text{Ta}_2\text{O}_5$  structure on 7440 glass is shown in Figure 8 for both TE and TM modes as a function of the normalized film thickness. The thin-film waveguide dispersion of a Corning 7059 glass structure on an  $\text{SiO}_2$  substrate is shown in Figure 9 for both TE and TM modes as a function of the normalized thickness. The effective refractive index approaches the bulk value for thick films and approaches the substrate for thin films. Each of these thin-film waveguide modes exhibit a cutoff

where  $n_e(m) = 1.53$  for Figure 8 and  $n_e(m) = 1.47$  for Figure 9 in a dielectric waveguide structure. Cutoff means the lack of wave binding to the film. An asymmetric dielectric structure cutoff leads to refraction into the substrate.

The dispersion for a two-layer structure for only the transverse electric modes is shown in Figures 10 and 11 where  $Ta_2O_5$  is employed as the overlayer of variable thickness  $T$  and where the underlayer normalized thickness is constant ( $kt = 2.37 \pi$ ) which is equivalent to a 7059 layer having a thickness of 0.75 microns and an optical wavelength of 0.63 microns. Each of the dispersion curves of Figures 10 and 11 exhibit an inflection representing the transition region where wave binding occurs to only the dense overlayer and where wave binding occurs in both layers. Figure 11 is an expansion of Figure 10 in the region where wave binding occurs in both layers showing the effect of substrate refractive index.

The dispersion for a two-layer structure for only the transverse electric modes where 7059 is employed as the overlayer of fixed thickness and where the underlayer of  $Ta_2O_5$  of variable thickness  $T$  is shown in Figures 12 and 13. The fixed thickness waveguide ( $kt = 2.37 \pi$ ) is equivalent to a 7059 layer having a thickness of 0.75 microns for the optical wavelength of 0.63 microns. Each of the dispersion curves of Figures 12 and 13 again exhibit an inflection representing the transition region where wave binding occurs to only the dense underlayer and wave binding occurs in both layers. Figure 13 is an expansion of Figure 12 in the region where wave binding occurs in both layers showing the effect of substrate refractive index for the same three values of refractive index.

This dispersion data is sufficient for design of homogeneous and inhomogeneous refractors, reflectors and geodesic lens systems. In general, only transverse electric modes are employed in the lowest order to minimize loss. Restriction to the TE mode is achieved by input coupling polarization. The thickness of some lenses will permit the presence of a multiplicity of mode orders, however, most transitions are sufficiently gradual to minimize excitation of higher order modes. Location of the highest index layer adjacent to the substrate minimizes conversion to the next higher order mode which is odd. It is also possible to prohibit mode conversion by symmetry, that is, by interleaving the denser film between two separate halves of the waveguide.

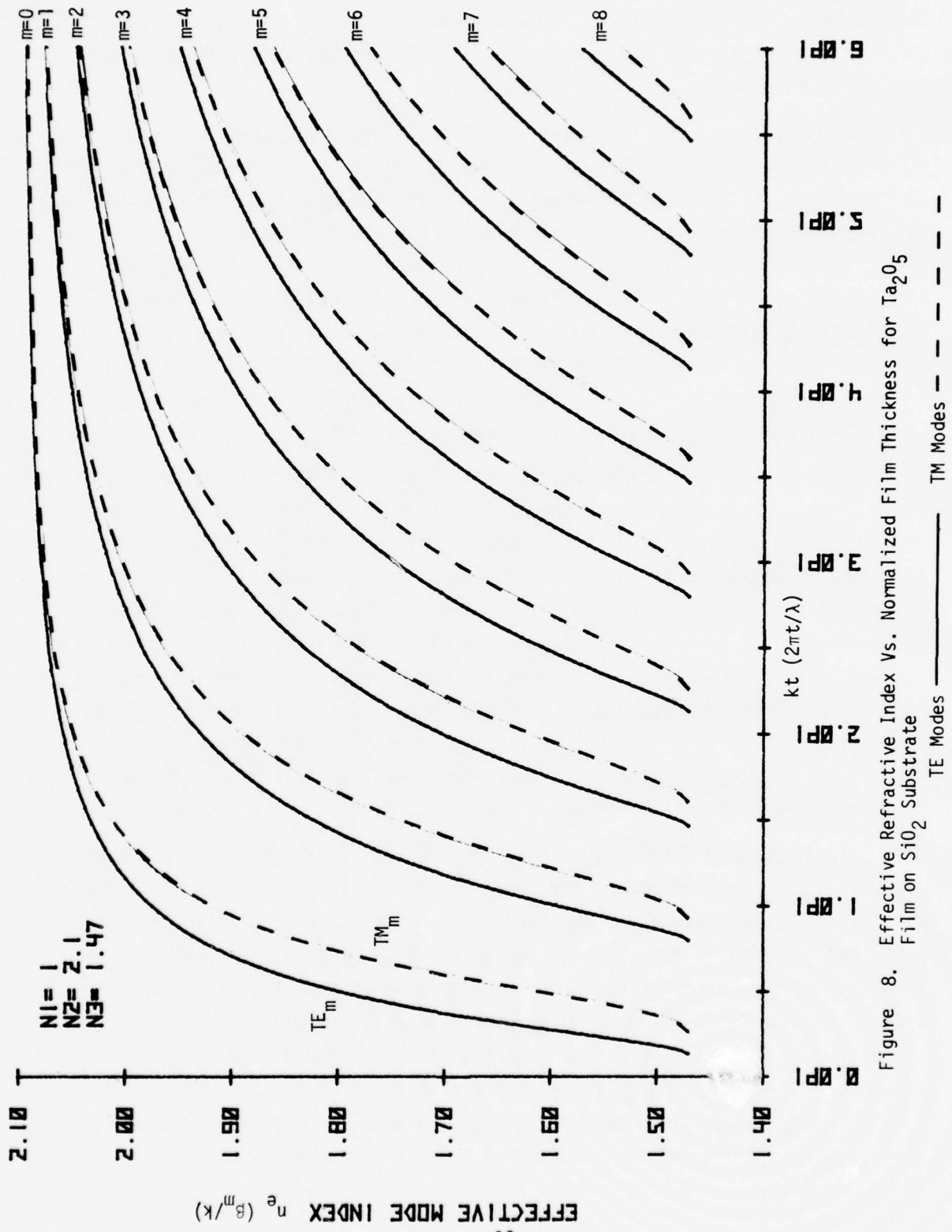


Figure 8. Effective Refractive Index Vs. Normalized Film Thickness for Ta<sub>2</sub>O<sub>5</sub> Film on SiO<sub>2</sub> Substrate

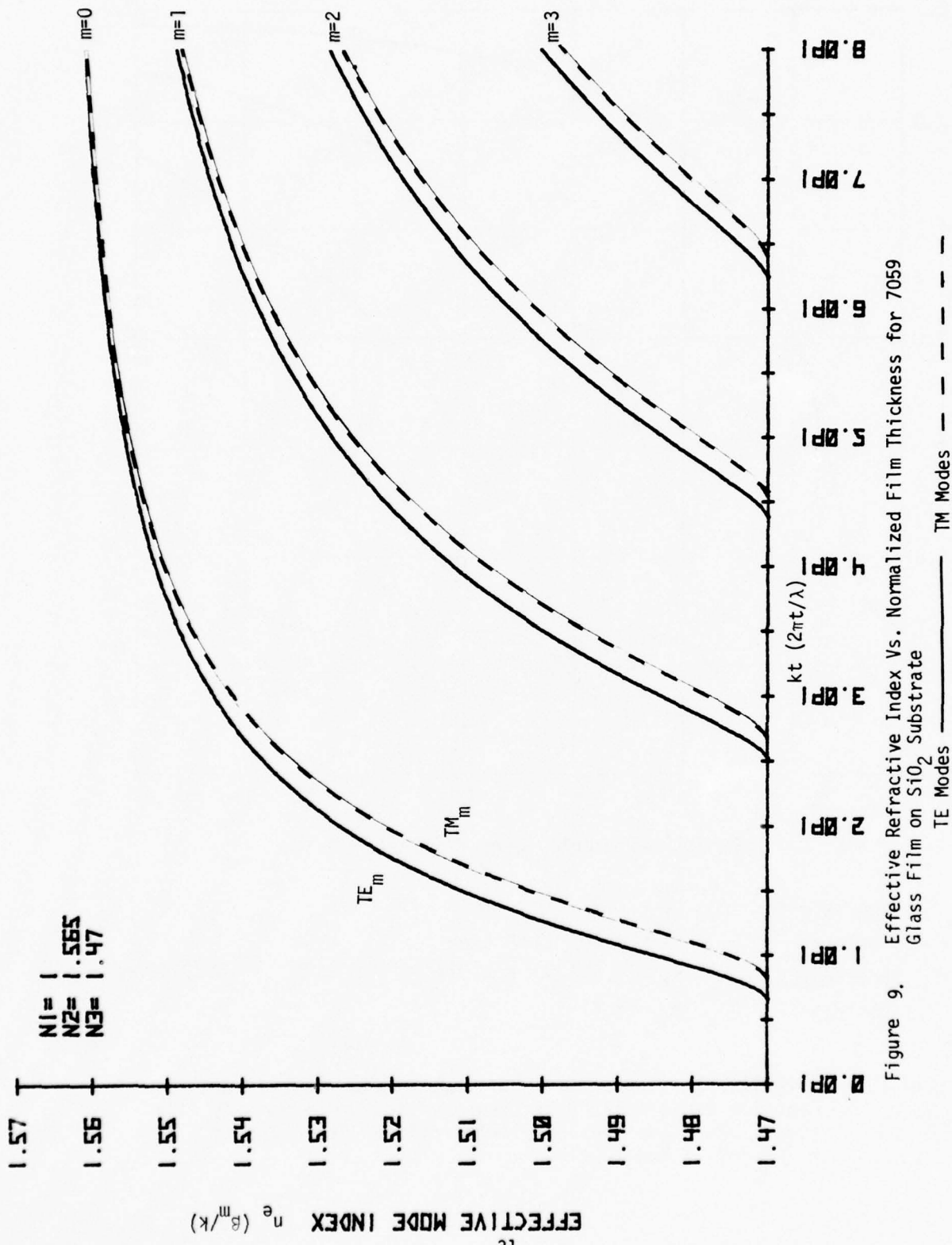
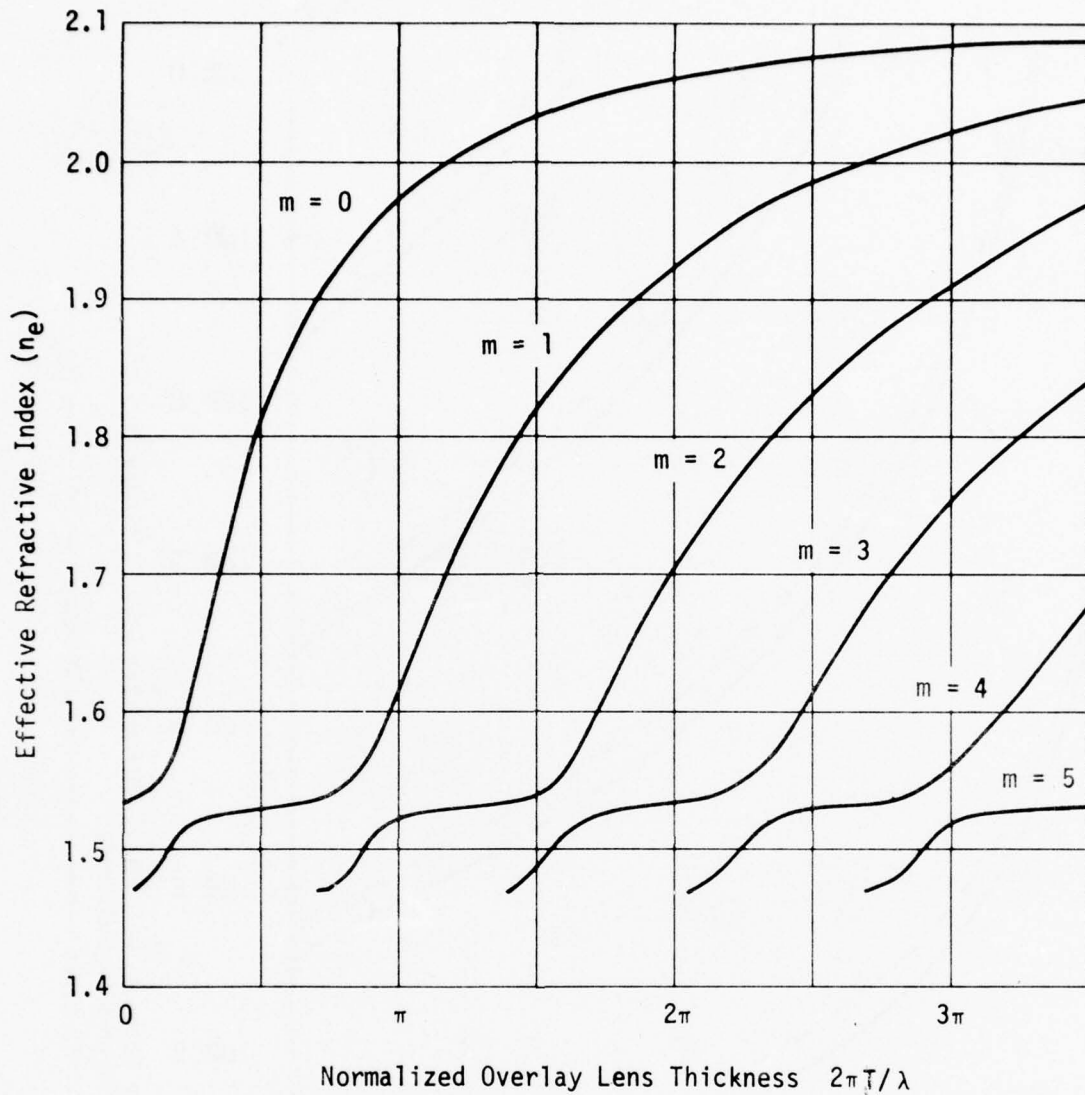
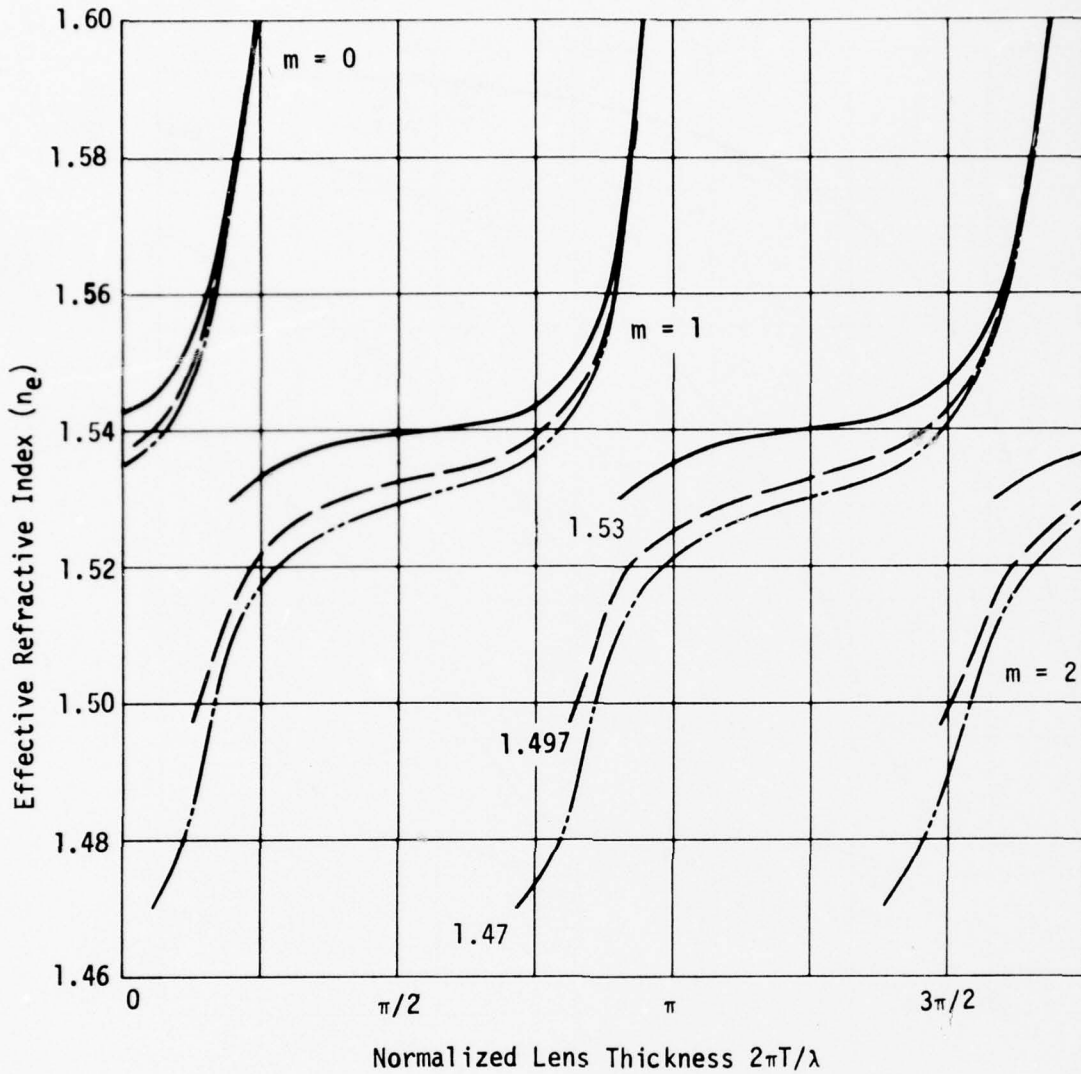


Figure 9. Effective Refractive Index Vs. Normalized Film Thickness for 7059 Glass Film on SiO<sub>2</sub> Substrate



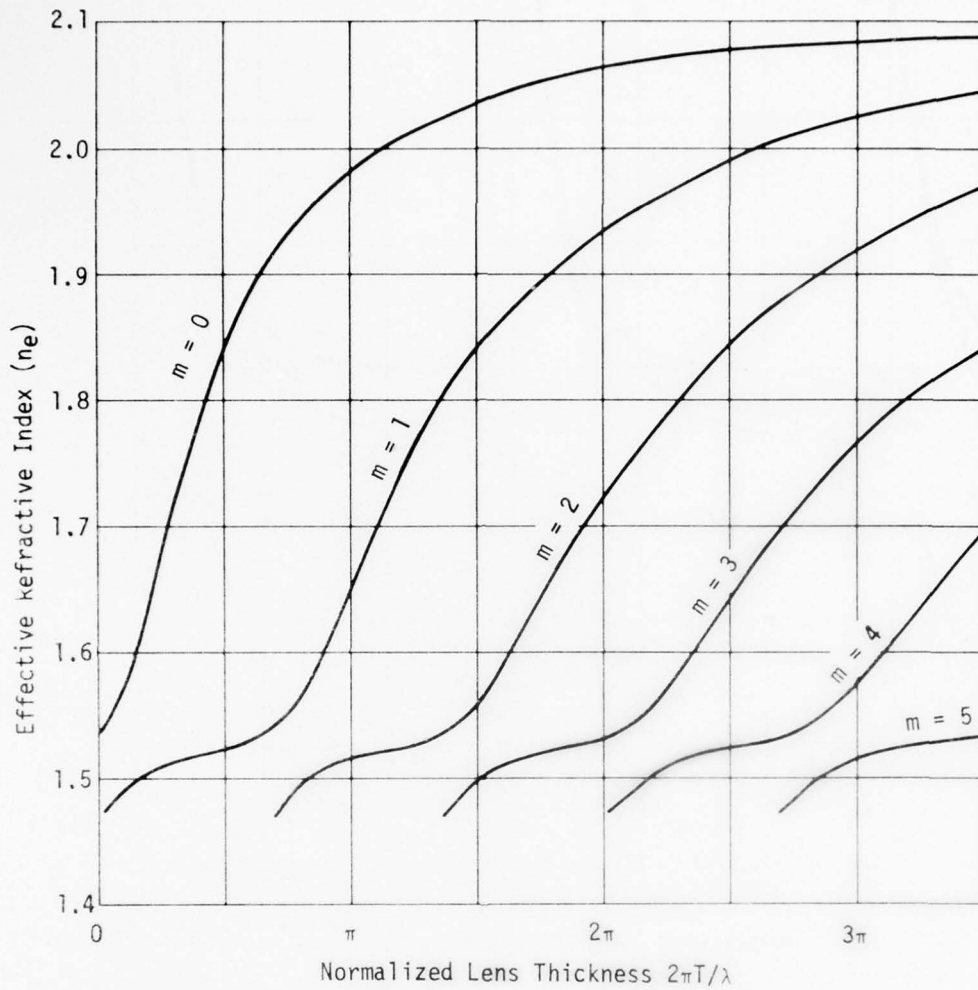
Superstrate	$n_1 = 1.0$	
Overlayer	$n_2 = 2.1$	$kT$ Lens
Underlayer	$n_3 = 1.565$	$kt = 2.37\pi$ ( $t = .75\mu$ @ $\lambda = .63\mu$ ) Waveguide
Substrate	$n_4 = 1.47$	

Figure 10. Effective Refractive Index of Composite Structure as a Function of Normalized Thickness of the Dense Overlay Film (Lens) Where the Overlay Film Normalized Thickness  $kt = 2.37\pi$  for TE Modes Only



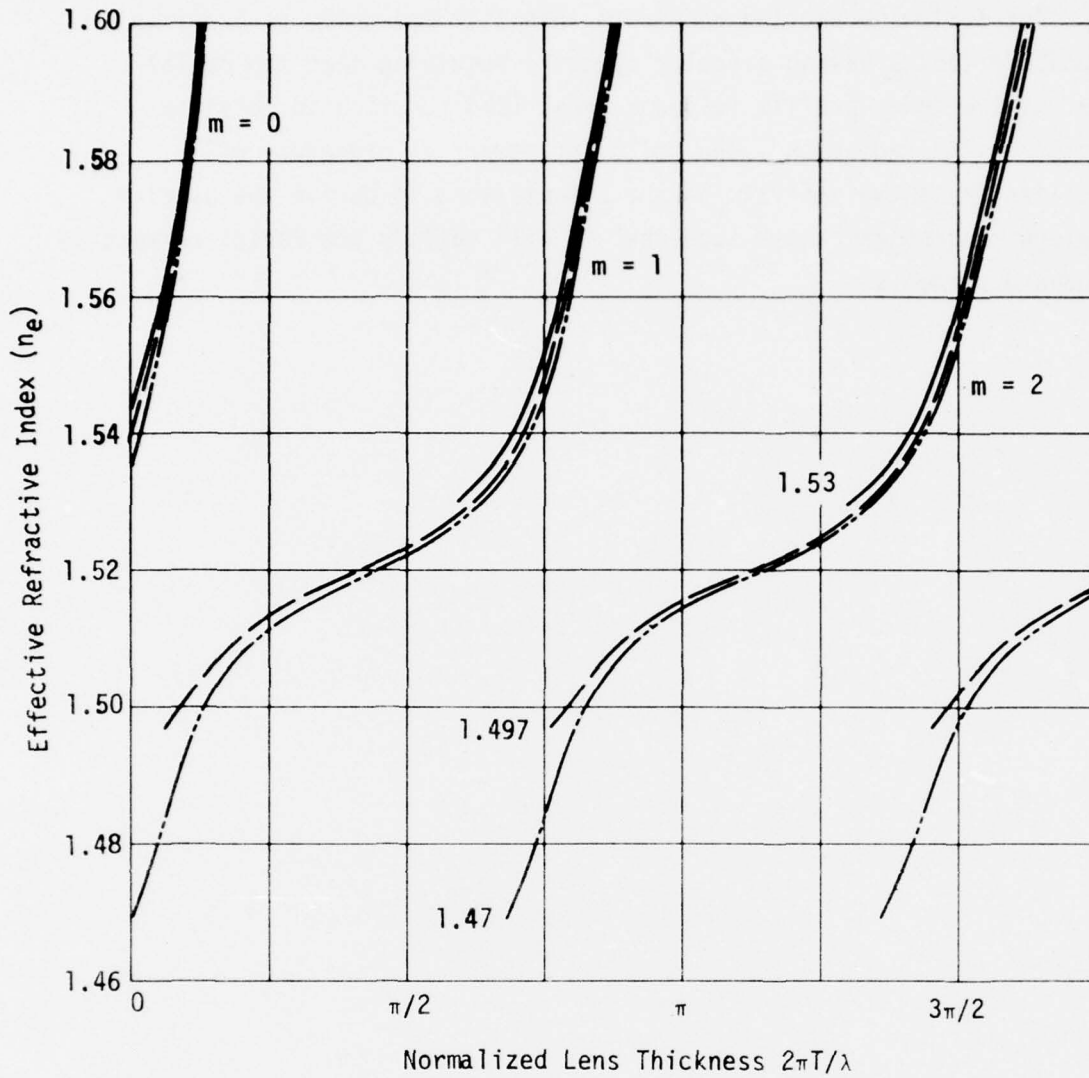
Superstrate	$n_1 = 1.0$	
Overlayer	$n_2 = 2.1$	kT Lens
Underlayer	$n_3 = 1.565$	kt = $2.37\pi$ ( $t = .75\mu$ @ $\lambda = .63\mu$ ) Waveguide
Substrate	$n_4 = 1.47, 1.497, 1.53$	

Figure 11. Expanded Scale of Figure 10 Showing the Effect of Three Substrates for TE Modes Only



Superstrate	$n_1 = 1.0$
Overlayer	$n_2 = 1.565$ $kt = 2.37\pi$ ( $t = .75\mu$ @ $\lambda = .63\mu$ ) Waveguide
Underlayer	$n_3 = 2.1$ $kT$ Lens
Substrate	$n_4 = 1.47$

Figure 12. Effective Refractive Index of Composite Structure as a Function of Normalized Thickness of the Dense Underlay Film (Lens) Where the Underlay Film Normalized Thickness  $kt = 2.37\pi$  for TE Modes Only



Superstrate	$n_1 = 1.0$
Overlayer	$n_2 = 1.565$ $kt = 2.37\pi$ ( $t = .75\mu$ @ $\lambda = .63\mu$ ) Waveguide
Underlayer	$n_3 = 2.1$ $kT$ Lens
Substrate	$n_4 = 1.47, 1.497, 1.53$

Figure 13. Expanded Scale of Figure 12 Showing the Effect of Three Substrates for TE Modes Only

The following section considers thin-film waveguide generalized Luneburg lenses having circular symmetry requiring that the radial refractive index profile follow a prescribed function to obtain a focus of the radiation. The following numerical procedure will utilize the above analysis in the computations to derive the overlay waveguide-lens thickness such that it will satisfy the radial refractive index dependents.

### C. INHOMOGENEOUS REFRACTIVE WAVEGUIDE LENS SYSTEMS

Conventional optical lens systems employ homogeneous dielectric and spherical surfaces in various combinations to correct aberrations. In general, inhomogeneous materials are avoided, particularly when perturbations are randomly distributed. Generally, the perturbations are weak except for certain processes applicable to surfaces. Lenses requiring the large refractive inhomogeneities obeying prescribed functions such as Maxwell's fish-eye<sup>36</sup> and the Luneburg lens<sup>37</sup> have not been realized in the optical portion of the spectrum. Thin-film optical waveguide provides the opportunity to produce thin-film inhomogeneous dielectric sections using homogeneous materials by variation of the film thickness.

#### 1. "Classical" Luneburg Lens<sup>37</sup>

Luneburg lens is an inhomogeneous positive refractor with radial symmetry which images a plane wave front to a microscopic hemispherical spot located on the opposite boundary of the refractor. Interest in the Luneburg lens arises because of its  $4\pi$  field of view and because it is free of all aberrations except field curvature. For integrated optics, its simplicity of fabrication in a thin-film structure realized reproducibly is an important attribute.<sup>35</sup> The circular symmetry is of particular interest where the substrate area is limited because folding of the optical axis may use the same lens for several purposes. The waveguide Luneburg lens has a further advantage that all refractive index variations are continuous, smooth and slow functions with respect to the optical wavelength. Mode conversion in the lens is suppressed by the graded thickness profile and by symmetry.

A generalized Luneburg lens will form a perfect geometric image of two given concentric circles on each other.<sup>38</sup> The perfect focusing property may be achieved in various regions. If one of the circles is of infinite radius, the lens may be designed to focus on another circle outside of, at the boundary, or inside of, the Luneburg lens. Luneburg found a solution for the refractive index function which had a conjugate foci for two given points outside of the lens. The solution for a parallel beam array which focuses on the opposite lens interface requires

that the refractive index  $n(r,m)$

$$n(r,m) = n_e(m) \sqrt{2 - (r/r_0)^2} \quad r \leq r_0 \quad , \quad (28)$$

where  $n_e$  is the refractive index of the medium surrounding and lens,  $r_0$  is the lens radius, and  $r$  is the radial coordinate for mode (m). The trajectory of rays through a "classic" Luneburg lens is illustrated in Figure 14.

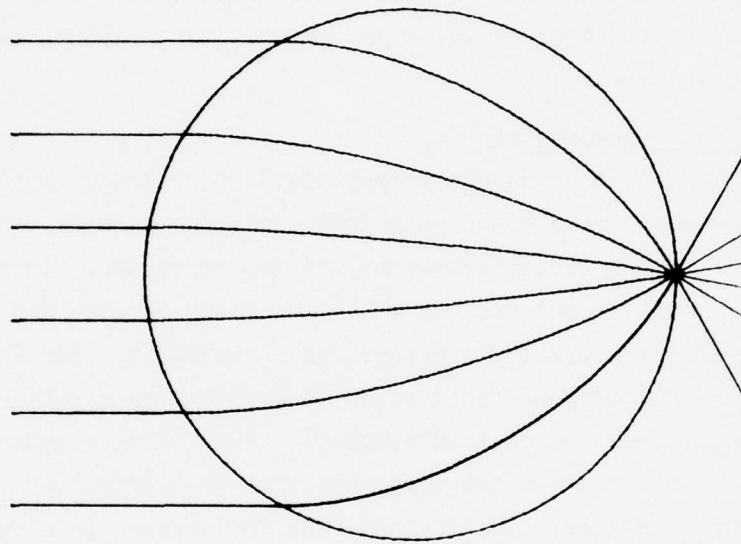
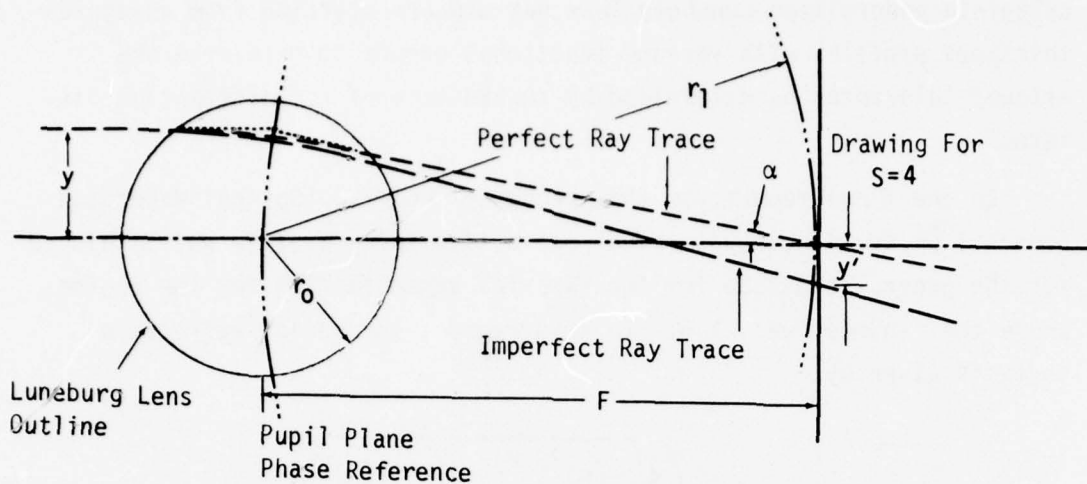


Figure 14. Ray Trajectory Through Luneburg Lens Where f-Number = 0.5, S=1.

The technique of ray tracing through an inhomogeneous refractor is delineated in Appendix E by Southwell entitled, "Inhomogeneous Optical Waveguide Lens Analysis."

## 2. Generalized Luneburg Lenses

The "classic" Luneburg lens has been generalized by Morgan<sup>38</sup> developing a radial refractive index profile which will focus one circle on another in the region beyond the edge of the lens radius  $r_0$ . The



"Classic"

$$F=r_0, f=F/r_0=1/2, S=1, \alpha=90^\circ$$

Generalized

$$F>r_0, f>1/2, S=2f>1, \alpha<90^\circ$$

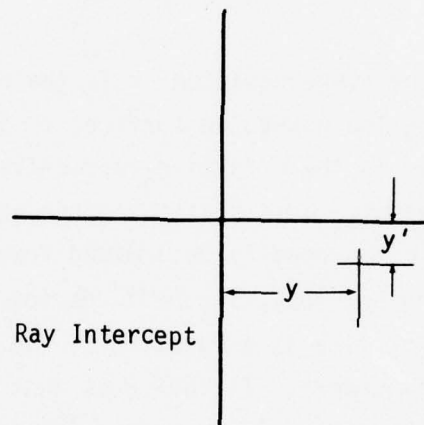


Figure 15. Ray Trace Geometry Through Luneburg Lens and Ray Trace Intercept Plot.

increased focal length reduces the range of refractive index variation required to form the lens. Extending the focus outside of the lens region increases the f-number and thus the diffraction pattern width in the focal region.

The geometry of a generalized Luneburg lens is depicted in Figure 15 showing a perfect ray trace from which a ray intercept plot is developed which is also included in the figure. In the following section, numerous ray traces are calculated yielding the ray intercept plot from which the phase wavefront has been derived followed by the calculated intensity diffraction pattern. This procedure has provided the means to

calculate generalized Luneburg lens performance starting from waveguide thickness profiles with various functional errors to determine the allowed tolerances as determined by degradation of the diffraction pattern.

In the final report for the preceding program, "Optical Waveguide Lenses I<sup>16</sup>," the functional radial refractive index profile was developed for the generalized case for the paraxial approximation for the regime where the f-number was >1.5. In this region, the radial refractive index is given by

$$n(r,m) = n_e(m) \exp \left( \frac{\sqrt{n_e(m)^2 r_0^2 - r^2 n^2(r,m)}}{\pi n_e(m) r_f} \right). \quad (29)$$

In the above equation,  $r$  is the radial coordinate from the lens center along the waveguide surface,  $r_0$  is the radius of the lens region,  $r_f = F$  and  $n_e(m)$  is the effective refractive index for the waveguide mode ( $m$ ) of interest. Note that the above equation is not solved for  $n(r,m)$ , but  $n(r,m)$  is readily determined from Eq. (29) numerically as a function of  $r_f$ . Using Eq. (29), Figure 16 depicts the normalized effective refractive index profile as a function of the normalized lens radius for several values of f-numbers. It indicates that the transverse profile becomes more uniform having a lower refractive index over a larger central region of the lens as the focal length is increased. Figure 17 depicts the minimum required effective refractive index at the center of the lens relative to its ambient waveguide effective refractive index as the lens focal length is increased. For the classic Luneburg lens  $n(0,0) = \sqrt{2}$ , a high index layer like  $Ta_2O_5$  or  $Nb_2O_5$  is required on Corning 7059 for  $F/D = 0.5$ . Generalized Luneburg lenses may be formed with these materials using thinner films or using films with lower index and thicker layers. Generalized Luneburg lenses have been realized using an "all" 7059 thin film when  $F/D > 6$ . Lenses which are formed from a single composition by changes of the layer thickness exhibit substantially less scattering and further suppress the excitation of higher order modes.

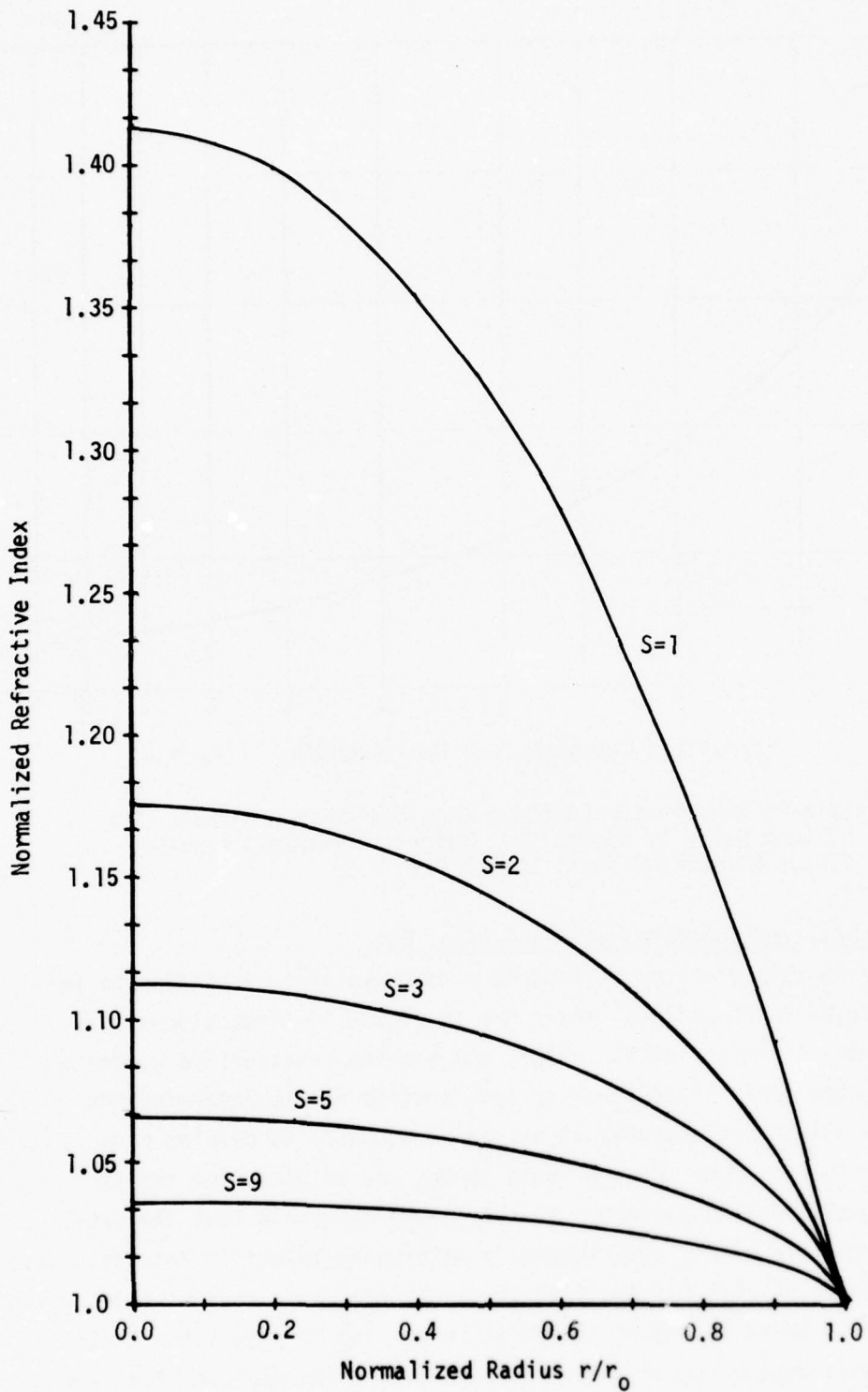


Figure 16. Normalized Refractive Index Profile for Generalized Luneburg Lenses for Various S-Parameters Listed by Morgan and Southwell ( $f$ -Number =  $S/2$ ).

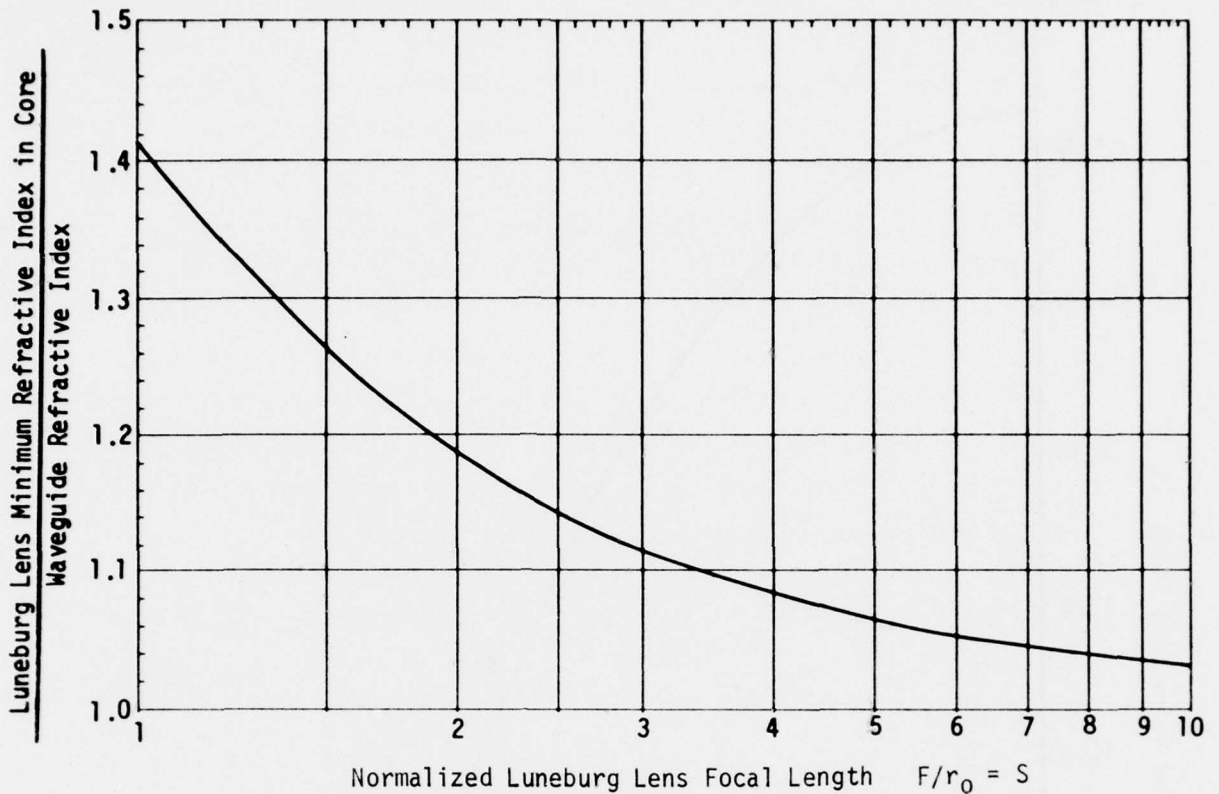


Figure 17. Thin-Film Waveguide Luneburg Lens Design Requirement (the Minimum Ratio of Refractive Indices at Center Perimeter Versus Normalized Focal Length  $F/r_0 = S$ )

### 3. Generalized Luneburg Lens Analytical Data

During this effort, the procedure to numerically evaluate the performance of inhomogeneous lenses has developed in three stages. To complement the experimental effort and provide constructive guidance shaping the generalized Luneburg lens profile and to determine the various allowed tolerances, it has been necessary to develop procedures to ray trace through these lenses and to determine the resulting diffraction pattern. It was deemed desirable that the procedure utilize either experimentally determined thin-film lens thickness profiles or utilize mathematical functions descriptive of profiles which could be altered to adjust the focal length and to adjust the radial functional dependence so as to be related to masks employed for lens depositions. The first analytical procedure for ray tracing through Luneburg lenses represented the radial thickness profile by a series

of stepped refractive index annuli. Snell's law was applied at the step between each annulus. It was found that 500-2000 annuli were necessary to obtain ray traces which pictorially represent a classic Luneburg lens using the Hewlett-Packard 9830 computer with graphical display. The procedure proved to be relatively slow with questionable accuracy for the marginal rays.

A second method of ray tracing through waveguide lenses was developed by Southwell and further refined yielding accurate results with considerable reduction of computational time in the H-P 9830 without exceeding its capacity. The procedure was extended to determine the ray intercepts from which the wavefront could be determined and, thus, the resulting intensity diffraction pattern. Only this latter procedure and its refinement will be delineated herein. Specific mathematical development of the procedure is contained in Appendices E and F by W. H. Southwell entitled, "Inhomogeneous Optical Waveguide Lens Analysis," and "Index and Waveguide Thickness Profiles for Generalized Luneburg Lenses." The procedure is briefly summarized here, followed by an ensemble of data. This data illustrates how various Luneburg lens refractive index profiles and errors of same influence the diffraction patterns. In several cases, the numerically devised results can be related to the experimental results of the following section.

The Southwell procedure essentially traces the wavefront normal by way of a numerical solution to the differential equation governing the fields because no closed-form solutions are available. Taylor series expansions are used for both the wave vector and the ray-position vector. Terms up to the second and third order are retained. The expansion derivatives are thus expressed in terms of the ray path, curvature and rate of change of the curvature. The major factor saving computational time results from a new extrapolation algorithm. Basically, the technique employs the well-known Richardson extrapolation except that the higher order terms are included to account for changes due to curvature. As each incremental step of the ray trace is taken, a test is taken to see whether the new ray trace position will fall within the waveguide lens region. If it does not, it becomes necessary to locate the precise position of the boundary along the ray path. An iterative technique, using Newton's method, was developed.

To evaluate the accuracy of this ray trace algorithm prior to extrapolation, a "classical" Luneburg refractive index profile was used to trace several errors. The results, using Southwell's procedure and an H-P 9830 computer, are shown in Figure 18. The classical profile was chosen because it is known to produce perfect focusing at a point on the opposite edge of the lens. The actual ray trace intercept represents ray trace errors because the rays should intercept at zero. The computational time to trace rays through the lens is inversely proportional to the step size used in the expansion. A plot of this ray intercept error vs step size is shown in Figure 4 of Appendix E.

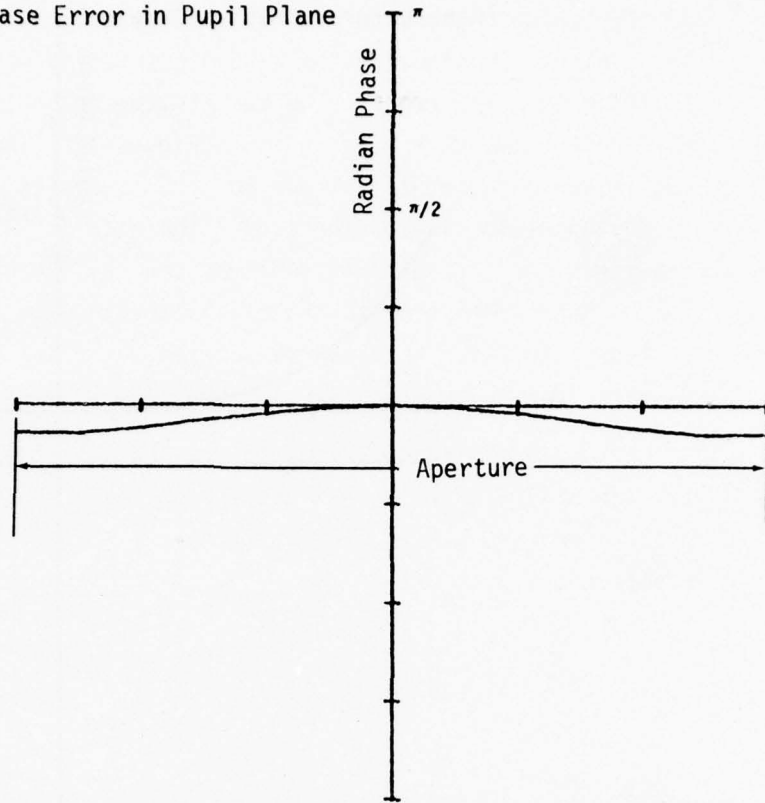
For near diffraction-limited optical systems, ray tracing does not provide a direct comparison between the computer results and the measurements which appear as diffraction patterns. An algorithm for deriving the pupil function  $P(x,y)$  is:

$$P(x,y) = \exp \left[ \frac{i2\pi}{\lambda} W(x,y) \right] , \quad (30)$$

where  $W(x,y)$  is the wave front error over the pupil coordinates  $x$  and  $y$ . The purpose for obtaining the pupil function (30) is so that it may then be Fourier transformed to provide the diffraction pattern in the specified image plane. The theory for this pupil function derivation from ray trace data is based upon solutions to "characteristic equations" which are, in turn, based upon the optical Eikonal Equation.<sup>39</sup> An intermediate curve-fitting step is employed which tends to keep the number of rays to a minimum. A plot of the phase error across the aperture as a wave front traverses the classical Luneburg lens of Figure 14 is shown in Figure 18. The presence of non-zero phase error for the "perfect" classical Luneburg lens indicates the residual computational error in the algorithm. The maximum computational phase error in Figure 18 is  $\lambda/25$ . This residual error is a function of the computational time and may be made arbitrarily small.

When the pupil function has been evaluated, the digital fast Fourier transform is used to obtain the diffraction pattern. Figure 18 is the

Phase Error in Pupil Plane



Diffraction Pattern

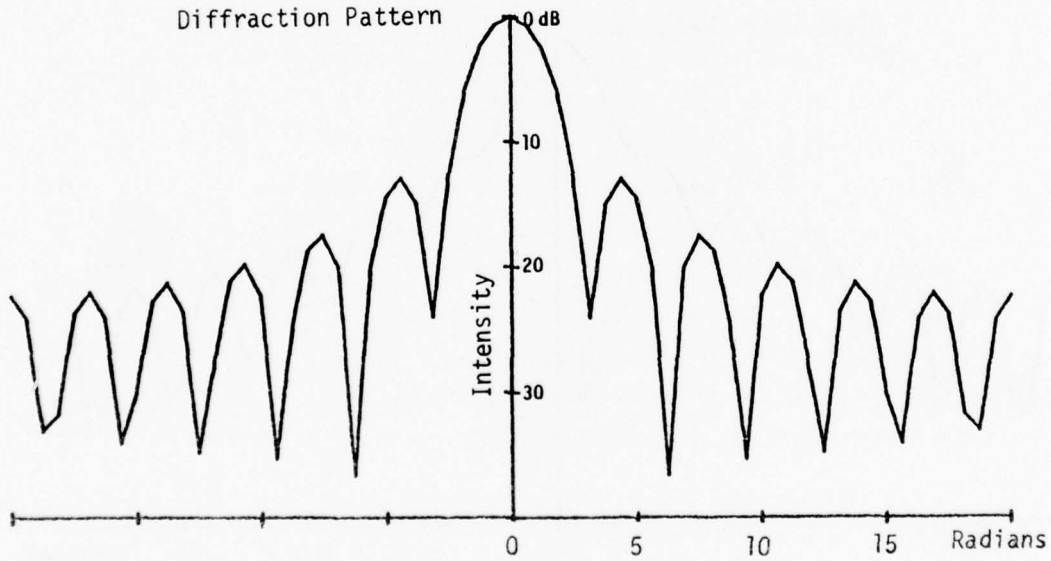
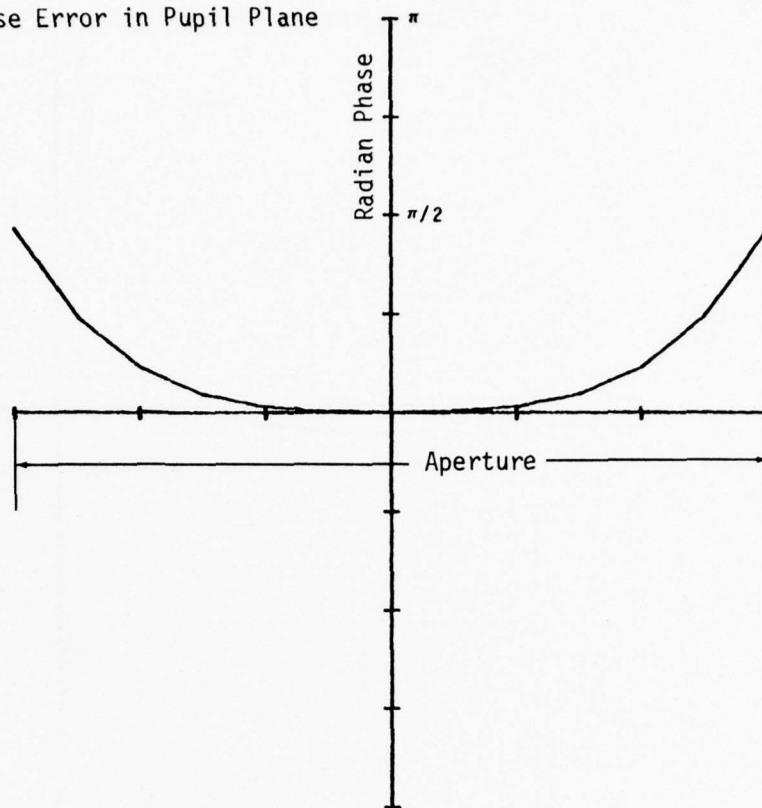


Figure 18. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for "Classic" Geodesic Lens Ray Traced in Figure 14 for Perfect Radial Profile.

Phase Error in Pupil Plane



Diffraction Pattern

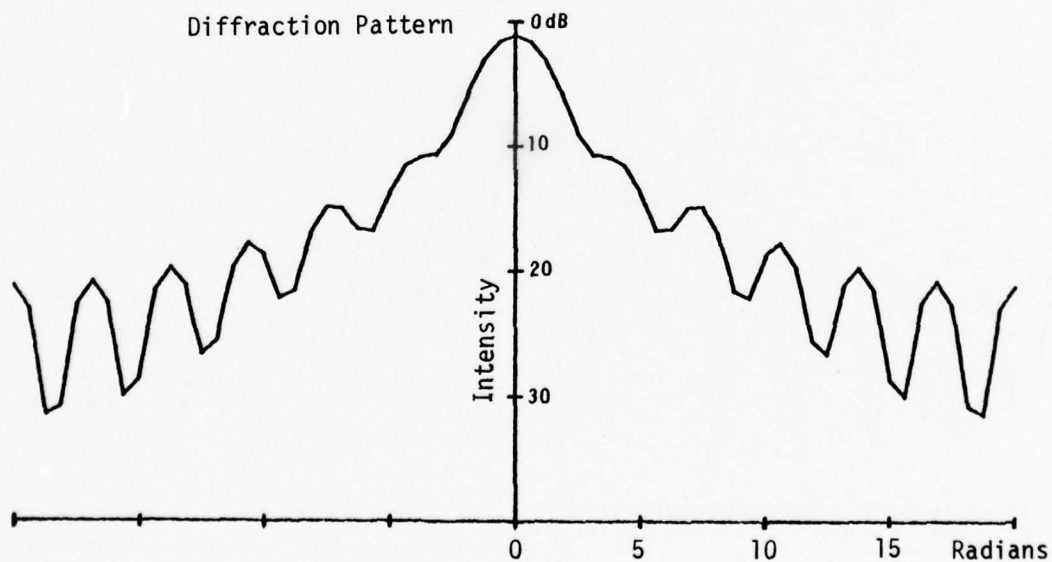
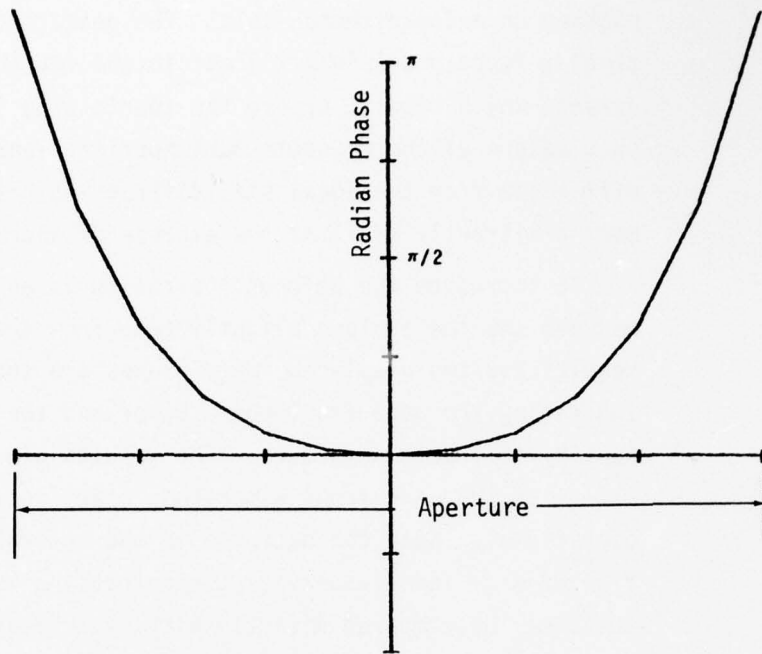


Figure 19. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for "Classic" Geodesic Lens Ray Traced in Figure 14 for Perfect Radial Profile Where the Image Plane Has Been Displaced by  $.5\mu$  Yielding the Defocus Aberration.

Phase Error in Pupil Plane



Diffraction Pattern

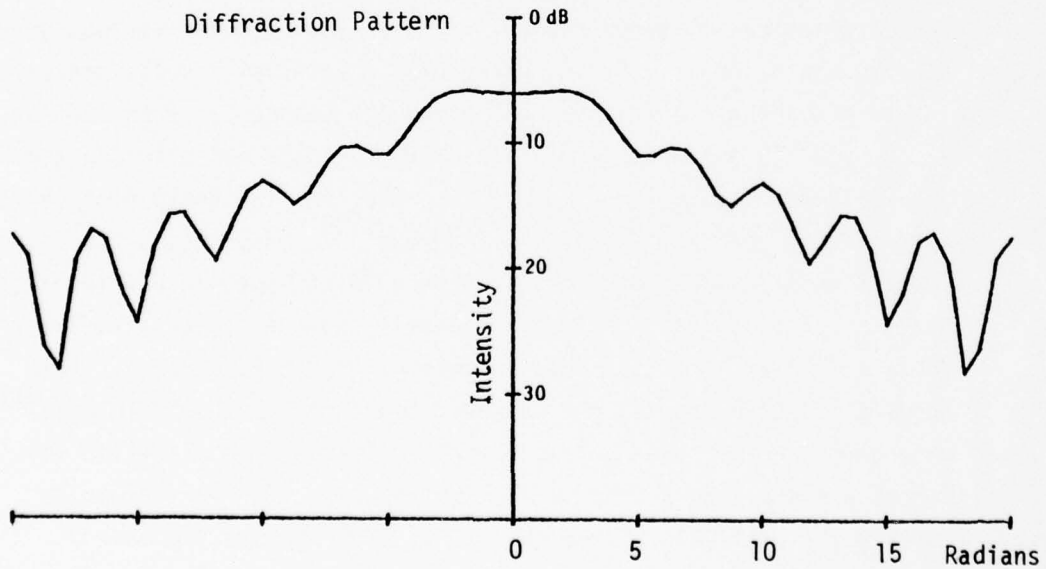


Figure 20. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for "Classic" Geodesic Lens Ray Traced in Figure 14 for Perfect Radial Profile Where the Image Plane Has Been Displaced by  $1.0\mu$  Yielding the Defocus Aberration.

diffraction pattern for the "classical" Luneburg lens at the focus plotted on a logarithmic scale. The pattern is identical to the  $\text{sinc}^2 x$  functions ( $\sin^2 x/x^2$ ) out to the fourth side lobe. The difference which results beyond the fourth side lobe is due to the periodic nature of the discrete fast Fourier transform algorithm. The difference from the ideal sinc diffraction pattern can likewise be made arbitrarily small at the expense of increased computational time.

To introduce the defocus aberration in an otherwise perfect system, we move the image plane slightly away from the edge of the lens. The results for two displaced image planes are shown in Figures 19 and 20 indicating the wave front phase error and the resulting defocused intensity diffraction pattern. The results are as expected which indicate that the wave front algorithm, starting from the ray trace, is operational. Note the decrease in the central peak intensity and the rise of side lobe imagery as the defocusing is increased. These results may be compared directly with experiments (see Figures 68 and 69) and the microwave literature.<sup>40</sup>

This numerical ray tracing procedure, which allows determination of the ray intercepts, the wave front phase error and the intensity diffraction pattern, as verified for the classic Luneburg lens yielding diffraction-limiting results, has been employed for various generalized Luneburg lenses. First, using Boyd's paraxial results contained in the preceding effort, "Optical Waveguide Lenses I," AFAL TR76-54, (Figure 36), a best-fit simulation of Boyd's data was obtained for a generalized Luneburg lens  $f$ -number 2. The lens thickness profile was simulated by  $\cos^{0.18}$ ,  $\cos^{0.211}$  and  $\cos^{0.25}$ . Ray traces for each of these simulations are depicted in Figure 10 of Appendix E which suggests that the profile  $\cos^{0.211}$  is a reasonable representation yielding a good focus so far as it is possible to determine from ray traces. This best-fit focused generalized Luneburg lens thickness profile ( $\cos^{0.211}$ ) was used as a reference for tolerance analysis. The resulting ray traces are depicted in Figure 21, Section (a). The ray traces in Section (b) of Figure 21 are the result of a uniform increase of thickness by 10 percent as may be obtained by increasing the deposition time. Note that the increased thickness results in a shorter focal length and the onset of spherical aberration because the marginal rays

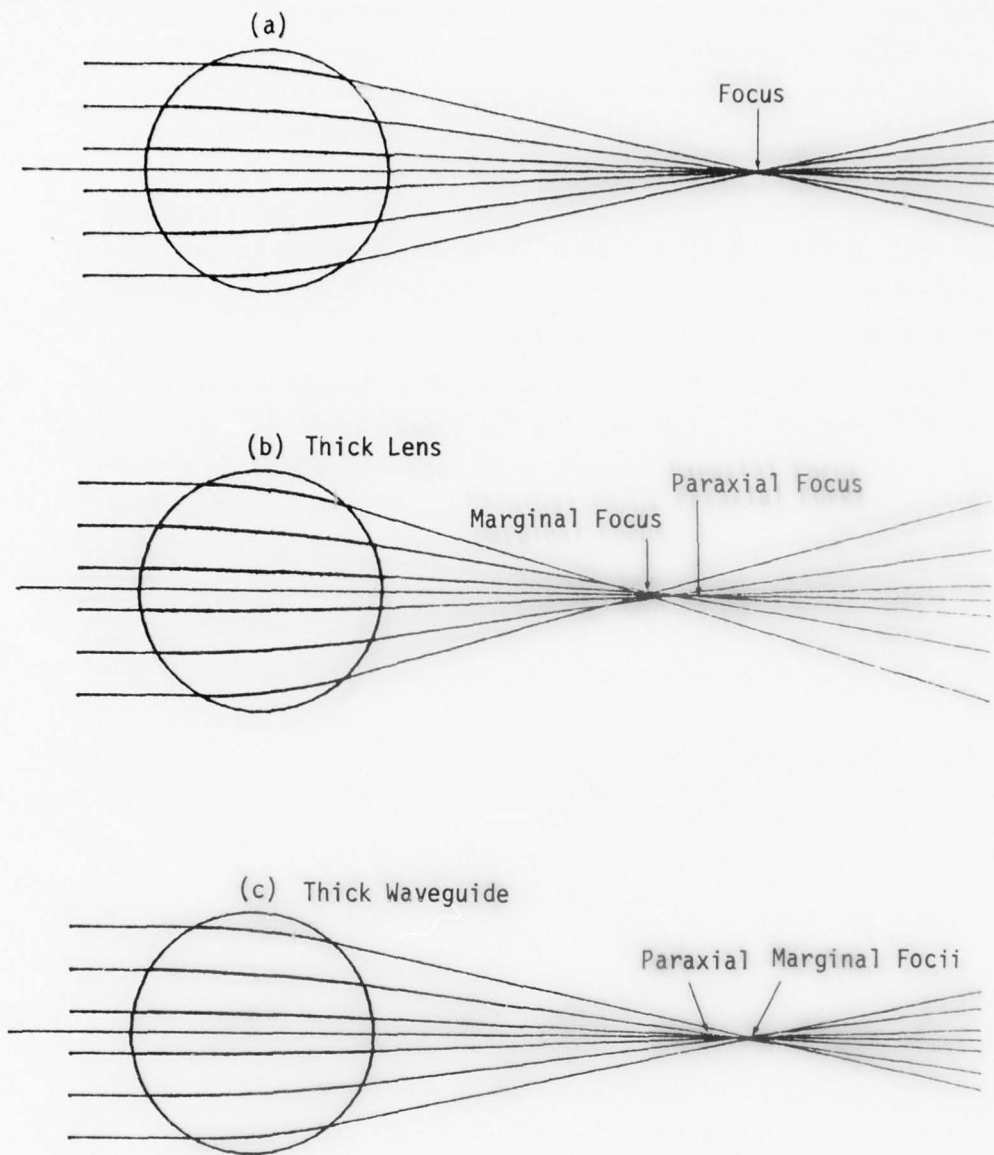


Figure 21. Comparison of Computer Ray Traces for Luneburg Lenses with f-Number of 2 for Refractive Index Profile  $\cos^{0.211}$  Where (a) Thicknesses are Correct, (b) the Lens Thickness Has Been Increased by 10 Percent and (c) Underlying Waveguide Thickness Has Been Increased by 10 Percent.

focus at even a shorter length. The ray traces depicted in Section (c) of Figure 21 are the result of increasing the ambient waveguide thickness by 10 percent without altering the lens thickness profile, i.e., Section (a). These ray traces for an increased waveguide thickness show an increased focal length and the onset of spherical aberration by further increasing of the marginal ray focus. Thus, the performance of thin-film Luneburg lenses is sensitive to the thickness of both the lens and ambient waveguide. Errors of the deposition time will affect the focal length and the onset of aberrations.

Although the use of  $\cos^{0.211}$  profile yields a focused ray trace, this profile simulation is not sufficiently exact to obtain a well-defined diffraction pattern. Therefore, it became necessary to derive more exact expressions for the refractive index profile of generalized Luneburg lenses. We extended the work of Morgan<sup>38</sup> and Luneburg<sup>37</sup> which is fully delineated in Appendix F by Southwell entitled, "Index and Waveguide Thickness Profiles for Generalized Luneburg Lenses." The normalized index profile is given in terms of a transcendental equation

$$n/n_0 = \exp[\omega(\rho, S)], \quad (31)$$

where

$$\omega(\rho, S) = p_1(1-\rho)^{1/2} + p_2(1-\rho)^{3/2} + p_3(1-\rho)^{5/2} + p_4(1-\rho)^{7/2} + p_5(1-\rho)^{9/2} \quad (32)$$

where  $\rho = rn/r_0 n_0$  and where Morgan's parameter  $S = 2f = 2F/r_0$ . Eq. (32) is a parametric generalization of the data that has been tabulated in Morgan and in Appendix F with several additional significant figures. From these profiles, we generate the lens thickness profile in terms of waveguide parameters delineated in Section B.

Using this procedure, a series of figures have been generated for generalized Luneburg lenses having perfect and various types of defective profiles where the defects have been introduced as changes of the  $p_n$  parameter. Most of the data has been calculated for the  $s$  parameter value of 2 and several cases for 3 and 5 where the lens f-number is 1/2 of  $S$ .

These figures depict the overlay waveguide thickness profile for a standard set of waveguide parameters. An overlay lens of  $Ta_2O_5$  having a refractive index  $n_1 = 2.1$  has been assumed for all cases. The waveguide

effective refractive index has been assumed to be 1.535 for all cases which can be derived from a Corning 7059 thin film  $n_w=1.565$  having a thickness  $t=1.0665\mu$  using  $0.9\mu$  radiation. The substrate, in all cases, is  $\text{SiO}_2$  having a refractive index of  $n_s=1.47$ .

Ray traces for each lens waveguide thickness profile is included in the figures together with the ray intercepts in the image plane where the ray intercept is defined in Figure 15. The ray trace intercept utilizes "x" marks corresponding to individual ray trace calculations to which a smooth curve has been fitted for subsequent calculation. Deviations from the abscissa represent the blur width in the image plane corresponding to the ray traces.

Together with each tabulation of generalized Luneburg lens parameters included in these figures is a companion set of figures containing wave front phase error and the corresponding intensity diffraction pattern. In certain cases, more than one wave front error and diffraction pattern is included. These additional figures represent adjustment of the image plane to obtain a better focus by inspection of the ray intercept slope.

Figures 22 and 23 illustrate the case for a perfect generalized Luneburg lens  $S=2$  showing the overlay waveguide lens thickness profile, lens ray traces, ray intercepts, wave front phase error, and corresponding intensity diffraction pattern. Note that the intensity diffraction pattern is the expected  $\text{sinc}^2$  x function which is nearly identical to Figure 18 except for the residual computational errors. Figure 24 utilizes the parameters in Figure 22 with an intentional shift of the image plane to depict the effect of defocusing in the same manner as Figure 19. This figure is included because it is representative of one experimental result discussed later.

The effect of altering the p parameters ( $p_1'=.95p_1$ ,  $p_2'=.7p_2$ ) so as to increase the lens thickness in the central zone ( $1/3$ ) and decrease the lens thickness in the outer annular zone in the region of  $r/r_0=2/3$  is illustrated in Figure 25. This type of defective profile can arise from an incorrectly shaped deposition mask. The wave front and corresponding diffraction pattern are illustrated in Figure 26. This type of profile defect is excessive

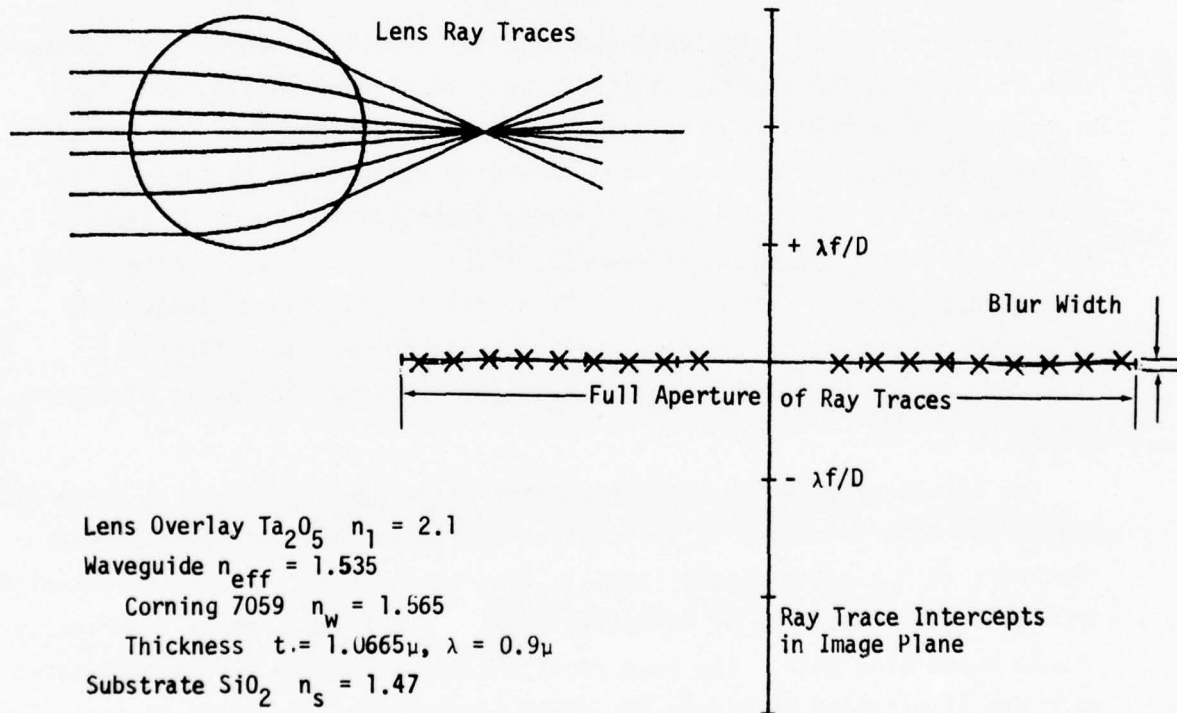
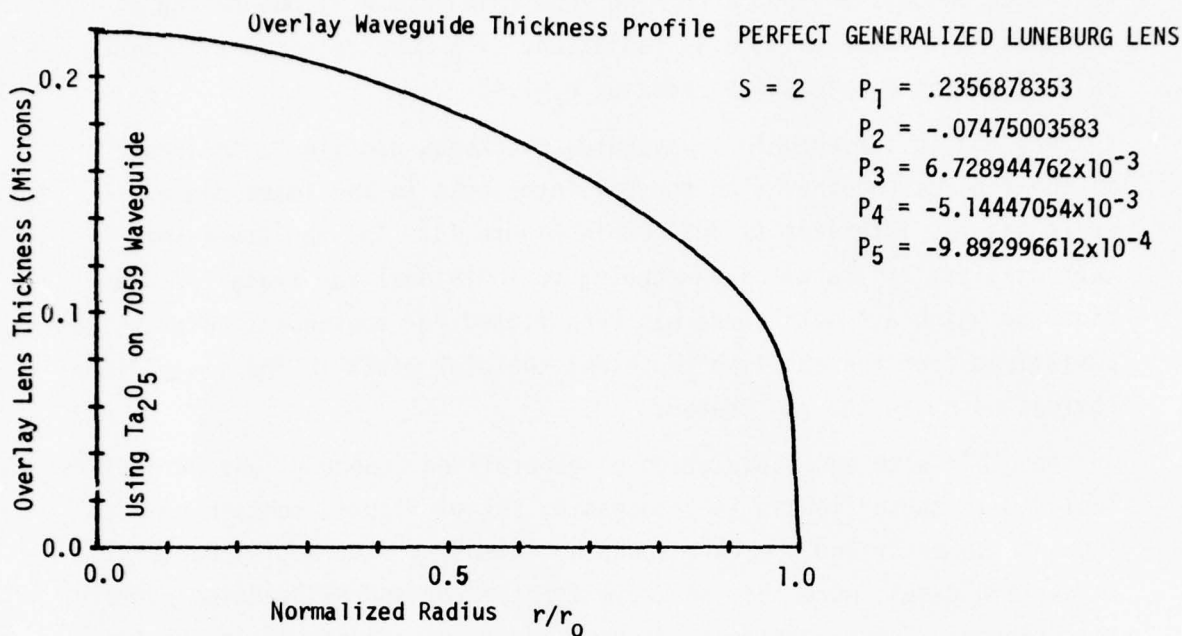
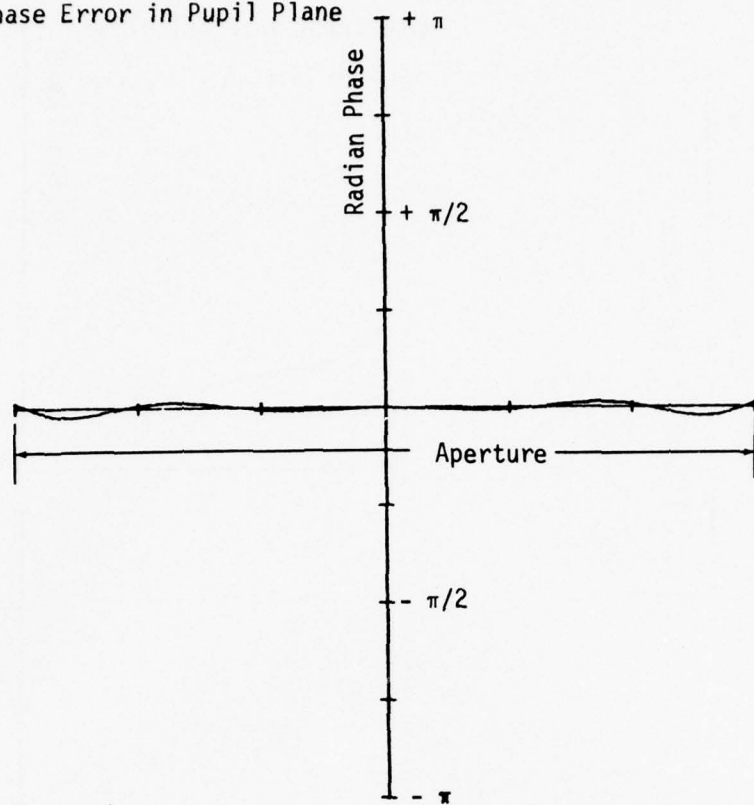


Figure 22. Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (Perfect Luneburg Lens).

Phase Error in Pupil Plane



Diffraction Pattern

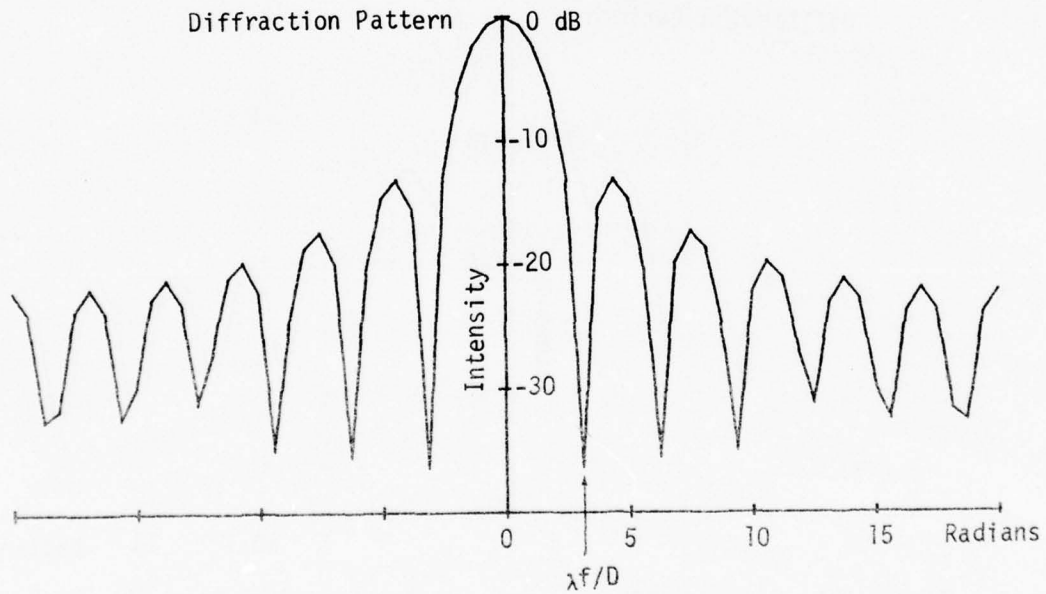
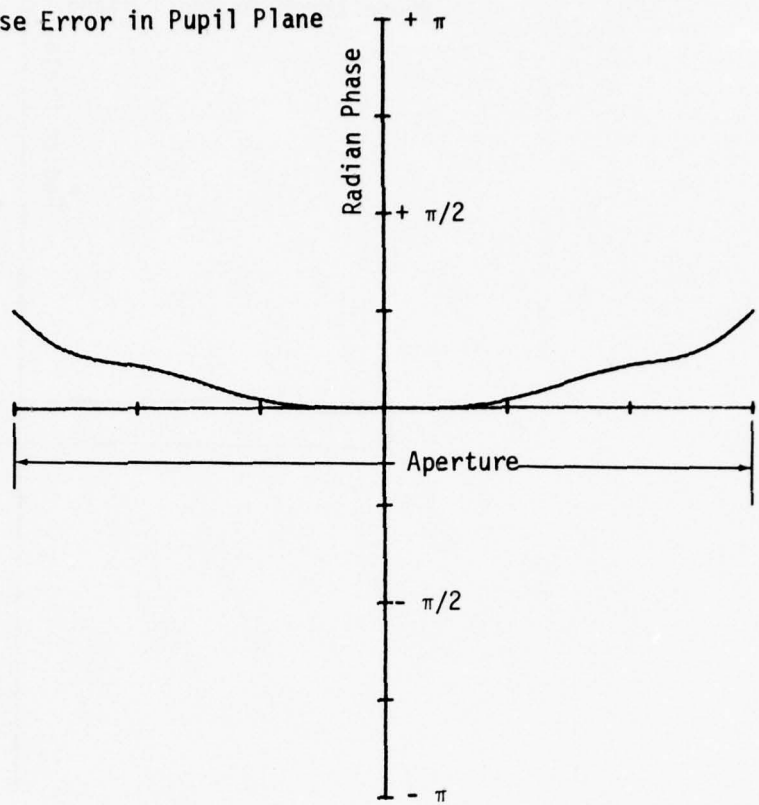


Figure 23. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 22 (Perfect Luneburg Lens).

Phase Error in Pupil Plane



Diffraction Pattern

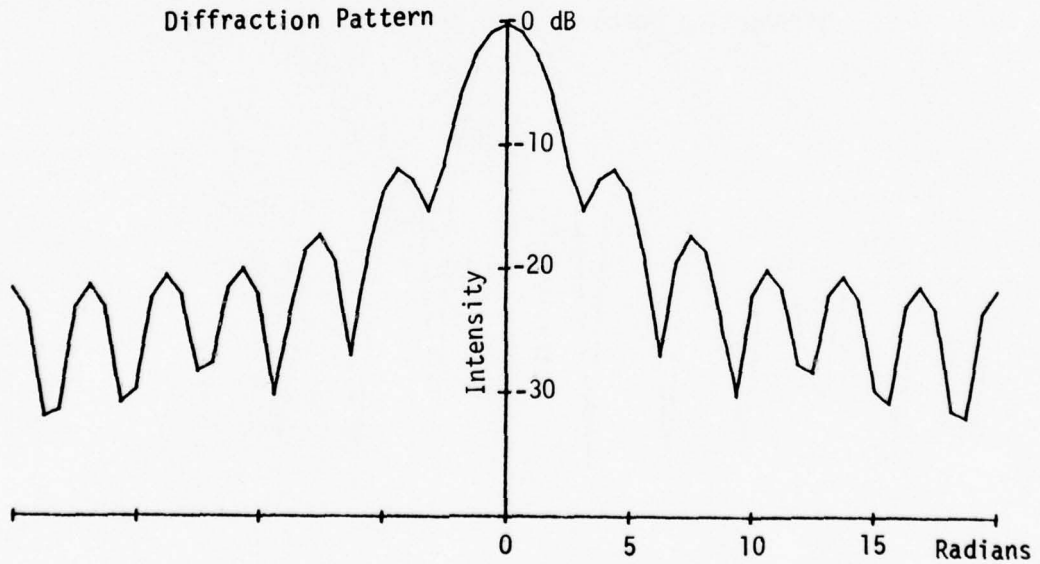


Figure 24. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 22 (Perfect Luneburg Lens) Where Defocusing Has Been Introduced to Create a  $\pi/4$  Phase Error Across the Aperture.

because it destroys the focus. Inspection of the ray trace intercept or wave front error suggests that stopping down the aperture to remove some marginal rays and refocusing will improve the diffraction pattern. Figure 27 contains the same type of defective profile, however, with a much less distortion, ( $p_1' = .995p_1$ ,  $p_2' = .997p_1$ ). The same characteristic wave front error shape is observed with a similar degradation of the diffraction pattern, both of which are less than that of Figure 26; however, of serious consequence. Therefore, the radial weighting is an important parameter to be determined by the deposition mask.

The effects of another type of defect in the overlay waveguide lens thickness profile is shown in Figures 28 and 29 where the zone in the region of  $r/r_0 = 0.5$  is excessively thick ( $p_1' = 1.04p_1$ ,  $p_4' = 10p_4$ ). For this case, the desired single-lobed diffraction pattern at the focus is completely destroyed. Note that stopping down the lens will remove some marginal rays which contribute to the excessive blur width. Again, reducing this type of distortion by altering the p parameters ( $p_1' = 1.0004p_1$ ,  $p_4' = 1.1p_1$ ), similar wave front errors of lesser magnitude are observed in Figure 30 while the principal lobe is somewhat restored. Again, the radial weighting is an important parameter in determining the deposition mask shape.

We will now consider the case of an accurately shaped profile where the deposition time has been allowed to increase producing a uniform radial percentage error, thus, the p parameters are ( $p_1' = 1.02p_1$ ,  $p_2' = 1.02p_2$ ,  $p_3' = 1.02p_3$ , and  $p_4' = 1.02p_4$ ). The resulting overlay waveguide thickness profile lens ray traces and ray trace intercept are depicted in Figure 31 with the resulting wave front error and intensity diffraction pattern depicted in Figure 32. The intensity diffraction pattern has been taken in the same position as in the previous distorted cases. Inspection of the ray trace intercept shows that the beam is defocused and, therefore, the image plane should be shifted. The effect of a lesser degree of overlay waveguide lens thickness percentage error is shown in Figures 33 and 34 ( $p_1' = 1.0002p_1$ ,  $p_2' = 1.0002p_2$ ,  $p_3' = 1.0002p_3$ , and  $p_4' = 1.0002p_4$ ). Again, the

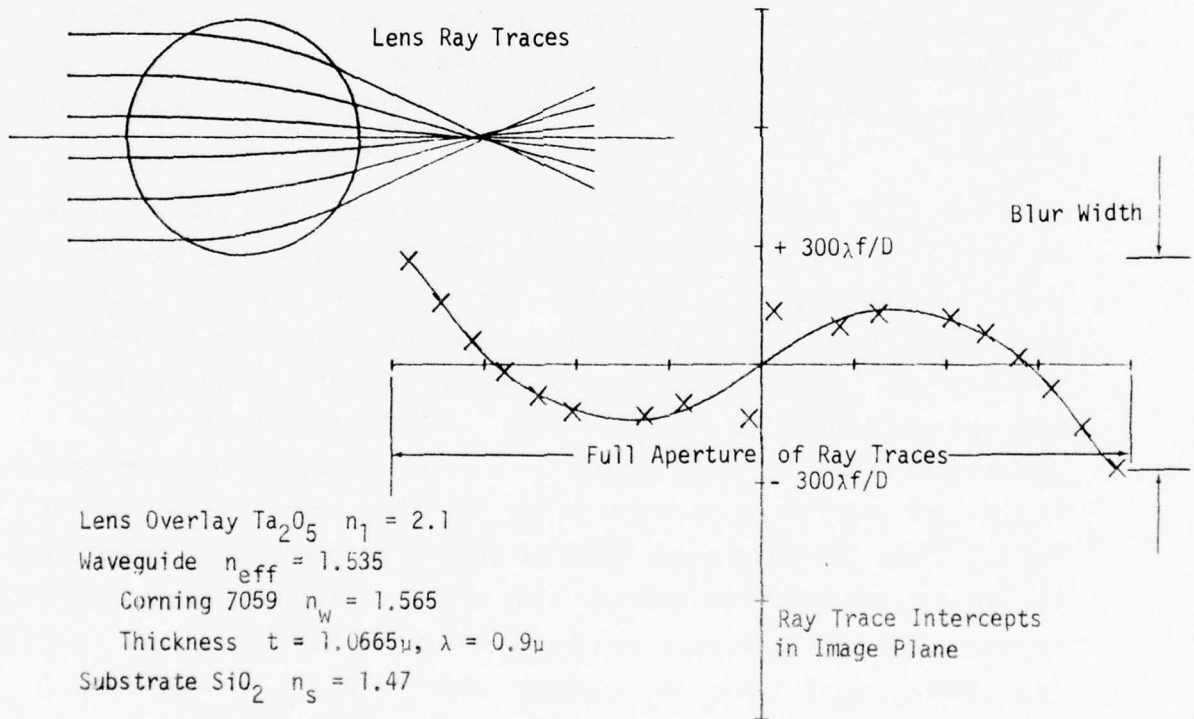
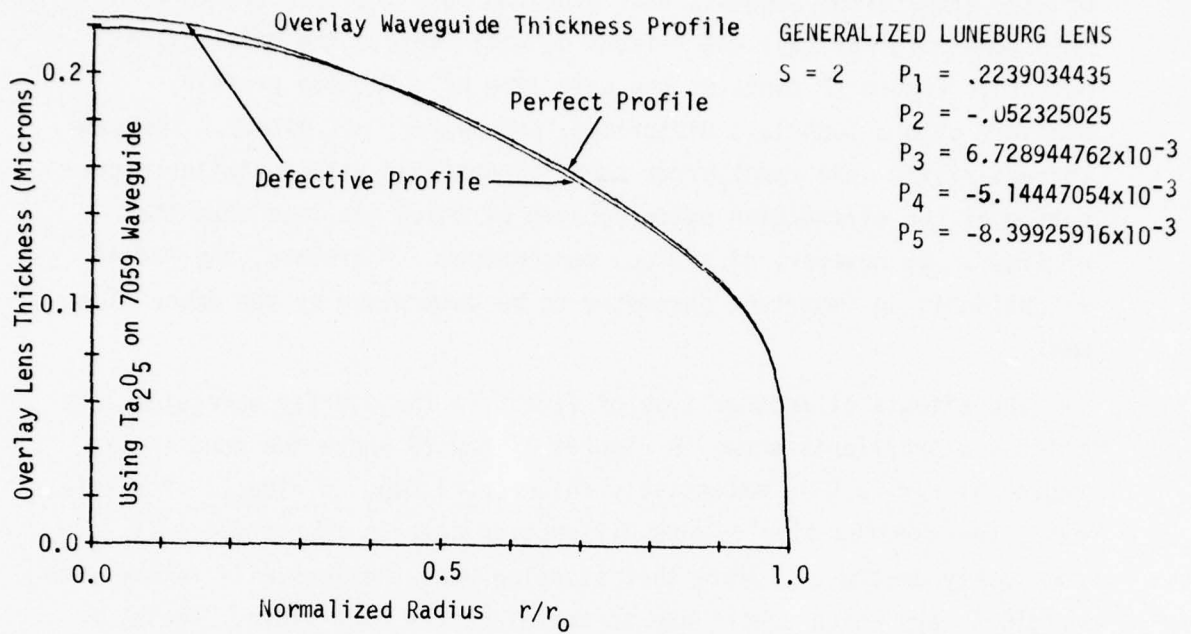


Figure 25. Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane ( $.95 P_1$ ,  $.7 P_2$ ,  $8.4901 P_5$ ).

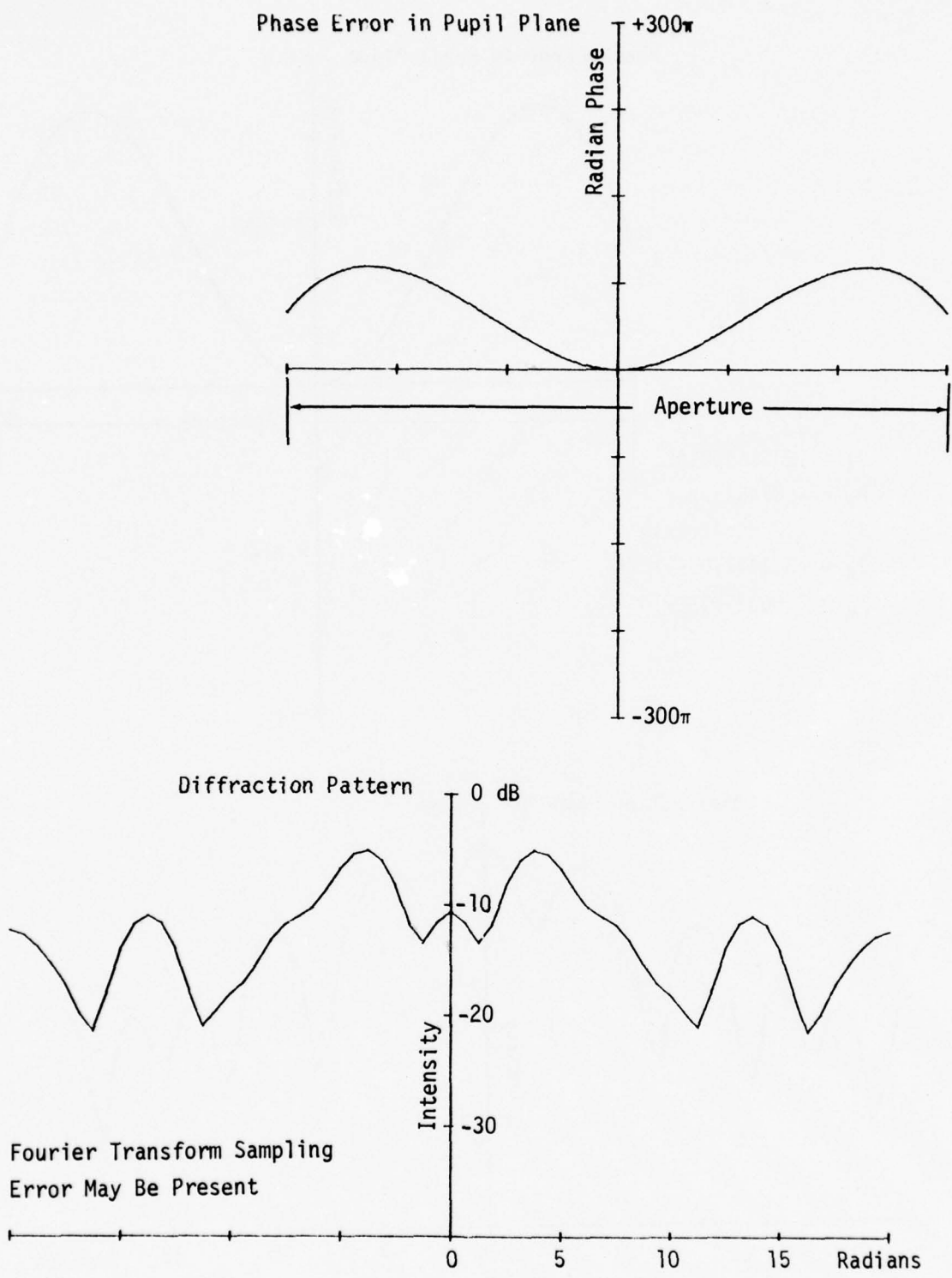


Figure 26. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 25

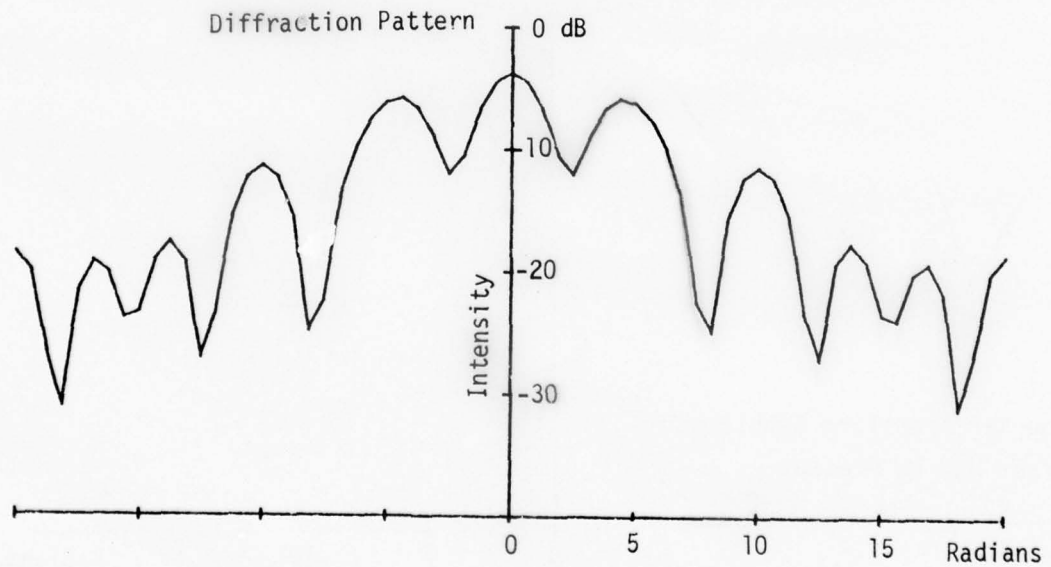
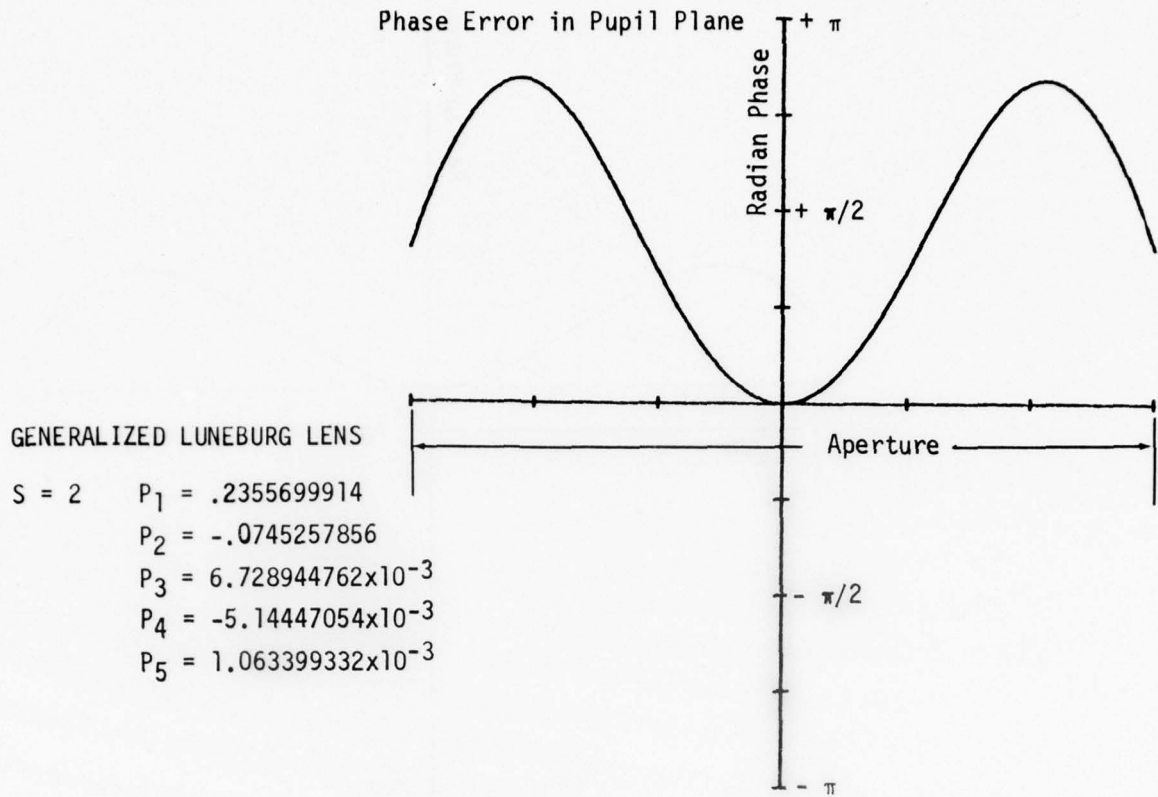


Figure 27. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 25 (.9995 P<sub>1</sub>, .997 P<sub>2</sub>, -1.0749 P<sub>5</sub>).

same shape wave front phase error is observed with substantially less distortion while the diffraction pattern is diffused and the principal lobe identifiable. Inspection of the ray trace intercept shows that the beam is defocused and, therefore, the image plane should be shifted. This has been done for Figure 34 by reducing the focal length  $4\mu$ . The resulting refocused wave front phase error and diffraction pattern correspond to the results of the idealized profile as exemplified in Figure 23.

Figures 31 through 34 are applicable to lens thickness profiles having uniform percentage increase or a uniform thickness decrease of the underlying waveguide. The following five figures are applicable to overlay waveguide thickness profiles having a uniform percentage less than the perfect profile or due to the underlying waveguide having an excessive thickness. Figures 35 and 36 are applicable for the p parameters ( $p_1'=.98p_1$ ,  $p_2'=.98p_2$ ,  $p_3'=.98p_3$ , and  $p_4'=.98p_4$ ). Note that the ray intercept and wave front phase error indicate the opposite effects to that in the preceding four figures. Inspection of the ray intercept plot and wave front phase error suggests movement of the image plane to obtain refocusing. This has been done in Figure 37 by increasing the focal length  $375\mu$ . This refocusing has substantially reduced the quadratic wave front distortion and defocusing to a somewhat excessive length leaving higher order spatial phase errors.

Reduction of the uniform distortion in the same manner as before for p parameters ( $p_1'=.9998p_1$ ,  $p_2'=.9998p_2$ ,  $p_3'=.9998p_3$ , and  $p_4'=.9998p_4$ ) yields the wave front error and diffraction pattern shown in Figure 38. Inspection of the ray intercept plot shows that the image plane should be repositioned. This has been done and the result illustrated in Figure 39 by increasing the focal length  $4\mu$ . The result is, thus, identical to the perfect profile shown in Figure 23 and the refocused profile shown in Figure 34. Thus far, these results indicate that the focal length may be adjusted by altering the waveguide thickness or the deposition time through a mask having the shape capable of producing the correct profile.

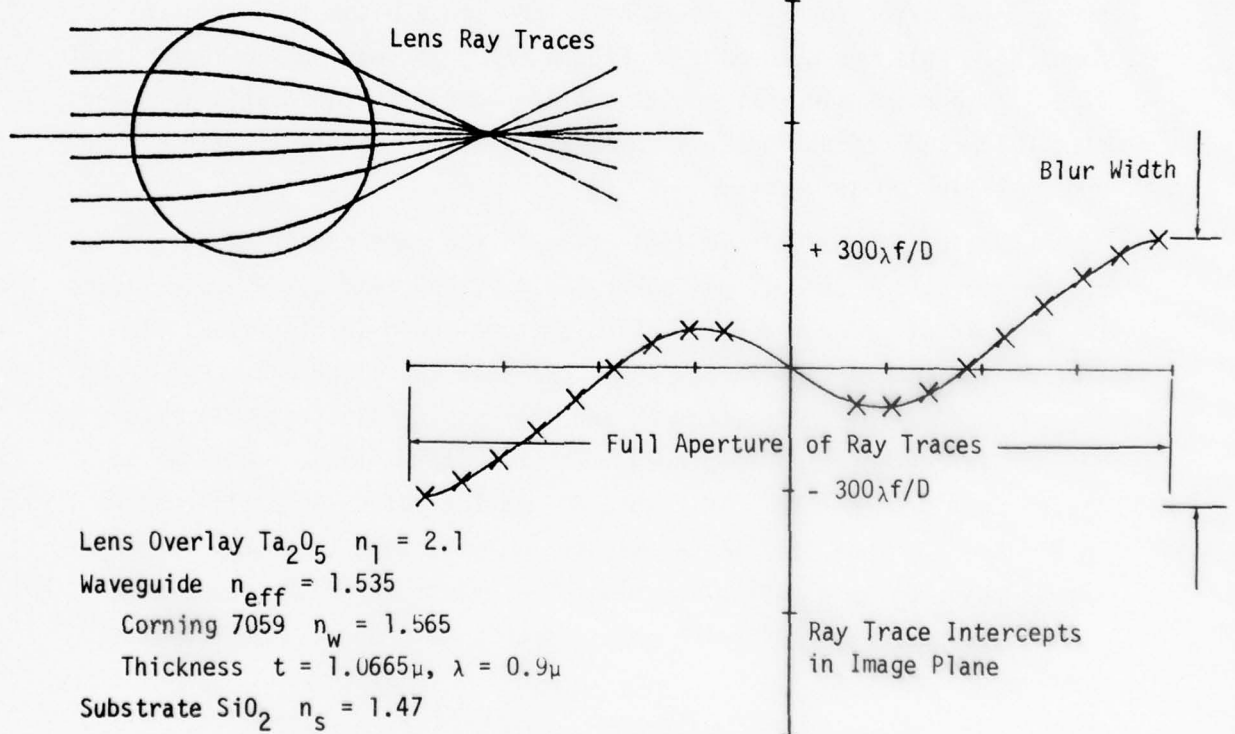
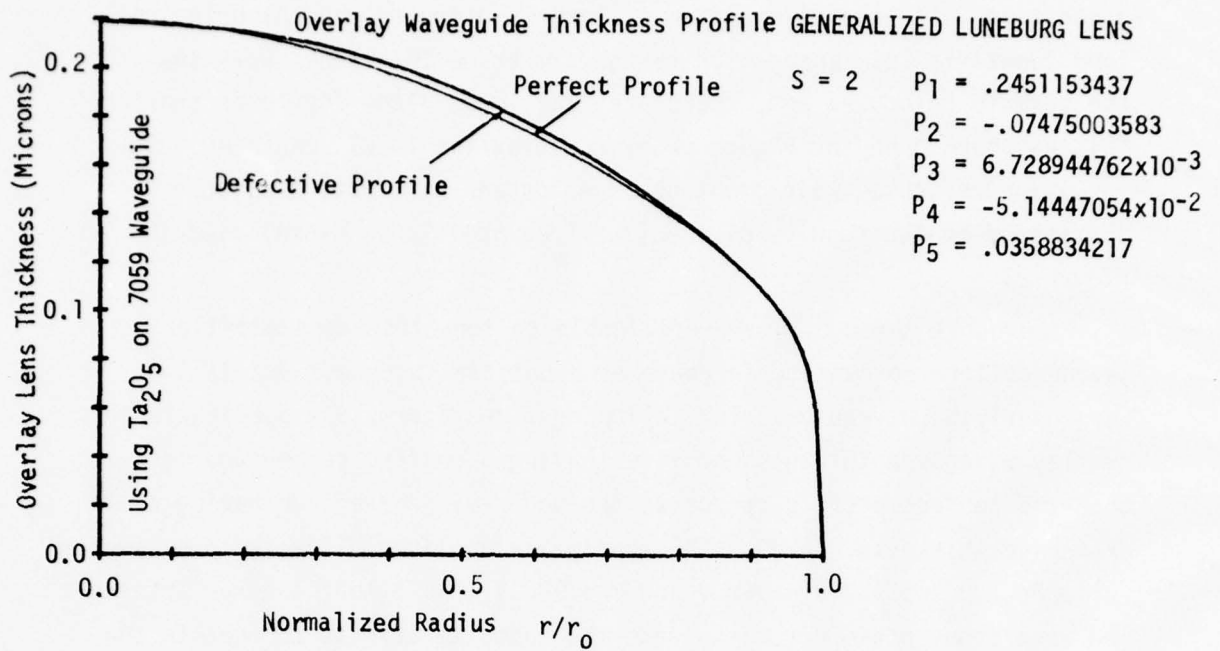


Figure 28. Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane ( $1.04 P_1, 10 P_4, -36.2715 P_5$ ).

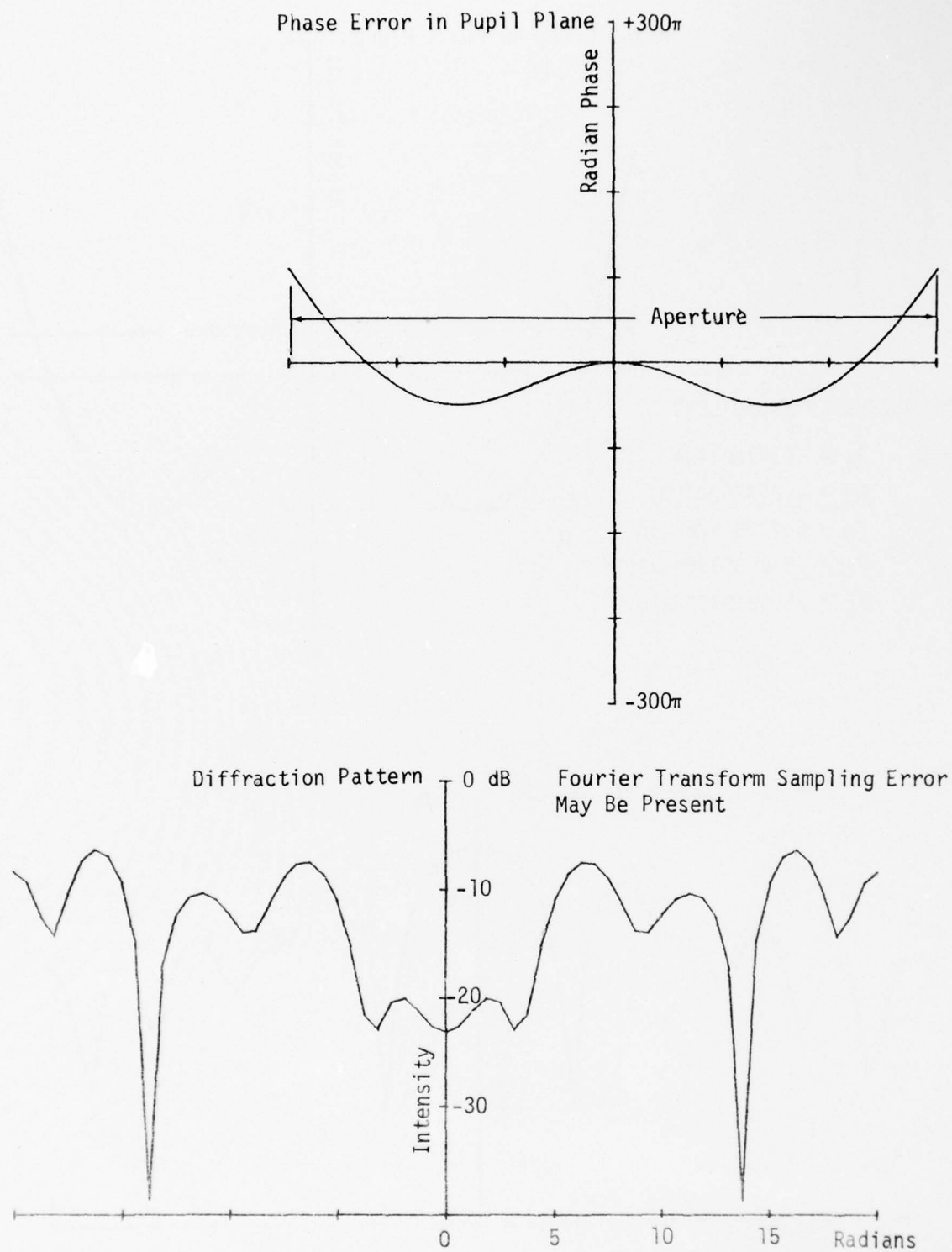


Figure 29. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 28

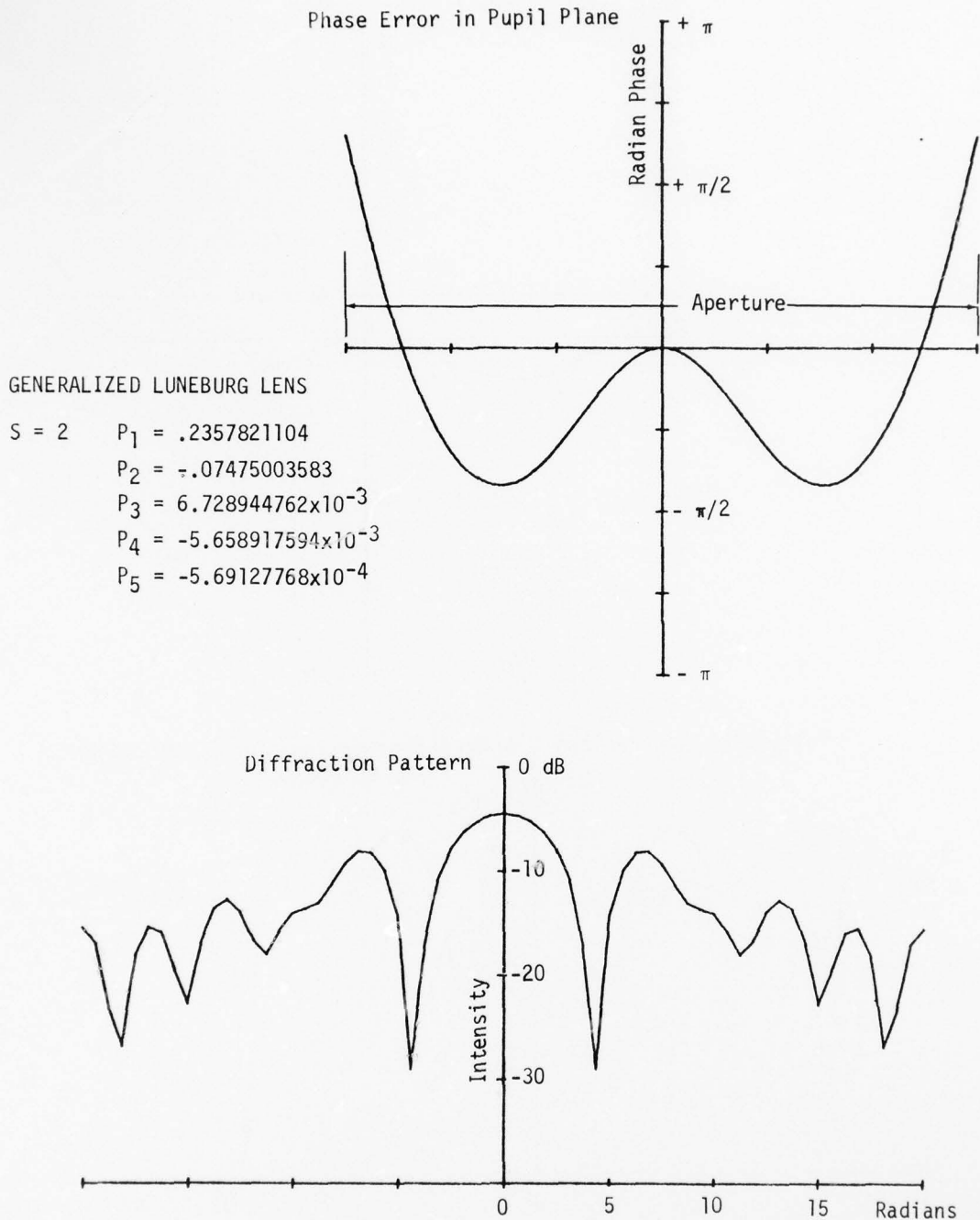


Figure 30. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 28 (1.0004 P<sub>1</sub>, 1.1 P<sub>4</sub>, .5752 P<sub>5</sub>).

Another type of defective profile considered employs a central zone ( $1/2$ ) of reduced thickness and an outer zone in the region of  $r/r_0=3/4$  of increased thickness by lesser value is illustrated in Figures 40 and 41 for the  $p$  parameters ( $p_1'=1.05p_1$ ,  $p_2'=1.35p_1$ ). This type of distortion is similar to that of Figures 25 and 26, however, producing the opposite effects.

Similarly, Figures 42 and 43 having the opposite zonal distortion to that of Figures 28 and 29 are illustrated in Figures 42 and 43 for the  $p$  parameters ( $p_1'=.96p_1$ ,  $p_4'=-10p_4$ ). Similarly, this type of defect has been reduced using the  $p$  parameter ( $p_1'=0.996p_1$ ,  $p_4'=-1.1p_4$ ) which corresponds to the opposite effect of Figure 44, however, in each of these cases, producing ill-defined single lobe diffraction pattern. Thus, for each of the cases involving zonal distortions of the ideal profile, severe aberrations occur which destroy the desired single-lobed well-defined diffraction pattern inherent from perfect profiles. All of the above data has pertained to a generalized Luneburg lens with  $s=2$ .

The overlay waveguide lens thickness profile, lens ray traces, ray intercepts, wave front phase error, and intensity diffraction pattern for a perfect generalized Luneburg lens having  $s=3$  is depicted in Figures 45 and 46. Similarly, for the perfect generalized Luneburg lens having  $s=5$ , the results are depicted in Figures 47 and 48. Introduction of defects in these latter longer focal length lenses has not been executed. However, the trends indicated for the  $s=2$  case should carry over.

Some of the diffraction patterns contain the note that an error may be present due to the Fourier transform sampling. The transform as implemented to derive these figures has utilized 64 "data" points to economize the computational time. Therefore, when the wavefront phase error fluctuates through wide excursions, the sampling error may distort the diffraction pattern. This is not considered a handicap because such large phase errors do not usually produce a well-defined principle lobe diffraction pattern. An improvement could be obtained with additional

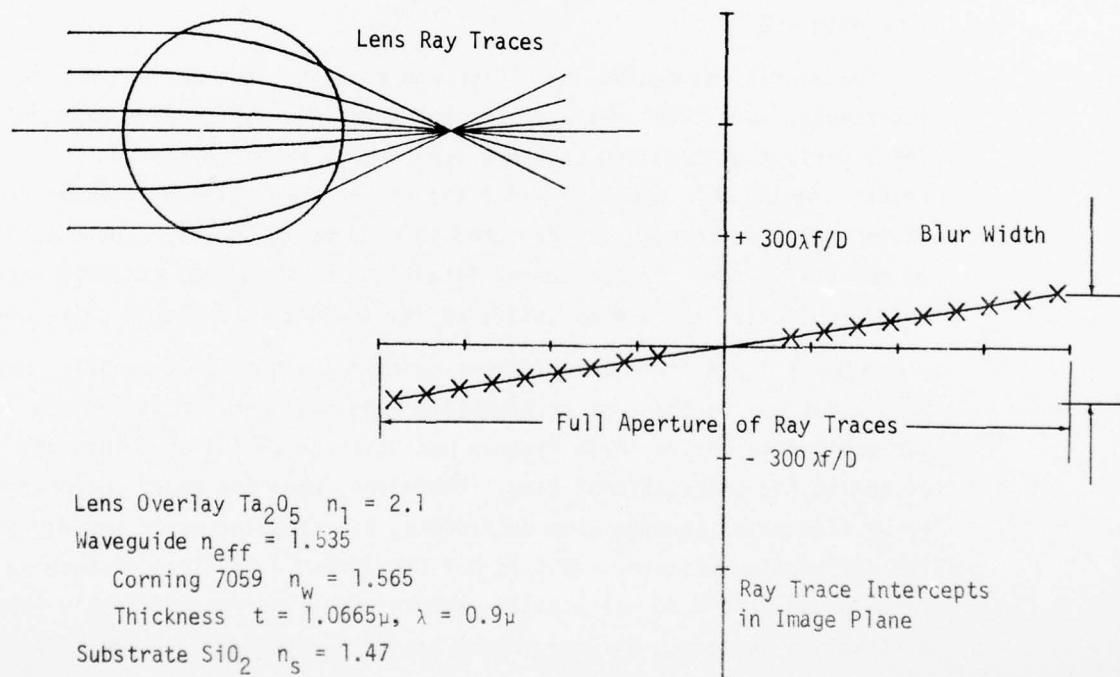
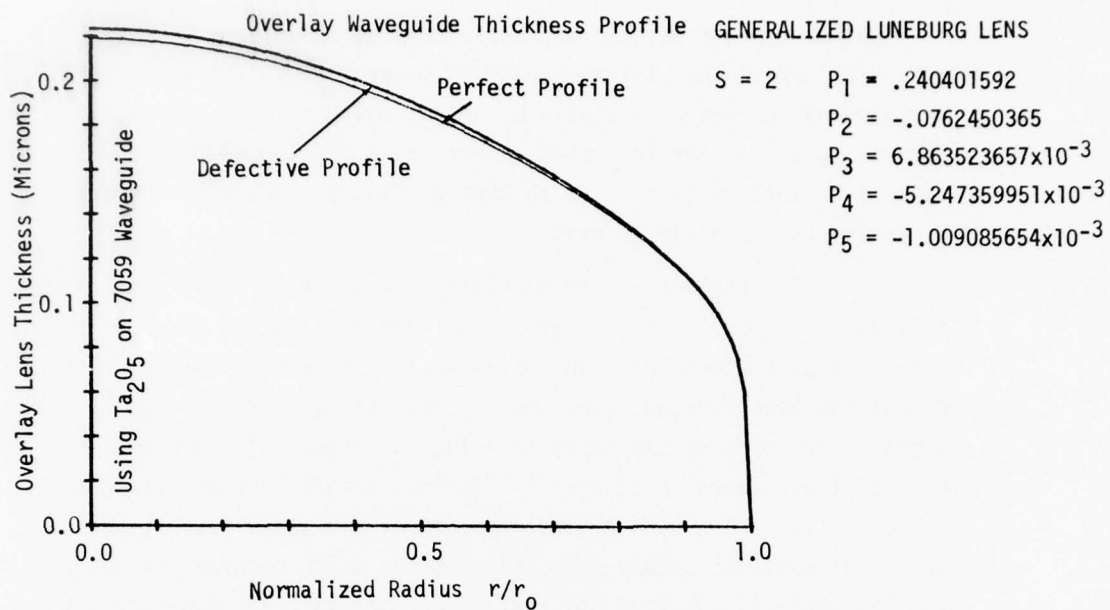


Figure 31. Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane ( $1.02 P_1$ ,  $1.02 P_2$ ,  $1.02 P_3$ ,  $1.02 P_4$ ,  $1.02 P_5$ ).

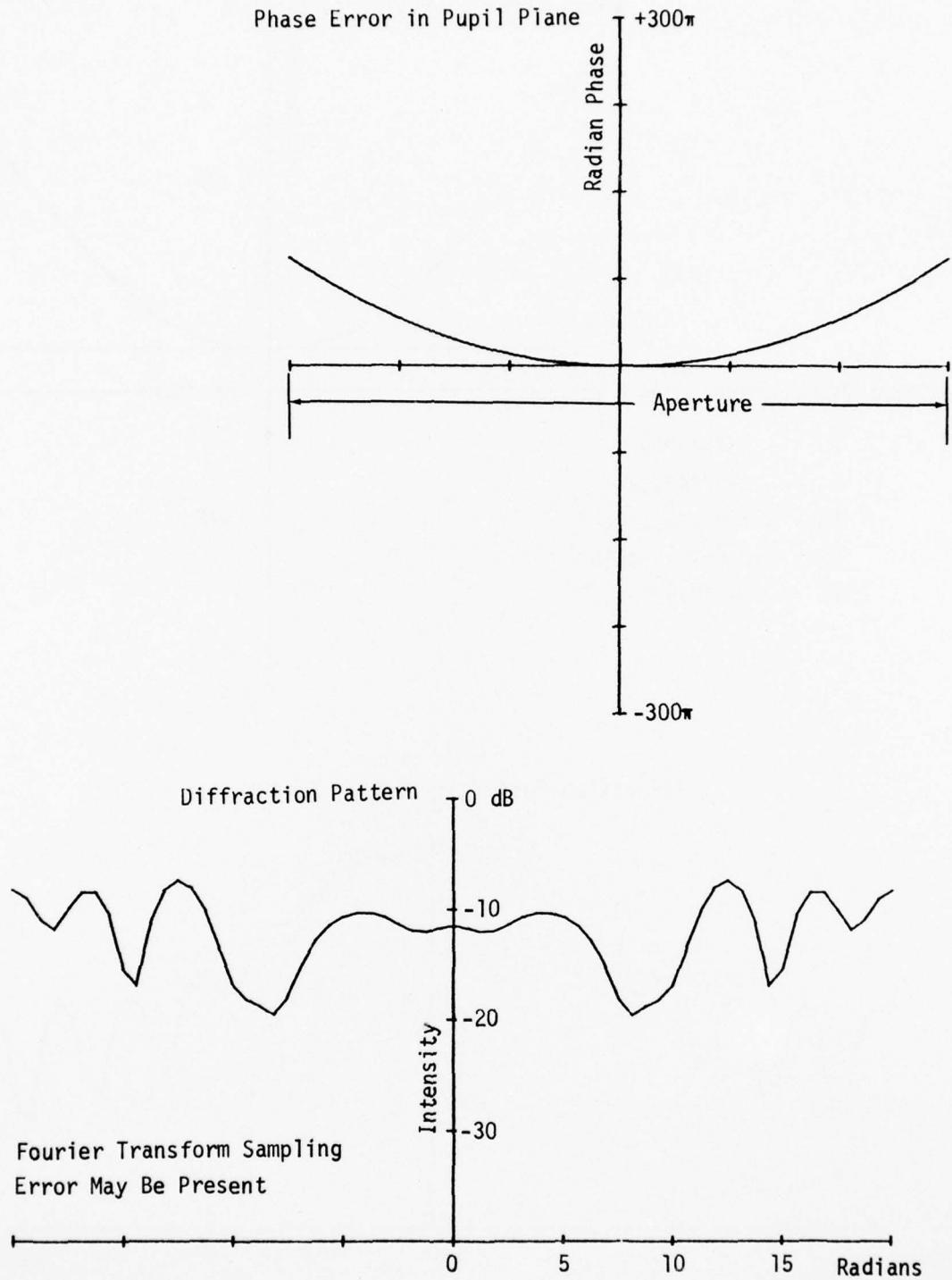


Figure 32. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 31

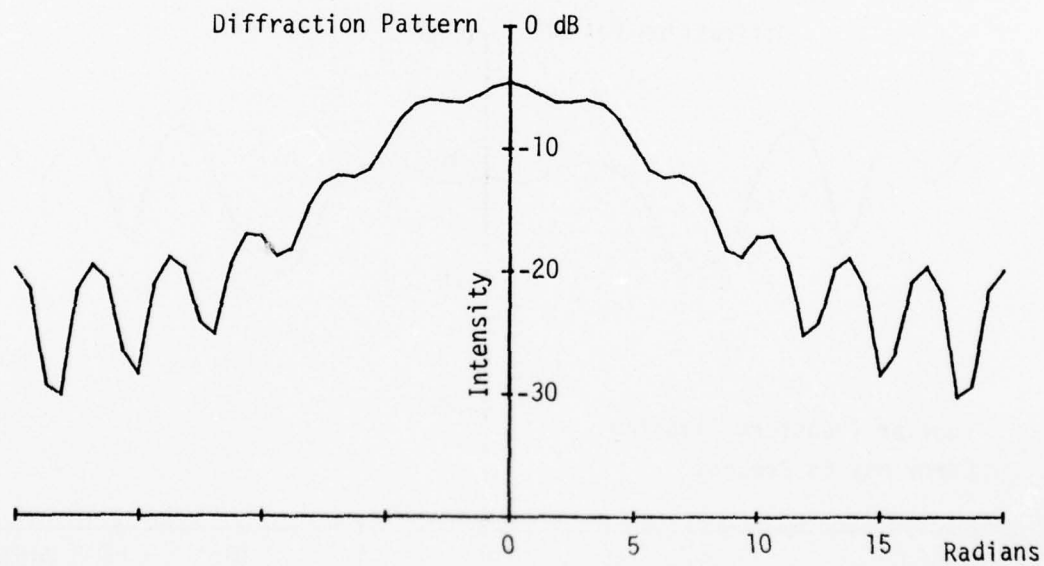
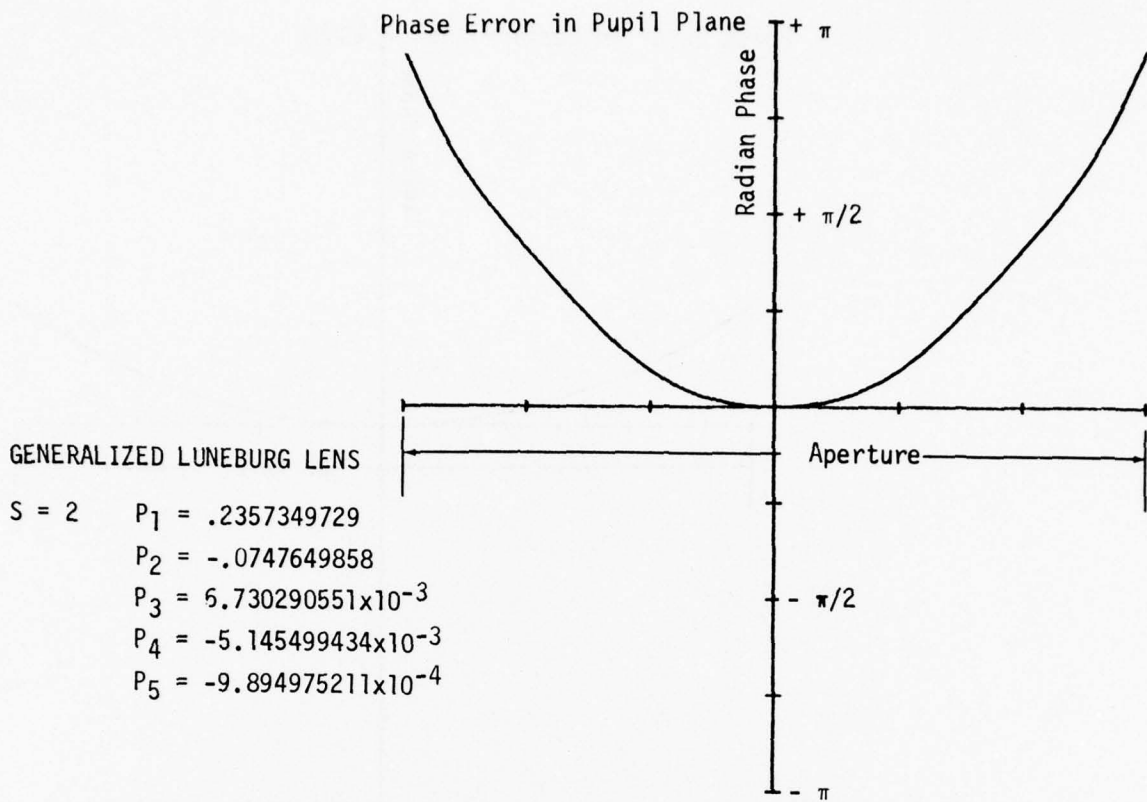


Figure 33. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 31 ( $1.0002 P_1$ ,  $1.0002 P_2$ ,  $1.0002 P_3$ ,  $1.0002 P_4$ ,  $1.0002 P_5$ ).

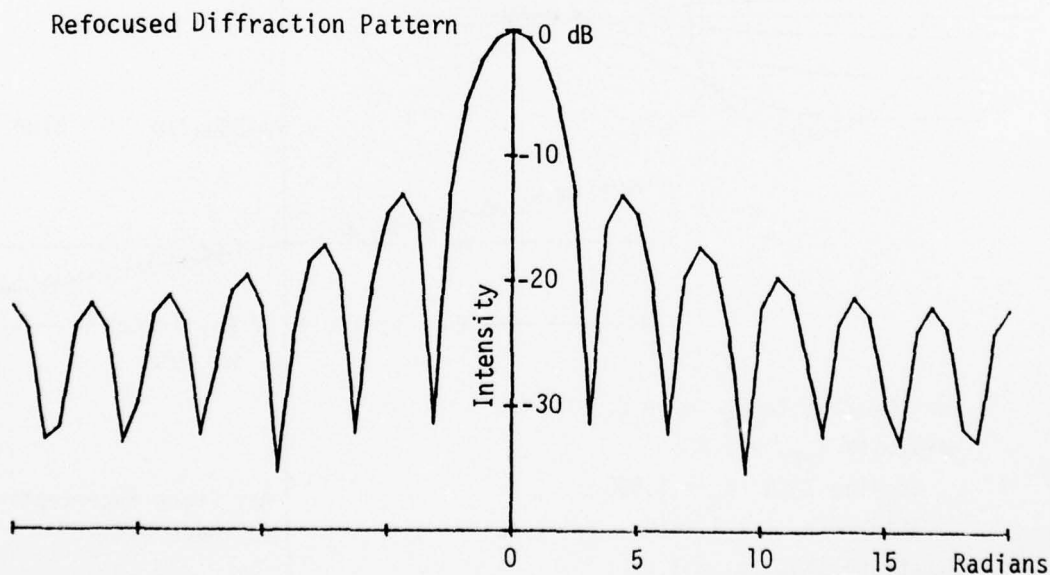
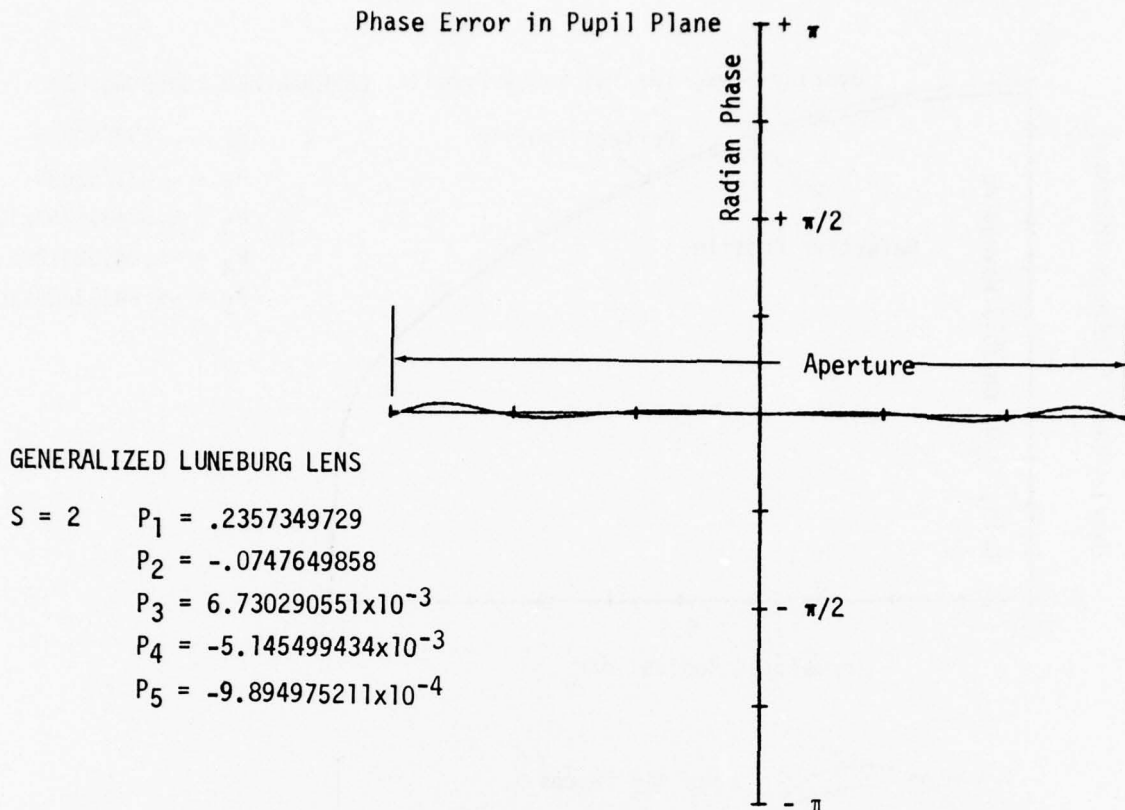


Figure 34. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 31 (1.0002 P<sub>1</sub>, 1.0002 P<sub>2</sub>, 1.0002 P<sub>3</sub>, 1.0002 P<sub>4</sub>, 1.0002 P<sub>5</sub>), New Focal Length -4μ.

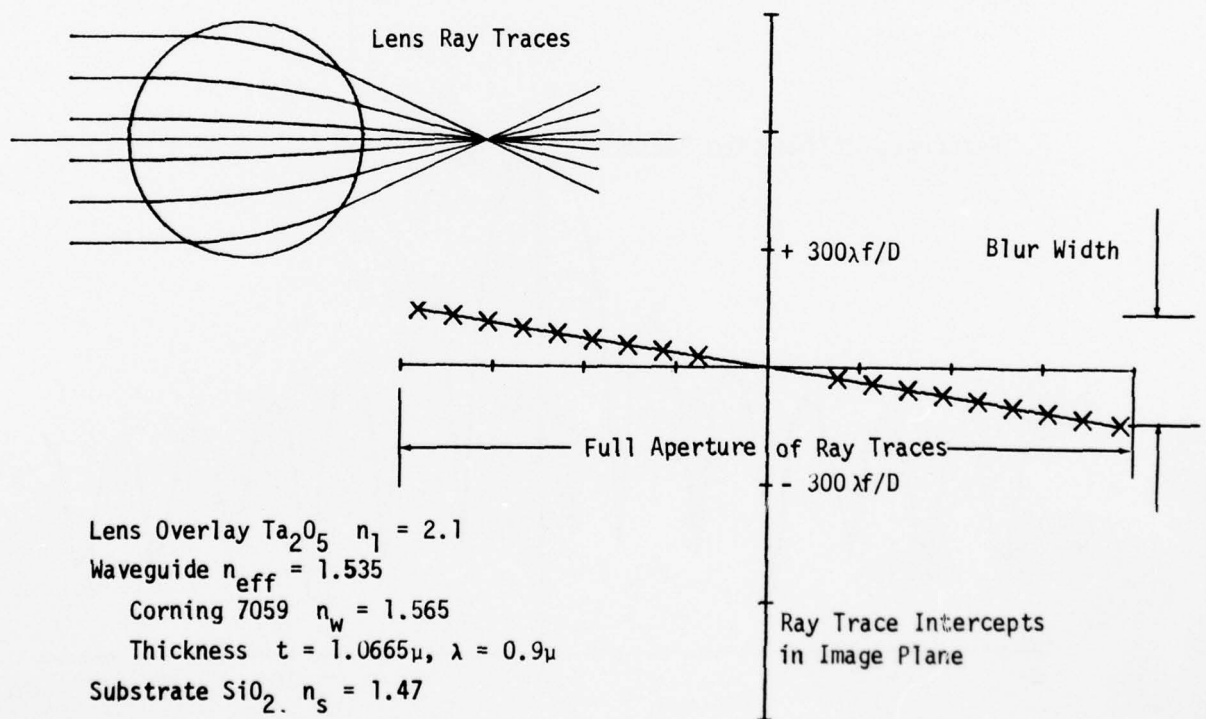
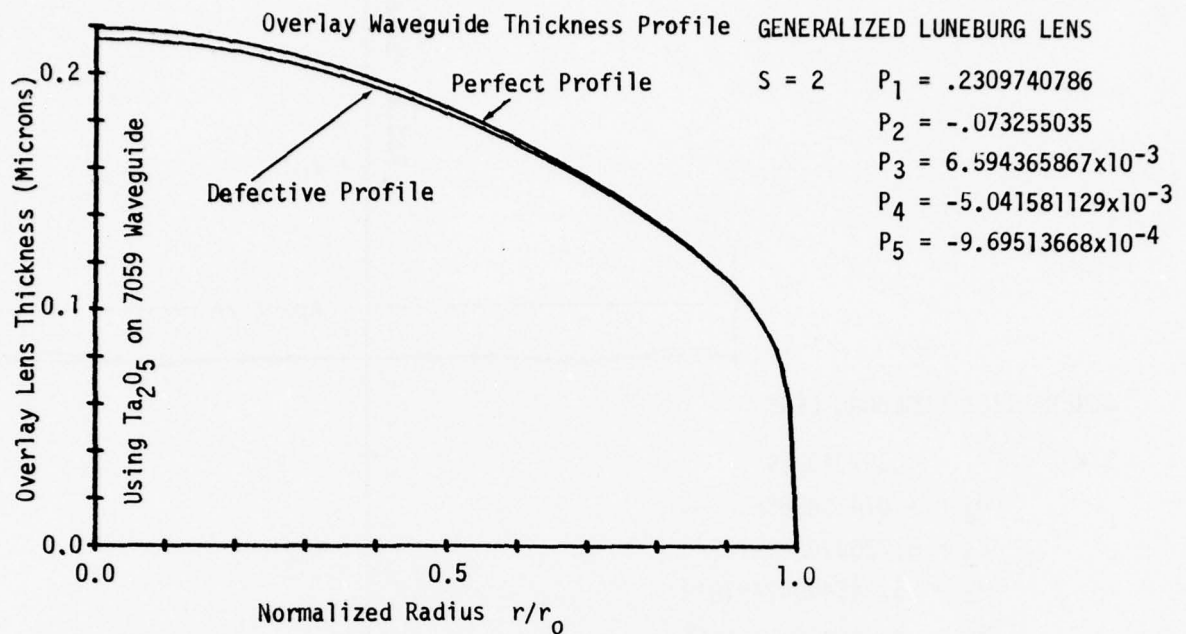


Figure 35. Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (.98  $P_1$ , .98  $P_2$ , .98  $P_3$ , .98  $P_4$ , .98  $P_5$ ).

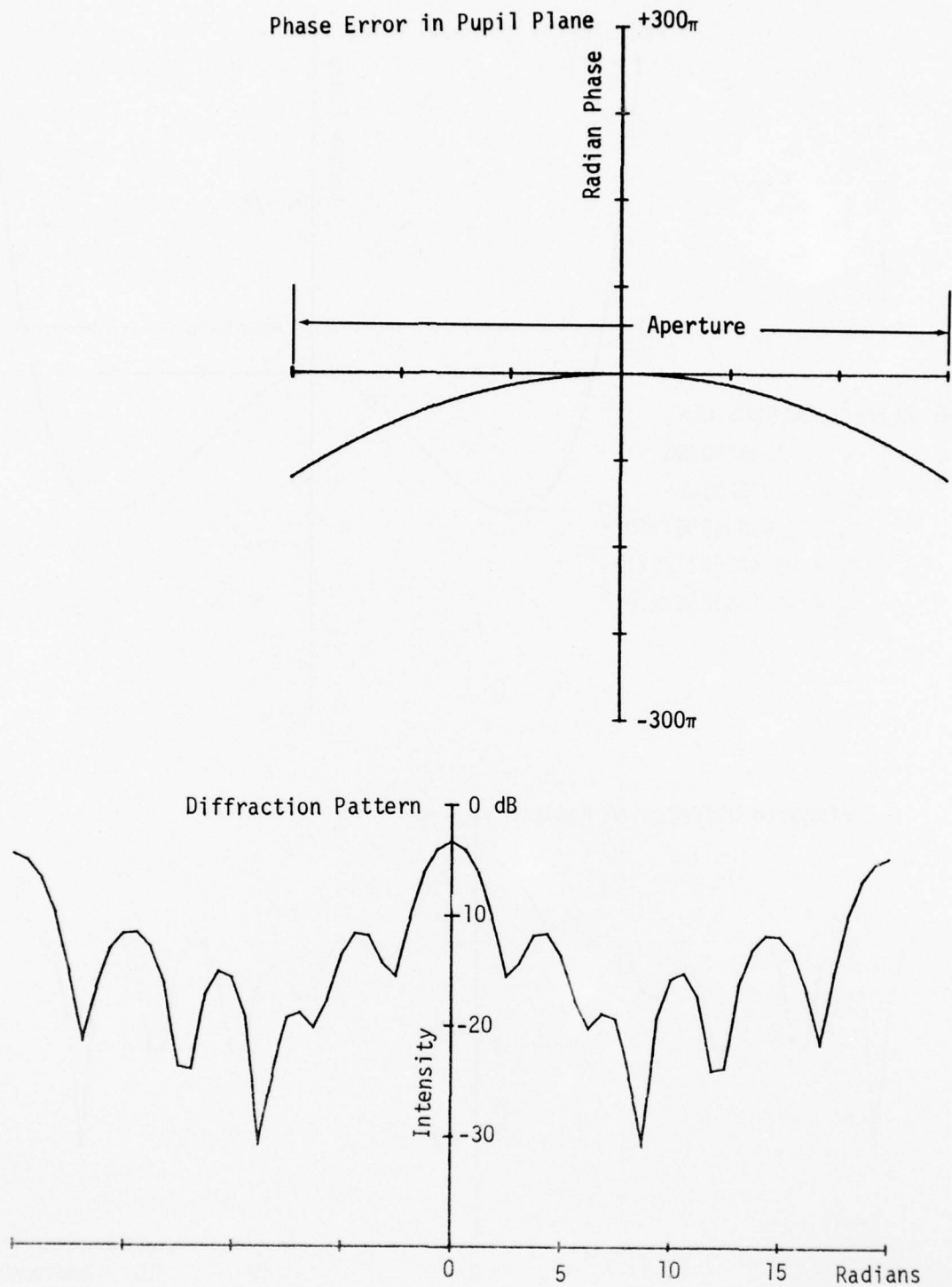


Figure 36. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 35.

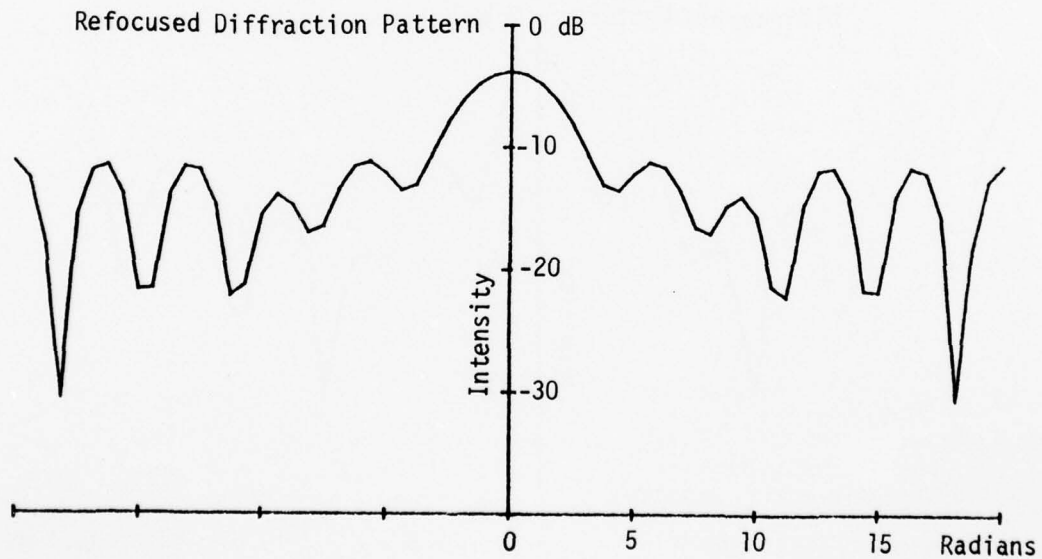
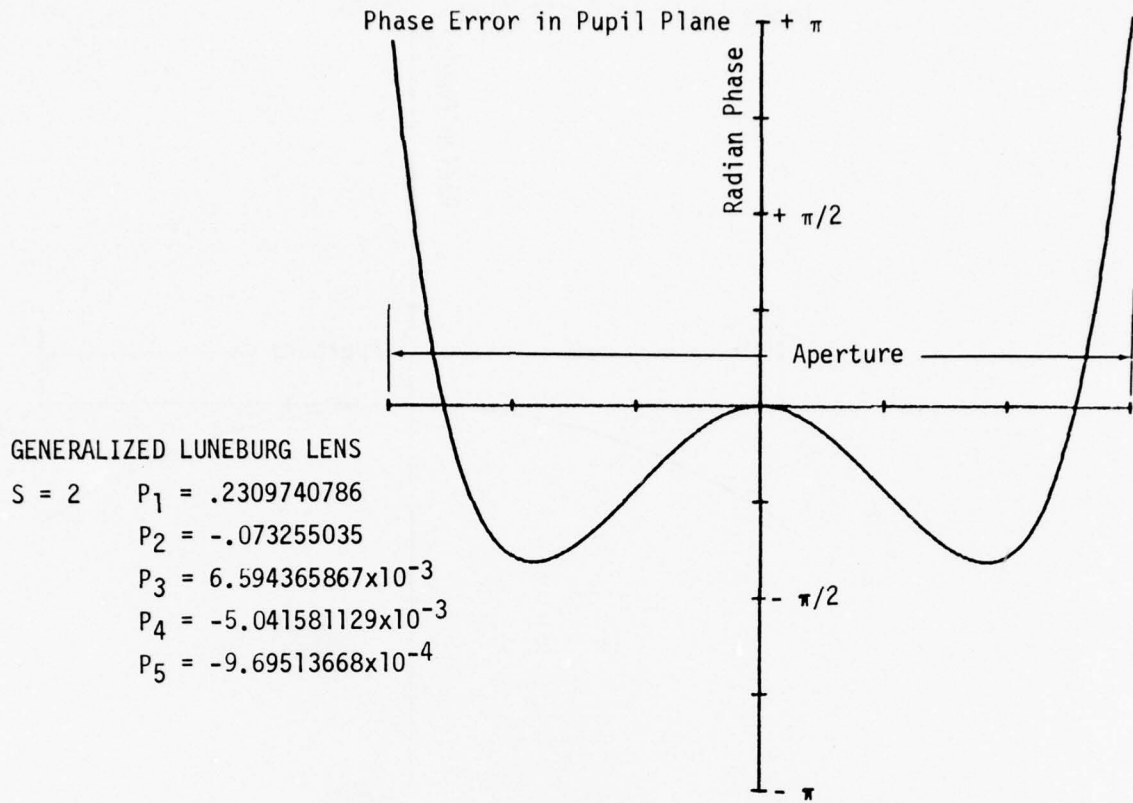


Figure 37. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 35 ( $.98 P_1, .98 P_2, .98 P_3, .98 P_4, .98 P_5$ ), New Focal Length  $+375\mu$ .

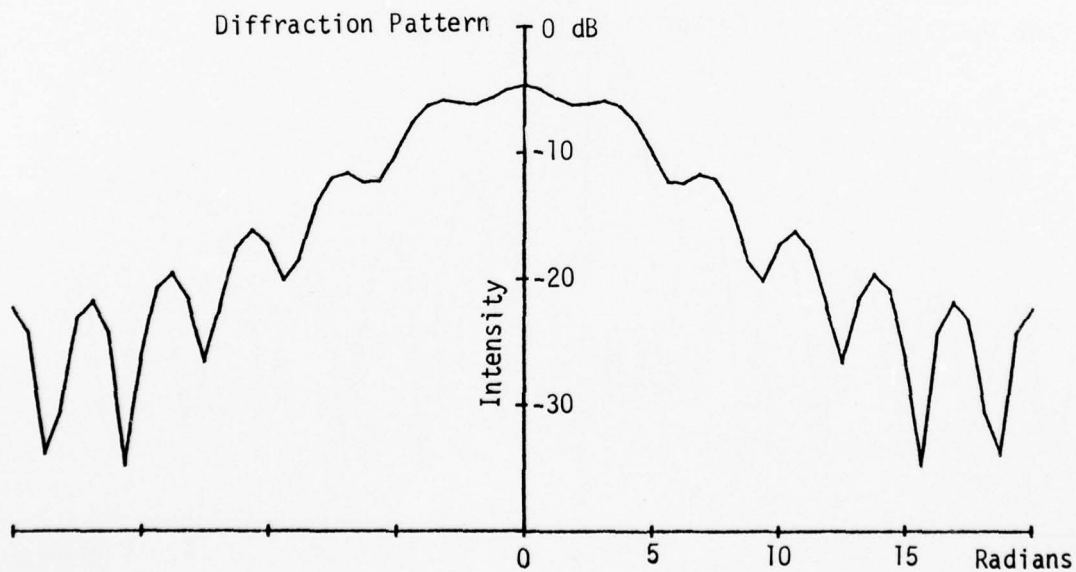
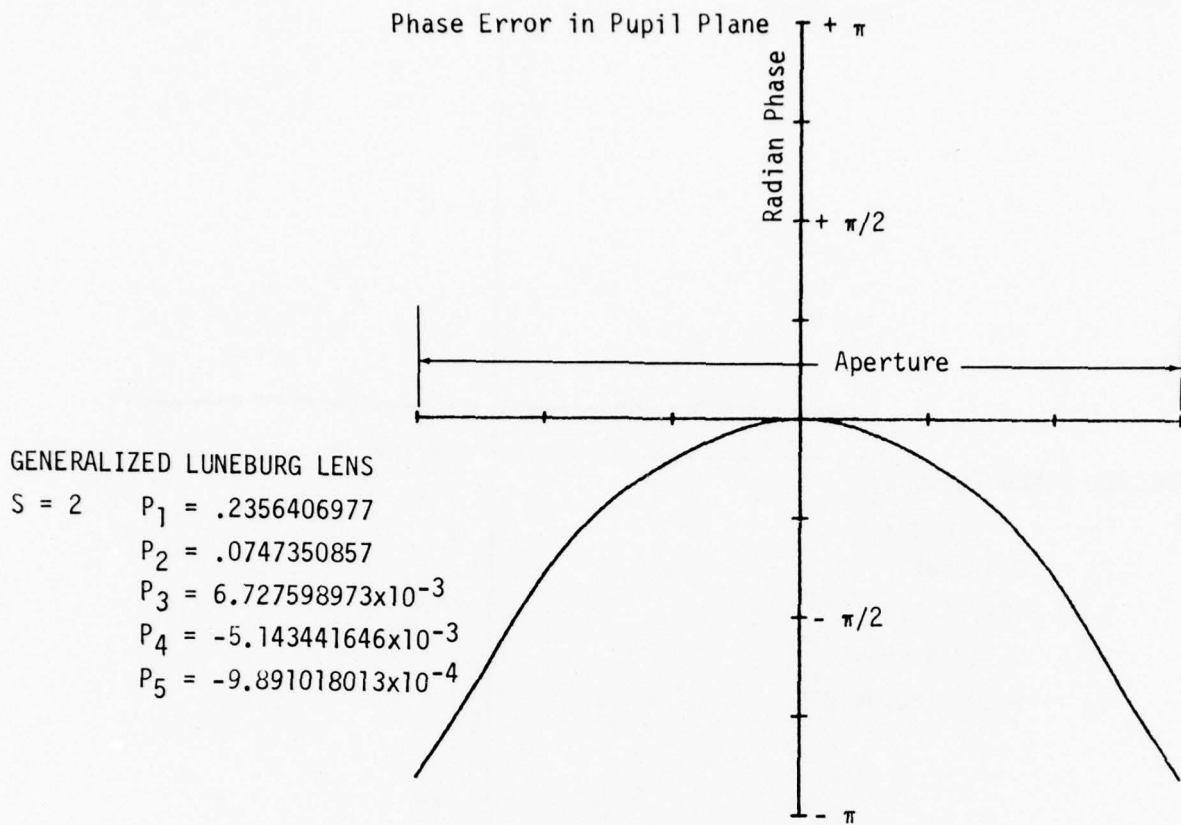


Figure 38. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 35 (.9998  $P_1$ , .9998  $P_2$ , .9998  $P_3$ , .9998  $P_4$ , .9998  $P_5$ ).

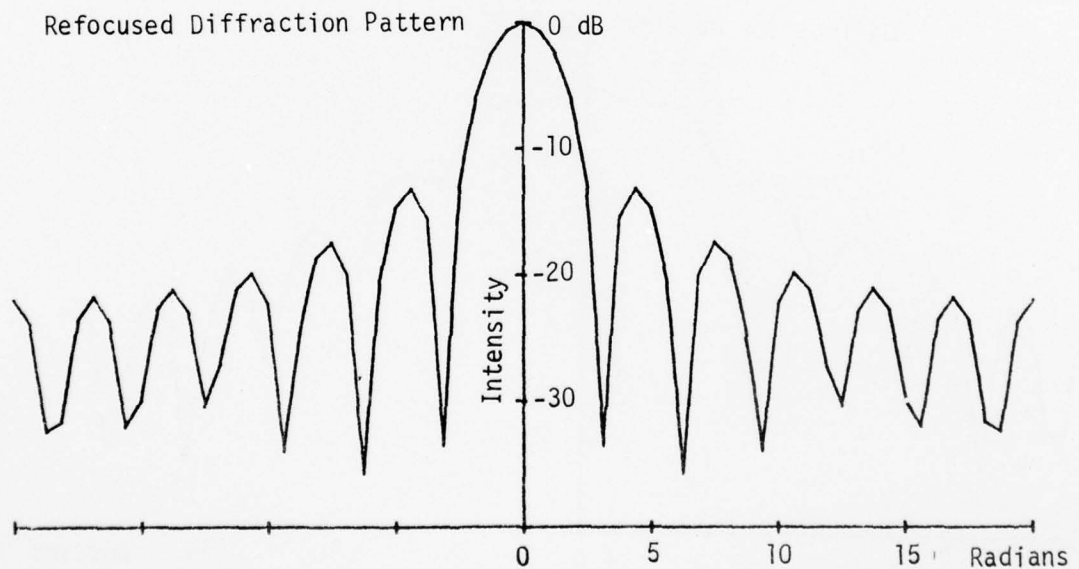
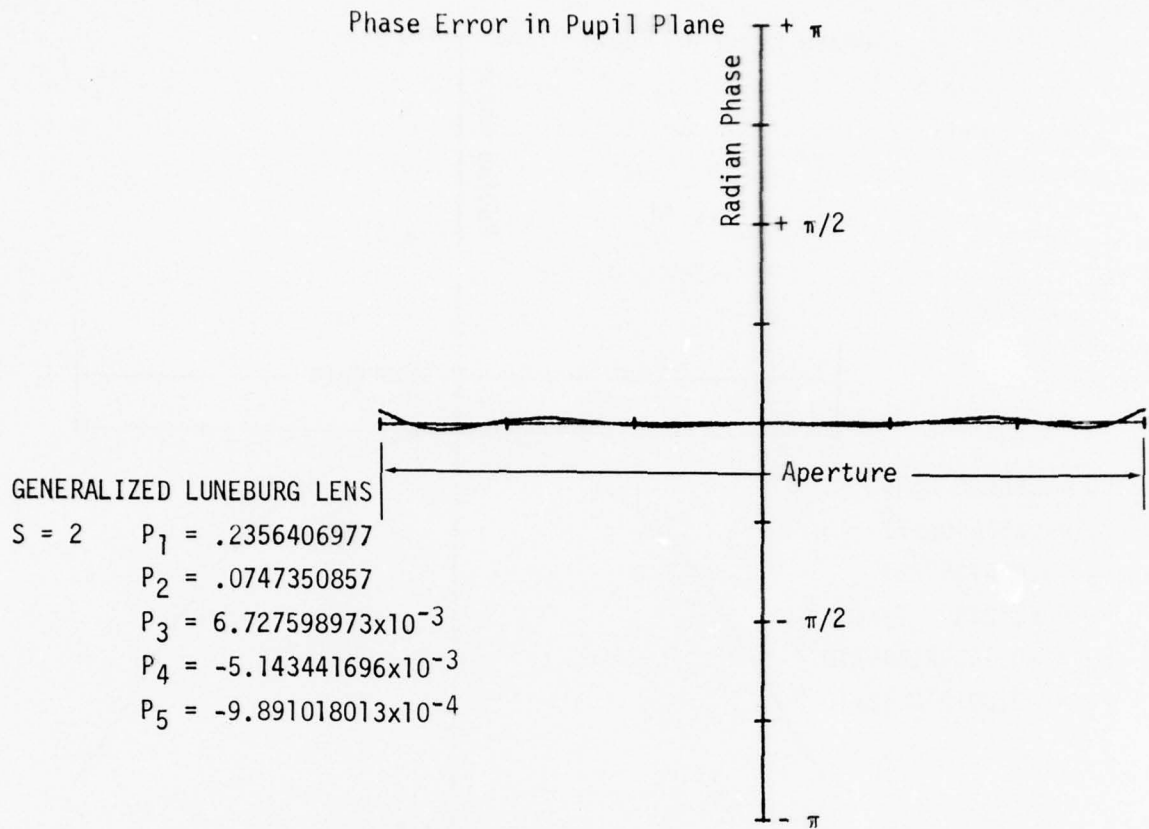


Figure 39. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 35 ( $.9998 P_1$ ,  $.9998 P_2$ ,  $.9998 P_3$ ,  $.9998 P_4$ ,  $.9998 P_5$ ), New Focal Length  $+4\mu$ .

data points at the expense of additional computational time. It should be remembered that these computations are based upon only 19 ray traces through the lens and that the resulting transform computations are based upon a curve-fit for these data points.

An error analysis of these lenses could be performed utilizing established techniques deriving the optical transfer function or modulation transfer function as currently utilized for characterizing the performance of lens systems used with incoherent radiation. It would require an extension to include consideration for coherent radiation, however, the above procedure is considered more direct and exact (within the computational time allowed). It provides the intensity diffraction pattern starting with thin-film waveguide radial profiles, each of which are experimentally determinable factors relating the analysis with measured lens performance in its ultimate application, the optical Fourier transform "chip". The data presented has incorporated various types of error perturbations in the ideal radial profile. It has indicated the type of errors allowed and correctable by refocusing and the errors which may be compensated by apodization or limiting of the useful aperture. Some further effort is required to more accurately refine the deposition process so that the radial waveguide thickness profile may be more closely matched to the ideal profile. It should be remembered that this match must be solved by each lens having different focal lengths.

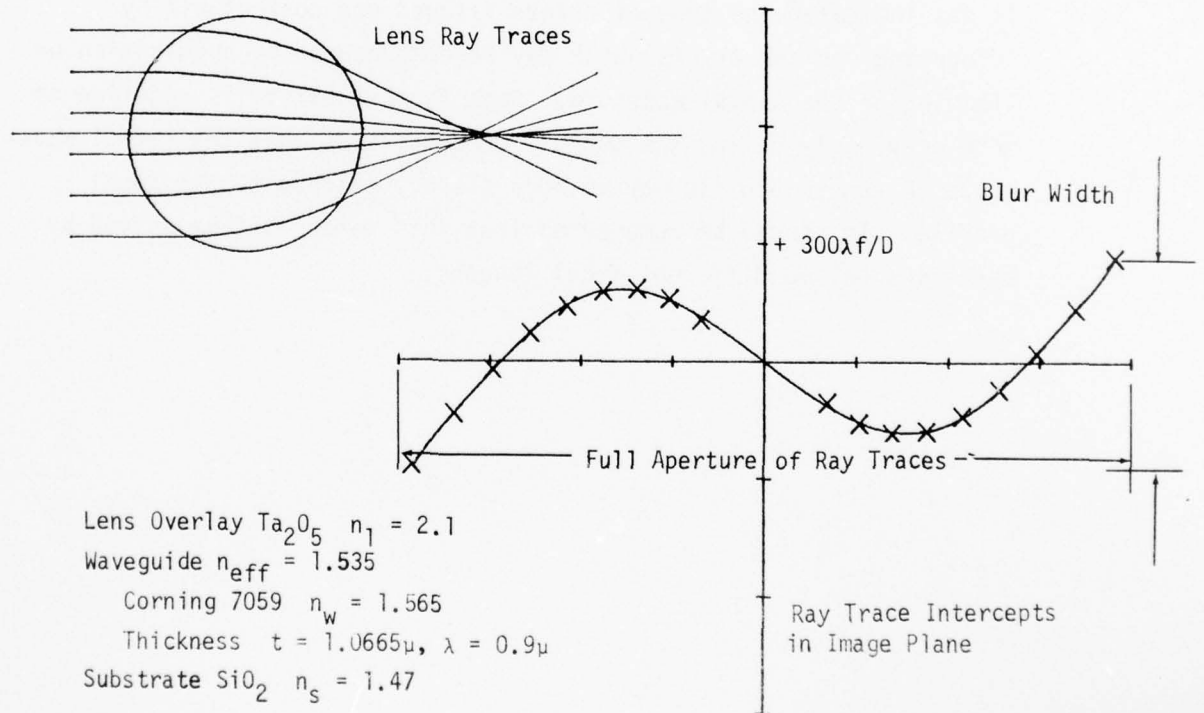
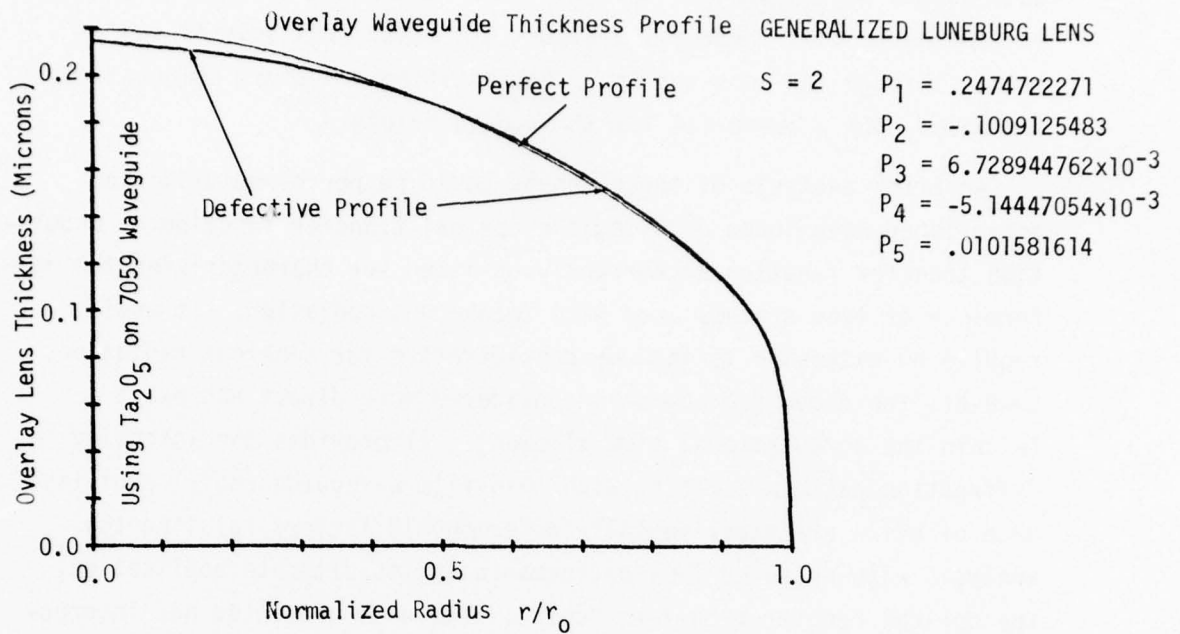


Figure 40. Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (1.05 P<sub>1</sub>, 1.35 P<sub>2</sub>, P<sub>3</sub>, P<sub>4</sub>, 10.2680 P<sub>5</sub>).

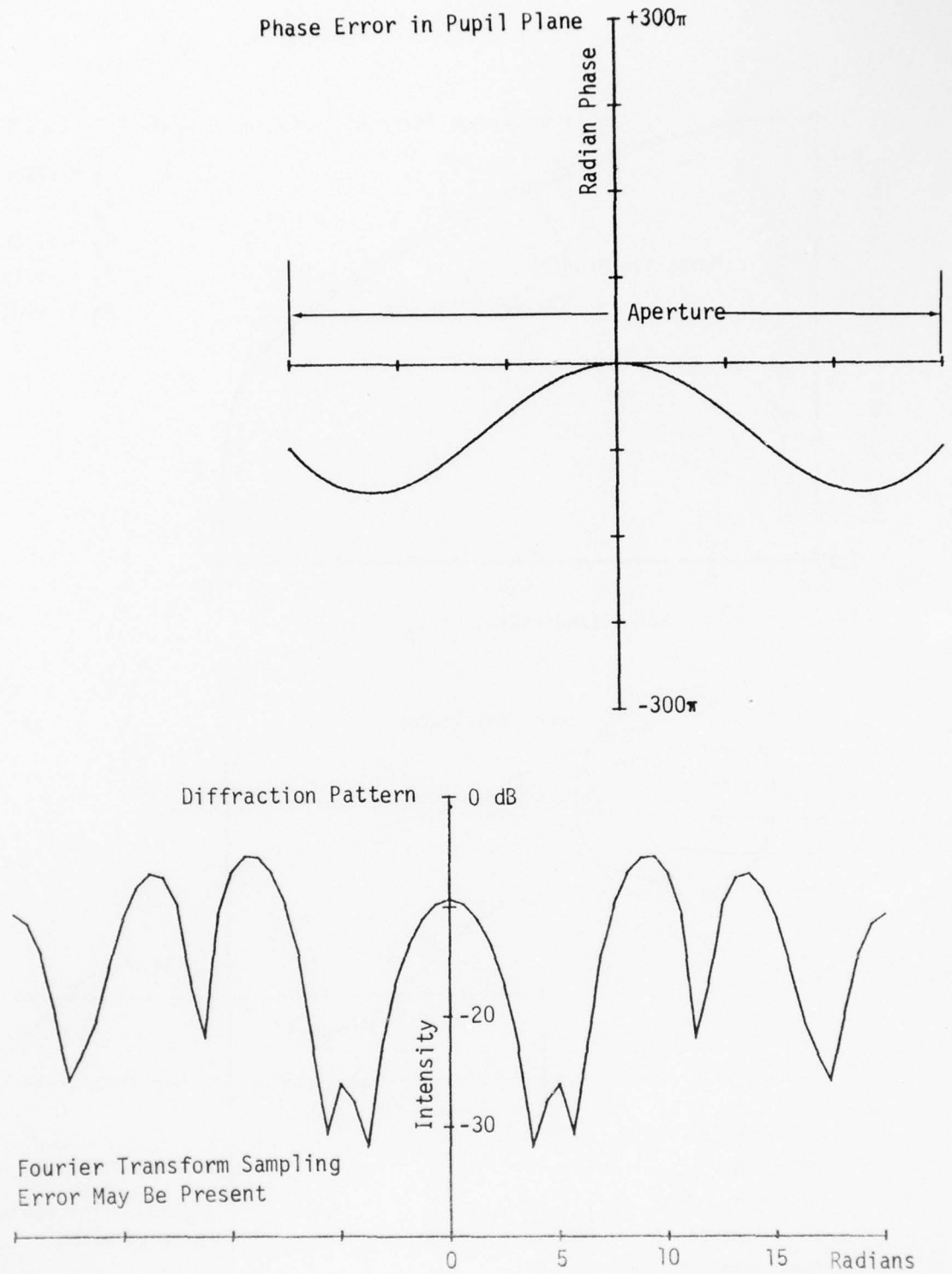


Figure 41. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 40.

AD-A044 207

ROCKWELL INTERNATIONAL ANAHEIM CALIF ELECTRONICS OPE--ETC F/6 20/6  
OPTICAL WAVEGUIDE LENSES. II.(U)

JUN 77 D B ANDERSON, R L DAVIS, J T BOYD

F33615-76-C-1040

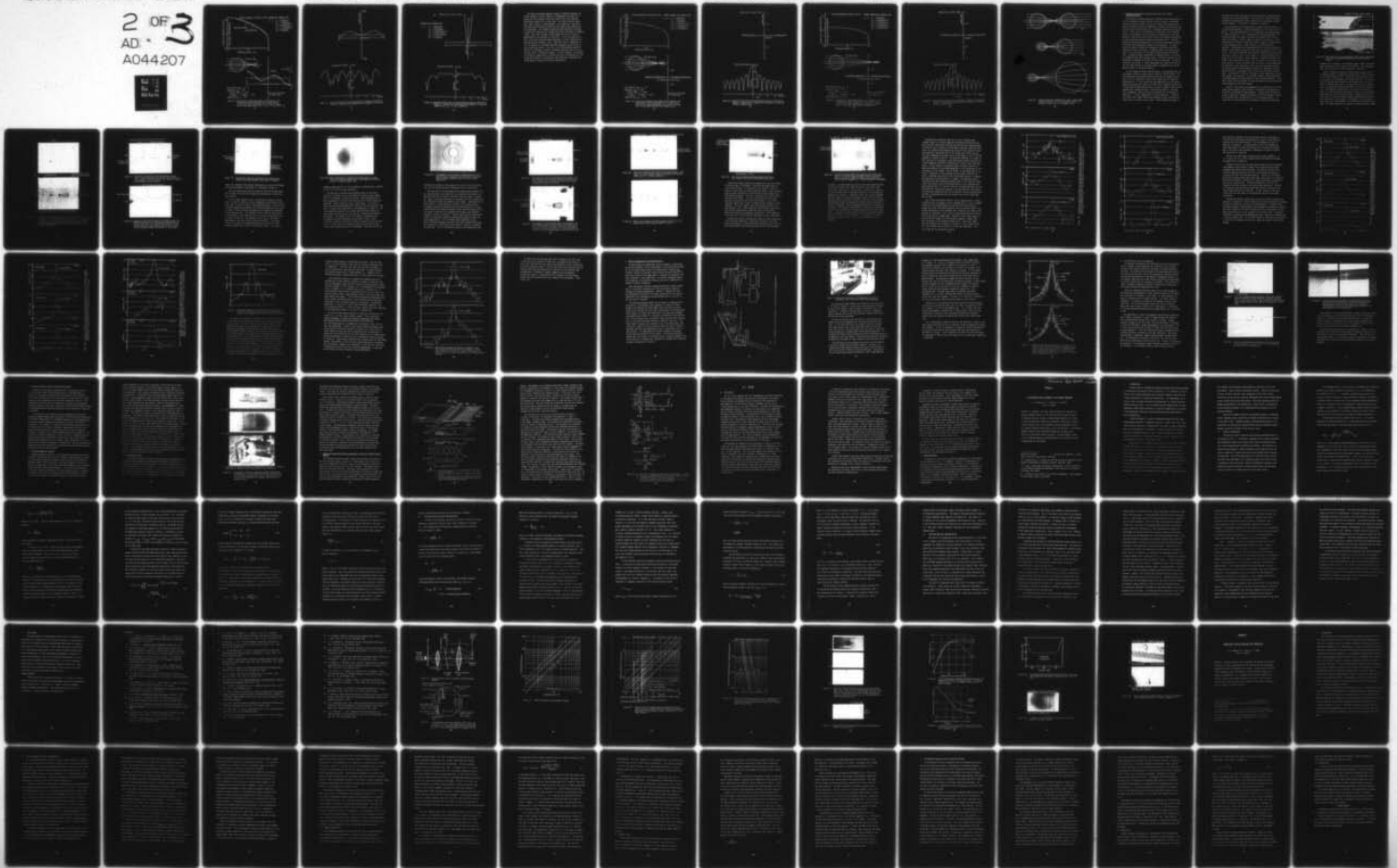
UNCLASSIFIED

C76-1187.13/501

AFAL-TR-77-60

NL

2 OF 3  
AD \*  
A044207



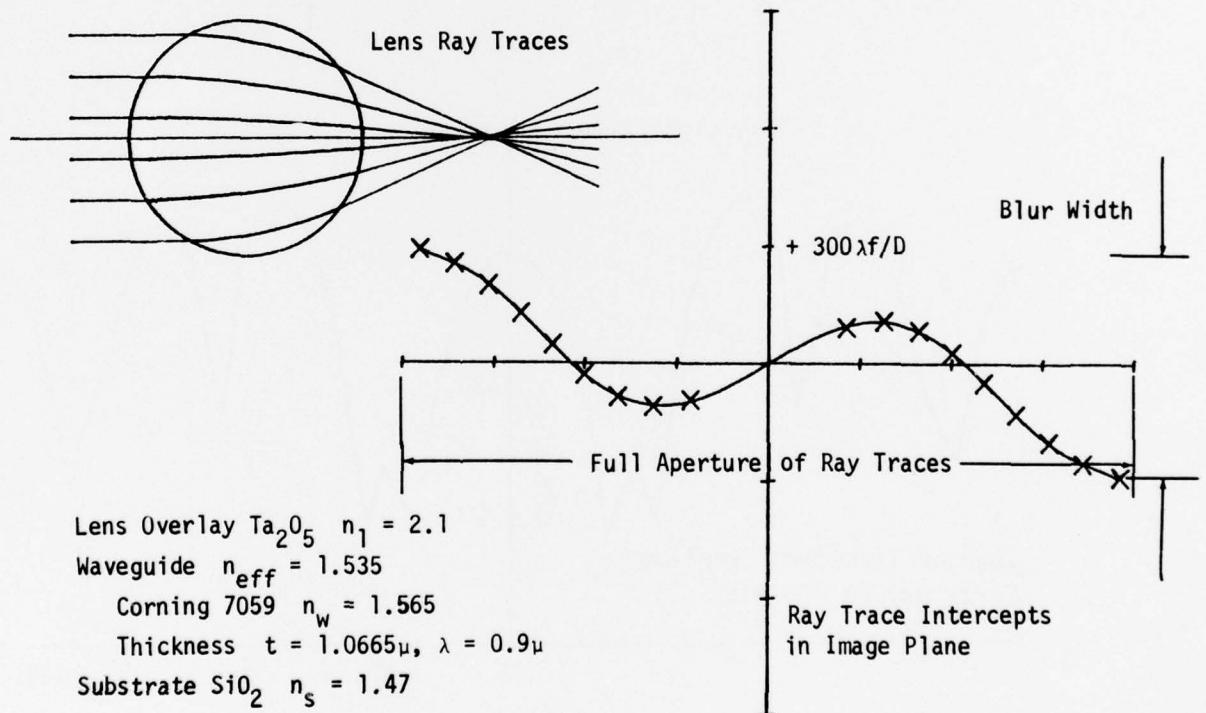
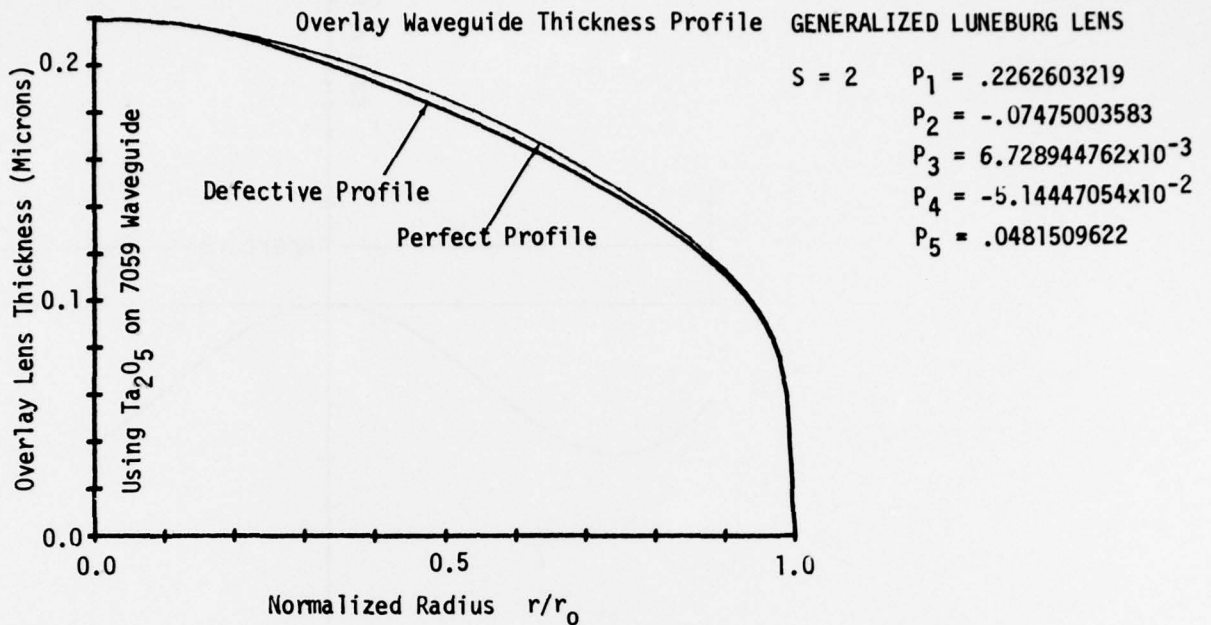


Figure 42. Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (.96 P<sub>1</sub>, P<sub>2</sub>, P<sub>3</sub>, -10 P<sub>4</sub>, 48.6717 P<sub>5</sub>).

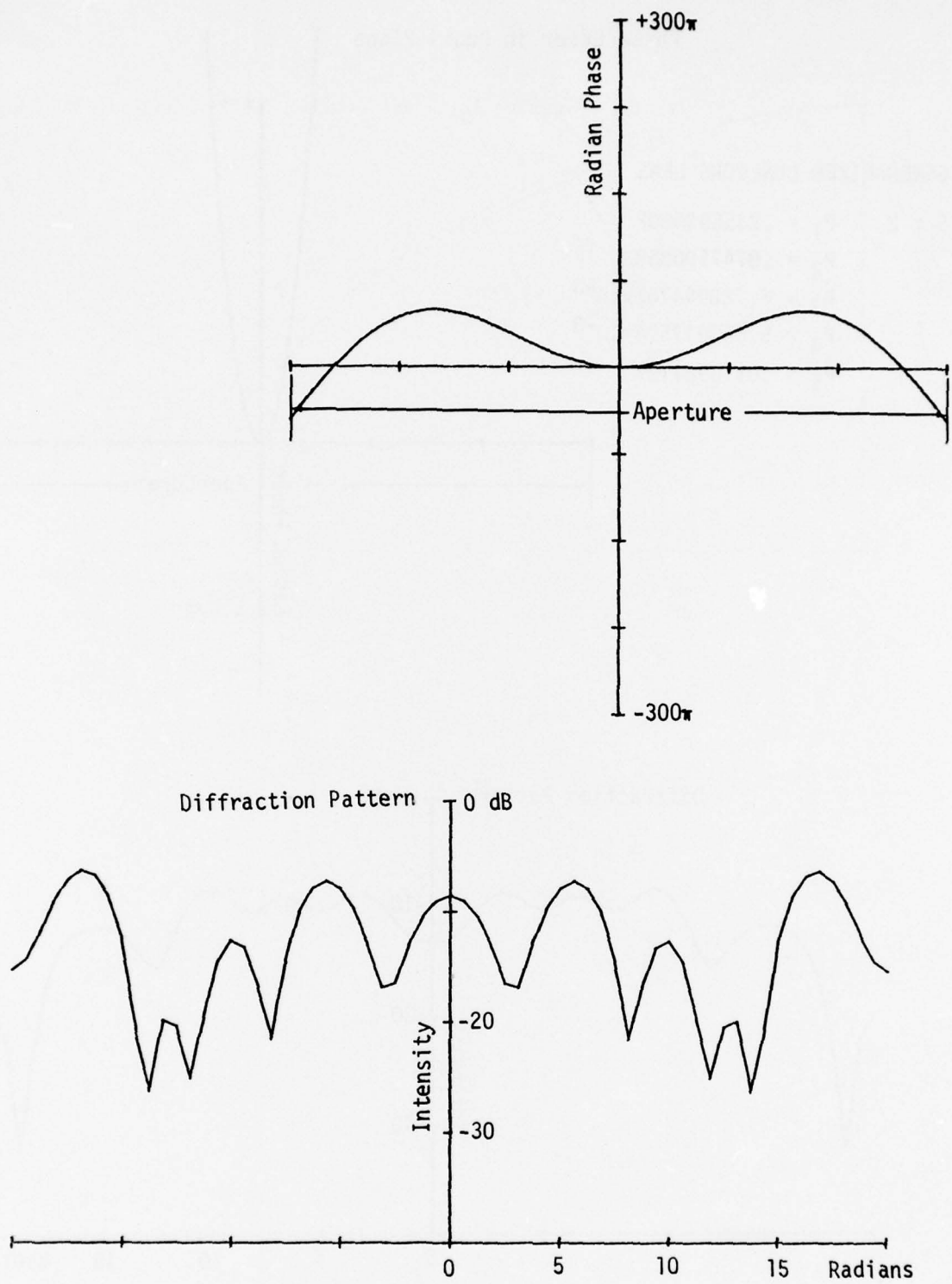


Figure 43. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 42.

Phase Error in Pupil Plane

GENERALIZED LUNEBURG LENS

S = 2    P<sub>1</sub> = .2355935602  
           P<sub>2</sub> = .07475003583  
           P<sub>3</sub> = 6.728944762x10<sup>-3</sup>  
           P<sub>4</sub> = 5.658917594x10<sup>-3</sup>  
           P<sub>5</sub> = .0116984127

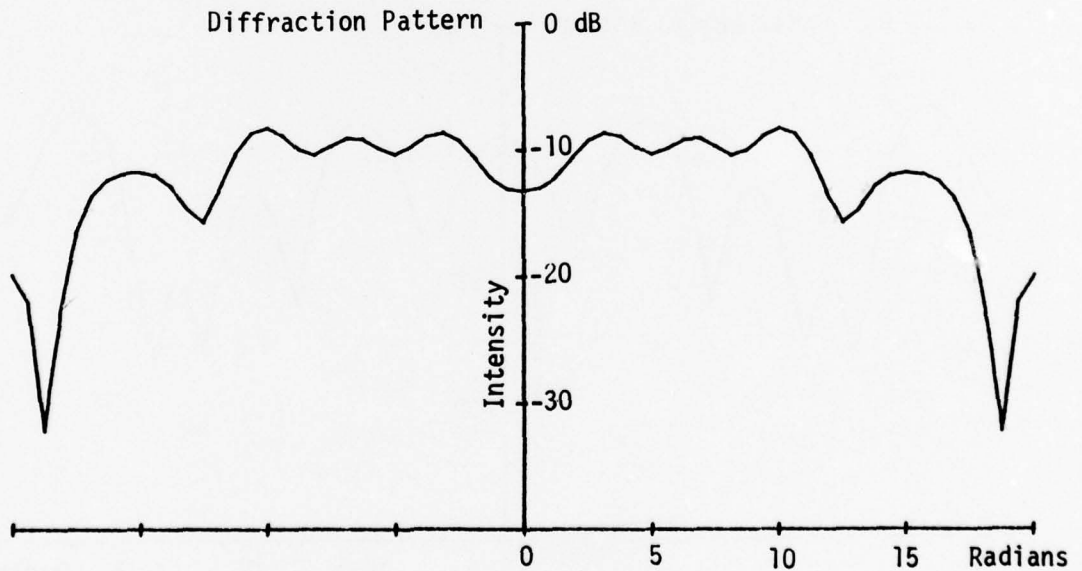
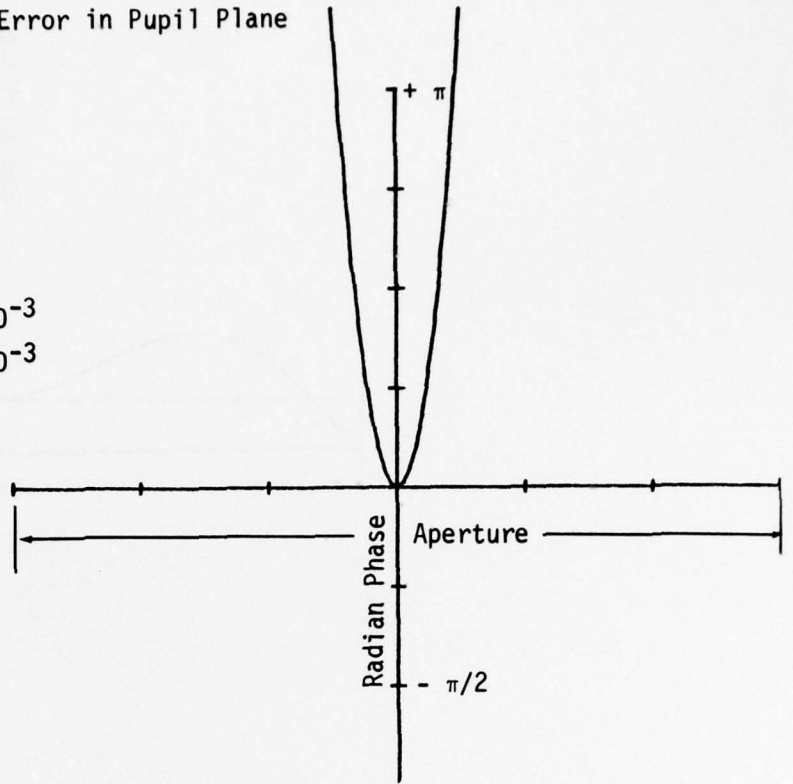


Figure 44. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 42 (.9996 P<sub>1</sub>, P<sub>2</sub>, P<sub>3</sub>, -1.1 P<sub>4</sub>, 11.8249 P<sub>5</sub>).

The above delineated numerical analysis procedure computes ray traces through a circular symmetric inhomogeneous refractor providing the ray intercept, wave front phase error, and intensity diffraction pattern for a single lens. The optical Fourier transform "chip" requires a beam expander, lens system and a transform lens matching the source aperture and the signal input aperture to be transformed. The computer program has been modified to include a second lens coupling rays through both lenses providing for magnification. Ray traces through a beam expander of unity, X2 and X4 magnification, are depicted in Figure 49. It will be necessary to add a third lens using the above procedures to fully synthesize the optical Fourier transform "chip." When this task is completed, it will be possible to introduce defective waveguide lens profiles in any of the three lenses. Thus far, all of the preceding numerical analysis has assumed a uniform illuminated aperture which will produce the  $\text{sinc}^2$  x diffraction pattern. It will, however, be desirable to include an apodization to improve the spatial distribution of the diffraction pattern by suppressing side lobes which compromise the system dynamic range and can lead to ambiguities.

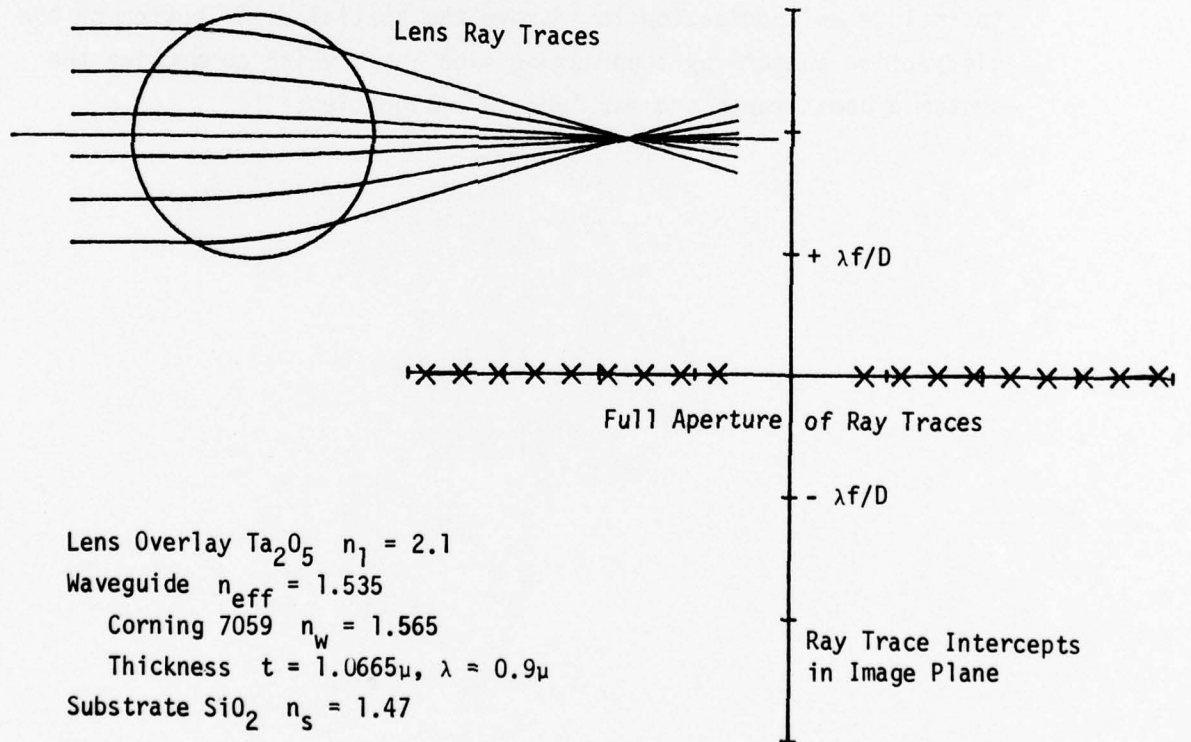
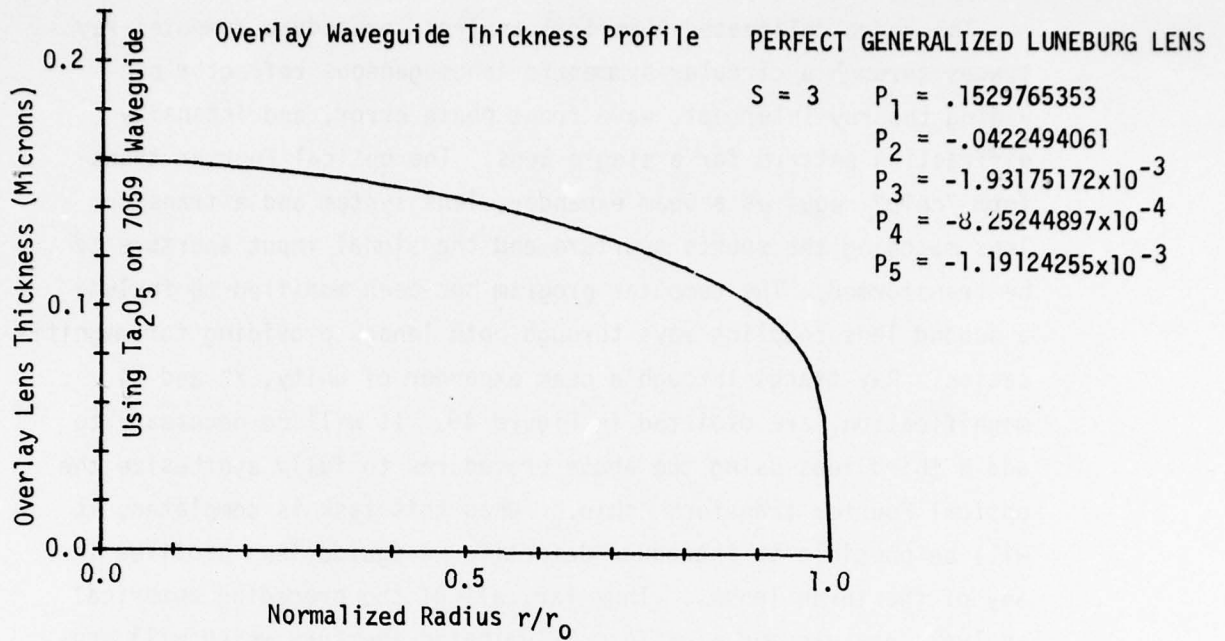


Figure 45. Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (Perfect Luneburg Lens).

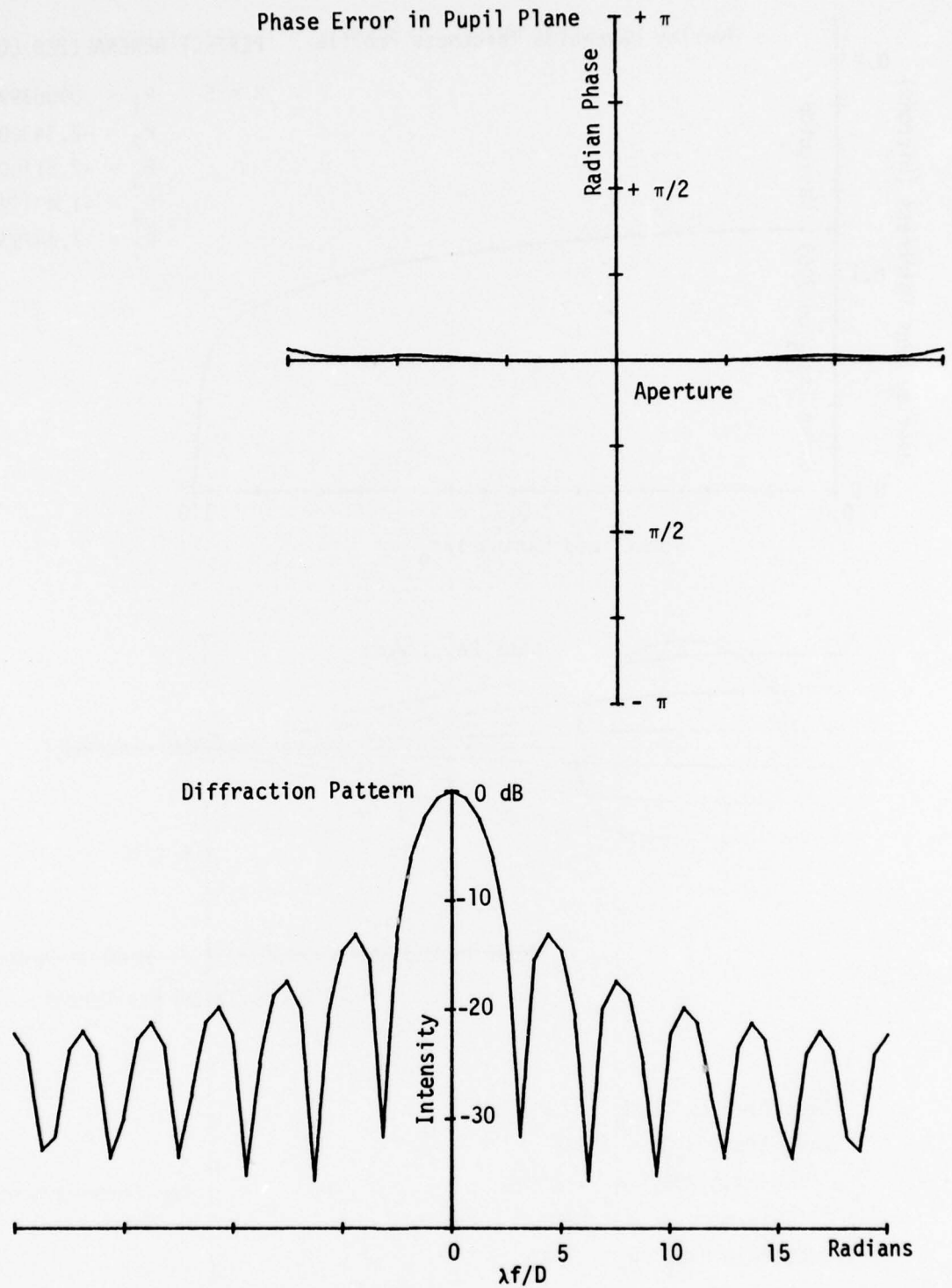


Figure 46. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 45 (Perfect Luneburg Lens).

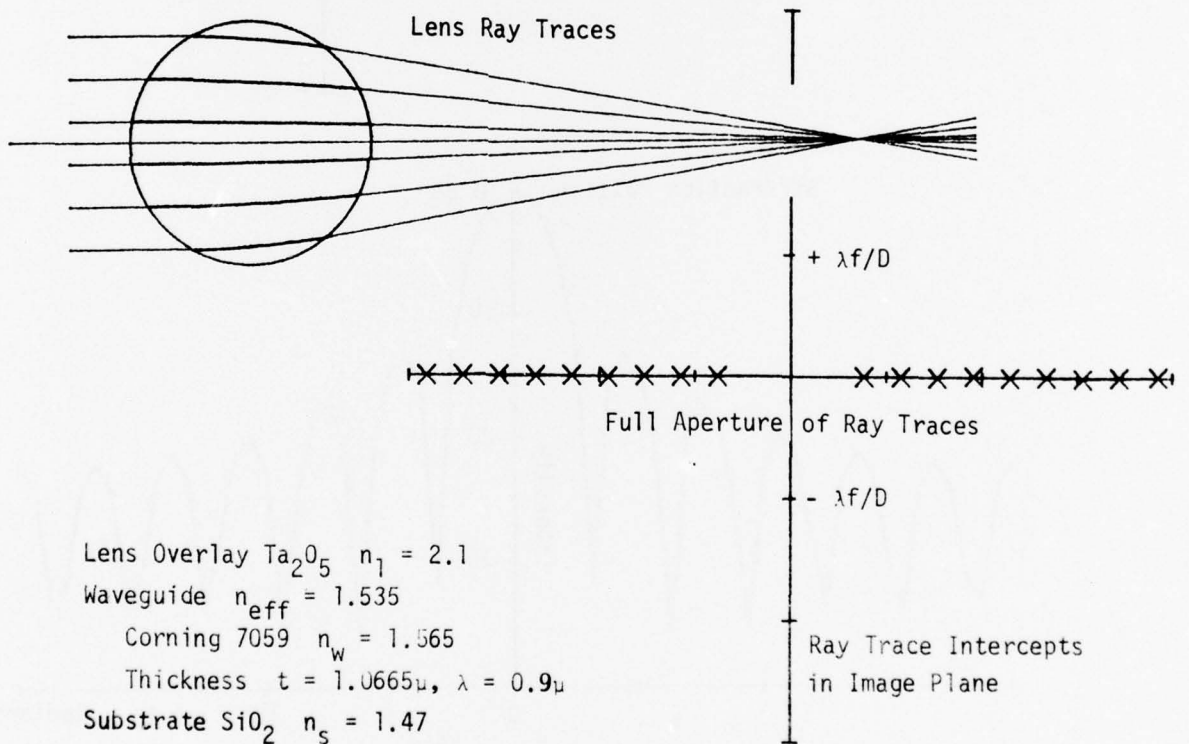
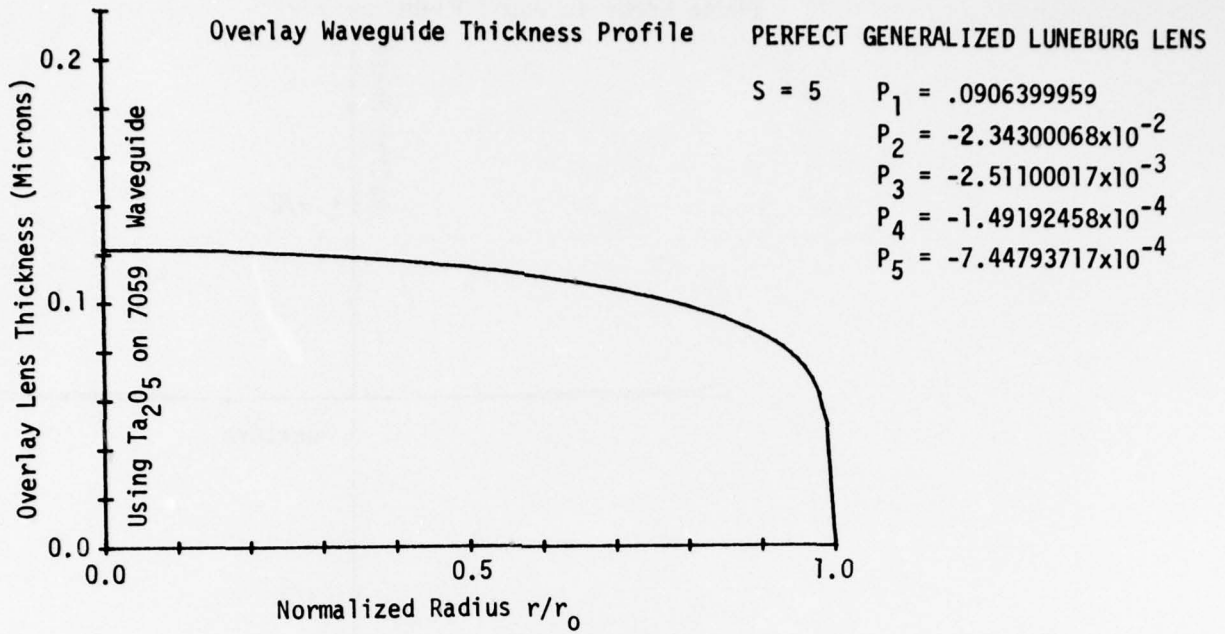
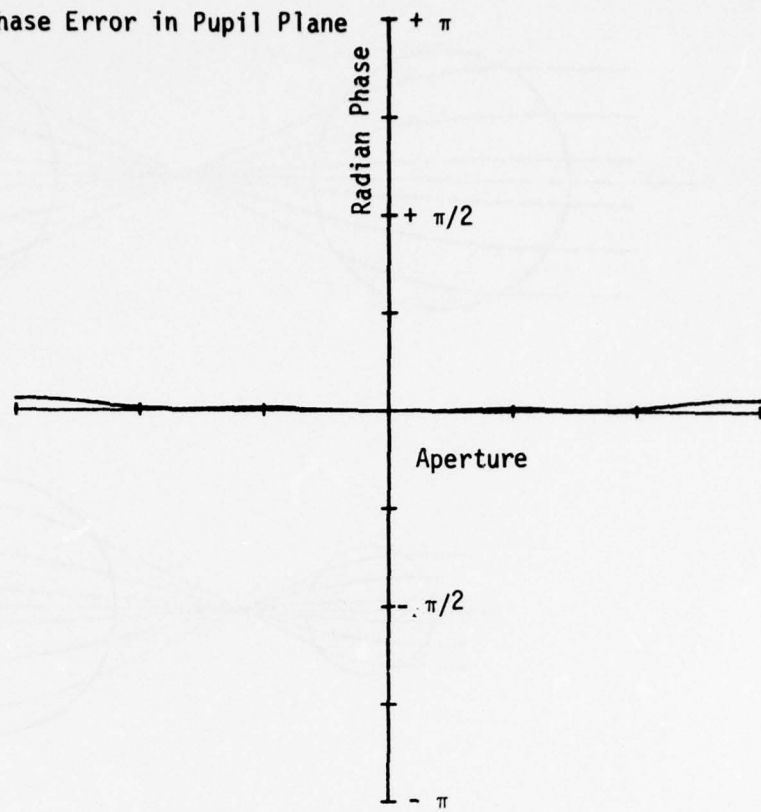


Figure 47. Tabulation of Generalized Luneburg Lens Parameters with Corresponding Overlay Waveguide Lens Thickness Radial Profile, Ray Traces through this Lens and the Intercept Error in the Image Plane (Perfect Luneburg Lens).

Phase Error in Pupil Plane



Diffraction Pattern

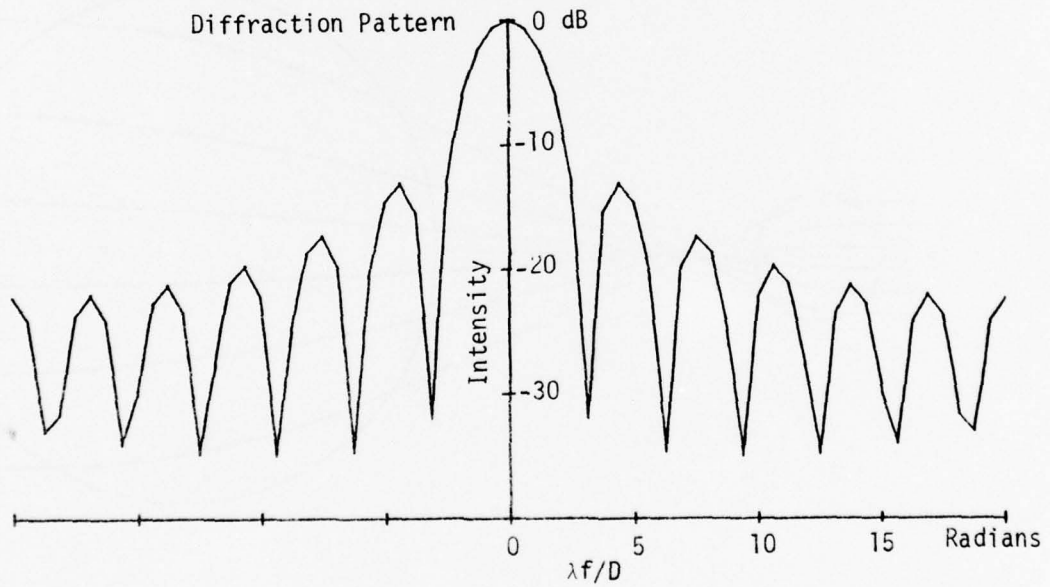
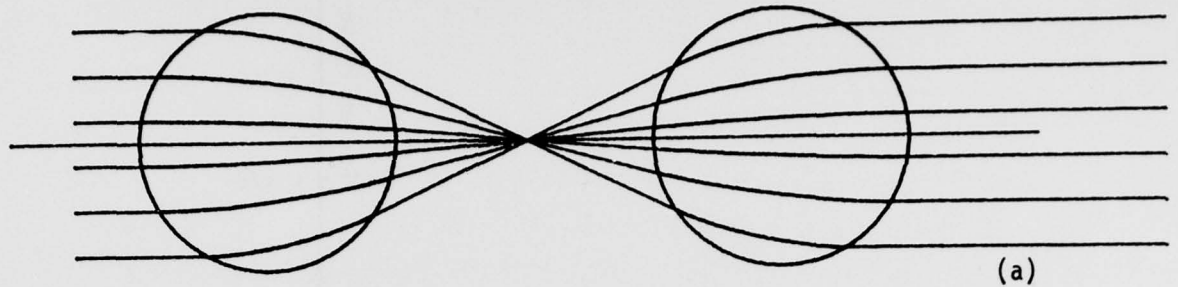
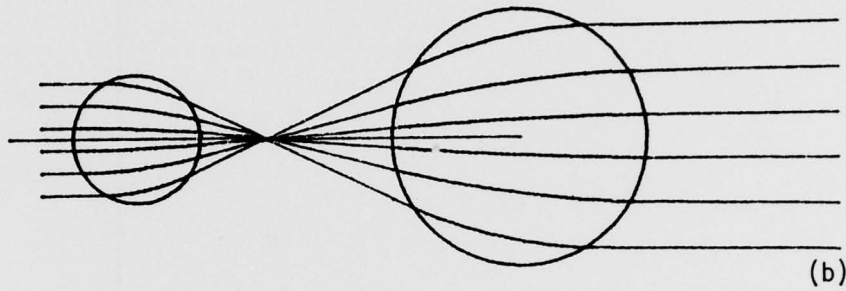


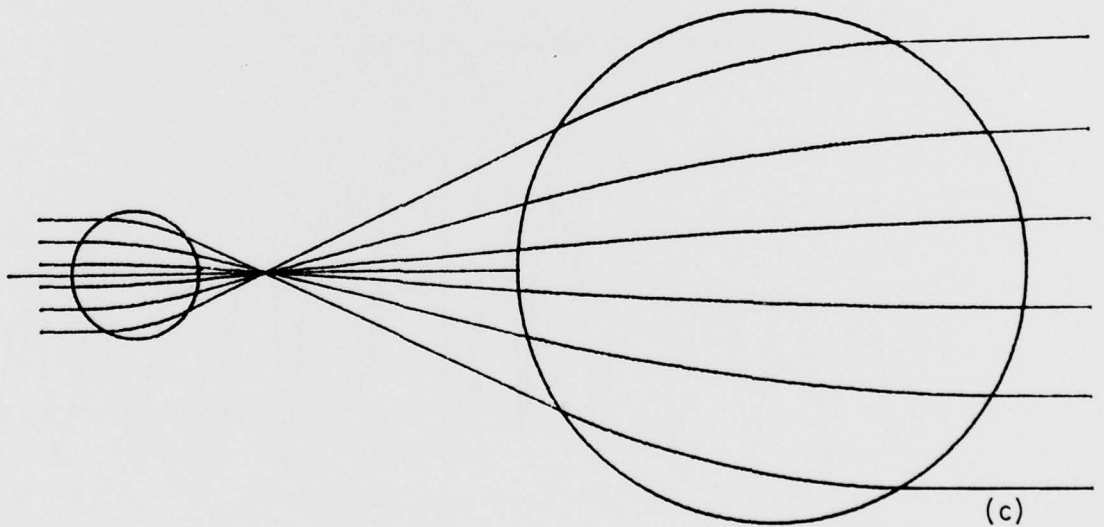
Figure 48. Wavefront Phase Error and Corresponding Intensity Diffraction Pattern for Generalized Luneburg Lens Delineated in Figure 47 (Perfect Luneburg Lens).



(a)



(b)



(c)

Figure 49. Computer-Generated (HP9830) Ray Traces Through Beam Expansion System for (a) Unity Magnification, (b) X2 Magnification, and (c) X4 Magnification.

#### 4. Waveguide Generalized Luneburg Lenses and Lens Systems Experimental Data

Two methods have been employed to characterize the performance of thin-film waveguide Luneburg lenses and lens systems. One method, yielding quantitative data, utilizes the lenses and waveguide with input and output couplers and apparatus to probe, scan and record the resulting diffraction pattern via a reimaging technique using magnification. These results are therefore a convolution of the coupling prisms, the waveguide, thin-film lenses, reimaging lens, and probe aperture. When diffraction-limited results are required, aberrations of the associated apparatus become an important factor. The other method has employed photography of the scattered wide-angle radiation associated with propagation through lossy waveguides. It readily identifies defects through the propagation path which affect the measured diffraction pattern. In general, good low-scattering waveguide is not observable in this manner without excessive exposure time. Although numerous photographs are employed herein, it should be remembered that their dynamic range is limited by sensitivity and saturation to somewhat more than one order of magnitude. The use of individual ray traces in these photographs has proven to be useful for the identification of multiple modes of propagation and for the identification of scattering defects.

All the waveguide lenses reported herein have employed  $Ta_2O_5$  as the highest refractive index material used for forming lenses. All the waveguides have employed Corning 7059 glass on thermally-grown  $SiO_2$  on Si as a substrate. Most of the lenses have utilized the dense overlay. All the lenses have been deposited by an RF sputter technique starting with metallic Ta and using a reactive process with  $Ar-O_2$  to form the deposition through a circular symmetric mask with an appropriately shaped aperture. A semi-cross-section of the mask, lens, waveguide, isolation layer and substrate are illustrated in Figure 50. A conical shaped mask is usually employed. In general, the longer focal length lenses have employed thinner overlays with masks having a reduced conical angle. The RF sputtering target is

substantially larger than that of the mask aperture so that molecular transfer occurs over wide angles. The pressure is controlled during the deposition procedure so that diffusion occurs producing a smooth surface topology. This effect is apparent in Figure 6.

The performance of two generalized Luneburg lenses utilized as an inverting beam expander is shown photographically in Figures 51, 52, 53 and 54. It has been designed for a 3X expansion ratio and provides an output aperture of 1 cm. The operation of the beam expander utilizing individual ray traces traversing the expander from left to right using 25 mW at  $0.63\mu$  is shown in Figure 51, Section (a). Rays traversing the individual lenses are clearly evident in some portions of the waveguide, while in other regions no scattering can be observed. Unfortunately this beam expander has a serious scattering defect in the substrate isolation layer near the focus (but not at the focus). The smaller expansion lens exhibits considerably more scattering than is typical, while in the latter it is more representative of  $Ta_2O_5$  thin-film overlays. Some scattering is apparent from the waveguide in the region of the input. This is due to a prior contact of a prism coupler. Section (b) shows that this region is more aggravated by additional prism contacting in both the input and output regions. The output aperture with throughput intensity is apparent from scattered radiation at the edge of the silicon wafer reflected by black paper. Section (b) of Figure 51 utilizes an input beam nearly filling the expander lens aperture. The expander objective shows two Newton rings made apparent by interference of the scattered radiation. Some dark streaks are also apparent in this lens which arises from the substrate damage near the focal region.

Figure 52 illustrates the propagation of a single axial ray of the same X3 beam expander, while Figure 53 illustrates the trajectory of an offset ray through the same expander. Figures 52 and 53 have utilized a substantial increase of exposure to shift the range of Figure 51 by another order of magnitude so as to accentuate defects. In Figure 52, the scattering halo surrounding a single ray through the

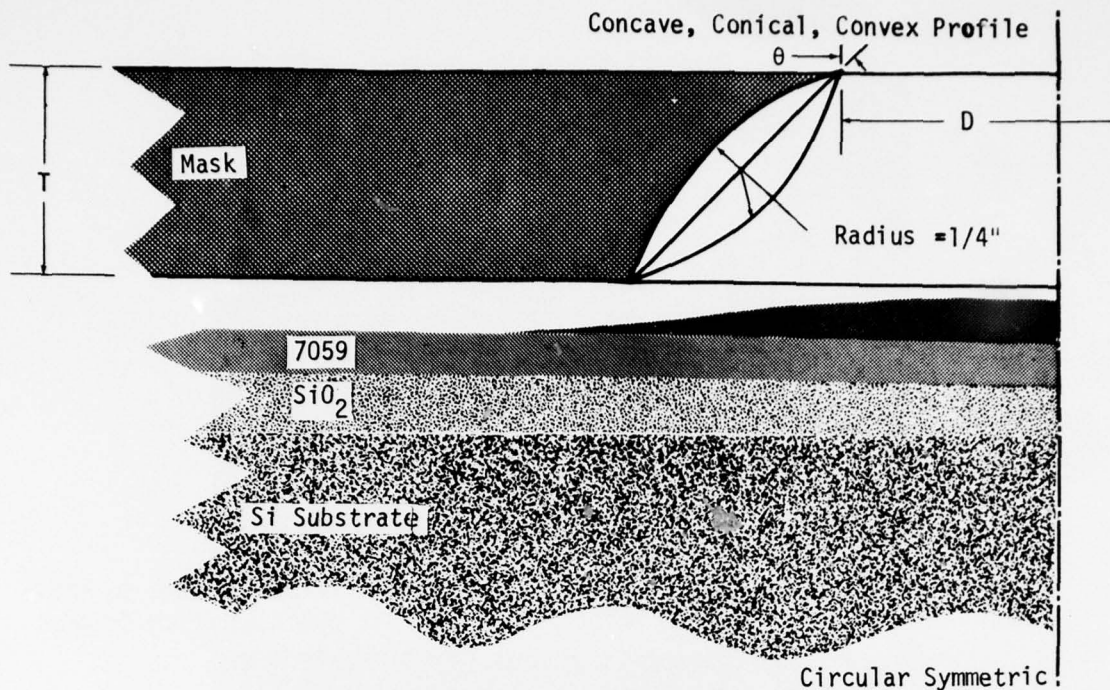
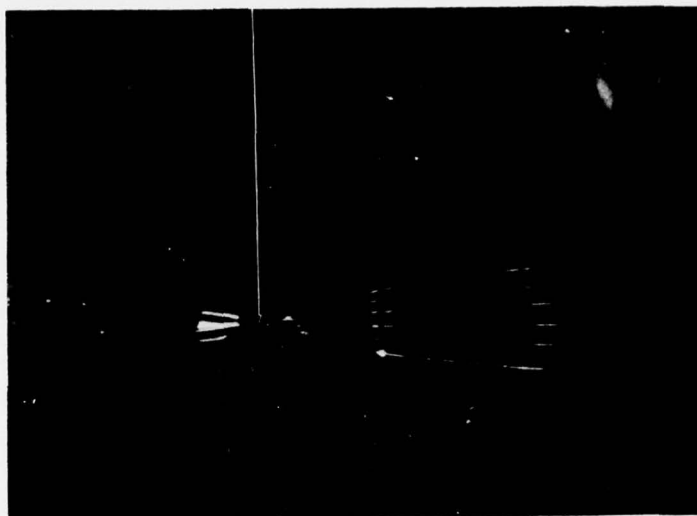


Figure 50. Cross Section of Various Deposition Mask Shapes Investigated to Control the Waveguide Luneburg Lens Radial Thickness Profile.

expander lens is apparent. The throughput power scatter from black paper exiting the silicon wafer is also apparent. This photograph shows that low-scatter loss 7059 waveguide is realizable.

Figure 53 shows the presence of mode conversion which occurs in the thicker expansion Luneburg lens and the lack of mode conversion in the thinner objective lens. Fractional mode conversion from  $TE_0$  to  $TE_1$  occurs at the expander lens entrance interface. The trajectory of these two modes separate in the expander lens, and the  $TE_1$  mode is converted again back to the  $TE_0$  mode at the exit interface where it propagates through the remainder of the system as another ray. The intervening waveguide will not support this second  $TE_1$  mode. This mode conversion process does not occur in the objective lens because of its thinner cross section. Mode conversion presumably occurs in Figure 52, however cannot be observed because each of the rays traverse the same path. The intensity of the ray due to mode conversion is approximately -10 dB relative to the lowest order mode. This mode conversion can further be reduced by using an under-

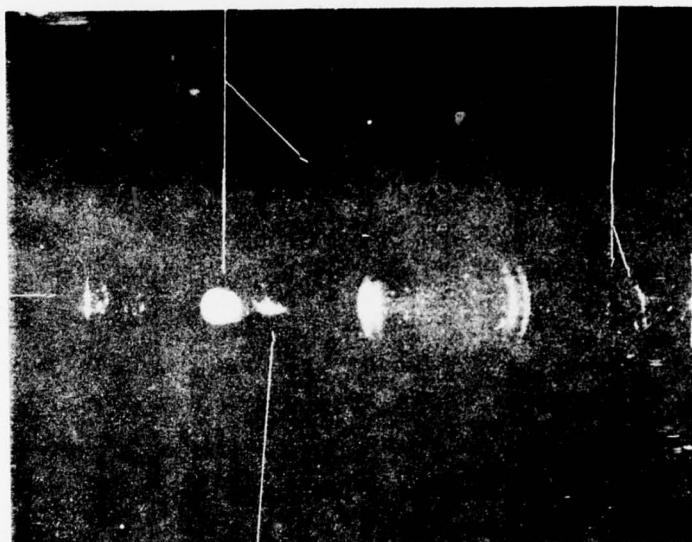
Focus



(a)

Luneburg Lenses

Scattering Due to Prior  
Coupling Prism Contact



(b)

Scattering Near Focus Due to Substrate Damage

Figure 51. Operation of Generalized Luneburg Lens Beam Expander (X3) Using  $Ta_2O_5$  on 7059 on Thermally-Grown  $SiO_2$  on Si (a) Scattering of Individual Ray Traces Through Lenses Using  $6328 \text{ \AA}$  Radiation Extending Over 1 cm Aperture (Output), (b) Scattering of Continuous Wide Aperture Beam Through Same Beam Expander Using Uniform Illumination.

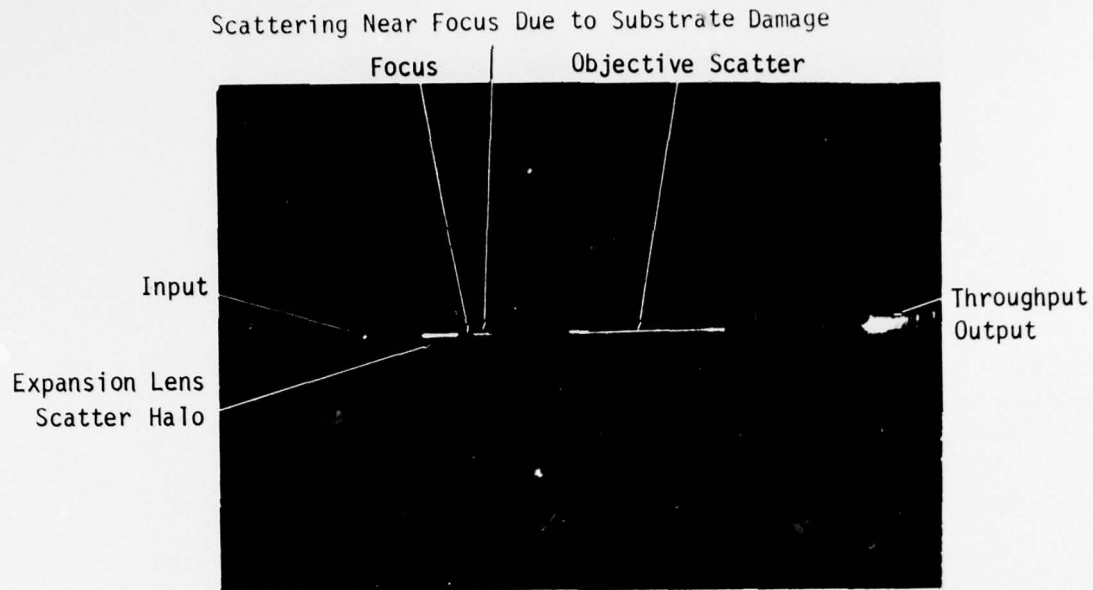


Figure 52. Axial Ray of Generalized Luneburg Lens Beam Expander (X3) of Figure 51 Showing Halo Scatter Around Expansion Lens, Scatter From Surface Defect, and Scatter of Objective and Throughput Intensity Output.

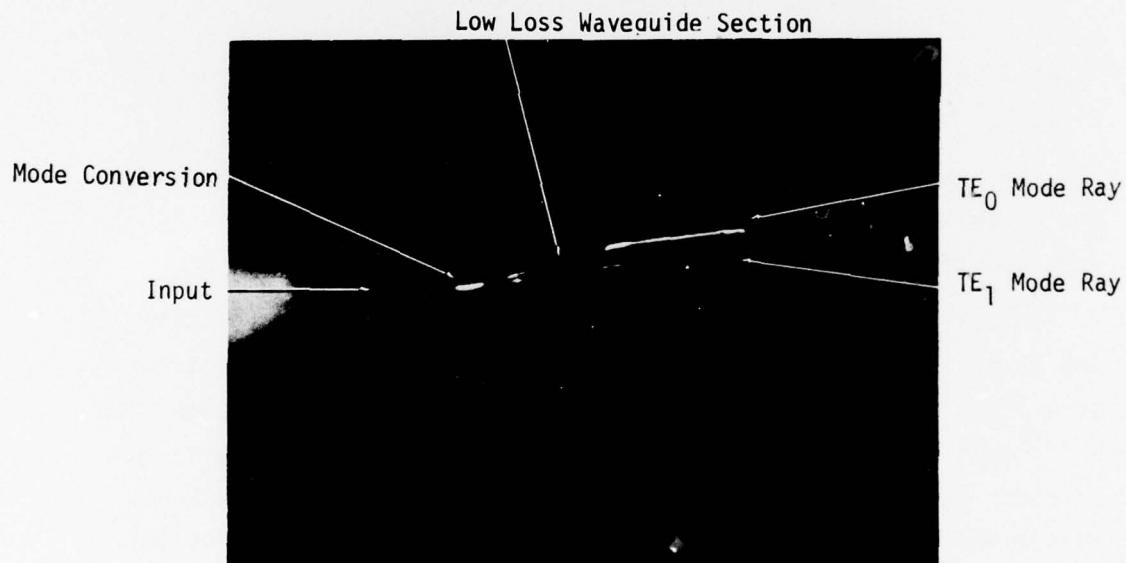


Figure 53. Operation of Generalized Luneburg Lens Beam Expander (X3) Showing Scattering of a Single Ray Where Mode Conversion Occurs in the First Lens Producing Two Refraction Angles and Mode Conversion Occurs Again Showing Two Ray Traces for the  $TE_0$  Mode Through the Remainder of the Expander

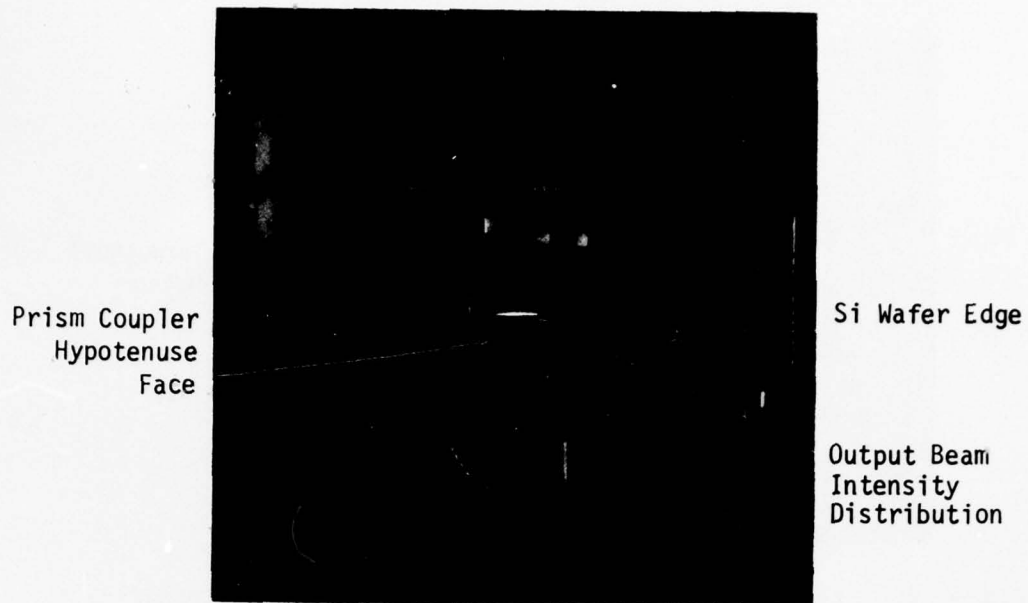


Figure 54. Output Beam Intensity Distribution From Generalized Luneburg Lens Beam Expander (X3) Shown in Figure 51

layer lens instead of the overlay configuration or can be eliminated by using the symmetric interleave as illustrated in Figure 2.

The near-field, exit-field distribution from this X3 beam expander is shown in Figure 54 by imaging the distribution in the prism exit coupler.

A much larger expansion ratio is required for coupling of GaAs lasers to the full aperture of the integrated optical Fourier transform "chip" to obtain a useful time-bandwidth-product. The plan view of another generalized Luneburg lens inverting expansion lens system is shown in Figure 55 where the Newton ring indicates the thickness of the objective lens. The expansion ratio is X90 for this design. An enlargement of the expansion lens, also showing the Newton rings, is shown in Figure 56. The diameter of this lens is  $250\mu$  and is approximately four times thicker than the objective. The Newton rings are not perfectly symmetrical, showing the effect of offset during the deposition relative to the source target. This type of

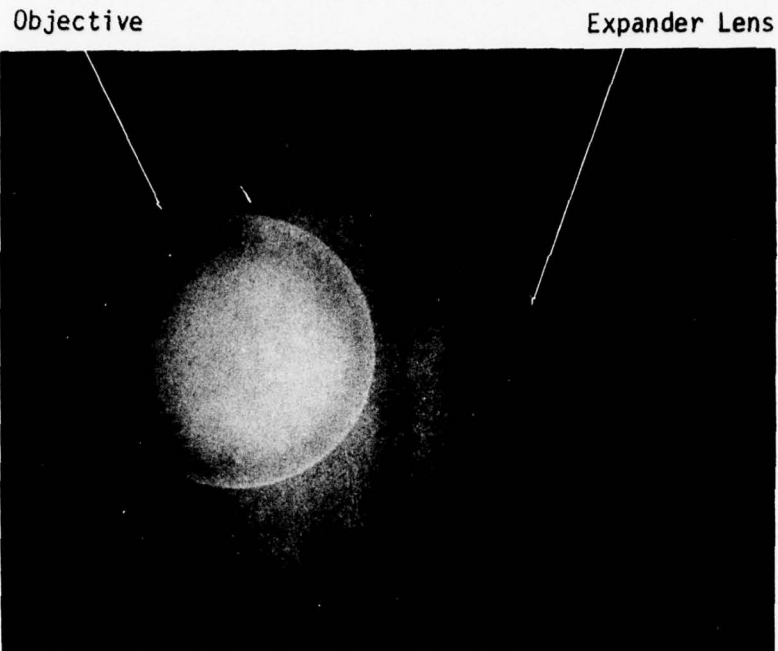


Figure 55. Macro Photograph of Luneburg Lens Beam Expansion System (Plan View) Showing Newton Ring of the Objective Thickness Profile. Expansion Ratio 90X.

asymmetry when used off axis can introduce an odd aberration, whereas, on axis, will yield an even aberration.

The operation of the 90X beam expander used with the output applied as individual rays on the objective producing beam compression is illustrated in Figures 57 and 58. These photographs have been overexposed to bring out the individual ray traces through the waveguide. Where scattering occurs, halos appear. In Figure 57 three rays have been employed which intersect with the expansion lens, which is apparent and identified in the photograph of Figure 57. The rays beyond the expansion lens rapidly become diffuse because the exit aperture of each ray is less than  $10\mu$ , producing divergence by diffraction. The angular size of this beam is evidenced by the throughput radiation scattering from the edge of the Si wafer. Figure 58 is identical to that of Figure 57 except that the two additional marginal rays do not intersect the expansion beam and thus traverse the substrate and exit as indicated. These two rays do not

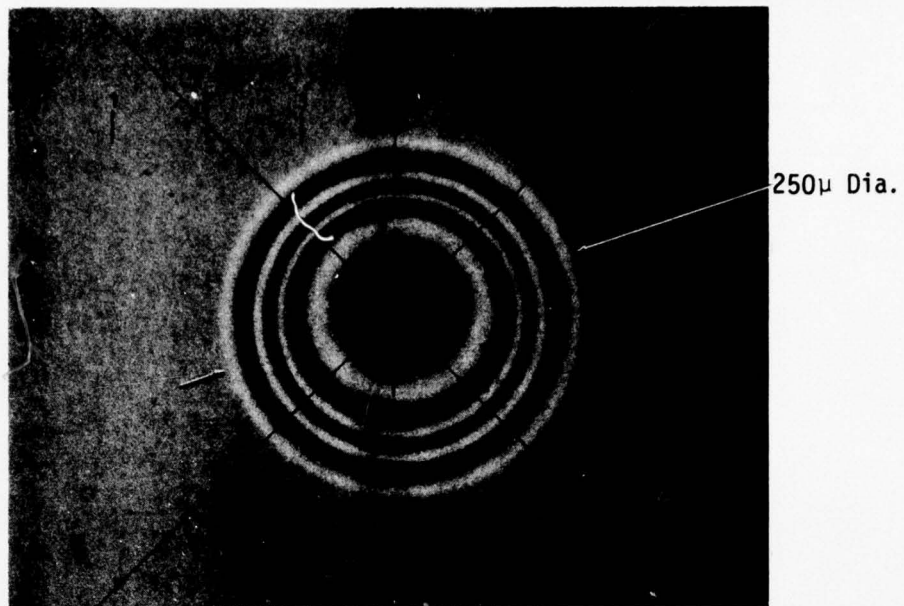


Figure 56. Enlargement of the Expansion Luneburg Lens in Fig. 55 Showing Newton Rings Depicting the Radial Thickness Profile (radial asymmetry due to off set during deposition).

intersect the expansion lens because of an error in the lens thickness profile causing spherical aberration for this outer zone.

The operation of the X90 generalized Luneburg beam expander with the input applied to the expansion lens traversing the system in an opposite direction to that of Figures 57 and 58 is shown in Figure 59. Again it has been necessary to overexpose the film to depict the ray trajectory through the expansion lens system. Scattering due to application of a prism coupler is evident in the output region. Throughput through the beam expansion has been obscured by a black screen showing the forward low angle scatter from the objective lens. The output collimation of the generalized Luneburg lens X90 beam expander is shown in Figure 60. The exit beam from the output prism coupler has been made visible by scanning white paper through the beam longitudinally. The collimated output beamwidth is 4mm. Several X90 beam expanders have been fabricated, demonstrating that the processing is sufficiently under control to obtain collimation for each unit. This is achieved by control of the deposition time.

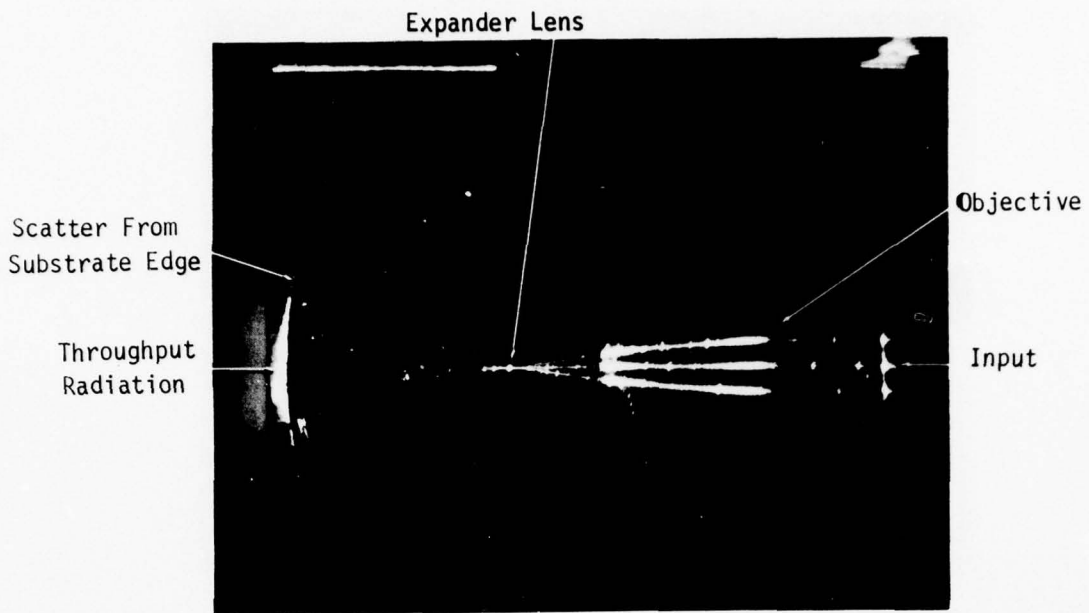


Figure 57. Individual Ray Traces Through Generalized Luneburg Lens Beam Expander (X90) With Input Applied to Objective Producing Convergence on Expander Lens Showing Throughput Scattered From Edge of Substrate.

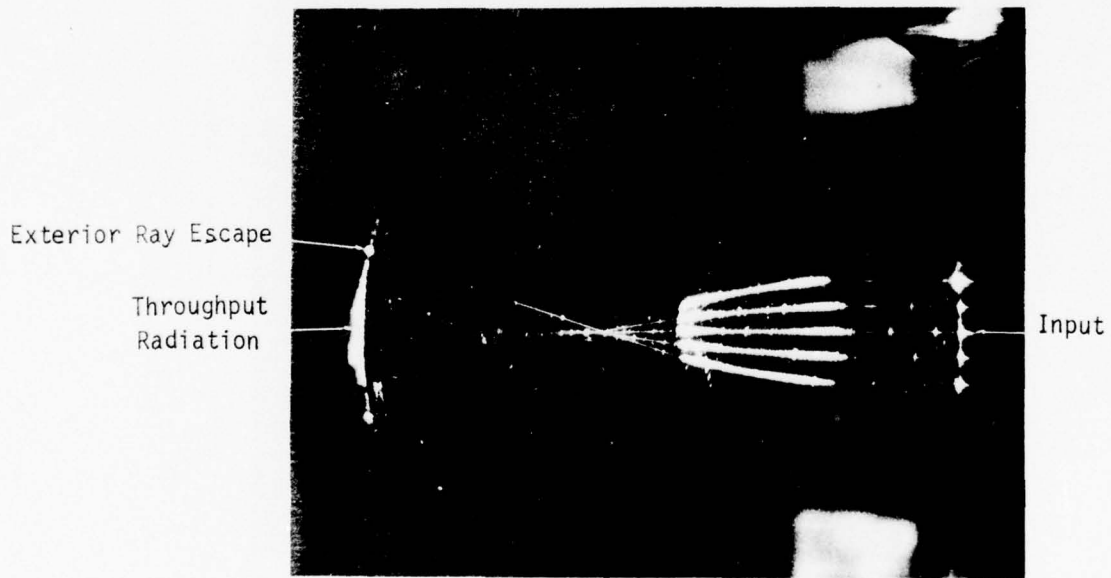
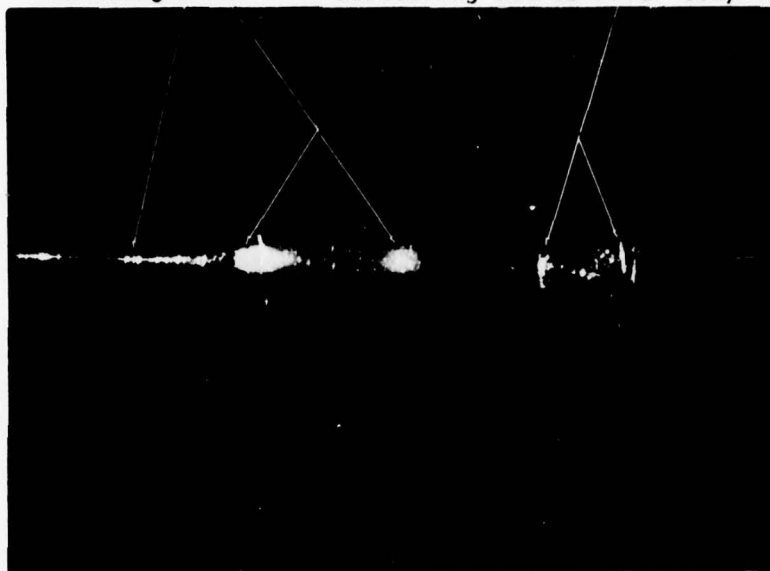


Figure 58. Individual Ray Traces Through Generalized Luneburg Lens Beam Expander (X90) With Input Applied to Objective Producing Convergence on Expander Lens Showing Throughput Scattered From Edge of Substrate With Two Additional Ray Traces Which Do Not Impinge Upon the Small Expansion Lens.

Luneburg Lenses

Scattering Due to Prior Coupling Prism



Output Scatter  
on Black Screen

Figure 59. Operation of Generalized Luneburg Lens Beam Expander (X90) Shown in Figure 55 Using  $Ta_2O_5$  Lens Overlays on Thermally-Grown  $SiO_2$  on Si (Same as Figure 51).

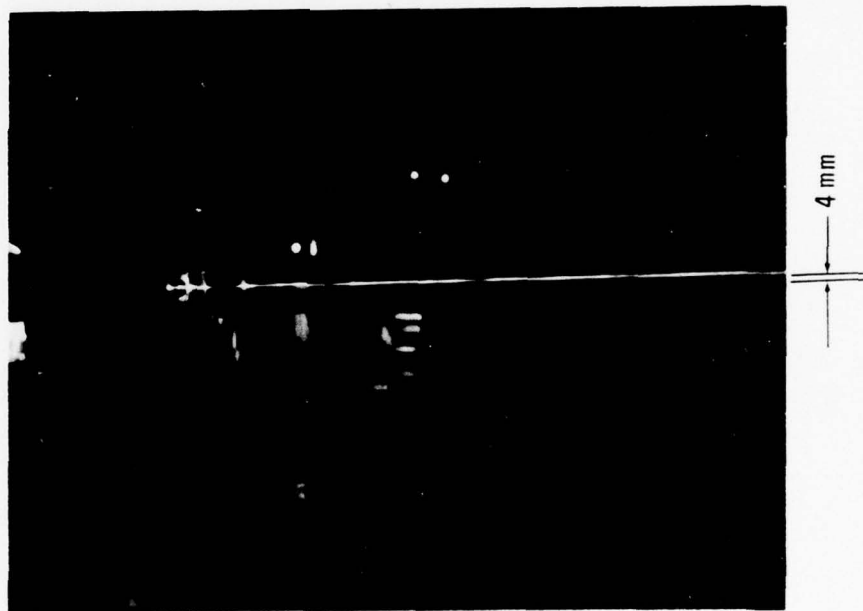


Figure 60. Generalized Luneburg Lens Beam Expander (X90) With Prism Output Coupler Showing Output Beam Collimation.

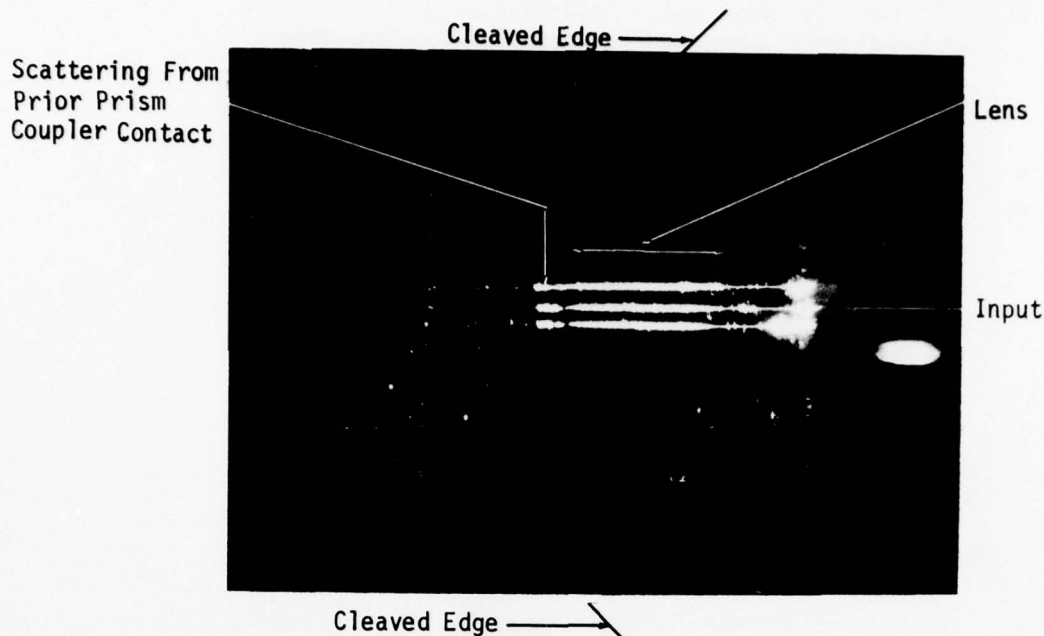


Figure 61. Ray Traces Through Generalized Luneburg Lens Having Focal Length of 7.5cm Using Cleaved Retroreflectors.

Generalized Luneburg lenses with comparatively long focal length are another type of requirement. They have been demonstrated by using retroreflectors. The operation of one example is shown in Figure 61 using three ray traces through the system. Again the photograph has been overexposed to partially depict rays traversing the Corning 7059 waveguide. The focus is obscured by the light shield of the input prism coupler. The exit lens interface has also been obscured by scattering from a prior prism contact. Each of the reflectors employ total internal reflectors using cleavage for their formation. The focal length of the lens depicted in Figure 61 is approximately 7.5cm. Close inspection of the incident rays and exit rays from the retroreflector shows that they are not parallel, whereas the angle due to cleavage is exactly  $90^\circ$ . This nonparallelism is due to a  $3^\circ$  offset from the {100 plane} in the Si substrate.

Another lens having a comparatively long focal length beyond that of the substrate dimensions is depicted in Figure 62. This lens shows the presence of a higher order mode and thus exhibits two foci. Rays traversing the lens and exiting the lens are of the  $TE_0$  mode.

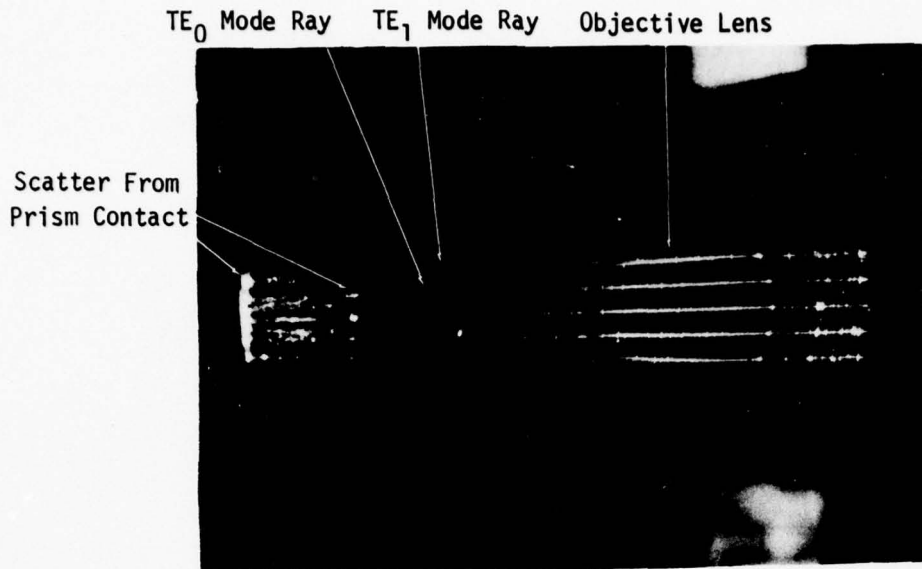


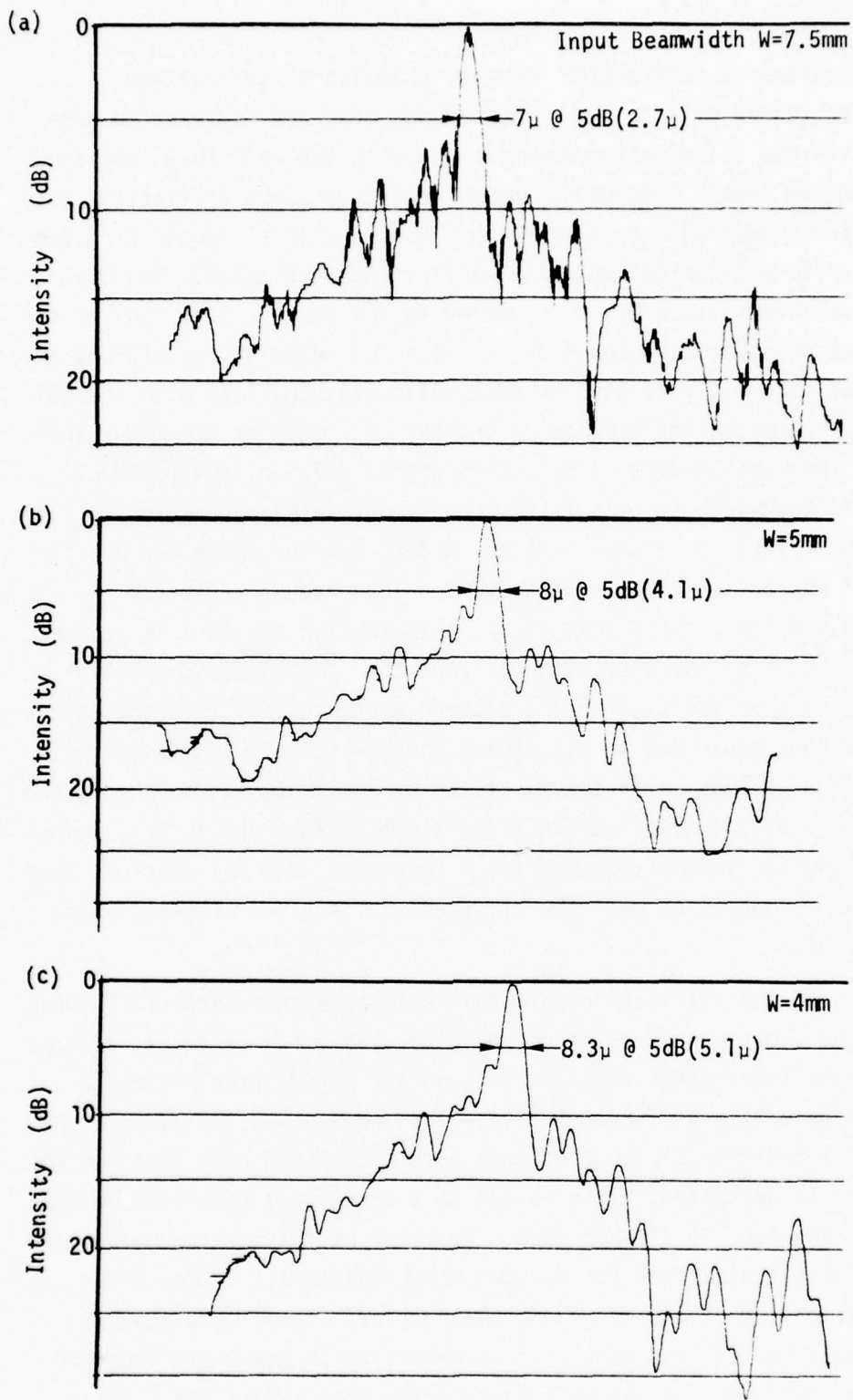
Figure 62. Ray Traces Through Generalized Luneburg Lens Showing Halo Scatter in the Lens Region and Mode Conversion With Equal Power in  $TE_0$  and  $TE_1$  Modes Providing a Focal Length of 3.4 cm and 10.1 cm, Respectively. (Selected Sample to Show Modes)

The power is divided between  $TE_0$  and  $TE_1$  modes approximately equally at the lens entrance face. Mode conversion of the higher order to the zero order occurs at the exit face. Suppression of mode conversion is accomplished by introducing symmetry in the waveguide as exemplified in Figure 2. Inspection of the radial refractive-index profile, Figure 16, and the corresponding radial thin-film overlay thickness profile, Figures 22, 45 and 47, show the relative thickness and thickness gradient at the edge of Luneburg lenses as the focal length is increased. Exploiting symmetry prevents the excitation of  $TE_1$  modes. The interface discontinuity will excite high order modes. Control of the thickness will prevent propagation of  $TE_2$  and higher orders. In general the sharp transitions are not realized experimentally (see Figure 42, AFAL TR-76-54). The photograph of Figure 62 also shows residual scratches due to prior contacting of prism couplers.

Quantitative diffraction data for a series of generalized Luneburg lenses will follow comparing the measured diffraction pattern with the illumination function and with the mask shape employed to form the lens.\* Figures 63 and 64 depict measured diffraction patterns for a generalized Luneburg lens having a focal length of 4.5cm using uniform illumination which will produce the  $\text{sinc}^2x$  function. The input beamwidth  $W$  has been varied in the range 7.5 to 1.0 for the sequence of Figures 63 and 64. The measured beamwidth in microns at the 5 dB point is indicated on each diffraction pattern with the calculated beamwidth enclosed in parenthesis for each of the input apertures. For the largest illumination width,  $W=7.5\text{mm}$ , the ratio of measured beamwidth to calculated beamwidth is 2.6, decreasing to 1.95 for  $W=5\text{mm}$ , 1.63 for  $W=4\text{mm}$ , 1.25 for  $W=3\text{mm}$ , 0.9 for  $W=2\text{mm}$  and 0.6 for  $W=1\text{mm}$ . Inspection of this sequence and the gradual reduction of near-in sidelobes shows that as the illumination aperture is reduced, the magnitude of the aberration is reduced. The measured results indicating that the diffraction pattern width is less than the calculated value should not be disturbing because it only indicates that the waveguide lens is in the far field of the input aperture iris and that the true illumination function is not uniform but is developing a distribution resembling the  $\text{sinc } x$  function. One may conclude that the lens is operating near the diffraction limit for an input aperture of 3mm.

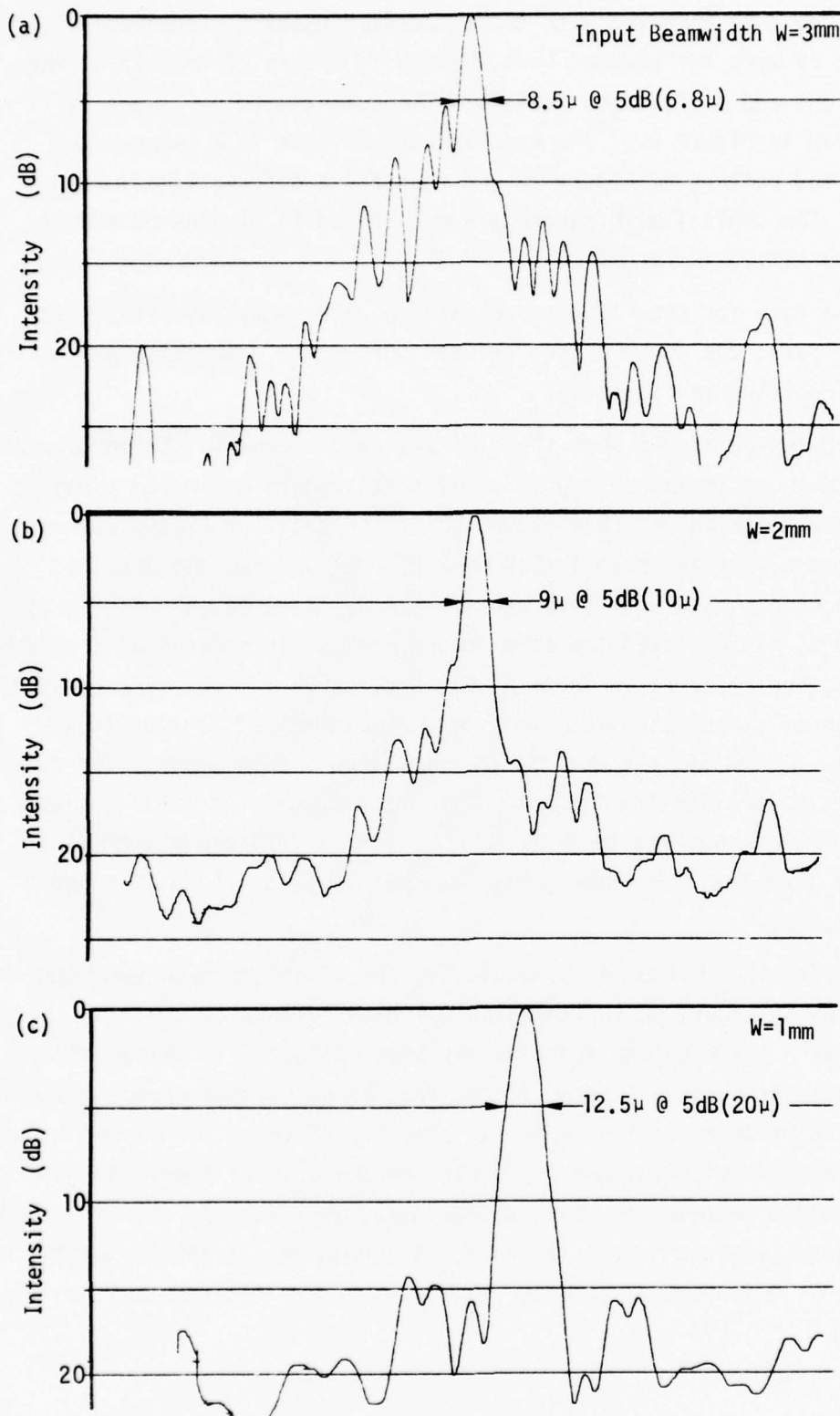
Each of the diffraction patterns in the sequence shown in Figures 63 and 64 shows an asymmetry of the sidelobes which is due to leakage around the fiber probe employed to scan the diffraction pattern. Inspection of the diffraction patterns for  $W=5,4$  and 3mm shows a consistent repetition of the sidelobes with increasing null depth as the aperture is decreased. This is due to a decreasing spherical aberration as the lens is stopped down. Reversal of this trend appears in the diffraction pattern for  $W=7.5\text{mm}$  which suggests a higher order even distortion of the quadratic phase error. These data suggest that the Luneburg lens thickness is excessive in the 3-5mm zone and that the thickness may be deficient in the zone beyond 5mm. This

\* See page 108 for experimental method



Mask: Conical  $\theta=30^\circ$ ,  $T=3.8\text{mm}$ ,  $D=19\text{mm}$

Figure 63. Collage of Diffraction Patterns for the Same Generalized Luneburg Lens Where the Input Aperture Has Been Varied to Observe the Zonal Effects Upon the Diffraction Pattern. Lens  $\text{Ta}_{2}\text{O}_{5}$ -on-7059 on  $\text{SiO}_{2}/\text{Si}$ . The Focal Length = 4.5 cm. Uniform Illumination



Mask: Conical  $\theta=30^\circ$ ,  $T=3.8\text{mm}$ ,  $D=19\text{mm}$

Figure 64. Continuation of Collage of Diffraction Patterns for the Same Generalized Luneburg Lens where the Input Aperture Has Been Varied to Observe the Zonal Effects Upon the Diffraction Pattern. Lens  $\text{Ta}_2\text{O}_5$ -on-7059 on  $\text{SiO}_2/\text{Si}$ . The Focal Length = 4.5 cm.

data should be compared with the calculated results illustrated in Figure 25 with the reduced perturbation of Figure 27 containing the wavefront and diffraction pattern. The accentuated ray trace is depicted in Figure 25. The experimental results fall between the distorted pattern of Figure 27 and that for a diffraction-limited beam. The conical mask parameters enumerated in Figures 63 and 64 are identified in Figure 50.

The data for some lenses presented herein shows asymmetry. It is, in part, due to an offset created during the deposition process as exemplified in Figure 56.

Figures 65 and 66 show the diffraction patterns for three generalized Luneburg lenses having a longer focal length employing three different mask shapes (See Figure 50). The data for Figure 65 has utilized a Gaussian beam ( $W=2.4$  mm @ 8.6 dB) whereas the data for Figure 66 has used a uniform beam ( $W=6$  mm). Section (a) of Figures 65 and 66 has employed the same convex mask cross section of Figure 50. Diffraction patterns in Section (b), Figures 65 and 66, correspond to the use of a conical mask. Diffraction patterns of Section (c), Figures 65 and 66, are due to the concave mask edge shape. The data of Figure 65 using the Gaussian beam input should not exhibit side lobes except that due to truncation. It does indicate a promising result that the side lobes can be suppressed into the 25 dB range and beyond.

Diffraction patterns showing the gross effect of mask thickness are depicted in Figure 67 for three values with cylindrical and conical shapes. A Gaussian illumination function has been employed. A change of mask thickness produces a shadow effect from the deposition target and controls the rate of decay of the radial thickness profile in the manner in which these errors build up in the vicinity of the primary lobe. In general, the profile reported by Zernike<sup>35</sup> approaches very closely that required for a classic Luneburg lens. As the focal length is increased, the thickness of the film is reduced and the cone is opened up toward a cylinder and beyond.

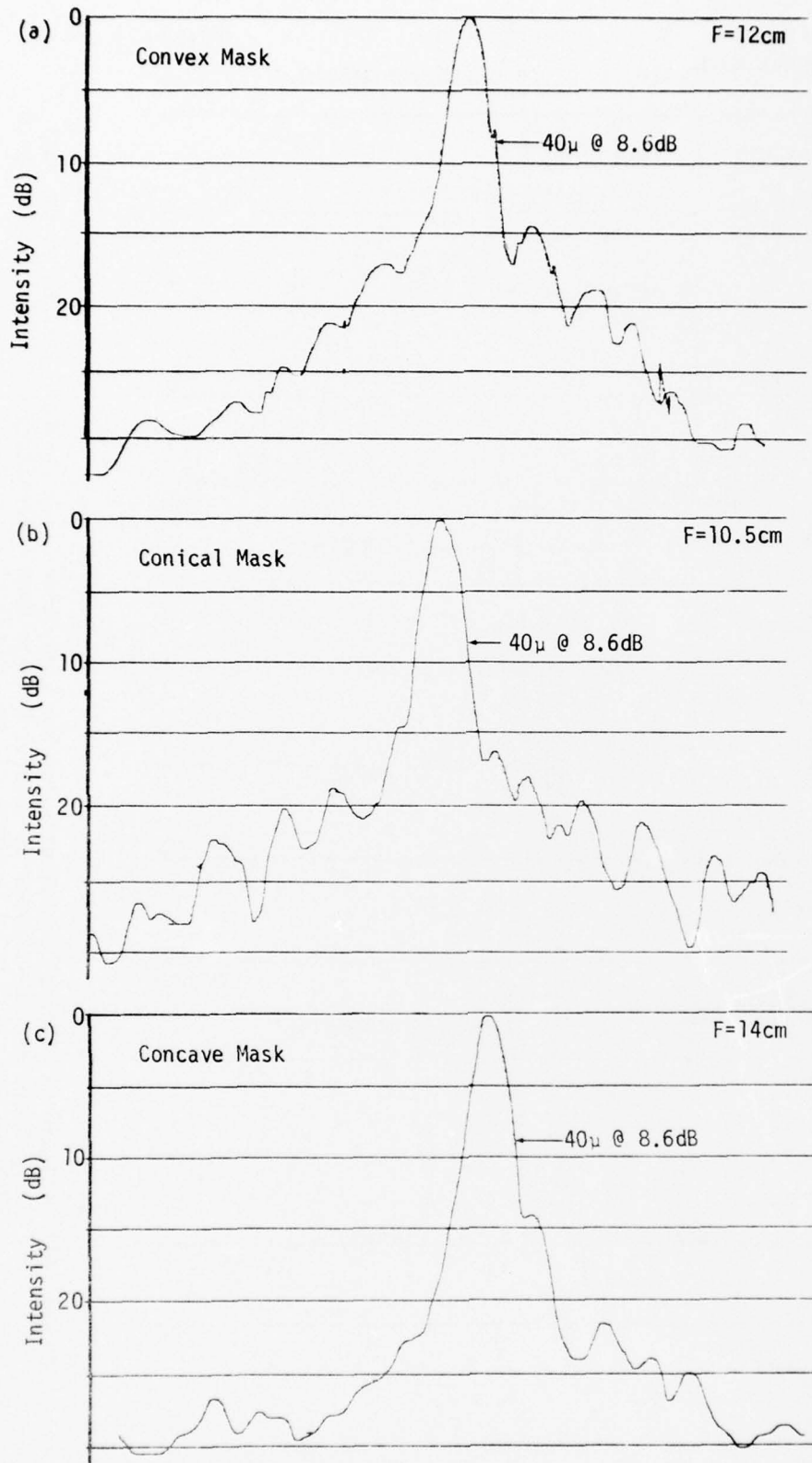


Figure 65. Collage of Diffraction Patterns for the Same Generalized Luneburg Lens Where the Mask Edge Shape Has Been Varied to Observe Effects Upon Diffraction Pattern. Lens  $\text{Ta}_2\text{O}_5$ -on-7059 on  $\text{SiO}_2/\text{Si}$ . Focal Length = 11 cm. Input Gaussian Beam Width 2.4mm @ 8.6dB

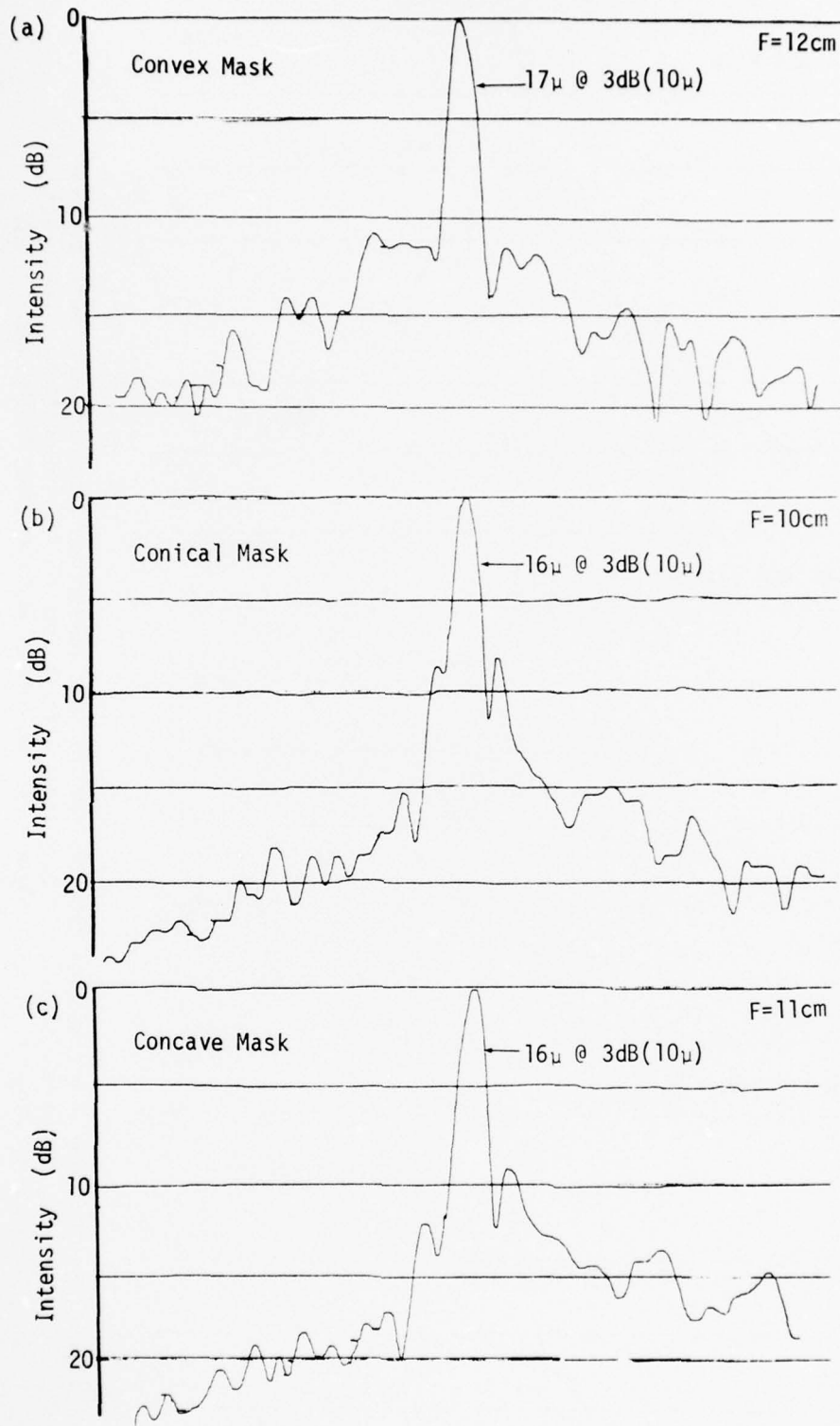


Figure 66. Collage of Diffraction Patterns for the Same Generalized Luneburg Lens Where the Mask Edge Shape Has Been Varied to Observe Effects Upon Diffraction Pattern. Lens  $\text{Ta}_2\text{O}_5$ -on-7059 on  $\text{SiO}_2/\text{Si}$ . Focal Length = 11 cm. Input Illumination Uniform.  $W=6\text{mm}$

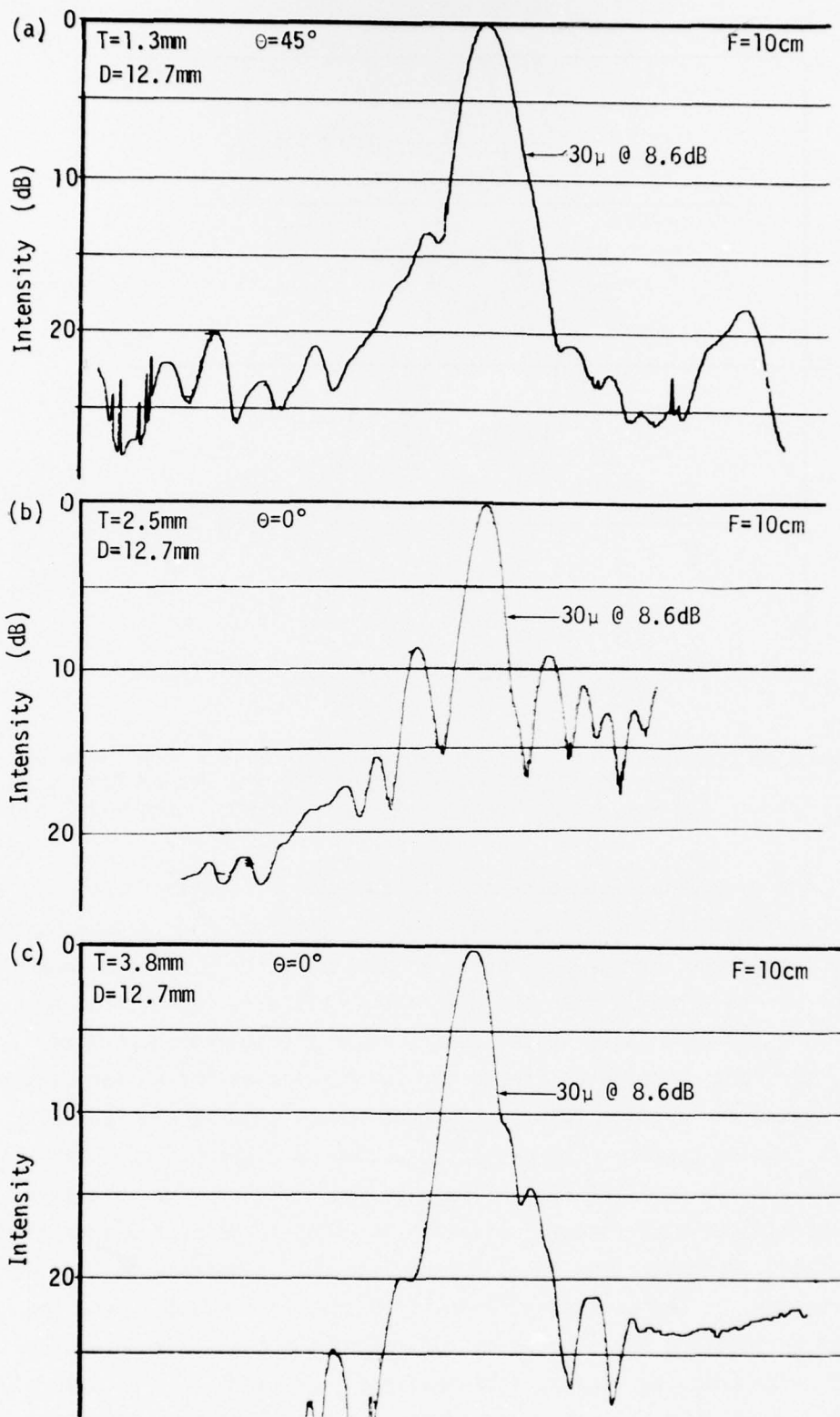


Figure 67. Collage of Diffraction Patterns for Generalized Luneburg Lens Where the Mask Thickness and Conical Edge Has Been Varied to Observe Effects Upon Diffraction Pattern. Lens  $\text{Ta}_2\text{O}_5$ -on-7059 on  $\text{SiO}_2/\text{Si}$ . Focal Length = 10 cm. Gaussian Beam Width 2.4 mm @ 8.6 dB.

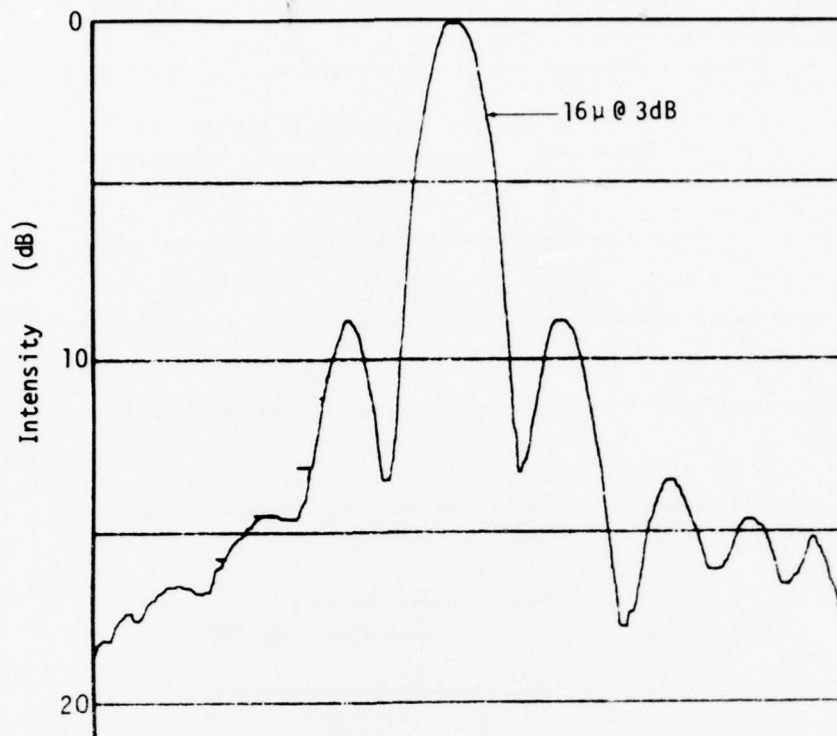


Figure 68. Generalized Luneburg Lens Diffraction Pattern (Same as Figure 66, Section (b), Except for the Use of Reimaging System), Focal Length  $F=10$  cm, Uniform Illumination  $W=6$  mm.

The generalized Luneburg lenses depicted in Figures 64, 65, 66 and 67 have comparatively long focal lengths, some of which extend beyond the substrate. For these lenses, an optical fiber probe has been employed to directly scan the diffraction pattern, rather than employing the re-imaging system described in the following section. The diffraction pattern, Figure 68, is the same as the pattern depicted in Figure 66, Section (b), except that it has been remeasured using a re-imaging system. The results depicted in Figure 68 were obtained using a Zeiss metallographic (long working distance) 40X objective. This refractive microscope objective is known to be near-diffraction limited. For this long focal length lens on a substrate of limited dimension, it was necessary to position the prism coupler near the lens so that the focal point is outside of the thin-film waveguide and prism coupling region. The measured beam width is approximately 1.6 greater than the calculated diffraction limited beam width using

a nearly uniform aperture illuminations 6 mm wide. The side lobe level is at 8 dB instead of the 13 dB for uniform illumination and is symmetrical. From this side lobe level and the null depth, it can be inferred that some spherical aberration is present and that the wavefront phase error is approximately  $\pi/2$ . Symmetry of the diffraction pattern indicates the lack of a cubic phase error (coma).

The diffraction pattern of a generalized Luneburg lens with a substantially larger numerical aperture is shown in Figure 69. The lens has employed a  $Ta_2O_5$  overlay on BaO-rich 7059 waveguide on 7059. The lens f/number is 1.07, however, it is illuminated so as to operate with an f/number of 2.4 in Section (a) and 4.8 in Section (b). A large diameter Gaussian beam is employed with an iris as a source so that the smaller beam is approximately uniform, while the larger beam approximates the cosine. This diffraction pattern was measured using the re-imaging system described in the following section where the properties of the re-imaging lenses are illustrated. The measured beam width is 5 microns @ 3 dB for both diffraction patterns. The calculated beam width is 1.8 and 3 microns, whereas the ratio, measured to calculated beam widths, is 2.7 and 1.6, respectively.

The inferior performance measured in Figure 69, particularly the former (a), is in part due to several causes. First, the prism coupler introduces a significant spherical aberration and second, the measured results are the convolution of the thin-film lens performance and the re-imaging lens performance, which for this case, are comparable. Further, these results should be compared with the calculated diffraction patterns of Figure 24 or Figure 33 with a larger spherical aberration due to defocusing and its correction in Figure 34 by the slight shift of the focal position or its inverse phase distortion depicted in Figure 38 and its refocused diffraction pattern in Figure 39. These results show that small focused spots are realizable, however, improvements of thin-film lens performance and/or re-imaging lens performance, together with suppression of the spherical aberration introduced by the prism (using an aplanatic hypotenuse), is required to more nearly achieve diffraction limited performance.

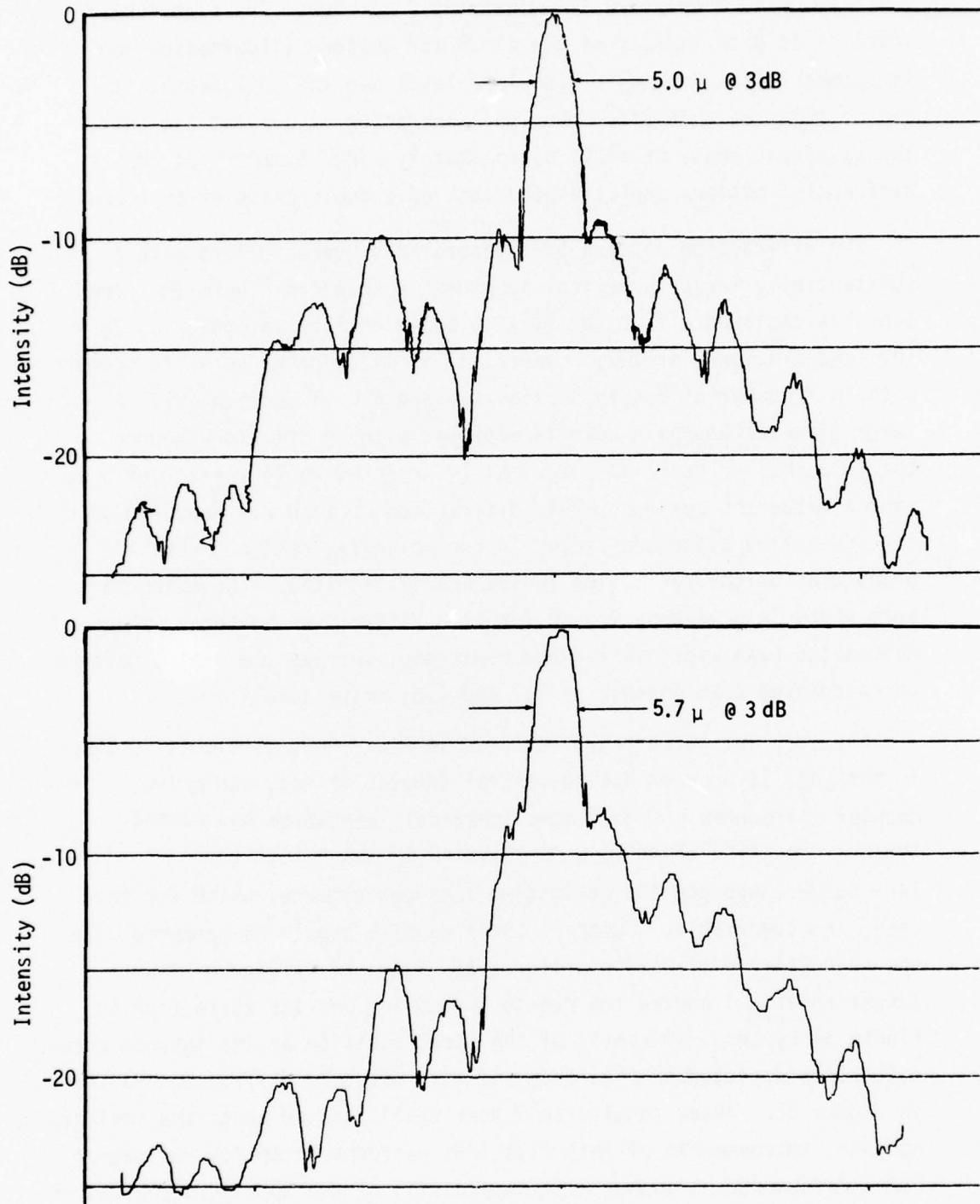


Figure 69. Generalized Luneburg Lens Diffraction Pattern,  $Ta_2O_5$  Lens-on-BaO-rich 7059-on-7059, Lens Diameter 11.2 mm, Focal Length 12 mm, Using (a) Cosine Illuminated 5 mm Aperture and (b) 2.5 mm Irised Section of (a) Approximately Uniform).

The fact that the side lobe level and its decay on the left side of the diffraction pattern in Figure 69 is substantially different is due to the fact that the input beam, when extended in width, encompasses a visible scattering center. The fact that the wide lobe period and the primary lobe width are substantially identical in both patterns when the aperture is increased, strongly suggests that the measured diffraction pattern is dominated by the re-imaging lens performance, rather than being determined by the Luneburg lens performance. (See Figure 72).

## 5. Optical Waveguide Lens Characterization

The performance of conventional optical elements is determined by various procedures such as measurement of the diffraction pattern for an accurately known source or by measurement of modulation transfer function for periodic sources having variable period.<sup>41,42</sup> In each case, access to the image plane is required for probing of the field intensity in the image plane. For optical waveguide lenses, this technique is not practical because the lens is immersed in an ambient dielectric waveguide.

When the ambient dielectric waveguide exhibits uniform scattering it is possible to observe the field distribution spatially through the scattering mechanism. However, in general the lens and waveguide which exhibit sufficient scattering for this type of observation also represents an unsatisfactory lens for use in an optical Fourier transform.

The technique employed herein has utilized a re-imaging procedure which is illustrated in the schematic of Figure 70. Prism couplers are employed to launch beams within the thin-film waveguide, which traverse the lens under investigation utilizing another prism coupler to extract the field which is relayed and re-imaged with magnification where it is possible to probe the field distribution in this latter plane. An optical fiber probe has been employed with its entrance face metalized which contains a thin slit. The fiber probe is mechanically scanned in any of the three major axes providing a signal to drive a recorder, while the optical signal is detected, amplified and compressed to give a logarithmic scale for the recorder. All experimental diffraction patterns reproduced herein have been measured in this manner. The physical apparatus showing the laser source, collimation optics, waveguide assembly with prism couplers, re-imaging lens, mechanically scanned fiber probe and recorder are depicted in Figure 71.

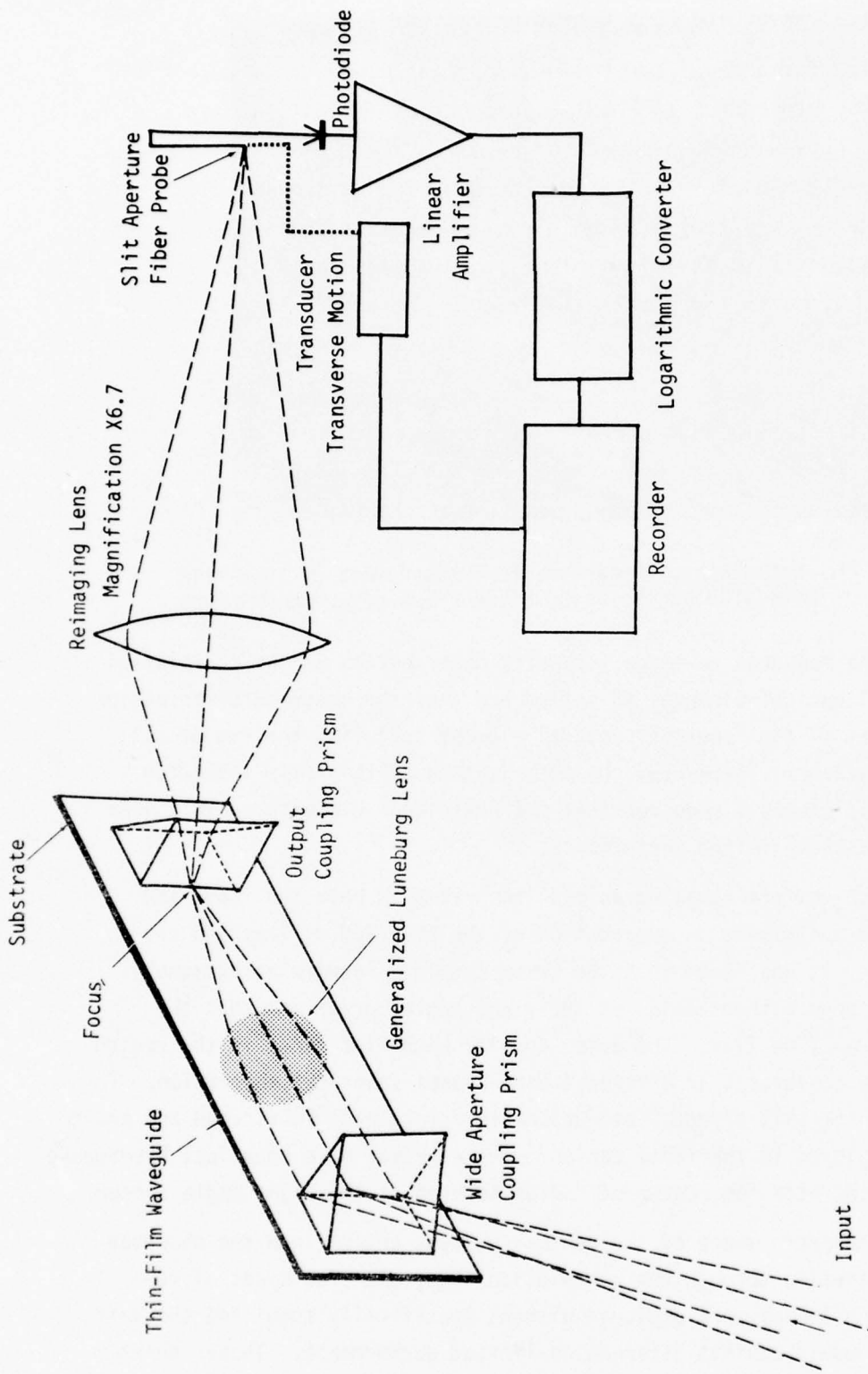


Figure 70. Schematic of Reimaging Technique to Characterize Thin Film Waveguide Lenses

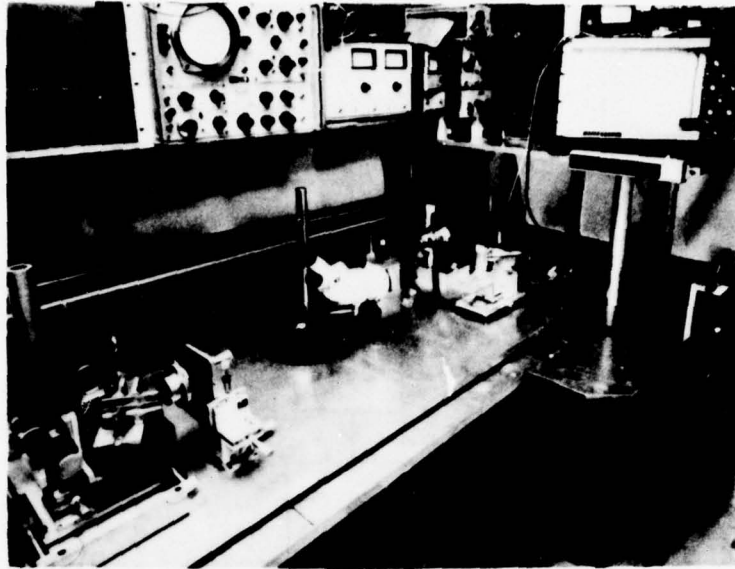


Figure 71. Photograph of Apparatus for Measurement of Thin-Film Waveguide Lenses Using Fiber Probe of Re-imaging Beam

The measured re-image intensity distribution is the convolution of all optical elements in series and thus the measured distribution is that of the "poorest" optical element including the sum of all aberrations. Therefore, characterization of thin-film waveguide optical elements requires that the additional elements exhibit near diffraction-limited performance.

Non-uniform coupling across the prisms in both the input and output contribute to degradation of the observed diffraction patterns. It was found that the prism couplers require an extremely sharp edge without chips at the right angle corner and that the faces must be flat. The prism coupler with flat faces in the region of the convergent or divergent beam causes spherical aberration. To eliminate this effect, some aplanatic prisms were fabricated and are to be employed in the focal region. These prisms have spherical hypotenuse surfaces with the center of radius located at the right angle corner.

The performance of the re-imaging lens enters into the observed distribution through the convolution integral. Two types of re-imaging lenses were employed without specifically acquiring the unit which would exhibit diffraction-limited performance. These lenses are (a) Spectra-Physics Model 333 Objective, focal length 86mm and

f-number 3.5, and (b) Wollensak Oscillo-Raptar, focal length 75mm and f-number 1.9. Using a  $1\mu$  diameter pinhole and  $6328 \text{ \AA}$  radiation, the measured transverse field intensity distribution is shown in Figure 72 for several cross sections in a region of the focus. Cross sections before and after focal region are included. The re-imaged pinhole should yield theoretically diffraction patterns identical to that of Figures 23, 46, and 48, except for the scale factor due to magnification. The measured re-image diffraction patterns of the pinhole fall short of the theoretical diffraction pattern in several ways. The nulls between the first sidelobe and the primary lobe are partially filled in, and the level of the first sidelobe is slightly higher indicating the presence of spherical aberration in the re-imaging lens. The more rapid decay of sidelobes and nearly complete fill-in of nulls indicates the effect of scattering from within the relay lens elements. Further, it is difficult to determine the focus accurately without measuring numerous cross sections.

Inspection of the measured diffraction patterns through the depth of field will show how the relay lens can affect the observed diffraction pattern of a thin-film waveguide lens. It is evident that more precise measurements extending over a larger dynamic range with less scattering is required to more accurately characterize waveguide lenses which are required to achieve near diffraction-limited operation.

It is interesting to note the rate of side lobe decay in each of the relay lenses which must be due to internal scattering between the various lens elements. It will be necessary to reduce this effect substantially so as not to contribute to the observed side lobes and scattering in the thin-film lenses. At this juncture, the thin-film lens performance is comparable to that of the relay lenses so far as wide angle scattering is concerned.

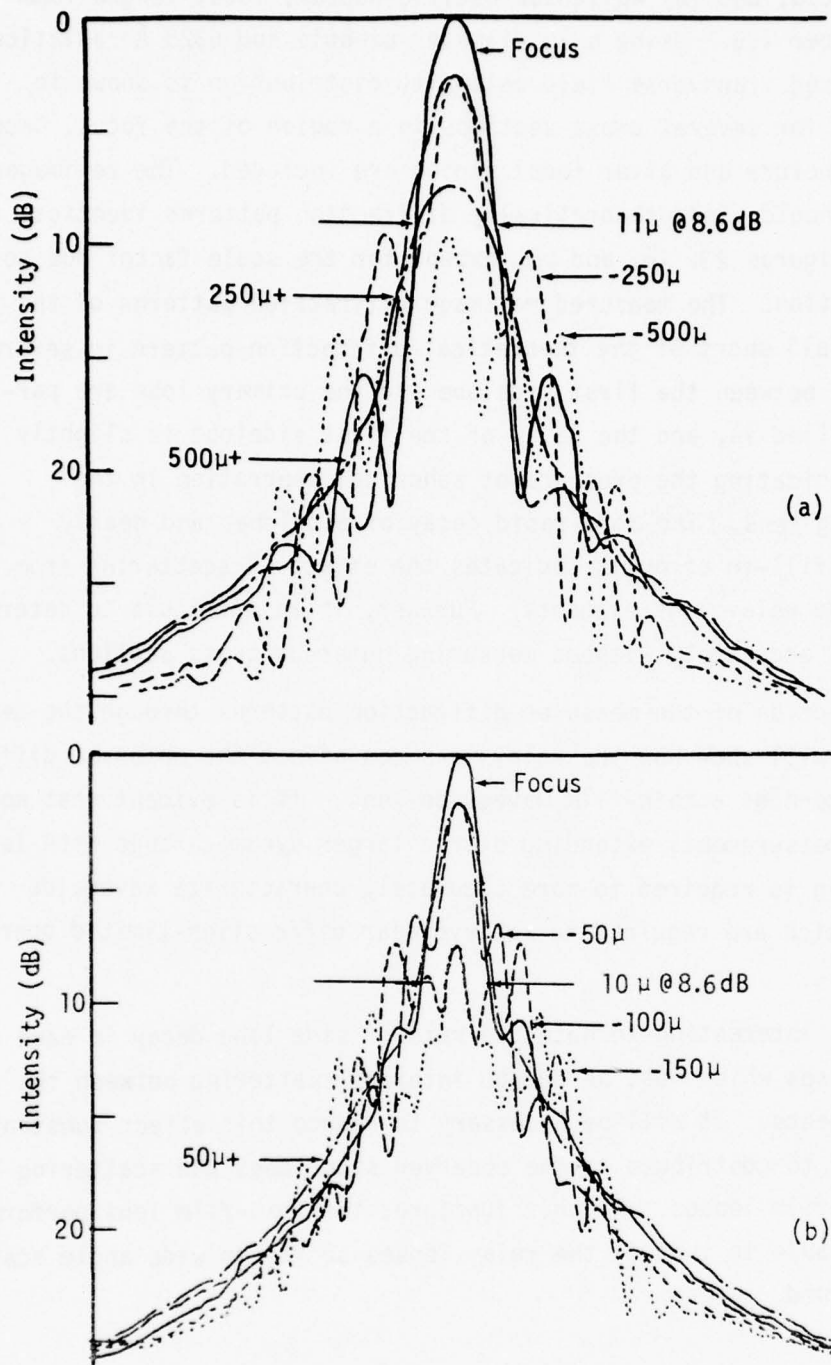


Figure 72 Measured Transverse Beam Intensity Profiles in the Region of the Focus for Two Types of Reimaging Lenses on Both Sides of the Focus Using a 1-Micron Diameter Pin Hole and 6328 Å Radiation (a) Spectra-Physics Model 333 Objective, FL=86 mm,  $f=3.5$  and (b) Wollensak Oscillo-Raptar FL=75 mm,  $f=1.9$ .

#### D. REFLECTORS FOR THIN-FILM WAVEGUIDE

An important consideration for the design of thin-film waveguide optical systems is the requirement for reflectors so as to enable folding of the optical system on a substrate of limited dimensions and area. The reflector in the plane of the waveguide must function efficiently and not give rise to the scattering or radiation losses. An important consideration in the design of waveguide reflectors is the angular range over which they function efficiently and the means to achieve reflectivity at any angle of incidence. This section considers reflectors formed by cleavage in single-crystal substrates that extend through the waveguide thin films.

Dielectric waveguide reflectors which utilize sharp boundaries are based upon the phenomena of total internal reflection, and therefore the angle of incidence is restricted. For 7059 waveguide the angle of incidence must be greater than  $39^\circ$ . For lesser angles of incidence it is necessary to metalize the boundary to obtain total reflection. Aside from waveguide losses, the loss of reflectors based upon total internal reflection or single metallic reflections in the near infrared have proven to be insignificant, i.e., less than 0.3 dB.

The operation of a thin-film waveguide retro-reflector employing total internal reflection is shown in Figure 73 where the substrate has utilized thermally-grown  $\text{SiO}_2$  on {100} Si surface. Silicon nominally cleaves on the {110} face. The retro-reflector illustrated in Figure 73 indicates a slight convergence of the return beam. This is due to the fact that the Si wafer is offset from the {100} plane by approximately  $3^\circ$ . The first reflective surface is perfect and the scattered radiation indicates no loss upon reflection. The second cleavage edge is imperfect, showing some wide-angle forward scattering. The reflected ray traverses a section of very low loss waveguide before intercepting scattering particles. Figure 74 illustrates the operation of a metallized cleaved reflector operating at near normal incidence. This reflector exhibits some wide angle scatter.

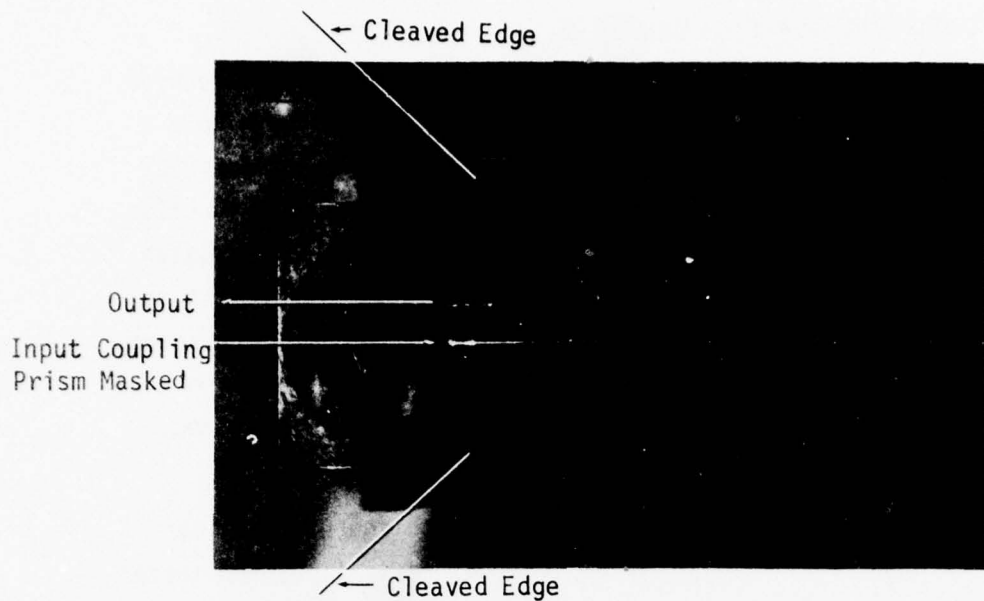


Figure 73. Thin-Film Waveguide Retro-reflector Using Total Internal Reflection Employing 7059 Waveguide on Thermally-Grown  $\text{SiO}_2$  on {100} Si with Input Ray Incident on Near Perfect First Cleaved Edge and with Imperfect Reflector at Second Edge.

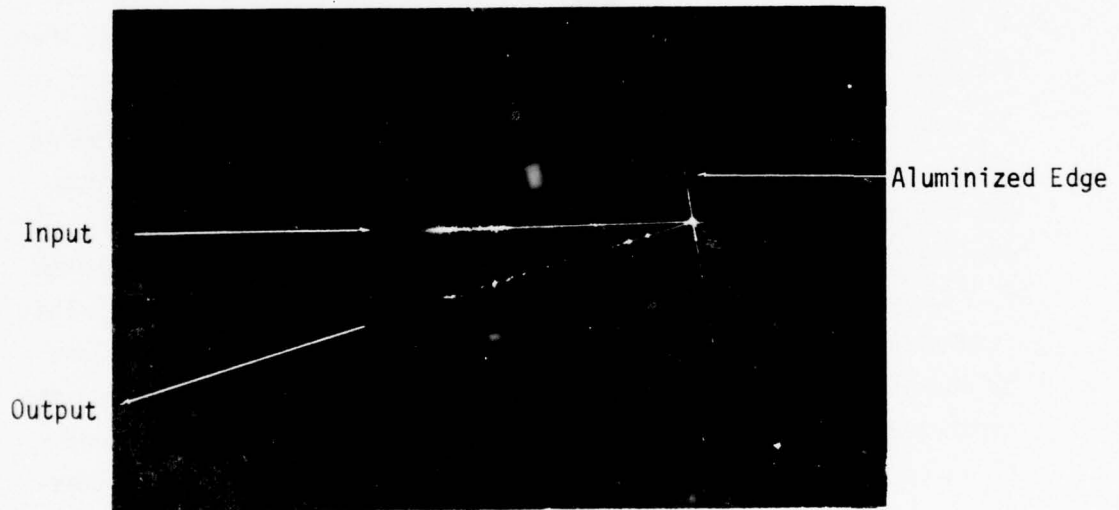


Figure 74. Thin-Film Waveguide Reflector Employing 7059 Waveguide on Thermally-Grown  $\text{SiO}_2$  on Si Using {110} Cleaved Edge with Aluminization on Edge Only.

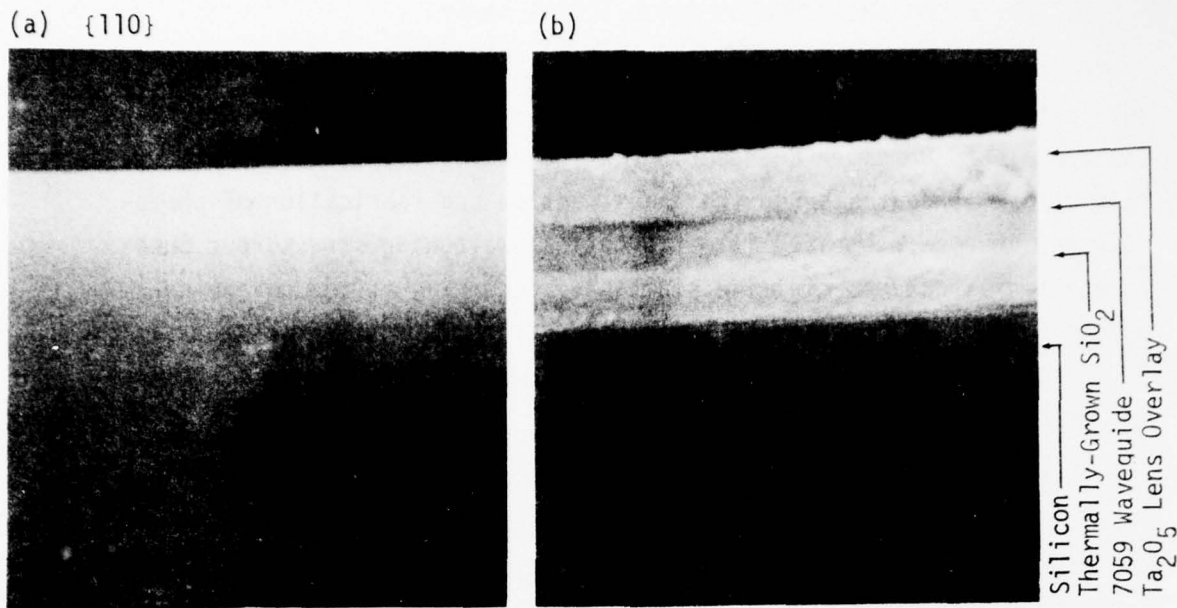


Figure 75. Scanning Electron Micrograph of Cleaved Reflector Through Ta<sub>2</sub>O<sub>5</sub> Overlay Luneburg Lens on Corning 7059 Waveguide on Thermally-Grown SiO<sub>2</sub> Isolation Layer on Si Substrate: (a) Untouched {110} face, (b) Intentionally etched (HF) to delineate each of the oxide layers.

The perfection of the cleaved reflector surface through the single crystal substrate and the polycrystalline thin films is illustrated in Figure 75. Section (a) is the native cleaved surface. Because the various layers are not apparent, an etch has been intentionally employed to delineate the oxide layers. The combined thickness of the thermally-grown oxide and Corning 7059 waveguide is  $1\mu$ .

Reasonably perfect reflectors are obtained with lengths of several centimeters with conventional metallographic techniques when both segments being cleaved are of comparable dimensions. Near the edge of a large diameter wafer ( $>10$  cm), some evidence of imperfection is apparent presumably due to the nature of the crystalline growth for the larger diameters.

## E. OPTICAL WAVEGUIDE COUPLED PHOTODETECTOR ARRAYS

A portion of this Optical Waveguide Lens II program was carried out in the Solid State Electronics Laboratory of the Department of Electrical and Computer Engineering at the University of Cincinnati. This effort concentrated on the investigation and fabrication of photodetector arrays integrated into the optical waveguide structure. Such integrated structures minimize scattering occurring at the waveguide-detector coupling so that the limitations on resolution and dynamic range in integrated Fourier transform processing devices imposed by scattering are minimal.

In the course of the program, several photodetector arrays with carefully prepared tapers were fabricated at the University and delivered to Rockwell International for subsequent deposition of the waveguide and lens and which were subsequently delivered to the Air Force Avionics Laboratory. This program, in conjunction with another sponsored by the Air Force Office of Scientific Research, demonstrated the first integrated charge coupled device image array with an optical waveguide structure. Some results of these combined efforts are contained in the preprint and reprint, Appendices C and D, entitled, "Integrated Optical Waveguide and Charge Coupled Device Image Array" and "Linear Charge Coupled Device Detector Array for Imaging Light Propagating in an Integrated Thin-Film Optical Waveguide," respectively. The following sections expand upon the work reported in the appendices avoiding duplication and, therefore, should be read together:

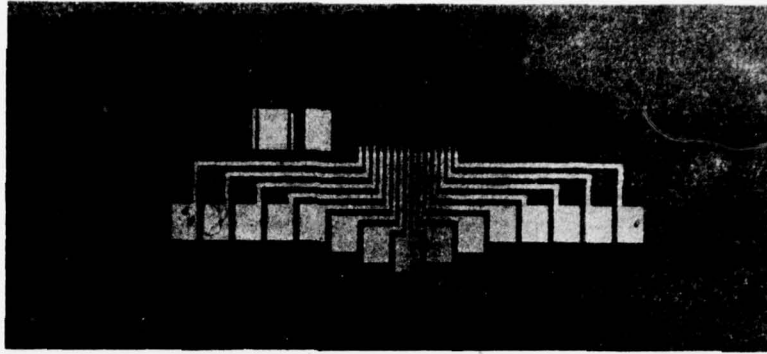
### 1. Waveguide-Detector Coupling

Waveguide-detector coupling is an important consideration for applications of the integrated structure to Fourier signal processing in that efficient coupling maximizes detector signal sensitivity and maximize adjacent channel signal rejection. The latter property is due to the fact that light which is not coupled from the waveguide into the detector can be scattered into adjacent channels. For the devices fabricated during this program (see Appendix C, Figure 2C and Appendix D, Figure 1D, for example), the  $\text{SiO}_2$  layer isolating the optical waveguide from the silicon surface tapers to vanishing thickness in the detector region.

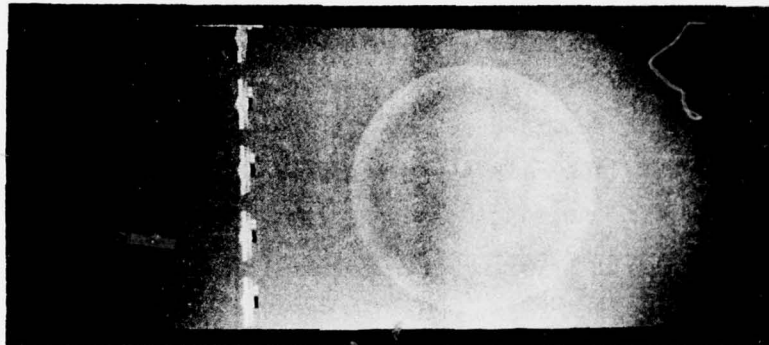
Light propagating in the optical waveguide is then multiply-refracted into the detector region.<sup>15</sup> As we note elsewhere in this report, minimizing the array element center-to-center spacing allows the resolution to be maximized. Such spacings are expected to be limited by lithography considerations. On the other hand, the photodiode length along the direction of light propagation needs to be sufficiently long so that nearly all the light incident is multiply-refracted into the silicon substrate. This length should not be long enough to require large aspect ratios which would disrupt normal device processing. We determined this length  $L_0$  for the  $TE_0$  mode and plotted this optimum value of detector length as a function of waveguide thickness  $d$  for a waveguide refractive index of  $n_g=1.61$ . This refractive index is characteristic of 7059 sputtered glass waveguides. The result of the calculation is shown in Figure 2D included in the Appendix for  $\lambda=.9 \mu\text{m}$  and  $.6 \mu\text{m}$ . The portions of the curves to the left of the dotted vertical lines are the regions in which only a single TE mode can exist. In the single mode regions, the optimum detector lengths would allow fabrication of efficient photodiodes with reasonable aspect ratios and with center-to-center spacings approaching photolithographic limits. However, for multimode waveguides, the corresponding optimum detector lengths become quite long. It is fortunate that, in many signal processing applications such as spectrum analysis, use of a single-mode waveguide is advantageous in view of other considerations. In Fourier optical processing utilizing optical waveguide lenses, the integrated waveguide-detector array described herein is utilized in focal plane imaging. If  $L_0$  exceeds the depth of focus for such applications, then an array of channel waveguides with one passing directly over each photodiode would be required to preserve signal integrity.

## 2. Photodetector Array

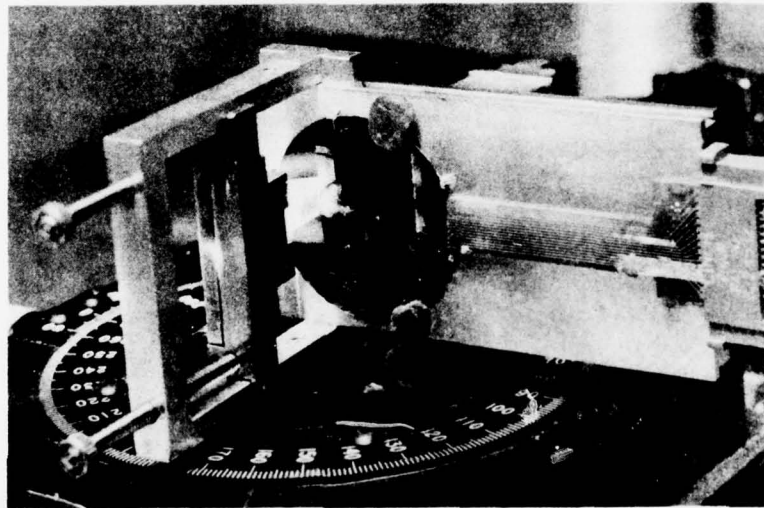
The photodiode arrays fabricated in The University of Cincinnati Solid State Electronics Laboratory and delivered to Rockwell International for further processing are shown in Figure 76. Each {100} oriented wafer contained approximately 8 such arrays along a line located near the wafer edge. Over the remaining area of the wafer, a thick layer of thermally-grown  $\text{SiO}_2$  was formed ( $1 \mu\text{m}$ ) so as to provide sufficient isolation of the waveguide from the silicon substrate. An etched taper in the  $\text{SiO}_2$  layer was formed



(a) Plan View of Waveguide-Coupled Photodetector Array with Lead Fan-Out



(b) Luneburg Lens with Waveguide-Coupled Photodetector Arrays



(c) Experimental Apparatus Employed to Demonstrate Operation of Luneburg Lens Focus on Detector Array (Scattering of Lens Apparent)

Figure 76. Photographic Collage of Waveguide Coupled Photodetector Array Showing (a) Plan View of Array With Lead Fan-Out, (b) Array With Luneburg Lens, and (c) Apparatus Employed to Demonstrate Operation of Luneburg Lens Focused on Detector Array.

approaching the photodiode regions to provide a gradual transition from the thick layer of  $\text{SiO}_2$  to a layer of vanishing thickness in the detector region. This taper was formed by undercutting in which the HF etching solution temperature and concentration were carefully controlled.

Each detector array contained 19 elements having a center-to-center spacing of  $32 \mu\text{m}$ . Of the  $32 \mu\text{m}$ , the device width is  $25 \mu\text{m}$  along with  $7 \mu\text{m}$  of isolation. Preferentially-etched V-grooves were formed utilizing KOH as the etchant between photodiodes to prevent leakage. The photodiodes were characterized by a uniform breakdown voltage of 120 volts at  $10 \mu\text{a}$ . We expect that the use of the V-groove isolation would allow arrays having devices of similar high quality to be fabricated having 1/2 of the above center-to-center spacing. The arrays were processed using n type substrates having a resistivity of 8 ohm-cm. The p diffusion of boron was performed utilizing a boron nitride source. Estimated concentration of the p regions is  $10^{16} \text{ cm}^{-3}$ . In all, 5 mask steps were utilized in the fabrication process. The photographic collage of Figure 76 depicts the waveguide coupled photodetector array in Section (a) with its lead fan-out contacts. The individual detector sections are apparent. The tapered  $\text{SiO}_2$  transition region coupling the waveguide to the detector is evidenced by Newton fringes. The macroscopic view in Section (b) indicates the presence of a thin-film Luneburg lens positioned to focus the beam on the central detector array. Section (c) of Figure 76 indicates apparatus for coupling of radiation into the waveguide optic section showing the scattered transmission through the lens section which focuses the radiation onto one photodetector array with leads attached to extract the signal.

### 3. Integrated Waveguide-Coupled Photodetector Arrays with Charge Coupled Readout

The integrated waveguide-charge coupled device detector array devices have the structure shown in Figure 77. These detector arrays consist of an array of photodiodes formed in n-type silicon connected in parallel by means of a series of gates to a CCD shift register. The charge transfer portion of the device utilizes a two-phase, overlapping-gate structure consisting of one level of polysilicon electrodes insulated by an additional layer of  $\text{SiO}_2$  from a second level of overlapping aluminum electrodes.<sup>43</sup> One CCD unit cell corresponds to each photodiode. Channel isolation is maintained through the series of gates by the presence of channel stopping n+

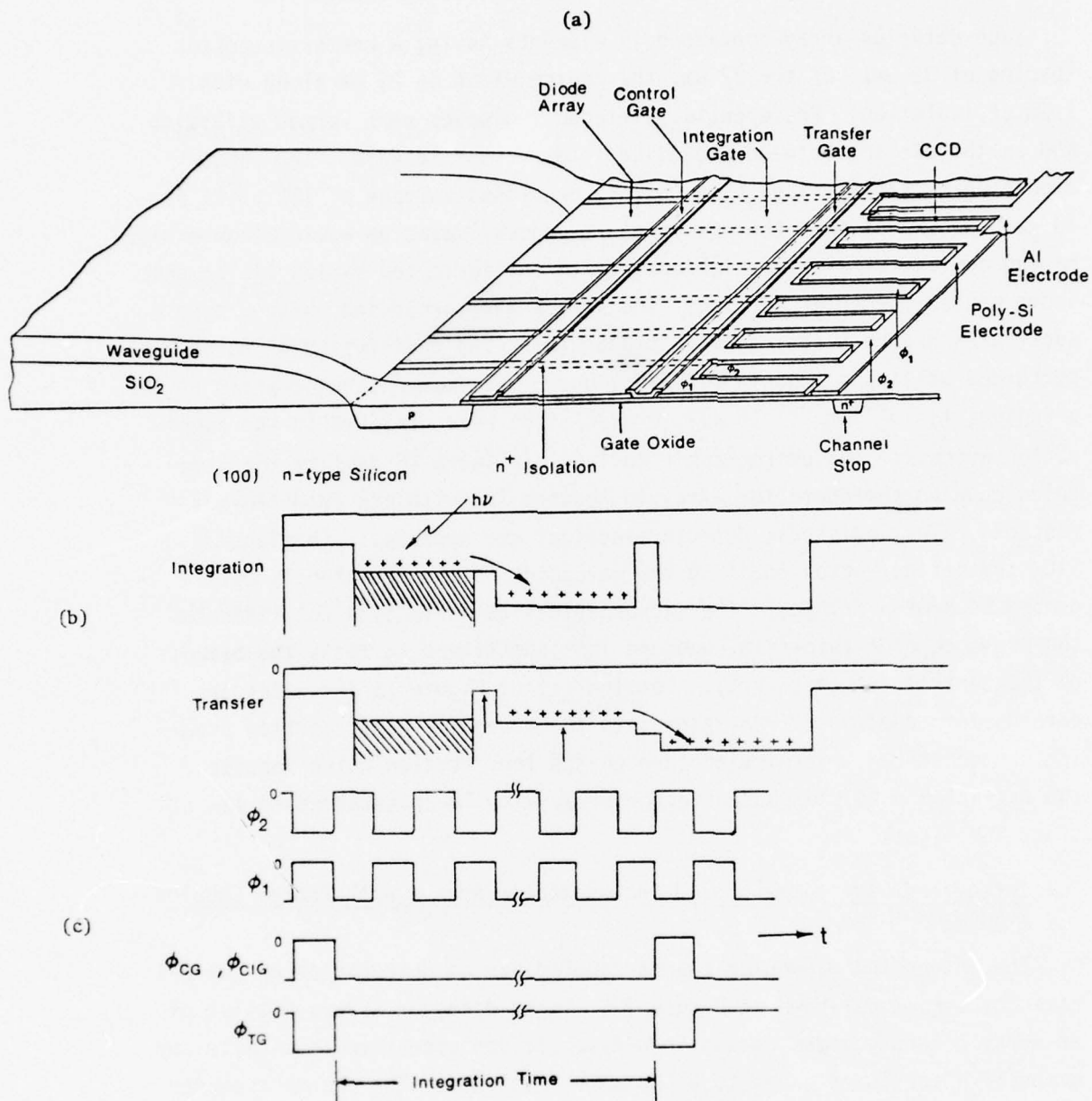
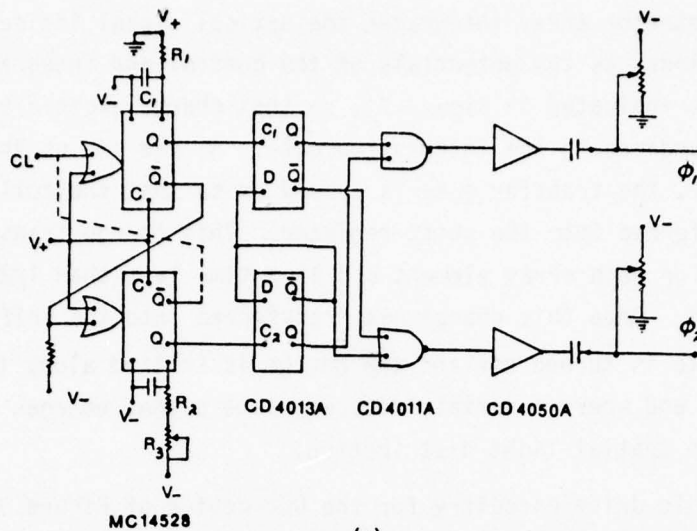


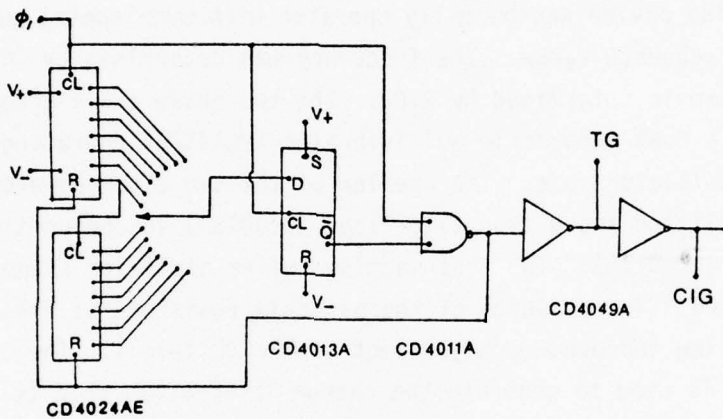
Figure 77. (a) Device Configuration of the Integrated Optical Waveguide-CCD Detector Array  
 (b) Surface Potential Profile During Integration and Transfer Cycles  
 (c) Electrode Waveforms for the Control Gate (CG), the Charge Integration Gate (CIG), the Transfer Gate (TG), and the Phase 1 and Phase 2 Gates ( $\phi_1$  and  $\phi_2$ )

regions. The detector array integrates the optical signal incident on the array of photodiodes as the potentials of the control and integration gates are adjusted, as indicated in Figure 77, so that charge excited by incident light collects underneath the integration gate. At the end of the integration period  $T$ , the transfer gate is turned on so that the collected charge is transferred into the shift register. This charge transfer occurs simultaneously for each array element and in a time less than  $1/2$  of the CCD clock period. Once this charge has transferred into the shift register, the transfer gate is turned off and the charge is shifted along the register to the end where a serial, discrete-time signal emerges representing the spatial light distribution.

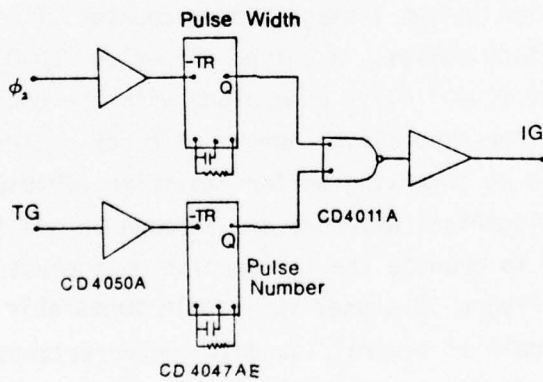
The electronic drive circuitry for the CCD device of Figure 77 is shown in Figure 78. The two-phase clock generator is shown in Figure 78-a. The device was normally operated with overlapping pulses in the 100Khz frequency range. The frequency was determined by  $(R_2+R_3)C_2$ , while the overlap is determined by  $R_1C_1$ . The two-phase clock generator is formed from a dual monostable multivibrator (MC14528) operating in a free-running oscillator mode. The overlap of the two clock waveforms is obtained by utilizing two D-type flip-flops (CD4013A) in conjunction with two NAND gates (CD4011A). Two noninverting buffer amplifier stages (CD4050) are also included. The presence of the variable resistors at the  $\phi_1$  and  $\phi_2$  terminals allow independent adjustment of the DC levels. The circuitry in Figure 78-b is used to generate the charge integration gate (CIG) electrical waveform and the transfer gate (TG) electrical waveform. The phase 1 clock voltage  $\phi_1$  is applied to two 7-stage binary counters (CD4024AE) in series which count the clock pulses. A D-type flip-flop (CD4013A) in conjunction with a NAND gate (CD4011A) is used along with the counter to generate a clock pulse after a specified number of clock cycles. This pulse then passes through an inverting buffer amplifier (CD4049A) to produce the transfer gate electrical waveform and through an additional inverting buffer amplifier to produce the integration gate electrical waveform. The circuitry in Figure 78-c uses two single monostable multivibrators (CD4047) to generate a train of several low-duty cycle rectangular pulses for measurement of CCD transfer inefficiency. These pulses are separated by a clock period and are injected into the CCD serial input gate (IG). The train of several pulses is followed by a long period in which no pulses are generated. This pattern is then repeated periodically. Details of the experimental determination of transfer inefficiency are given in Appendix C.



(a)



(b)



(c)

Figure 78. (a) Circuitry for Generating Two-Phase Clock Voltages ( $\phi_1$  and  $\phi_2$ )  
 (b) Circuitry for Generating the Transfer Gate (TG) and Charge Integration Gate (CIG) Electrode Waveforms  
 (c) Circuitry for Generating Serial Input Gate (IG) Signal for CCD Charge Transfer Efficiency Measurement

### III. REVIEW

#### A. CONCLUSIONS

The thin-film waveguide positive inhomogeneous refractor identified as the generalized Luneburg lens has been investigated, calculating the performance and demonstrating its operation with quantitative measurement of its diffraction patterns, together with its use as a beam expander and its use with reflectors. The detailed considerations have emphasized factors of interest for application to an integrated optical Fourier transform "chip" that may be employed as a real time microwave spectrum analyzer. Consideration of the reflector has been included as a means to fold the optical axis so as to employ a minimum substrate area. An unusually large expansion ratio has been demonstrated for application to the coupling of a GaAs laser to the full aperture required of a Fourier transform lens. The effort has included the demonstration of waveguide coupled photodetector arrays for application in the spatial frequency plane of the transform lens. The photodetector array has also been demonstrated with a charge coupled read out mechanization. This latter waveguide coupled photodetector array and CCD effort has been performed by the Department of Electrical and Computer Engineering at the University of Cincinnati.

The approach has emphasized the application of  $Ta_2O_5$  as the high index lens film used together with Corning 7059 as a waveguide, all of which are deposited upon thermally-grown  $SiO_2$  as an isolation layer on a silicon substrate. This structure permits the integration of the optical components with their electronic counterpart on a single substrate. The problem of scattering and its effect upon the dynamic range and the resolution of the Fourier transform has received consideration which, in part, led to the choice of this preferred material-structure because the thermally-grown oxide has yielded the smoothest low scattering surface thus far identified upon which thin-film waveguide lenses and other associated integrated optical components can be deposited.

A numerical procedure has been developed to compute the performance of thin-film waveguide generalized Luneburg lenses and lens systems. Starting from the waveguide lens thickness profile determining the ray traces, the ray trace through the inhomogeneous lens is determined together with the ray intercept in the image plane. With this data, the wavefront phase error is determined and the resulting intensity diffraction pattern is calculated. The procedure allows the introduction of various types of waveguide thickness profile errors to be introduced and the calculation of the effect upon the diffraction pattern. Numerous examples have been included. Some of these computer results correlate with experimental observations.

Luneburg lenses having  $F/D$  extending from 0.5 to 10 have been fabricated. Some representative diffraction patterns characterizing their performance have been included. Various shapes of deposition masks have been employed to control the radial lens thickness profile. Some representative data showing these effects upon the diffraction pattern has been included. Depending upon the aperture employed, the performance of these lenses approach diffraction-limited operation in varying degrees ranging from 2.5 with data at 1.6 and extending down to near unity. Measured diffraction spot widths approaching 5 microns has been achieved. The measured results, utilizing a re-imaging technique, have shown that this performance is comparable to that of the re-imaging lenses. The presence of the prism coupler normally introduces spherical aberration into the measured results which can, however, be eliminated.

Several beam expanders have been demonstrated showing that the lens mask positioning can yield a collimated beam reproducibly. Cleavage through the substrate and overlaying films can produce an interface of sufficient perfection to implement total internal reflectors.

Waveguide coupling to photodetector arrays has been demonstrated. The fabrication of lenses, which focus on these detectors accurately, has been reproducibly demonstrated.

In general, the focal length of Luneburg lenses is adjusted by the lens radius and shaping of the lens conical mask together with control of the lens thickness. Minor adjustments of the focal length by control of the thickness have been demonstrated by way of the numerical analysis and by way of scaled experiments.

Substantial further improvement of these lenses should be possible, providing for their use with larger numerical apertures by matching of the radial thin-film thickness profile more exactly to the required computed thickness profile. Further effort reducing the scattering of both the lens films and waveguide films is required. Inversion of the deposition process and an improved level of cleanliness is essential. Some results attained thus far are equal to or exceed any other films reported thus far. Reproducibility of these results is required over a larger substrate area. Scattering of the lens film must be reduced. Suppression of mode conversion must be incorporated. Means to satisfy both of these requirements are suggested herein. The beam expansion lens system will eventually require a spatial filter to improve the transverse mode purity.

Results, thus far, based upon the use of thin-film Luneburg lenses on a thermally-oxidized silicon substrate, provide one attractive approach to the implementation of an integrated optical Fourier transform "chip". This approach uses well known established manufacturing processes and thus the chip can be implemented economically and integrated with its associated electronics.

#### B. ACKNOWLEDGEMENTS

In addition to the various interfaces acknowledged in the Foreword, the contribution of Dr. W. H. Southwell, currently an independent consultant for Optical Science Consultants, Placentia, CA, and Rockwell International, Canoga Park, CA, is sincerely appreciated. Specifically, for recognition that the previously developed computational procedures could be greatly simplified and extended yielding data in an observable format in an economical, expeditious fashion. Most of the results illustrated in Section II.C.3 are due to Mr. V. G. Kreismanis. Further, various processing procedures due to Mr. J. E. Coker are gratefully acknowledged.

APPENDIX A

AN INTEGRATED OPTICAL APPROACH TO THE FOURIER TRANSFORM

D. B. Anderson, J. T. Boyd, M. C. Hamilton,  
and R. R. August

Abstract - A wideband, real-time, spectrum analyzer is examined as a viable integrated optical circuit for processing electronic signals. The spectrum analyzer includes a Luneburg beam expansion lens system, a surface elasto-optic Bragg spatial modulator, reflectors, a Luneburg Fourier transform lens, and a waveguide coupled photodetector array; all formed on thermally-grown  $\text{SiO}_2$  on Si as the substrate. A distributed-feedback (GaAl)As laser with hybrid coupling is included as the carrier for the optical Fourier transform. The developmental status of this integrated optical spectrum analyzer and its essential design considerations are delineated.

---

Manuscript received . This work was supported, in large part, by the Air Force Avionics Laboratory.

D. B. Anderson and R. R. August are with the Electronics Research Division, Rockwell International Corporation, Anaheim, California 92803.

J. T. Boyd, a consultant for Rockwell International, is with the Electrical and Computer Engineering Department of the University of Cincinnati, Cincinnati, Ohio 45221.

M. C. Hamilton is with the Air Force Avionics Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio 45434.

## I. INTRODUCTION

Coherent optical information processing employs diffraction phenomena as manifested by the optical Fourier transform. It is admirably suited to execute linear analog operations such as matrix products, transforms and related convolution or correlation integrations. Its development over a score of years has been motivated by the potential for large information handling capacity [1,2]. This is achieved by data manipulation in a two-dimensional image format processed in a parallel organization in contrast to one-dimensional electronic signal processing which often employs a serial organization.

Current equipment for optical information processing with large time-bandwidth-products is expensive and bulky. Some of the large information handling capacity is compromised at the input or output interfaces when real-time operation is required. It requires precision related to the optical wavelength which, in turn, requires a mechanical structure with sufficient mass to obtain the necessary rigidity. Thus far, miniaturization has not had a significant impact.

Application of an integrated optics format to the Fourier transform provides the potential for a significant reduction in size and weight. Use of a single substrate and planar lithographic processes provides for rigid optical alignment. Planar batch fabrication processing can lead to a substantial reduction of cost. However, optical signal processing in an integrated optics format is limited to a single transverse dimension. For applications involving signals as a function of time, such as RF spectral analysis [3,4], this one-dimensional characteristic is of no consequence. However, an integrated optical approach to spectral analysis

must compete with alternative technologies on the basis of cost and performance. Some of these alternatives include: a bank of narrow band filters, digital transistor logic organized for the "fast" Fourier transform, and the chirp-Z algorithm implemented with either charge-coupled [5] or surface elastic wave [6] devices. Real-time operation with wide bandwidth approaching 1 GHz obtained on a single "chip" is expected to be the primary attributes of an integrated optical approach to an RF spectrum analyzer.

Some of the theory related to the spectrum analyzer is developed herein, together with an exposition of design considerations as related to the whole "chip". Companion papers [7,8] delineating specific considerations for the optical waveguide lenses and the waveguide coupled detector array are included in this special issue.

## II. THEORY OF OPERATION

The optical Fourier transform configuration considered herein is illustrated in Fig. 1. It requires a coherent source (single transverse and longitudinal mode) and an optical lens system to expand the beam with a prescribed aperture distribution and width. The transform configuration also employs a spatial modulator which Bragg diffracts the optical radiation in linear proportion to the applied signal frequency and amplitude. This diffracted radiation is collected by the Fourier transform lens and emerges as a transverse spatial distribution which is detected in the focal plane. Because the detectors respond to the intensity spatial distribution in the transform plane, the resulting electrical signal is a Wiener spectrum of the input signal.

An integrated optical circuit layout to implement the RF spectrum analyzer on a single substrate is depicted in Fig. 2 as representing the schematic of Fig. 1. It includes a Luneburg beam expansion lens system, a surface elasto-optic Bragg diffraction modulator, reflectors, a Luneburg Fourier transform lens, and a waveguide-coupled photodetector array; all arranged as thin-film waveguides on thermally-grown SiO<sub>2</sub> on a common Si substrate. A distributed-feedback (GaAl)As laser with hybrid coupling to the waveguide is included to provide the optical carrier. The optical axis could obviously be folded into other configurations.

Considering the optical geometry shown in Fig. 1 as a planar waveguide, the field amplitude  $E(y_2)$  in the transform plane is related to the field amplitude in the input plane  $E(y_0)$  according to [9]

$$E(y_2) = b \int_{-\infty}^{\infty} E(y_0) e^{i \frac{k N_e(m) y_2}{F} y_0} dy_0, \quad (1)$$

where  $y$  is in the waveguide surface perpendicular to the axis of wave propagation ( $z$  axis) and the  $x$  axis is normal to the waveguide surface. The  $x$  dependence of the field contains the form of the waveguide modes and will be suppressed here for conciseness, however, its effect on Bragg diffraction has been incorporated [10]. In (1)  $F$  is the lens focal length,  $N_e(m)$  is the thin-film waveguide mode effective refractive index,  $k = 2\pi/\lambda$  where  $\lambda$  is the optical wavelength, and  $b$  is a constant of proportionality. For a uniform plane wave over the input aperture  $D$ , the spatial output has the familiar form:

$$E_0^m(y_2) = bD \operatorname{Sinc}\left(\frac{kN_e^{(m)} Dy_2}{2F}\right), \quad (2)$$

where  $\operatorname{sinc} x = \sin x/x$ . The half-width between nulls of this diffraction pattern is

$$\Delta y_2 = \frac{\lambda f}{N_e^{(m)} D} \quad (3)$$

which represents the smallest resolvable interval in the Fourier transform plane.

The optical axis in Fig. 1 and the surface elastic wave propagation axis are oriented so as to satisfy the Bragg condition at the signal center frequency. The z axis in Fig. 1 is thus at an angle  $2\theta_B$  with respect to the optical axis of the incident wave where  $\theta_B$  is the Bragg angle defined as

$$\sin\theta_B = \frac{\lambda f_{s0}}{2N_e^{(m)} v_r}, \quad (4)$$

where  $f_{s0}$  is the signal center frequency and  $v_r$  is the Rayleigh wave velocity. The interaction of the incident optical wave and the surface elastic wave has been treated elsewhere [10-13]. For operation of the spectrum analyzer, it is necessary to closely approximate the surface elastic wave as consisting of uniformly-weighted plane wave components within a diffraction angle  $\delta\phi$  and no components beyond  $\delta\phi$  where  $\delta\phi$  is assumed sufficiently large so that the elasto-optic bandwidth is limited

by the transducer bandwidth [10]. Such a close approximation is possible through the use of tilted transducer arrays [14,15]. It is reasonable to assume the beam spread of the input optical wave is much less than  $\delta\phi$ . For this case, the optical beam spread will not be significantly altered by the elasto-optic interaction [16,18]. We further restrict our attention to the Bragg regime so as to eliminate the possibility of ambiguities caused by multiple scattering. Furthermore, as noted by Giallorenzi and Milton [16], second-order multiple scattering is avoided if  $k_{s \max} < 2 k_{s \min}$ , where  $k_{s \min}$  and  $k_{s \max}$  are the minimum and maximum values of elastic wave propagation constant  $k_s$  over the range of the signal band.

Operation of the spectrum analyzer requires a linear relationship between the diffracted field amplitude and the signal amplitude spectrum, which is achieved by limiting the surface elastic wave intensity so that the input optical intensity is not significantly depleted. Cumulative and thus efficient energy transfer from the signal input to the diffracted optical beam only occurs when momentum conservation is satisfied [19]. Restricting our attention to only the surface elastic wave angular component which satisfies momentum conservation, the transverse electric field distribution in the Fourier transform plane  $E(y_2)$  is given as.

$$E(y_2) = ab \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(f_s) w(y_0) e^{-i \frac{2\pi}{v_r} (f_s - f_{s0}) \cos\theta_B y_0} e^{i \frac{kN_e(m)y_2}{F} y_0} dy_0 df_s . \quad (5)$$

In (5)  $f_s$  is signal frequency,  $G(f_s)$  is the Fourier transform of the input signal  $g(t)$ ,  $y_0$  and  $y_2$  are transverse spatial coordinates as indicated in Fig. 1,  $a$  is a collection of constants including the elasto-optic diffraction efficiency and  $w(y_0)$  is a window function defined such that

$$w(y_0) \begin{cases} \neq 0, & |y_0| < D/2 \\ = 0, & |y_0| > D/2 \end{cases} \quad (6)$$

We have chosen to evaluate the transform over the infinite interval and include the effect of a finite beam by means of the window function [20]. Carrying out the integration in (5) yields

$$E(y_2) = a \int_{-\infty}^{\infty} G(f_s) W \left[ y_2 - \frac{\lambda f \cos \theta_B}{N_e^{(m)} v_r} (f_s - f_{s0}) \right] df_s, \quad (7)$$

where  $W(y_2)$  is the Fourier transform of the window function.

The expression (7) for the transverse field distribution in the transform plane is the usual result of performing a truncated Fourier transform in that it is a convolution of the Fourier transform of the input signal and the Fourier transform of the window function. In the limit of no truncation and uniform weighting  $W(y_2)$  approaches a delta function so that (7) reduces to

$$E(y_2) = \frac{abv_r}{\cos \theta_B} G \left( f_{s0} + \frac{v_r N_e^{(m)}}{\lambda f \cos \theta_B} y_2 \right) \quad (8)$$

For no truncation the field  $E(y_2)$  is thus a direct mapping of the Fourier transform of the input signal along the  $y_2$  axis with scale factor  $(\lambda f \cos \theta_B) / N_e(m) v_r$ . In the case of finite truncation, the convolution (7) will yield an accurate mapping of the Fourier transform of the input signal if the spectral width of  $W(y_2)$ , given by (3) for an optical plane wave over the aperture  $D$ , is much less than the input signal spectral width, i.e.,

$$\frac{D \cos \theta_B}{v_r} \Delta f_s \gg 1. \quad (9)$$

For case of interest,  $\theta_B$  is of the order of a few degrees,  $\cos \theta_B \approx 1$  and (9) reduces to

$$T \Delta f_s \gg 1 \quad (10)$$

where  $T = D/v_r$  is the transit time of the surface elastic wave across the optical aperture. Thus, the condition for negligible effects due to truncation leads to the requirement that the time-bandwidth-product be much greater than unity. Although the convolution (7) of the signal transform with the transform of the window function provides a spectral estimate of  $G(f_s)$ , an improved estimate can be achieved by weighting the signal window [20]. A uniform weighting function produces the sinc  $x$  distribution for  $W(f_s)$  which leads to a spectrum analyzer with finite adjacent-channel response for a continuous single electronic signal input. A tapered weighting function, however, will suppress the sidelobe of the sinc  $x$

function and Gaussian weighting will eliminate the sidelobes.

### III. SPECTRUM ANALYZER DESIGN CONSIDERATIONS

To examine the frequency resolution, consider an electronic signal frequency  $f_s$  departure from the signal center frequency by an amount  $\delta f_s$ . The corresponding diffracted wave component departs from the  $z$  axis by an angle  $\delta\theta$ , where

$$\delta\theta = \frac{\lambda}{N_e(m)v_r} \delta f_s \quad (11)$$

For a wave propagating at this angle with respect to the  $z$  axis and having constant amplitude within the aperture width  $D$ , the resulting diffraction pattern in the transform plane is given by (2) except for a displacement  $\delta y_2$  of the position of the maximum, where

$$\begin{aligned} \delta y_2 &= f\delta\theta \\ &= \frac{f\lambda}{N_e(m)v_r} \delta f_s \quad (12) \end{aligned}$$

Using the Rayleigh criteria for resolution, the minimum frequency difference which can be resolved occurs when  $\delta y_2 = \Delta y_2$ , i.e.,

$$\begin{aligned} \delta f_s \min &= \frac{v_r}{D} = 1/T \quad \text{Uniform Weighting} \\ &= 1.41/T \quad \text{Truncated Gaussian Weighting} \end{aligned} \quad (13)$$

where the truncation width is at the  $1/e$  value [21]. If  $\Delta f_s$  is the electrical signal bandwidth, then the number of resolvable frequency intervals  $N$  is given as

$$N = \frac{\Delta f_s}{\delta f_{s \text{ min}}} = \Delta f_s T, \quad (14)$$

Thus, as in other transform techniques, the number of resolvable frequency intervals is the appropriate time-bandwidth-product.

Assuming an optical waveguide structure having a Rayleigh velocity  $v_r = 4.2$  km/s, the time-bandwidth-product of a spectral analyzer using (14) is depicted in Fig. 3 for several values of transform aperture. Thus, for a lens aperture of 1.5 cm and a surface elastic wave transducer bandwidth of 280 MHz yields a time-bandwidth-product of 1000.

For an optical wavelength of  $0.9 \mu\text{m}$  and an optical waveguide effective refractive index of 1.6, the relationship of temporal frequency resolution corresponding to the spatial interval in the transform lens output frequency plane is depicted in Fig. 4, using (13). The limits imposed by diffraction are also included in the figure for a lens aperture of 1 and 2 cm as a frequency band determined by the exact weighting function utilized. The spectrum analyzer frequency resolution for several Fourier transform lens focal lengths is thus related to the photo-detector array element spacing depicted in Fig. 4. Thus, if the minimum detector period is  $6 \mu\text{m}$ , due to photolithographic limits for the detectors and the required frequency resolution is 0.5 MHz, the required lens focal length becomes greater than 8.9 cm, which may be obtained with a lens

diameter of 1 cm with a uniform weighting function. However, with a truncated Gaussian, either a longer focal length or a reduced detector period must be employed. If, on the other hand, the focal length is reduced to 1 cm for the same temporal frequency resolution, the lithography requirements are increased; that is, the lithography art employed must achieve a detector spacing of  $0.7 \mu\text{m}$ . This latter dimension is currently considered impractical for a photodetector array. It is possible to define an array of rectangular image line waveguides with this center-to-center dimension, however, and use a waveguide fan-out array for coupling between the focal plane and a detector array with a larger period. This tradeoff between detector array lithographic resolution is dependent upon the focal length employed and the ability to fold the optical axis across the available spectrum analyzer substrate area, as indicated by the example in Fig. 2.

In the preceding analysis we assumed an idealized plane wave optical input. In practice the input optical wave would have both a finite beam spread and a finite frequency linewidth. If we consider an input beam spread  $\Delta$ , then Bragg diffraction of the various input wave angular components will occur for different surface elastic wave angular components corresponding to a constant frequency  $f_s$ . Such behavior could lead to a compromise in frequency resolution of the spectrum analyzer unless

$$\Delta \leq \delta\theta_{\min} \quad , \quad (15)$$

where  $\delta\theta_{\min}$  is the diffracted wave angular change corresponding to the

minimum resolvable frequency  $\delta f_{s \text{ min}}$ . Using (13) and (11) in (15), the input optical beam spread will not compromise frequency resolution if

$$\begin{aligned} \Delta &\leq \frac{\lambda}{N_e(m)v_r} \delta f_{s \text{ min}} \\ &\leq \frac{\lambda}{N_e(m)D} \end{aligned} \quad (16)$$

Thus, the input optical wave must be near diffraction-limited so as to not degrade the temporal frequency resolution (13). This defines the requirement on the beam expansion collimation and transform lens focal length tolerances.

Now considering the effect of the optical wave finite frequency linewidth, the magnitude of  $k_i$  and  $k_d$  will change so that phase-matched deflection will occur at different angles for a constant signal frequency. A change in input laser frequency  $\Delta\omega_i$  will cause a change in the output diffracted angle  $\Delta\theta$  that can be expressed as

$$\Delta\theta = 2 \frac{\Delta\omega_i}{\omega_i} \sin\theta_B \quad (17)$$

Spectrum analyzer frequency resolution will not be compromised as long as the above angular change is less than  $\delta\theta_{\text{min}}$ , i.e.,

$$\frac{\Delta\omega_i}{\omega_i} = \frac{\Delta\lambda}{\lambda} = \frac{\lambda}{2 N_e(m)D \sin\theta_B} = \frac{\delta f_{s \text{ min}}}{f_{so}} \quad (18)$$

where  $\Delta\lambda$  is the linewidth in terms of wavelength. For  $\lambda = .9 \mu\text{m}$ ,  $N_e(m) = 1.6$ ,  $D = 1.0 \text{ cm}$ , and  $\theta_B = 5^\circ$  we find  $\Delta\lambda = 2.5 \text{ \AA}$ . Distributed-feedback (DFB) or distributed Bragg reflection (DBR) GaAs semiconductor lasers and gaseous lasers do exhibit lesser linewidth. The condition (18) and (16) which place stringent requirements on laser frequency linewidth and angular spread correspond to diffraction limited operation. If the spectrum analyzer resolution is instead limited by detector element center-to-center spacing, then the above conditions may be reduced to the point where

$$\Delta < \ell/f \quad (19a)$$

$$\frac{\Delta\omega_i}{\omega_i} = \frac{\Delta\lambda}{\lambda} < \frac{\ell}{2f\sin\theta_B} \quad (19b)$$

In (19)  $\ell$  corresponds to the detector array element center-to-center spacing. Thus, for  $\ell = 25 \mu\text{m}$  and  $f = 5 \text{ cm}$ , the maximum values of  $\Delta\lambda$  and  $\Delta$  which do not compromise resolution are increased from the previous example to  $22.5 \text{ \AA}$  and  $.5 \text{ milliradians}$ , respectively. The laser source emission wavelength must also be stable to preserve calibration of the spectrum analyzer. The emission wavelength of (GaAl)As DFB and DBR injection lasers is stabilized by the internal grating.

The performance of the integrated optical spectrum analyzer will be compromised by Rayleigh and/or Mie scattering originating in both the waveguide and lens regions. Scattering will adversely affect both frequency resolution and the dynamic range. Scattering will have a

greater effect on the dynamic range, the degree of which remains to be determined experimentally. The degree of Rayleigh and Mie scattering is largely dependent upon materials and processing. The effects of scattering are also position dependent along the optical axis. Analysis of the scattering process has shown that, as long as the scattering loss is not more than 1 dB/cm, frequency resolution will not be adversely affected [22].

#### IV. SPECTRUM ANALYZER IMPLEMENTATION

One form of an integrated optical spectrum analyzer is illustrated in Fig. 2 where, with the exception of the laser source, all of the components are combined on a single substrate. The surface of thermally-grown  $\text{SiO}_2$  is particularly useful because it has a low refractive index and can yield an extremely smooth surface. Corning 7059 is a typical low-loss, thin-film material applicable for use with the thermally-grown  $\text{SiO}_2$  as an isolation layer on Si as a substrate. Fig. 5 depicts the calculated waveguide absorption for Corning 7059 of several thicknesses as a function of the thermally-grown  $\text{SiO}_2$  isolation layer thickness due to the waveguide evanescent field penetration into the silicon substrate [23]. Use of silicon as a substrate has a further advantage that a detector array and the associated signal processing electronic circuit can be integrated into the same substrate [24].

The thin-film waveguide lenses shown are of the general Luneburg class [25,26,7]. These lenses are circular symmetrical and employ a gradual radial refractive index profile which minimizes interface scattering. Fabrication is simple and reproducible [25]. When properly designed, they

are free of the spherical aberration, coma, however, obviously exhibit circular field curvature. Fig. 6 illustrates a plan view of two Luneburg lenses for use as a beam expander. An overlay of  $Ta_2O_5$  on 7059 waveguide on a 7440 substrate has been employed. The Newton rings in section (a) of the figure indicates the profile. Sections (b) and (c) indicate separate ray traces through both lenses and around the circumference of the larger lens, respectively. Their f-number is  $F/D = 0.5$ . Keeping a constant radius and altering the radial refractive index profile allows the focal length to be increased.

Reflectors are necessary to fold the spectrum analyzer optical axis so as to be contained within the available substrate area. One successful technique to form reflectors for Corning 7059 waveguide on thermally-grown  $SiO_2$ -on-Si is by cleavage of the substrate along a  $\{110\}$  face when normal to the waveguide surface. Fig. 7 illustrates the operation of a retro-reflector employing the above materials. Comparison of the scattering loss between Figs. 7 and 6 dramatically demonstrates the merits of waveguide formed on thermally-grown  $SiO_2$ .

The surface elasto-optic spatial modulator requires a piezoelectric to launch Rayleigh waves. Zinc oxide has been successfully deposited by RF sputtering [27] for various elastic wave devices [28,29] and has been employed to launch Rayleigh waves to demonstrate the surface elasto-optic interaction on  $SiO_2$  [30] and on GaAs [31]. Optimum piezoelectric coupling is obtained by placing the interdigital transducer array between the ZnO and the waveguide with its substrate [32].

The diffraction efficiency of several surface Bragg-type, elasto-optic interactions is depicted in Fig. 8 [33,10] as a function of the

applied power in the elastic form. These experiments indicate the range where linearity occurs. In the range where high diffraction efficiency occurs, a large signal analysis is required which will show a deviation from the true transform. Use of the linear region permits a greater flexibility in the choice of waveguide material because a high photo-elastic constant is not essential. This condition also relaxes the requirement for minimum electrical to elastic conversion efficiency, thus permitting the achievement of a wider band transducer design. One important parameter influencing the spectrum analyzer design and time-bandwidth-product is the elastic wave velocity of the multiple layered structure in the elasto-optic interaction region. Penunuri [34] has calculated the velocity for Rayleigh and Love waves for the thermally-grown  $\text{SiO}_2$  on Si structure as a function of the frequency-overlay-film-thickness product which is depicted in Fig. 9. The thickness film product has units of velocity and for the regime of interest, yields a Rayleigh velocity range of 4.0-4.5 km/sec. Propagation losses of this waveguide-isolation-layer-substrate structure remain to be determined. Excessive losses will alter the aperture weighting function and limit the useful aperture. However, the available data derived from similar delay lines suggests that these losses will not be serious. Wideband elasto-optic interactions have been demonstrated using a multiple array of interdigital transducers stagger-tuned and tilted to satisfy the Bragg condition. An elasto-optic bandwidth of 358 MHz has been demonstrated using diffused waveguide on y-cut  $\text{LiNbO}_3$ . Following the design principle of Tsai [14], we have calculated the expected performance of a four element design

depicted in Fig. 10. The calculated electronic-elastic conversion loss of a four transducer stagger-tuned and tilted array on thermally-grown  $\text{SiO}_2$  with a ZnO overlay is indicated. The material constants used in the calculation were extrapolated from the results of Hickernell [29]. A series inductor for each of the transducers connected in parallel is assumed. If performance equivalent to that depicted in Fig. 8 is achieved, a diffraction efficiency of 4% is estimated with an input electrical power of 100 mW at an optical wavelength of 0.9  $\mu\text{m}$ . This diffraction efficiency is near the upper limit allowed for a spectrum analyzer.

The combination of a thin-film Luneburg lens deposited on a substrate containing an integrated waveguide-detector array is shown in Fig. 11. The lens has  $F = 1.2$  cm and  $D = 1.1$  cm. The waveguide is coupled to the photodetector junction by removing the thermally-grown  $\text{SiO}_2$  isolation layer. Radiation from the waveguide couples to the detectors through the evanescent field using a taper in the  $\text{SiO}_2$  transition region [24]. The photodetectors in the array are isolated by preferentially-etched grooves. In an integrated optical spectrum analyzer it may be desirable to provide a serial readout of the signal power density spectrum contained in the photodetector array to minimize the interconnection problem with a multiplicity of detectors. Serial readout can be easily accomplished by coupling to a charge-coupled device [8].

A coherent source is required as the optical carrier for the spectrum analyzer. A gas laser coupled via a prism or grating coupler is one solution; however, a semiconductor laser directly coupled to the thin-film waveguide is more commensurate with the integrated optical approach. However, its emission must be stable in the lowest order mode and must have

the requisite narrow linewidth. The distributed-feedback (GaAl)As laser appears to fulfill the requirements. The hybrid coupling provides for independent evaluation, optimization and satisfaction of the heat sink requirements for continuous wave operation. The parallel end-butt coupling technique [35] appears to be an effective solution but requires an elaborate alignment. An alternate approach, more amenable, is a traveling evanescent side wall coupler. In such a coupler, a cleaved side wall parallel to the laser stripe axis and perpendicular to the junction exposes the laser field to the optical waveguide. Efficient evanescent wave coupling can then occur where the grating is formed on the thin-film waveguide contact surface [36]. This evanescent field side wall coupler excites the polarization crossed to that of the parallel end-butt technique.

A Fabry-Perot type GaAs electron injection laser has been employed to demonstrate side wall coupling to a  $\text{Ga}_{0.3}\text{Al}_{0.7}\text{As}$  thin-film waveguide epitaxially grown on  $\text{Al}_2\text{O}_3$  substrate. Fig. 12(a) is a macrophotograph of the laser chip mounted between the heat sink and pressed against the waveguide surface, while Fig. 12(b) depicts the infrared emission from the termination of the waveguide and some scattering along the waveguide. This coupling arrangement has the advantage that the laser may be positioned and aligned with respect to the spatial filter and optical axis of the spectrum analyzer configuration shown in Fig. 5.

## V. CONCLUSIONS

From the analysis and experimental results thus far obtained, it is concluded that a wideband, real-time spectrum analyzer is a viable application of the integrated optics technology when based upon the thermally-grown oxide on silicon substrate. Such a spectrum analyzer can function in a time-frequency regime which is not readily available through alternative technologies. Further experimental development is essential to verify this conclusion. Use of silicon provides the potential for integration with associated interface electronics. Use of the integrated optics format for signal spectrum analysis requires the use of a stable laser with narrow linewidth for the optical carrier, which can be best fulfilled by a distributed-feedback (GaAl)As laser.

## ACKNOWLEDGEMENTS

Fruitful technical discussions with Capt. W. J. Miceli, Air Force Avionics Laboratory, are gratefully acknowledged. Most of the experimental results are due to R. L. Davis and J. E. Coker, Electronics Research Division, Rockwell International. The photodetector array in Fig. 11 is due to C. L. Chen, University of Cincinnati, OH.

## REFERENCES

1. J. T. Tippett, D. A. Berkowitz, L. C. Clapp, C. J. Koester and A. Vanderburgh, Editors, Optical and Electro-Optical Information Processing, MIT Press 1965.
2. K. Preston, Jr., Coherent Optical Computers, McGraw-Hill 1972.
3. M. C. Hamilton and D. A. Wille, "Acousto-optic Diffraction in Optical Waveguides," Digest of Technical Papers, Topical Meeting on Integrated Optics, New Orleans, Louisiana, January 21-24, 1974.
4. M. C. Hamilton, D. A. Wille, and W. J. Miceli, "An Integrated Optical RF Spectrum Analyzer," IEEE 1976 Ultrasonic Symposium Proceedings, Annapolis, Maryland.
5. R. W. Broderon, C. R. Hewes, and D. D. Buss, "A 500-State CCD Transversal Filter for Spectral Analysis," IEEE Trans. Electron. Dev., Vol. ED-23, pp 143-151, 1976.
6. J. D. Maines and E. G. S. Paige, "Surface-Acoustic-Wave Devices for Signal Processing Applications," Proc. IEEE, Vol. 64, pp 639-652, 1976.
7. D. B. Anderson, R. L. Davis, J. T. Boyd, and R. R. August, "Comparison of Optical Waveguide Lens Technologies," This issue.
8. J. T. Boyd and C. L. Chen, "Integrated Optical Waveguide and Charge-Coupled Device Image Array," This issue.
9. J. W. Goodman, Introduction to Fourier Optics, McGraw-Hill 1968.
10. E. G. H. Lean, J. M. White, and C. D. W. Wilkinson, "Thin-Film Acousto-optic Devices," Proc. IEEE, Vol. 64, pp 779-788, 1976.
11. E. G. H. Lean, "Interaction of Light and Acoustic Surface Waves," in Progress in Optics, E. Wolf, Ed., Vol. 11, pp 123-166, North Holland, 1973.
12. N. Uchida and N. Niizeki, "Acousto-optic Deflection Materials and Techniques," Proc. IEEE, Vol. 61, pp 1073-1092, 1973.
13. Y. Omachi, "Acousto-optical Light Diffraction in Thin Films," J. Appl. Phys., Vol. 44, pp 3928-3933, 1973.

14. C. S. Tsai, M. A. Alkaider, L. T. Nguyen, and B. Kim, "Wideband Guided-Wave Acousto-optic Bragg Diffraction and Devices Using Multiple Tilted Surface Acoustic Waves," Proc. IEEE, Vol. 64, pp 318-328, 1976.
15. B. Kim and C. S. Tsai, "High-Performance Guided-Wave Acousto-optic Scanning Devices Using Multiple Surface Acoustic Waves," Proc. IEEE, Vol. 64, pp 788-793, 1976.
16. T. G. Giallorenzi and A. F. Milton, "Light Deflection in Multimode Waveguides Using the Acousto-optic Interaction," J. Appl. Phys., Vol. 45, pp 1762-1774, 1974.
17. R. V. Schmidt, "Acousto-optic Interactions Between Guided Optical Waves and Acoustic Surface Wave," IEEE Trans. Son. and Ultrason., Vol. SU-23, pp 22-32, 1976.
18. E. I. Gordon, "A Review of Acousto-optical Deflection and Modulation Devices," Proc. IEEE, Vol. 54, pp 1391-1401, 1966.
19. W. S. C. Chang, "Acousto-optical Deflection in Thin Films," IEEE J. Quant. Electron., Vol. QE-7, pp 167-170, 1971.
20. M. Schwartz and L. Shaw, Signal Processing: Discrete Spectral Analysis, Detection and Estimation, McGraw-Hill, 1975.
21. L. D. Dickson, "Characteristics of a Propagating Gaussian Beam," Appl. Opt., Vol. 9, pp 1854-1861, 1970.
22. J. T. Boyd, "Effect of Scattering on Thin-Film Waveguides and Waveguide Lenses as Applied to Optical Fourier Transform Processing," Appendix A in Technical Report AFAL-TR-76-54, Air Force Avionics Laboratory, 1976, and to be published.
23. C. L. Chen, "Thin Film Optical Waveguide and Integrated Photodetector," MS Thesis, Department of EE, Univ. of Cincinnati, 1975.
24. J. T. Boyd and C. L. Chen, "Integrated Optical Silicon Photodiode Array," Appl. Opt., Vol. 15, pp 1389-1393, 1976.
25. F. Zernike, "Luneburg Lens for Optical Waveguide Use," Optics Commun., Vol. 12, pp 379-381, 1974.

26. S. P. Morgan, "General Solution of the Luneburg Lens Problem," J. Appl. Phys. Vol. 29, pp 1358-1369, 1958.
27. F. S. Hickernell, "Zinc-Oxide Thin-Film Surface-Wave Transducers," Proc. IEEE Vol. 64, pp 631-635, 1976.
28. F. S. Hickernell, "The Acoustic Properties of Oxide Films and Their Application to Acoustic Surface Wave Devices," J. Sol. St. Chem. Vol. 12, pp 225-231, 1975.
29. F. S. Hickernell, "DC Triode Sputtered Zinc Oxide Surface Elastic Wave Transducers," J. Appl. Phys. Vol. 44, pp 1061-1071, 1973.
30. N. Chubachi, J. Kushibiki, and Y. Kikuchi, "Monolithically Integrated Bragg Deflector for an Optical Guided Wave Made of Zinc-Oxide Film," Elec. Lett. Vol. 9, pp 193-194, 1973.
31. K. W. Loh, W. S. C. Chang, W. R. Smith, and T. Grudkowski, "Bragg Coupling Efficiency for Guided Acoustooptic Interaction in GaAs," Appl. Opt. Vol. 15, pp 156-166, 1976.
32. G. S. Kino and R. S. Wagers, "Theory of Interdigital Couplers on Nonpiezoelectric Substrates," J. Appl. Phys. Vol. 44, pp 1480-1488, 1973.
33. D. A. Wille and M. C. Hamilton, "Acousto-Optic Deflection in Ta<sub>2</sub>O<sub>5</sub> Waveguides," Appl. Phys. Lett. Vol. 24, pp 159-161, 1974.
34. D. Penunuri, "Some Theoretical Aspects of Surface Acoustic Wave Propagation," PhD Thesis, Electrical Engineering Department, University of Southern California, 1976.
35. R. G. Hunsperger and A. Lee, "Parallel End-Butt Coupling of GaAs Laser Diode and a Thin-Film Waveguide," Technical Digest of the Topical Meeting on Integrated Optics, Salt Lake City, Utah, 1976.
36. J. T. Boyd and C. S. Kuo, "Composite Prism-Grating Coupler for Coupling Light into High Refractive Index Thin-Film Waveguides," Appl. Opt. Vol. 15, pp 1681-1683, 1976.

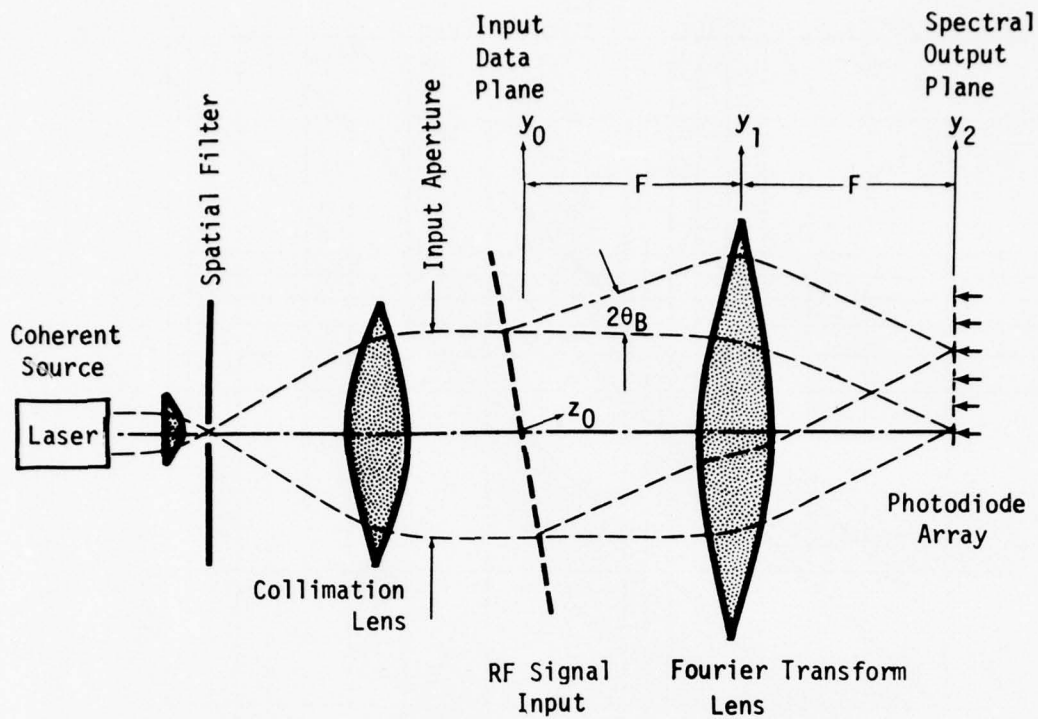


Figure 1A. Coherent Optical Fourier Transform Spectrum Analyzer Schematic

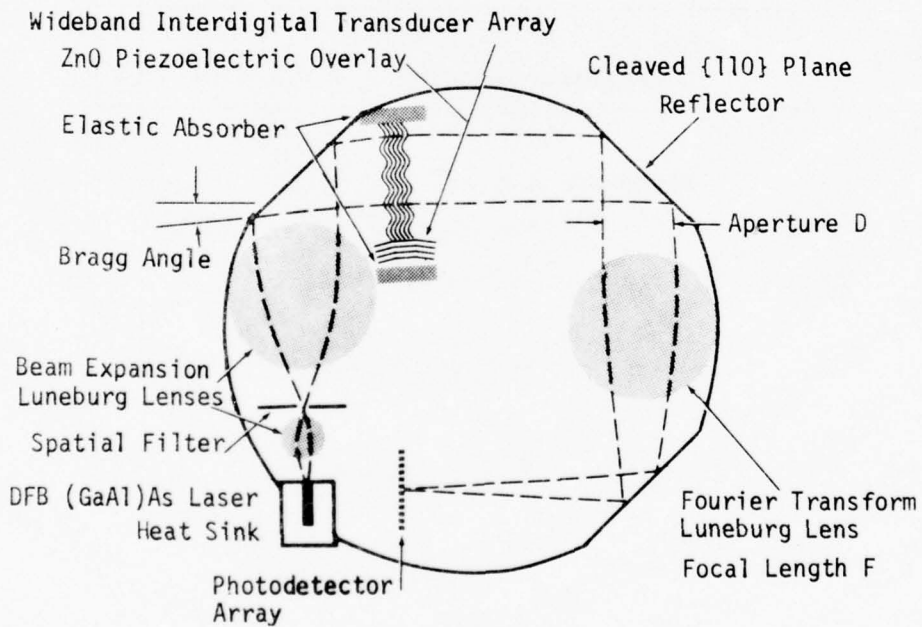


Figure 2A. Integrated Optical Fourier Transform "Chip" Layout for F/D 6 and 7.6 cm Dia. Structure includes Corning 7059 waveguide film on thermally-grown  $\text{SiO}_2$  isolation layer on {100} Si substrate with overlays of  $\text{Ta}_2\text{O}_5$ , ZnO, and Al.

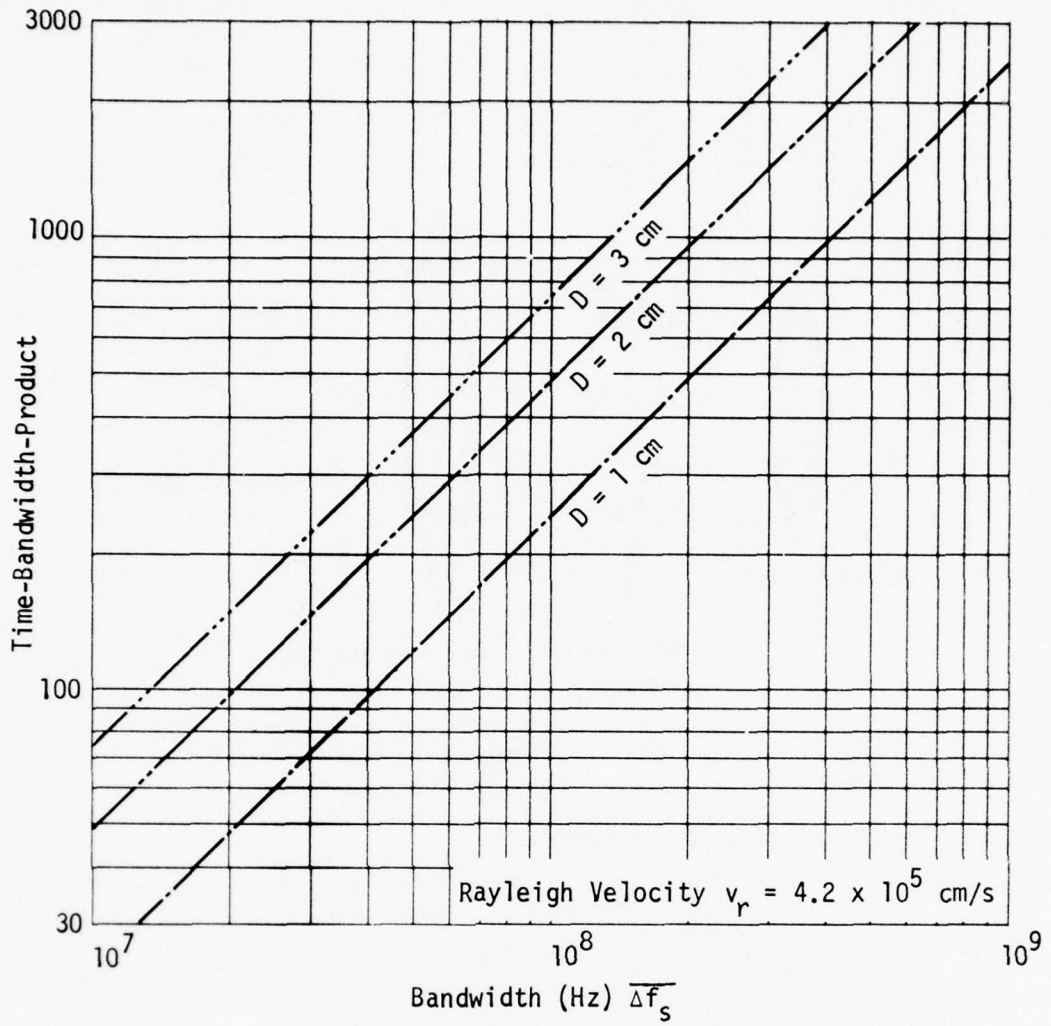


Figure 3A. Spectrum Analyzer Time-Bandwidth-Product.

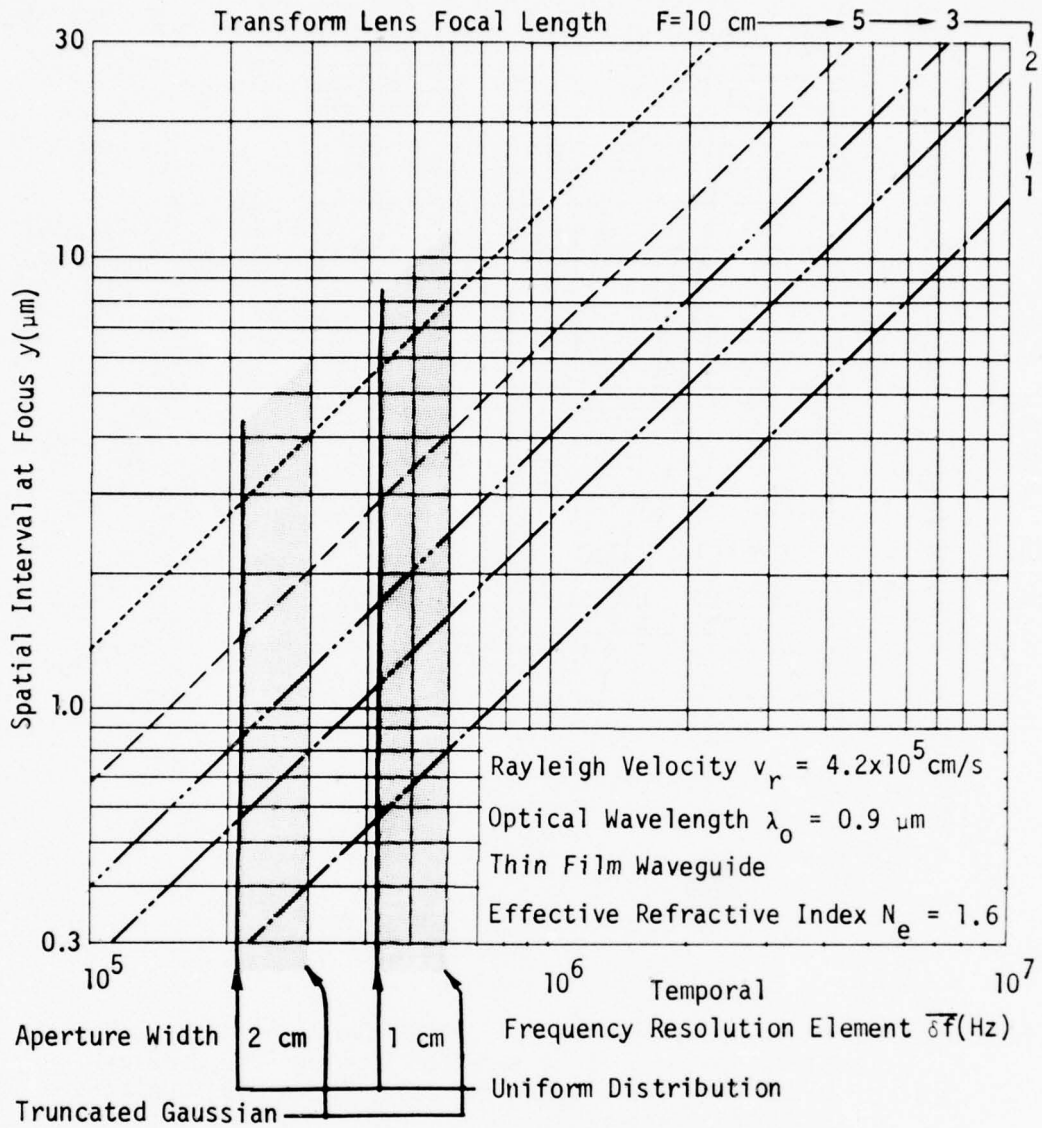


Figure 4A. Optical Fourier Transform Spatial-Temporal Resolution Limited by Either Detector Period or Aperture Diffraction where Aperture Distribution Ranges from Uniform to Truncated Gaussian.

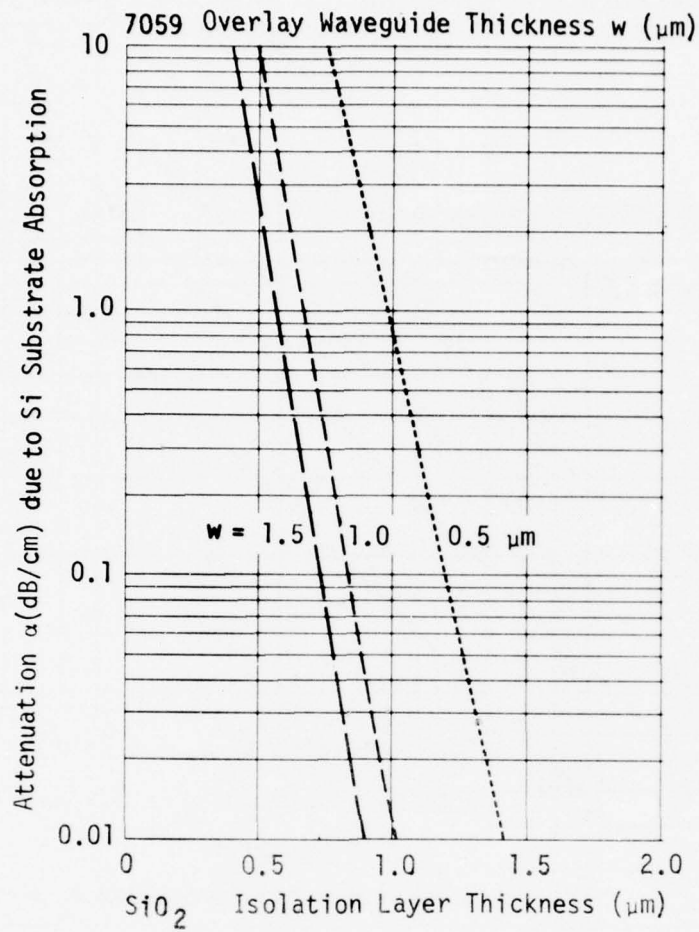


Figure 5A. Thin-Film Waveguide Attenuation due to Evanescent Field Absorption in Si Substrate for Corning 7059 Overlay Waveguide Thickness and Thermally-Grown  $\text{SiO}_2$  Isolation Layer Thickness [23].

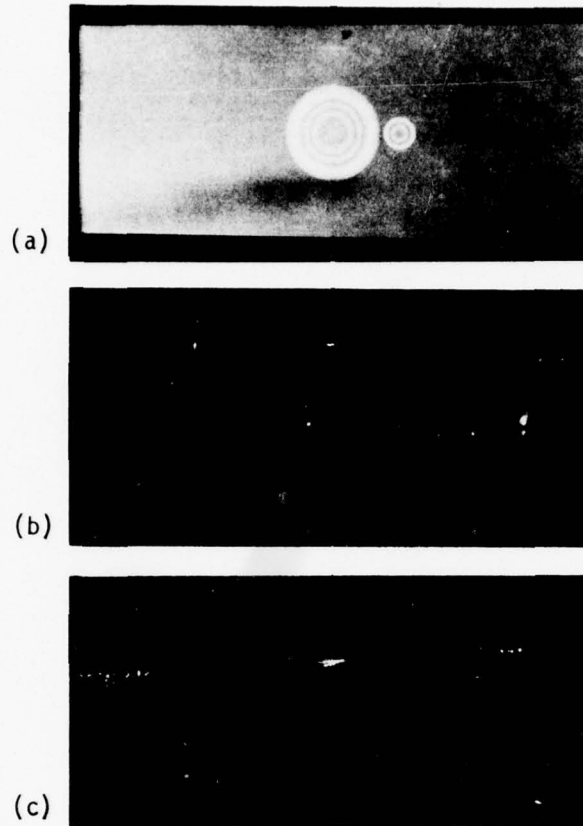


Figure 6A. Thin-Film Luneburg Lenses Using  $Ta_2O_5$  on Corning 7059-on-7440 Glass: (a) plan view of beam expansion system showing Newton rings indicating the radial tapered thickness profile, (b) scattering of ray traces through beam expansion system using 6328 Å radiation, and (c) circumferential ray trace around Luneburg lens.

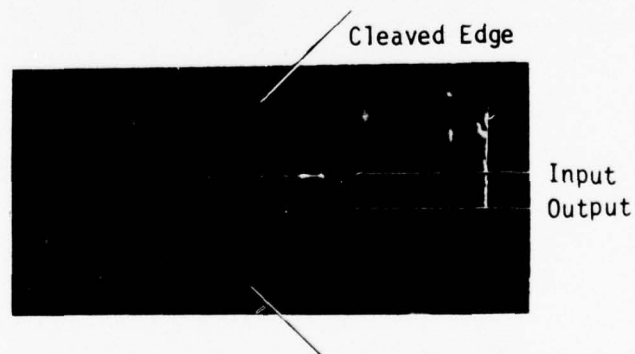


Figure 7A. Cleaved Retroreflector Employing Corning 7059 Waveguide on Thermally-Grown  $SiO_2$ -on-Si.

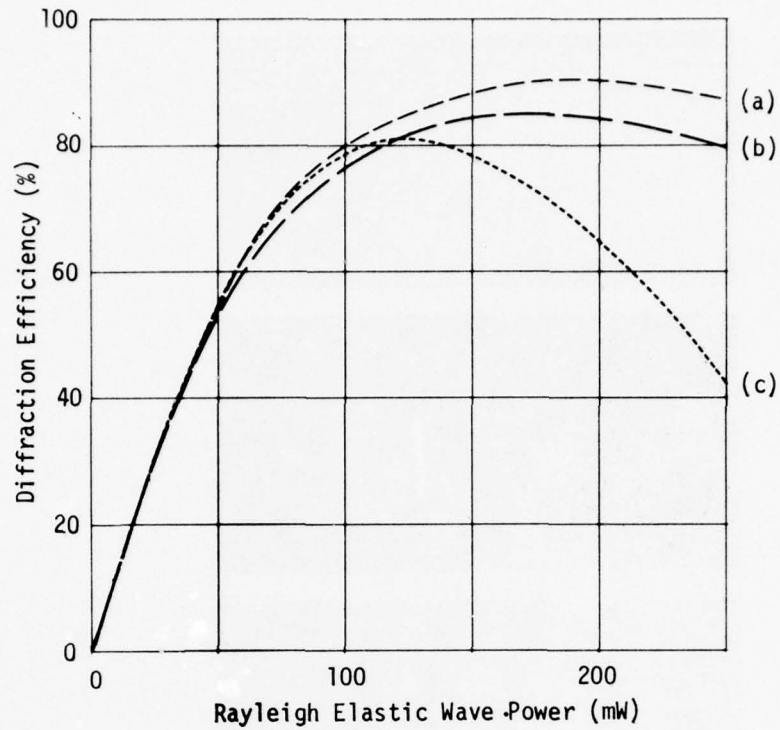


Figure 8A. Surface Elasto-Optic Bragg-Type Diffraction Efficiency for Waveguide Structures: (a)  $Ta_2O_5$ -on-Si [3], (b)  $Nb_2O_5$ -on- $LiNbO_3$ , and (c) Ti or Ni-indiffused- $LiNbO_3$  [10], for TM modes at 290 MHz.

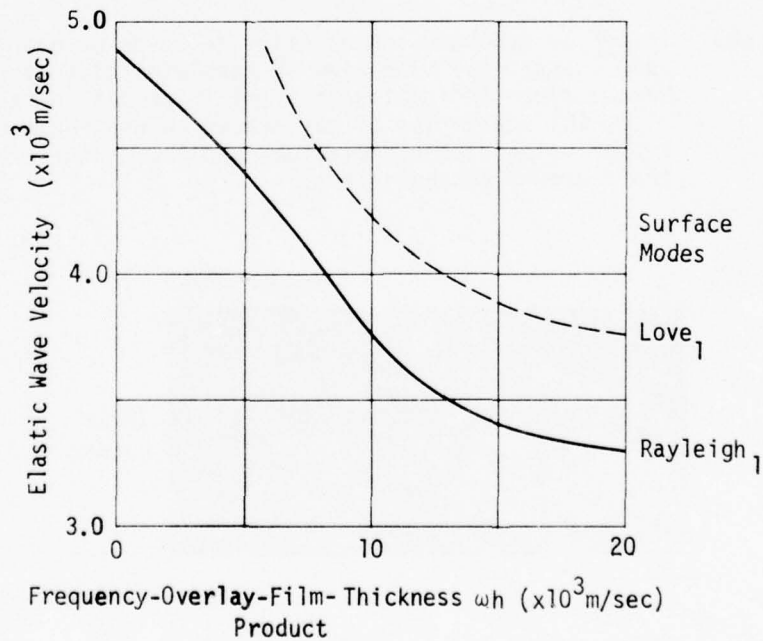


Figure 9A. Calculated Surface Elastic Wave Velocity Dispersion for Thermally-Grown  $SiO_2$  Overlay on Si Substrate (001) Cut, [100] Propagation, [33].

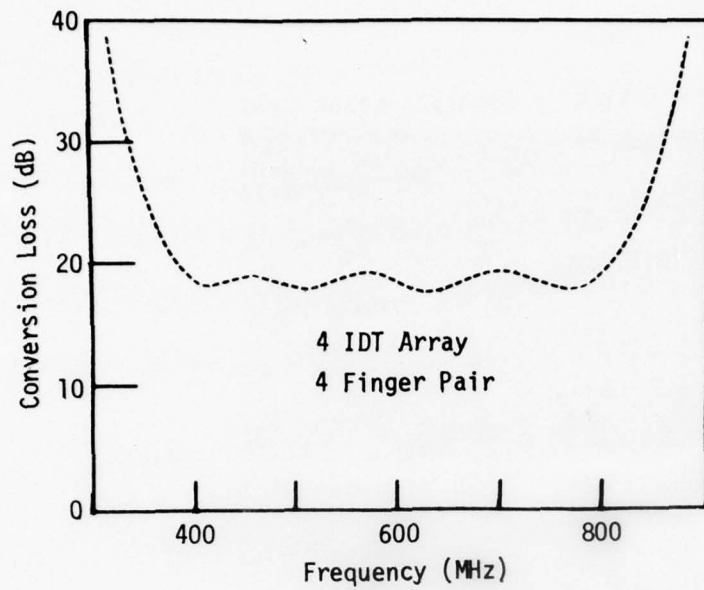
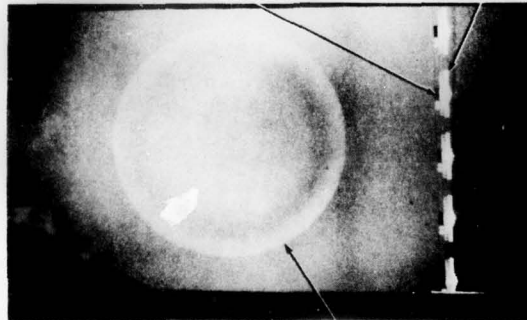


Figure 10A. Calculated Electronic-Elastic Conversion Loss for Two Wide-band, Bragg-Type Interdigital Transducer Arrays after Tsai [14].

Photodetector Array and Lead Fan-Out



Ta<sub>2</sub>O<sub>5</sub> Overlay Luneburg Lens

Figure 11A. A Luneburg Lens Integrated with a Linear Array of Photodetectors Arranged in Groups.

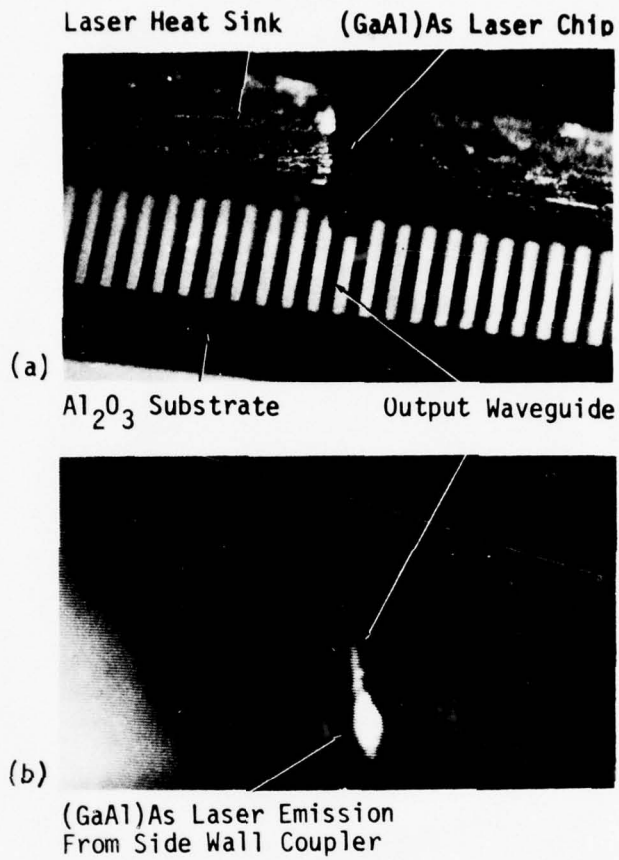


Figure 12A. Hybrid Coupling of (GaAl)As Laser to  $\text{Ga}_{0.3}\text{Al}_{0.7}\text{As}$  Waveguide Via the Laser Fabry-Perot Side Wall Evanescent Field.

## APPENDIX B

### COMPARISON OF OPTICAL WAVEGUIDE LENS TECHNOLOGIES

D. B. Anderson, R. L. Davis, J. T. Boyd,  
and R. R. August

Abstract -- Various materials, lens structures, and processes are examined relative to the lens requirements of an RF spectrum analyzer implemented through the use of an integrated optics format. Factors which distinguish optical waveguide lenses and reflectors from conventional imaging lens systems are enumerated. It is concluded that a thin-film Luneburg lens is the most viable planar approach based upon the use of oxides and, when high refractive index materials must be employed, the spherical depressed geodesic becomes a feasible alternate.

---

Manuscript received . This work is supported by the Air Force Avionics Laboratory under Contracts F33615-75-C-1017 and F33615-76-C-1040.

D. B. Anderson, R. L. Davis, and R. R. August are with the Electronics Research Division, Rockwell International Corporation, Anaheim, CA 92803.

J. T. Boyd, a consultant for Rockwell International, is with the Electrical and Computer Engineering Department of the University of Cincinnati, Cincinnati, OH 45221.

## I. INTRODUCTION

The application of an integrated optics approach to the Fourier transform signal processing function is being developed with the expectation of realizing a wideband, real-time, compact, economical spectrum analyzer as a functional component [1,2]. Coherent optical signal processing [3] requires refractors and reflectors with near diffraction-limited performance which are compatible with planar technology. For compactness and wavelength stability a distributed-feedback electron injection laser is preferred, which dictates the use of the near infrared. Economics, alignment stability, and small size compels the use of a single substrate which requires lenses of comparatively small f-number and reflectors for folding of the optical axis so as to be contained within the available substrate area. An optical spectrum analyzer also includes a photodetector array, a signal input spatial modulator and associated electronics. These elements can best be "integrated" with the optical lenses on a silicon substrate using the thermally-grown oxide for optical waveguide isolation.

The optical waveguide lens bibliography [4-10] is infinitesimal when compared with that of conventional optical lenses and their microwave counterparts. Lenses which conform to an integrated optics format exhibit various different degrees of freedom which are not available to conventional optical lens designers but are similar to waveguide structures exploited in the microwave antenna art [11,12]. Therefore, this paper will delineate the distinguishing differences and will treat materials and process considerations and their relative compatibility with thin-film waveguide lens structures.

## II. OPTICAL WAVEGUIDE LENSES CONSIDERATIONS

For an integrated optical spectrum analyzer, several additional considerations dictate a preference for the near infrared aside from the characteristics of GaAs lasers. The presence of Rayleigh scattering in thin-film optical waveguides and lenses directly limits the Fourier transform dynamic range. The effective refractive index of optical waveguides is in part controlled by the waveguide thin-film thickness. Rayleigh scattering is reduced and waveguide tolerances are relaxed by use of the longer wavelength red.

In the near infrared, a wide variety of waveguide material-structures have been demonstrated which exhibit comparatively low loss [13,14]. They include: (1) large band-gap III-V and II-VI semiconductors which exhibit large refractive indices; (2) a family of oxides of intermediate refractive index; (3) a family of glasses of lower refractive index; and (4) a family of organics having a refractive index slightly greater than glass substrates. Various techniques to prepare thin-film waveguides include: (1) homo- and hetero-epitaxy, (2) RF-DC sputtering, (3) evaporation, (4) ion in- or out-diffusion, (5) ion exchange, (6) ion implantation, and (7) nuclear bombardment. The first three of these processes can lead to relatively large, sharp refractive index discontinuities at the waveguide substrate interface as determined by material composition, while the latter processes result in relatively weak or diffused discontinuities at the interface.

The losses exhibited by thin-film waveguides in the red and near infrared are largely due either to the absorption "tail" of the electron band-gap or to the scattering from inhomogeneous depositions and surface roughness. In most oxide thin films, the latter is currently the dominant loss.

The method of thin-film deposition, the state of the substrate, its temperature, and the stoichiometry of the deposition have a dramatic control of the losses. The substrate surface roughness is of equal importance. For most of the thin-film lenses and waveguides reported herein,  $Ta_2O_5$  [15] is employed as an overlay or underlayer film for lenses, and Corning 7059 glass [16] is employed as the planar ambient dielectric waveguide. A variety of glasses and substrate polishing techniques have been investigated with the conclusion that thermally-grown  $SiO_2$  on Si yields the smoothest low-scattering substrate surface. Other surface preparation techniques investigated include rouge, super (wet), fire, and the chemo-mechanical process [14].

An additional scattering loss occurs in waveguides bounded in both transverse dimensions, or in reflectors with one transverse dimension, or at a waveguide-lens boundary, due to the edge roughness. This edge roughness arises from the lithographic mask and the method of etch, such as preferential chemical or ion etch. The most satisfactory means to define a waveguide-lens interface employs a graded gaseous diffusion around a lens mask during deposition. The waveguide thickness is thus tapered, however, care is required to prevent coupling into the substrate [5,17,18] or into higher order modes.

The optical waveguide material-structure selection is conditioned by the requirements for wave binding to a guide ( $n_{\text{waveguide}} > n_{\text{substrate}}$ ) and for minimization of losses. The optical power (convergence and divergence) of a lens system is, in part, determined by the refractive index differences employed between the lens and the refractive index in which the system is embedded. A lens system design, in general, requires the use of the largest practical range of refractive indices to minimize length. The use of materials where

the thin-film waveguide effective refractive index is only slightly greater than the substrate severely limits the numerical aperture. It is possible to circumvent this condition by the use of geodesic lenses which employ a nonplanar contour to control the lens optical thickness.

Conventional optical refractors employ two dimensions with spheric, aspheric, and cylindric surfaces and are usually immersed in free space having a refractive index of unity. The total range of refractive indices of materials in the red and near infrared extends between 1.3 and 3.6 whereas the more typical values are between 1.4 and 1.8. Positive lens elements are produced by convex surfaces and negative lenses are produced by concave surfaces. On the other hand, optical waveguide lens elements are always immersed in another dielectric which may have an effective refractive index greater than or less than the optical element (except geodesic). The maximum/minimum ratios of refractive indices for waveguide lens elements extend from approximately 2.5 to 0.4 whereas the typical range is contained within the ratio 1.4 to 0.7. Because the refractive index ratio may be less than unity, it is also possible to create positive waveguide lens elements using convex interfaces and negative waveguide lenses with concave interfaces.

Because the effective refractive index is also related to the film thickness, it is possible to create inhomogeneous refractors using homogeneous materials [4]. Thin-film waveguide refractors may be formed by (1) the insertion of another dielectric in the lens region, (2) the addition of another higher index film as either an overlay or underlay of the waveguide in the lens region, or (3) as changes of waveguide thickness. Changes of

the waveguide effective refractive index can be implemented as a partial undercut in the lens region or an overlay exterior to the lens region forming a part of the waveguide, or an undercut of the waveguide film external to the lens. Except for the materials and film thicknesses, each of these processes is distinguished by the order of deposition and/or ion etch through waveguide-lens masks. The wavelength dependence on thickness introduces a chromatic aberration which is greater than that inherent in the bulk material. When the waveguide thickness is sufficient to support additional modes, and when the waveguide-lens interfaces introduce mode conversion, the properties of a lens system will be multi-valued.

An example of homogeneous refractors used to form a non-inverting telephoto lens system is illustrated in the photograph collage of Fig. 1. The plan view of the negative element showing the thickness profile via Newton rings is depicted in Fig. 1(a). Both the positive and negative refractors employ  $Ta_2O_5$  as an overlay on the Corning 7059 waveguide. Individual rays and wide-beam transmission of  $6328 \text{ \AA}$  radiation through the lens system is evident in Sections (b) and (c), respectively. The telephoto ratio is 1/2 and a 1 cm aperture has been employed. Visibility of this propagation from the side is indicative of excessive Mie scattering. Further, the waveguide-lens interface scattering is also clearly evident and, thus, this lens system performance is not acceptable for use in the optical spectrum analyzer.

### III. PLANAR LUNEBURG LENS

The inhomogeneous planar circular refractor, due to Luneburg [19], has been investigated as an alternative. Interest in the Luneburg lens [11,12,19,20] arises because it is free of all aberrations except curvature of field and because of the simplicity of its fabrication as a thin-film

waveguide structure [6]. Fig. 2(a) illustrates the cross-section of a planar waveguide Luneburg lens with a higher index underlayer between the uniform thin-film waveguide and the substrate. The ray trajectory through the lens is depicted in Fig. 2(b). A Luneburg lens is a circular symmetric refractive structure which will form perfect geometric images of two given concentric circles on each other [20]. If one of the circles is of infinite radius, the lens will focus a collimated beam from any direction exactly to a point on the opposite focal edge. The lens is circular symmetric providing a  $2\pi$  field of view and employs a radial refractive index profile. This circular symmetric feature is of particular interest in integrated optics where the substrate area is limited because folding of the optical axis may use the lens for several purposes. The waveguide Luneburg lens has a further advantage, that all refractive index variations are continuous, smooth and slow functions with respect to the optical wavelength. Scattering and mode conversion are, therefore, less than in other type waveguide lenses.

Classical Luneburg lenses focus on the opposite edge yielding an f-number of 0.5, which is inconvenient for an integrated optical spectrum analyzer [2] because of the high resolution lithography required to resolve and detect radiation in the focal region. A generalized Luneburg lens having a focal point beyond the lens edge for a plane wave input, overcomes the above disadvantage of the classical Luneburg lens. The geometry for this generalized lens is illustrated in Fig. 2(b).

By following a procedure based on Fermat's principle and similar to that used by Brown [12] in deriving the index profile corresponding to the classical Luneburg lens, we have determined the constraint on index variation

$n(r)$  required to focus a beam of parallel rays at a point a distance  $r_1$  from the center of the circular lens region to be

$$n(r,m) = n_e(m) \exp \frac{\sqrt{n_e(m)^2 r_0^2 - r^2 n^2(r)}}{\pi n_e(m) r_1} \quad (1)$$

In the above equation,  $r$  is the radial coordinate from the lens center along the waveguide surface,  $r_0$  is the radius of the lens region, and  $n_e(m)$  is the effective refractive index for the waveguide mode ( $m$ ) of interest. Note that the above equation is not solved for  $n(r,m)$ , but  $n(r,m)$  is readily determined from Eq. (1) numerically as a function of  $r_1$ . The derivation of the constraint on the refractive index profile (1) involves an approximation which is reasonable for  $F/D = F/2r_0 > 1.3$ . Fig. 3 depicts the normalized effective refractive index profile as a function of the normalized lens radius for several f-numbers. It indicates that the transverse profile becomes more uniform having a lower refractive index over a larger central region of the lens as the focal length is increased.

Fig. 4 depicts the minimum required effective refractive index at the center of the Luneburg lens relative to its waveguide ambient refractive index as the lens focal length is increased. For the classic Luneburg lens  $n(0,0) = \sqrt{2}$ , a high index layer like  $Ta_2O_5$  or  $Nb_2O_5$  on 7059 [6] is required for  $F/D = 0.5$ . Luneburg lenses have been realized using an "all" 7059 thin film when  $F/D \gtrsim 6$ . The photographic collage of Fig. 5 illustrates a Luneburg lens refractive index profile via Newton rings (a) and the operation of a lens via the scattered rays (b,c), and when illuminated by a 1 cm wide beam (d). The photographs of Fig. 5 (b and c) include reflections from the substrate back surface in the region of the Luneburg lens. The structure employed consists of  $Ta_2O_5$  (2.2) lens overlay on 7059 (1.59) waveguide on a

7440 substrate. The lens,  $f$ -number=1.5, is obtained by use of a conical hole in a thick mask similar to that used by Zernike [6]. This cone base diameter is 1.14 cm, the cone half angle is  $15^\circ$ , and the mask thickness is 2.54 mm. Scattered radiation in Fig. 5 is a substantial reduction of that appearing in Fig. 1.

A comparison of Luneburg lens profiles is illustrated in Fig. 6 as a function of the normalized radius. The experimentally determined lens thickness using the Newton rings and by Tally-Surf is shown in Fig. 6 as a solid line (a). The curve marked (b) shows the calculated refractive index profile for ideal Luneburg lens. Curve (c) is the calculated refractive index profile using the experimentally determined thickness profile where the waveguide thickness is  $0.6 \mu\text{m}$ . It is obvious that the measured and calculated profiles are reasonably matched in the center region with a substantial deviation around the outer annulus. The transmission of individual rays through the Luneburg lens of Fig. 5(a) and profiles of Fig. 6 is shown in Fig. 5(b) and (d) when the lens has been stopped down to an  $f$ -number of 2. When the aperture is increased to an  $f$ -number of 1.6, aberrations appear at the focus in Fig. 6(c) which correspond to the exterior rays traversing the outer edge of the lens where the experimentally determined refractive index profile does not adequately match the required ideal profile. Reshaping of the mask to form the lens is required to more closely approach the ideal profile for the larger numerical aperture.

#### IV. GEODESIC LENS

All the lenses considered thus far have employed a change of effective refractive index by altering the thin-film composition and thickness to alter the wavefront in the guide, whereas, it is also possible to employ curved surface topology which alters the propagation length because rays

will propagate along geodesics of the surface according to Fermat's principle. Geodesic lenses are of particular interest when the waveguide refractive index is slightly greater than the substrate as occurs for in- and out-diffused  $\text{LiNbO}_3$  [21], ion exchange in glass [22], and for  $(\text{GaAl})\text{As}$  heteroepitaxial structures.

Nonplanar surfaces are usually not considered to conform to integrated optical format; however, simple spherical depressions in the substrate are easily fabricated by the ophthalmic optical industry for bifocals. These structures are considered herein because they provide the means to realize an effective refractive index beyond that available from useful materials.

Righini, et al, [7] and Toraldo di Francia [23] have fabricated a variety of geodesic lenses drawing from earlier work on microwave scanning antennas. Spiller and Harper [8] have pointed out that the aberrations of the spherical depression geodesic lens are opposite in sign to those of the refractive lens, and thus may be combined for its suppression. Verber, et al, [9] using ion exchange glass waveguide, have demonstrated uncorrected geodesic lenses. Rinehart [24] has considered a nonspherical surface of revolution as a means to achieve the Luneburg lens in the microwave regime, while Wood and Vahey [10] have considered oblate spheroids. It should be noted that the spherical depression geodesic lens is also functional for surface elastic waves exhibiting identical geometric properties [25]. The cross section of a spheric depressed geodesic lens is illustrated in Fig. 7 with the ray trace through the plan view. The paraxial focal length of a spheric geodesic lens [25] is given by

$$F = \frac{R_c}{2(1 - \cos \theta)} \quad (2)$$

where  $R_c$  is the radius of the depressed surface at the intersection with the plane and  $\theta$  is the half-angle of the chord. The geodesic lens f-number as a function of the angular sector of the spherical depression (2) is depicted in Fig. 8.

Several problems are associated with the geodesic lens. First, care is required to fabricate a sharp edge without chipping which creates wide-angle scattering at the intersection of the plane and sphere. This edge must be rounded to minimize scattering, radiation loss at the transition, and mode conversion. A method is required to uniformly produce a small radius reproducibly. Once the substrate is suitably prepared, a thin film must be formed on the surface to act as a waveguide, the thickness of which must be uniform over all surfaces to avoid unwanted refraction. Waveguides formed by diffusive processes satisfy this requirement [9]. For the large polar angles needed to achieve fast lenses, deposition of uniform film thickness over all the curved surfaces is difficult. It is possible to deposit a radially symmetric film to correct spherical aberration [8].

The performance of a quasi-Rinehart-Luneburg geodesic lens (non-spherical) is illustrated in Fig. 9 for the near tangential ray. A reflection from the substrate back surface of this ray is also evident. The concave geodesic lens (chord diameter 3.8 mm) employed a Corning 7059 thin-film RF-sputtered deposit on the 7440 substrate. A "super" polished finish was employed for both the planar and spherical surfaces. Rays traversing the planar substrate exhibit scattering loss of approximately 1 dB/cm, whereas, in the region of the transition and depression, considerably more loss occurs. Another problem with geodesic lens fabrication is the accurate control of the chord diameter and the accurate placement of the lens with respect to other optical elements, such as required for beam expansion.

## V. EXPERIMENTAL WAVEGUIDE LENS DIFFRACTION PATTERNS

The performance of optical waveguide lenses as determined by measurement of the diffraction pattern is encumbered by the ambient waveguide film and the intervening coupling to the free space diffracted beam. The technique we have employed utilizes wide aperture prism input and output couplers with the waveguide lens to be evaluated located between the couplers. Re-imaging with magnification is employed in the output beam with a fiber-coupled detector for scanning of the output intensity distribution. No correction for spherical aberration of the prism employed at the lens focus couplers has been introduced.

The diffraction patterns of a thin-film waveguide Luneburg lens (a) and an uncorrected spherical depression geodesic lens (b) are illustrated in Fig. 10 using a logarithmic intensity scale and a linear transverse scale reduced by the re-imaging magnification. The Luneburg lens employed  $\text{Ta}_2\text{O}_5$  on a barium-rich RF-sputtered 7059 waveguide on a 7059 substrate. The lens diameter is 11.2 mm and the focal length is 12 mm. The input beam was collimated and aperture-limited to produce a uniform distribution with a 5 mm beamwidth. The resulting diffraction pattern in Fig. 10(a) exhibits a comparatively well-formed sinc x function. The measured beamwidth referred to the focus is 5  $\mu\text{m}$  at the 3 dB point. The first sidelobe level should be 13 dB down, whereas, the observed sidelobes are approximately 10 dB down. The presence of nearly-symmetrical sidelobes elevated by 3 dB with reasonably defined nulls between the sidelobes is indicative of a quadratic phase error of approximately  $\pi/2$  at the edge of aperture. The symmetry and null depth suggests the absence of a cubic phase error. The lack of a systematic sidelobe decay on the left-hand side of the diffraction pattern is attributed to

a visible scatterer. The quadratic phase error (spherical aberration) could arise from the input coupling prism, or output coupling prism surface or contact figure, or the lack of correction for the prism thickness in the focal region or in the re-imaging system. The recorded data of Fig. 10 is the convolution of the optical waveguide lens, re-imaging lens and intervening coupling prisms. Detailed analysis to identify the major phase-front error contributor remains.

The performance of an uncorrected spherical depression geodesic lens using an RF-sputtered 7059 waveguide on a 7440 substrate is illustrated in Fig. 10(b). The lens diameter is 14.4 mm and its focal length is 28 mm. A Gaussian beam without truncation was employed for the input where its width was 2 mm at the  $1/e^2$  point. The measured output beamwidth at the lens focus is 11  $\mu\text{m}$  at the -8.6 dB point. This diffraction pattern is not well-ordered, that is, the sidelobes are not regular and do not exhibit a systematic decay which indicates that aberrations are dominant, which is to be expected because the lens is spherical and has not been corrected.

The presence of appreciable energy in the sidelobes and their slow decay to a residual level due to scattering becomes a serious compromise for an integrated optical spectrum analyzer, affecting both resolution and dynamic range. These diffraction results and the experience developed during an effort to reduce scattering has led to the use of a more promising waveguide material-structure. This structure employs Corning 7059 waveguide and  $\text{Ta}_2\text{O}_5$  as an underlayer lens, all deposited on a thermally-grown  $\text{SiO}_2$  isolation layer on an Si substrate. The thermally-grown  $\text{SiO}_2$  isolation layer with sufficient thickness ( $\sim 1 \leq 2 \mu\text{m}$ ) should approach the characteristics of low loss fibers because the material evolves from the same process, however, an excessive film growth or use of other processes yields an imperfect surface

giving rise to excessive scattering. Further, the use of 7059 over the  $Ta_2O_5$  suppresses the scattering of  $Ta_2O_5$  in the thin sections at the transition into the lens. As with the processing for low loss fibers, extreme purity and cleanliness is required during the processing. One problem not yet addressed is the requirement for a superstrate to isolate the integrated optical circuit from its external environment - presumably, an organic deposited from solution will evolve. The measured diffraction patterns depicted in Fig. 10 show that considerable effort remains to achieve near diffraction-limited operation, as required for an integrated optical spectrum analyzer [2]. A more accurate match of the Luneburg lens thickness profile to the required effective refractive index profile remains to be developed by shaping of the mask, the ion source and the deposition conditions.

The measured transverse distribution of propagation of a Gaussian beam is illustrated in Fig. 11 for an ultra-low loss 5 cm section of Corning 7059 waveguide RF-sputtered upon thermally grown  $SiO_2$  on Si. The beam profile, prior to entry into the input coupling prism, is illustrated in Fig. 11(a) without use of a re-imaging system. The beam profile, after traversing the waveguide and prism couplers, is depicted in Fig. 11(b). With exception of the recorded noise, this diffraction pattern is a reasonable facsimile of the input beam profile. It shows that the spurious responses are more than 25 dB down.

## VI. REFLECTORS

Another important consideration in the design of thin-film waveguide optical systems is the requirement for straight and curved reflectors. They must function efficiently and not give rise to scattering or radiation loss. A straight-line, tapered edge provides one effective solution for reflectors;

however, it is restricted to the angular range of total internal reflection. The minimum critical angle of incidence is

$$\alpha_{c \text{ min}} = \sin^{-1} \frac{n_s}{n_w} \quad (3)$$

where  $n_s$  is the refractive index of the substrate and  $n_w$  is the refractive index of the waveguide material. For waveguides having refractive index slightly greater than the substrate, this tapered edge approach restricts its use to near-grazing incidence. Again, care must be exercised to avoid the tapered edge acting as a coupler into the substrate [17,18].

An alternative approach employed successfully depends upon the use of thermally-grown  $\text{SiO}_2$  on Si as a single crystal substrate. It is possible to reproducibly cleave through the substrate, isolation layer and waveguide thin-film producing crystallographically perfect facets on the  $\{110\}$  face. When the silicon is oriented so that the waveguide plane is orthogonal to the cleaved plane, Eq. 3 may be used where  $n_s=1$  which leads to a much wider range of total internal reflection. The cleaved surface may be metallized permitting efficient reflection at normal incidence. The operation of a metallized cleaved reflector is illustrated in Fig. 12 using 7059 waveguide on thermally-grown  $\text{SiO}_2$  on Si as a substrate. The reflection loss is insignificant. The difference of ray trace intensity is due to less scattering. Observed losses in this waveguide on thermally-grown  $\text{SiO}_2$  on Si approached 0.1 dB/cm.

Curved reflectors cannot be produced by cleavage. Attempts at polishing to produce curved orthogonal edges consistently led to microscopic chips and wide-angle scatter. Large curvature reflectors formed by rounding of the substrate edge to fold the optical path from one side of the substrate to another, can be employed as a step toward confection systems [19]. Because tapered

edges are restricted to near-grazing incidence, curved reflectors must follow design procedure for deep conics [26].

#### VII. CONCLUSIONS

A variety of thin-film waveguide optical elements have been investigated with expectation that they may be employed in a Fourier transform signal processing function. Near diffraction-limited performance is required of these refractors and reflectors. It is concluded that a thin-film Luneburg lens is the most viable planar approach based upon the use of oxides, and when high-refractive index substrate materials must be employed the spherical depressed geodesic becomes a feasible alternative.

One problem identified is the presence of Rayleigh and Mie scattering which limits the dynamic range of the Fourier transform. Currently, thermally-grown  $\text{SiO}_2$  on Si yields the smoothest low-scattering isolation layer and substrate for deposition of waveguides, lenses, and cleaved reflectors, useful in the near infrared.

#### ACKNOWLEDGEMENT

Stimulating, provocative discussions with Capt. W. J. Miceli and Mr. M. C. Hamilton, Air Force Avionics Laboratory, are gratefully acknowledged.

Sincere appreciation is expressed here to Mr. J. E. Coker for various thin-film depositions and lithographic processes, and to Mr. D. C. Stafford for various types of optical polishing, both of the Electronics Research Division of Rockwell International.

AD-A044 207

ROCKWELL INTERNATIONAL ANAHEIM CALIF ELECTRONICS OPE--ETC F/6 20/6  
OPTICAL WAVEGUIDE LENSES, II.(U)

JUN 77 D B ANDERSON, R L DAVIS, J T BOYD

F33615-76-C-1040

UNCLASSIFIED

C76-1187.13/501

AFAL-TR-77-60

NL

3 OF 3  
AD  
A044207



END  
DATE  
FILMED  
10-77  
DDC

## REFERENCES

1. M. C. Hamilton, D. A. Wille, and W. J. Miceli, "An Integrated Optical RF Spectrum Analyzer," IEEE 1976 Ultrasonic Symposium Proceedings, Annapolis, Maryland.
2. D. B. Anderson, J. T. Boyd, M. C. Hamilton, "An Integrated Optical Approach to the Fourier Transform," this issue.
3. K. Preston, Jr., Coherent Optical Computers, McGraw-Hill 1972.
4. R. Shubert and J. H. Harris, "Optical Guided-Wave Focusing and Diffraction," J. Opt. Soc. Am., Vol. 61, pp 154-161, 1971.
5. R. Ulrich and R. J. Martin, "Geometrical Optics in Thin Film Light Guides," Appl. Opt., Vol. 10, pp 2077-2085, 1971.
6. F. Zernike, "Luneburg Lens for Optical Waveguide Use," Opt. Communications, Vol. 12, pp 379-381, 1974.
7. G. C. Righini, V. Russo, S. Sottini, and G. Toraldo di Francia, "Geodesic Lenses for Guided Optical Waves," Appl. Opt., Vol. 12, pp 1477-1481, 1973.
8. E. Spiller and J. S. Harper, "High Resolution Lenses for Optical Waveguides," Appl. Opt., Vol. 13, pp 2105-2108, 1974.
9. C. M. Verber, D. W. Vahey, and V. E. Wood, "Focal Properties of Geodesic Waveguide Lenses," Appl. Phys. Lett., Vol. 28, pp 514-516, 1976.
10. V. E. Wood and D. W. Vahey, "Aspherical Axially Symmetric Geodesic Lenses for Integrated Optics," 1976 Annual Meeting of the Optical Society of America, Tucson, Arizona.
11. R. C. Johnson, "Optical Scanners," R. C. Hansen, Editor, Microwave Scanning Antennas, Vol. 1, pp 213-261, Academic Press 1964.
12. J. Brown, "Lens Antennas," R. E. Collin and F. J. Zucker, Editors, Antenna Theory Part 2, pp 104-150, McGraw-Hill 1969.

13. W. S. C. Chang, M. W. Muller and F. J. Rosenbaum, "Integrated Optics," M. Ross, Editor, Laser Applications, Vol. 2, Academic Press, 1974.
14. T. Tamir, Editor, Integrated Optics, Springer-Verlag, 1975.
15. D. H. Hensler, J. D. Cuthbert, R. J. Martin, and P. K. Tien, "Optical Propagation in Sheet and Pattern Generated Films of  $Ta_2O_5$ ," Appl. Opt., Vol. 10, pp 1037-1042, 1971.
16. J. E. Goell, "Barium Silicate Films for Integrated Optical Circuits," Appl. Opt., Vol. 12, pp 737-742, 1973.
17. P. K. Tien, R. J. Martin, and G. Smolinsky, "Formation of Light-Guiding Interconnections in an Integrated Optical Circuit by Composite Tapered-Film Coupling," Appl. Opt., Vol. 12, pp 1909-1916, 1973.
18. P. K. Tien, G. Smolinsky, and R. J. Martin, "Radiation Fields of a Tapered Film and a Novel Film-to-Fiber Coupler," IEEE Trans., Microwave Theory Tech., Vol. MTT-23, pp 79-85, 1975.
19. R. K. Luneburg, Mathematical Theory of Optics, University of California Press, 1974, Reprint of mimeographed notes, Brown University Press, 1944.
20. S. P. Morgan, "General Solution of the Luneburg Lens Problem," J. Appl. Phys., Vol. 29, pp 1358-1369, 1958.
21. I. P. Kaminow and J. R. Carruthers, "Optical Waveguiding Layers in  $LiNbO_3$  and  $LiTaO_3$ ," Appl. Phys. Lett., Vol. 22, pp 326, 1973.
22. T. G. Giallorenzi, E. J. West, R. Kirk, R. Ginther, and R. A. Andrews, "Optical Waveguides Formed by Thermal Migration of Ions in Glass," Appl. Opt., Vol. 12, pp 1240, 1973.
23. G. Toraldo di Francia, "A Family of Perfect Configuration Lenses of Revolution," Opt. Acta, Vol. 1, pp 157-163, 1955.
24. R. F. Rinehart, "A Solution of the Rapid Scanning Problem for Radar Antennae," J. Appl. Phys., Vol. 19, pp 860-862, 1948.
25. T. Van Duzer, "Lenses and Graded Films for Focusing and Guiding Acoustic Surface Waves," Proc. IEEE, Vol. 58, pp 1230-1237, 1970.
26. H. P. Brueggemann, "Deep Conic Cassegrains," Chapter VIII, Conic Mirrors, Focal Press Limited, 1968.

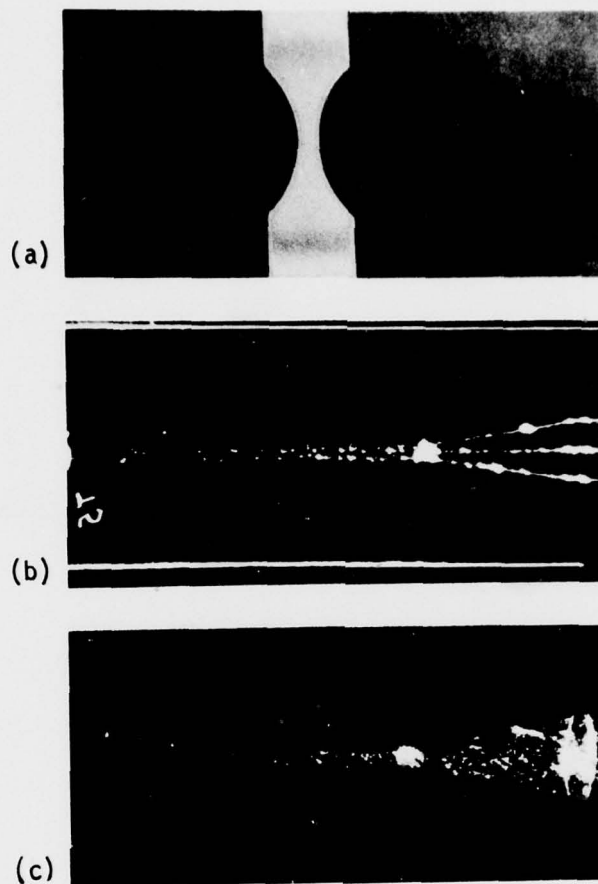


Figure 1B. Homogeneous Thin-Film Waveguide Refractors Using  $Ta_2O_5$  on Corning 7059 on 7440 Glass: (a) a plan view of negative refractors showing Newton rings indicating tapered edges, (b) scattering of ray traces through telephoto lens system using  $6328 \text{ \AA}$  radiation, and (c) same as (b) except using 1 cm wide input beam.

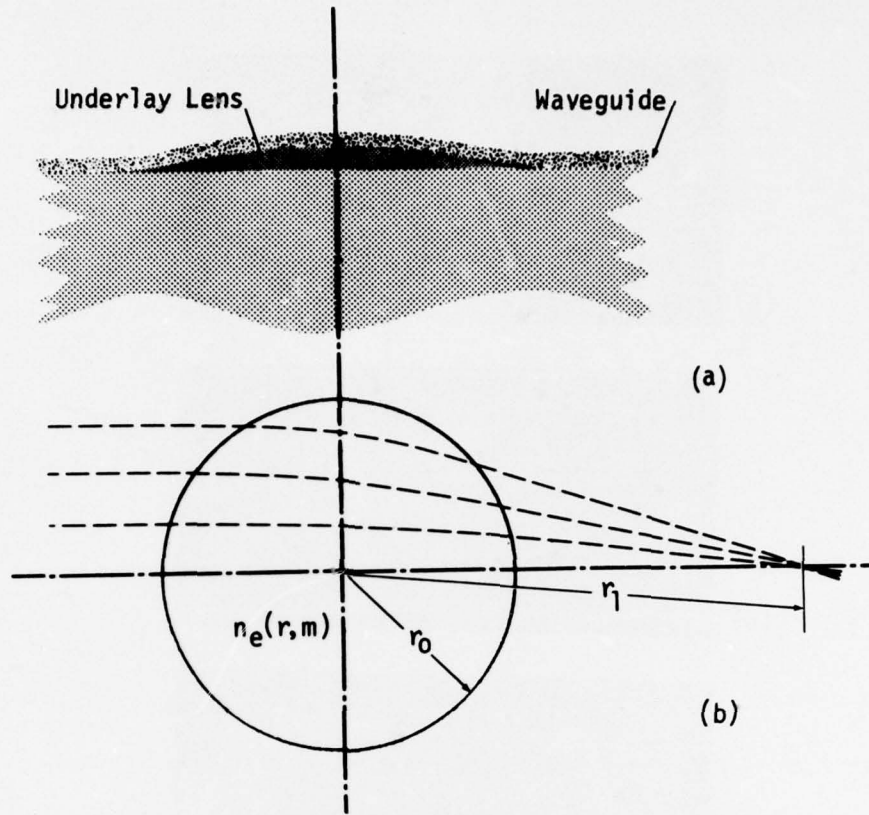


Figure 2B. Thin-Film Waveguide Luneburg Lens: (a) cross-section using high index underlayer with continuous waveguide, and (b) ray traces through generalized Luneburg lens.

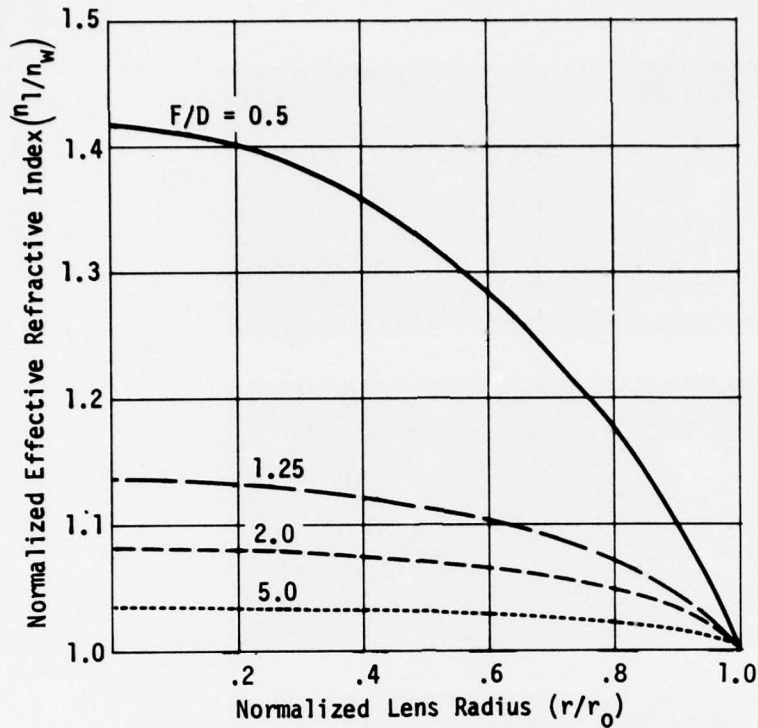


Figure 3B. Normalized Radial Effective Refractive Index Profile as a Ratio ( $n_{lens}/n_{waveguide}$ ) for Several Values of f-number (F/D).

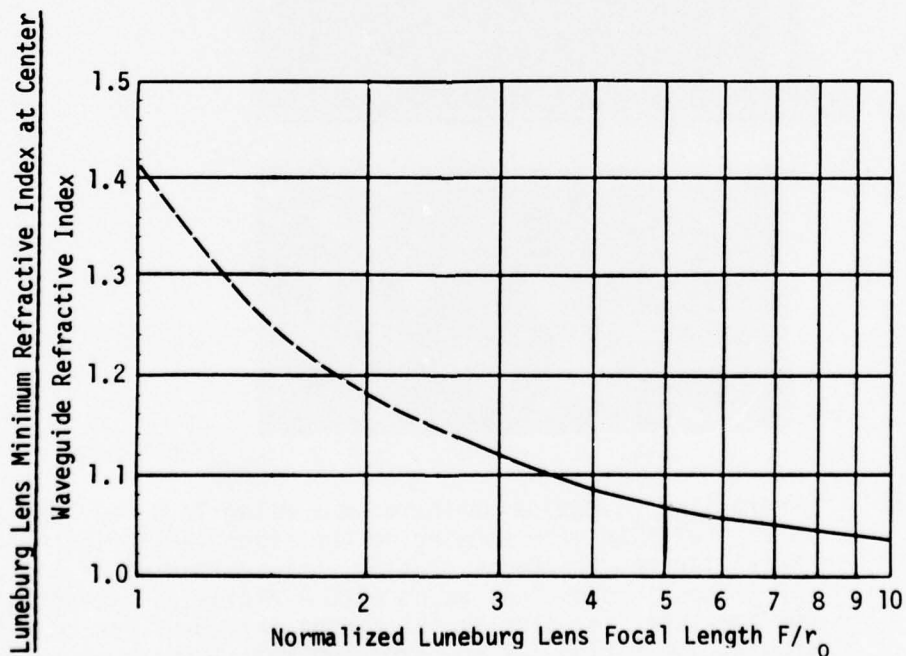


Figure 4B. Thin-Film Waveguide Luneburg Lens Design Requirement (the minimum ratio of refractive indices at center per perimeter versus normalized focal length ( $F/r_0$ )).

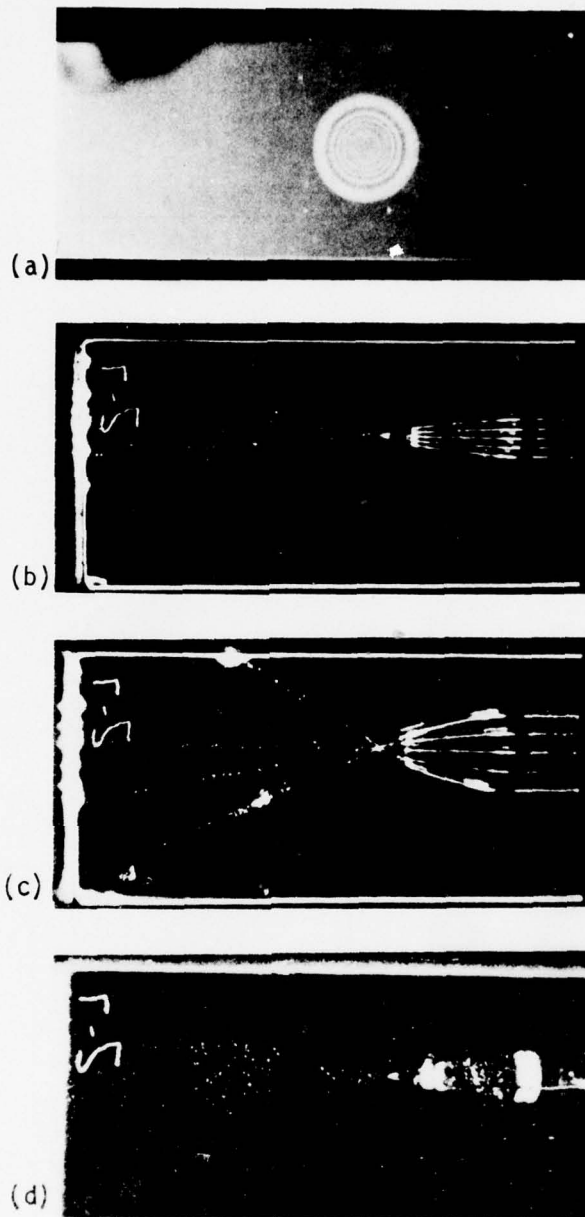


Figure 5B. Generalized Waveguide Luneburg Lens Using  $Ta_2O_5$  on 7059 on 7440: (a) plan view showing Newton rings indicating the radial tapered thickness profile, (b) scattering of individual ray traces through lens using 6328 Å radiation extending over 5mm aperture, (c) same as (b) except increased aperture is showing aberration due to incorrect radial thickness profile, and (d) same as (b) except using continuous 5mm wide beam.

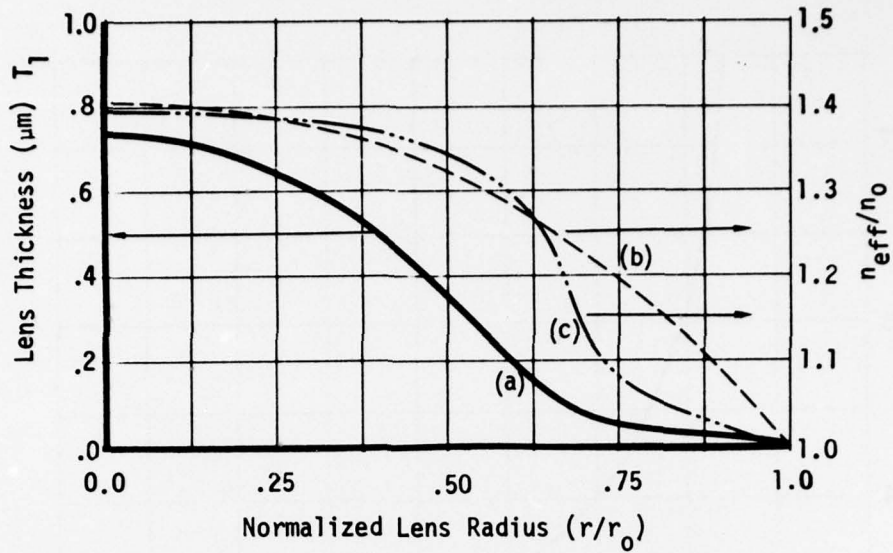


Figure 6B. Waveguide Luneburg Lens Radial Profiles: (a) radial lens thickness profile derived from Newton rings depicted in Fig. 5B, (b) ideal effective refractive index profile, and (c) calculated effective refractive index profile using data of (a).

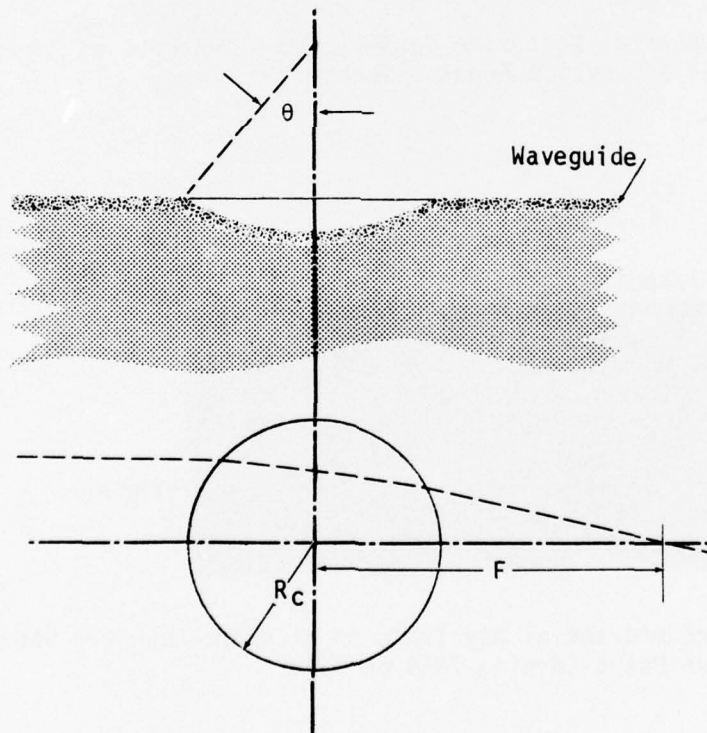


Figure 7B. A Thin-Film Waveguide Geodesic Lens: (a) cross-section, and (b) projected ray trace through geodesic lens.

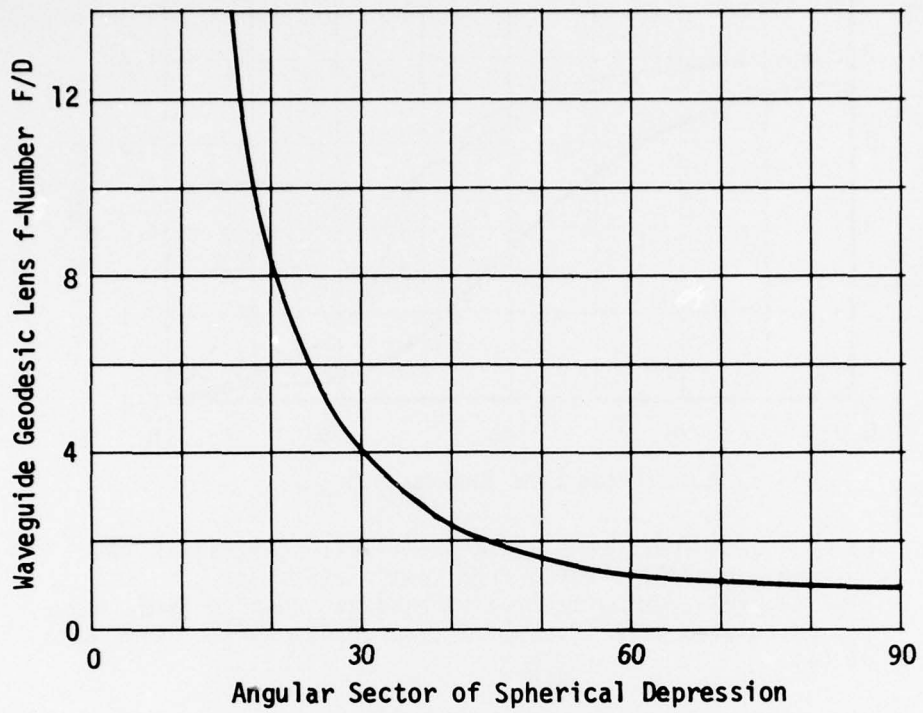


Figure 8B. Spherical Waveguide Geodesic Lens f-number as a Function of the Depression Angular Sector.

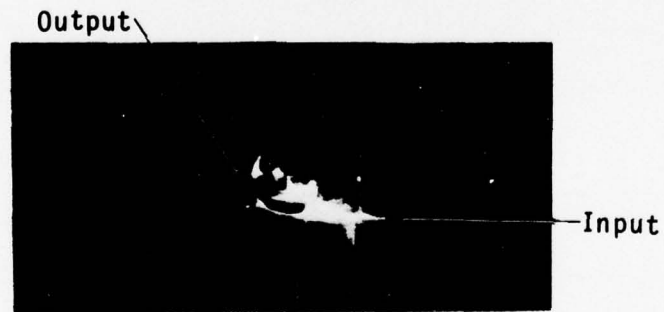


Figure 9B. Circumferential Ray Trace of Rinehart-Luneburg Geodesic Lens Using Corning 7059 on 7440.

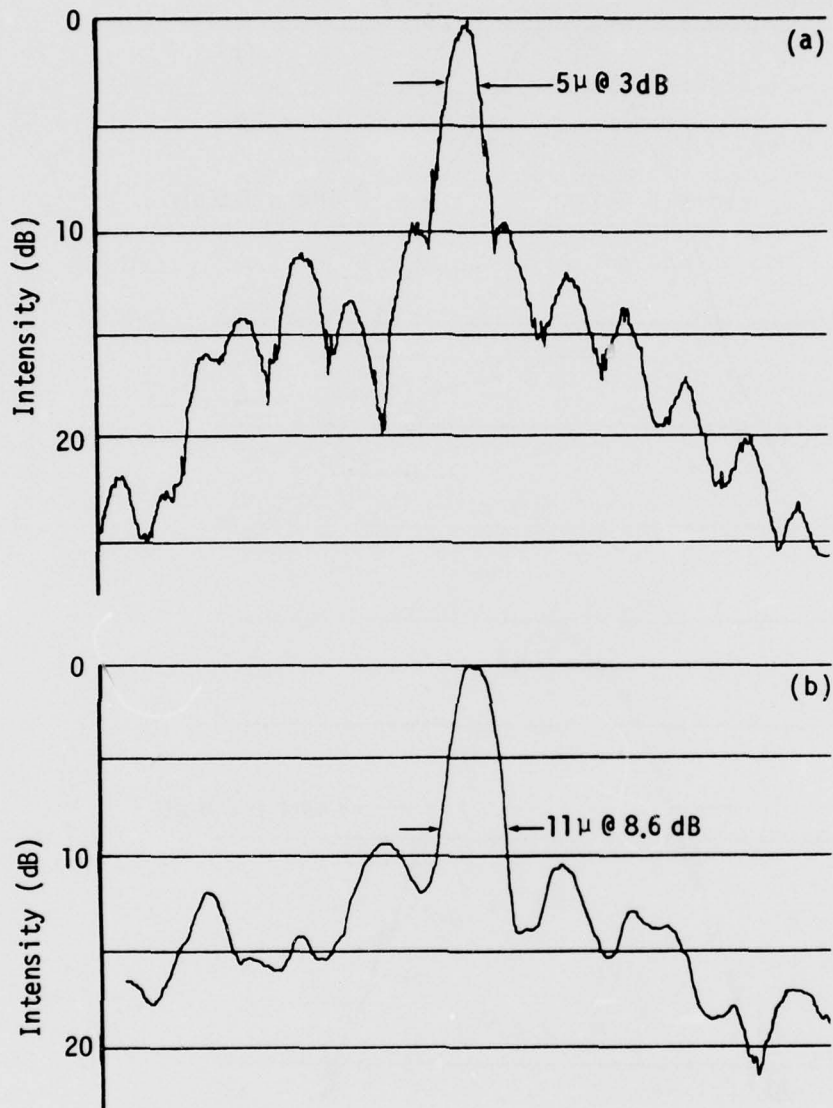


Figure 10B. Experimentally Measured Waveguide Lens Diffraction Patterns: (a) planar thin-film Luneburg lens using  $Ta_2O_5$  on BaO-rich 7059 and a uniform illuminated aperture of 5 mm,  $F=12$  mm, and (b) spherical depression waveguide geodesic lens using 7059 on 7440 using 7 mm Gaussian input beam depicted in Fig. 11B,  $F=20$  mm.

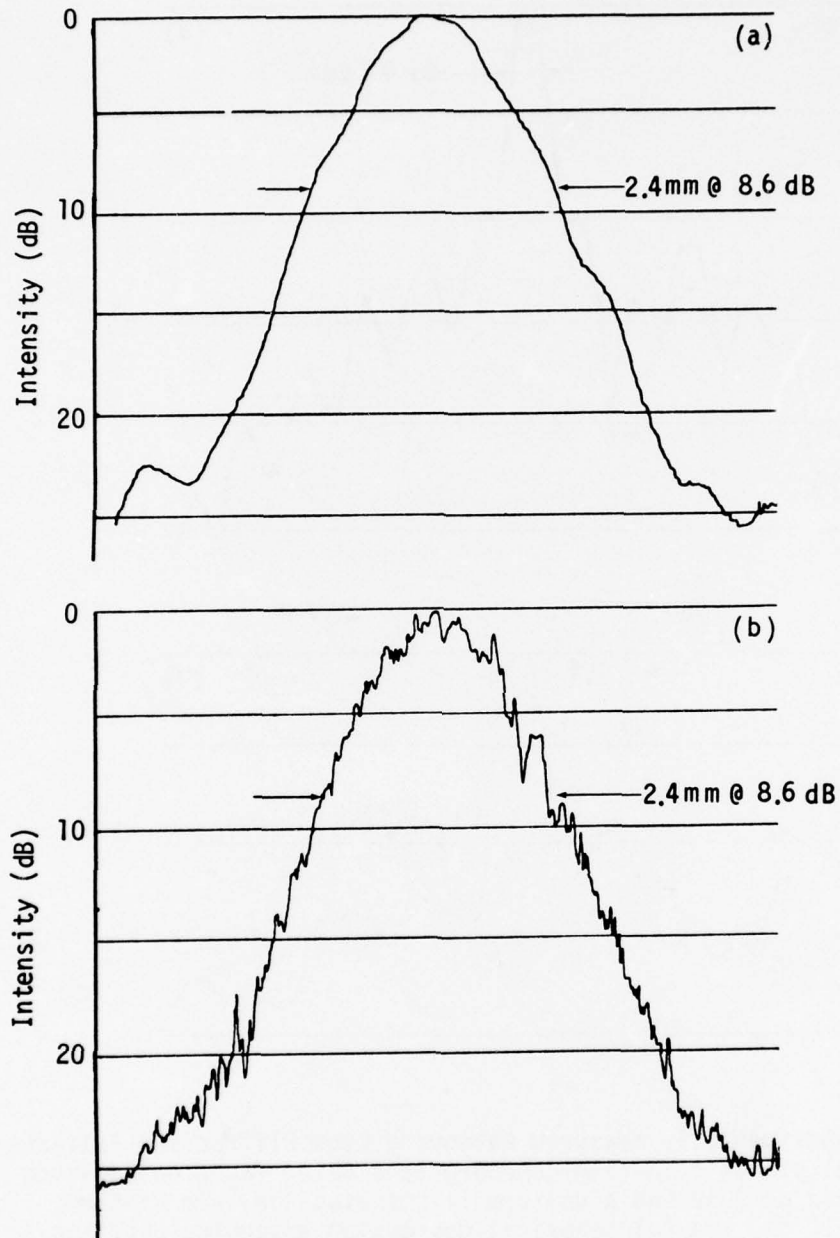


Figure 11B. Waveguide Scattering Using 7059 Waveguide on Thermally-Grown  $\text{SiO}_2$  on Si: (a) Gaussian input beam profile, and (b) measured output beam profile after propagating through BK-7 input/output coupling prisms and 5 cm of 7059 waveguide.

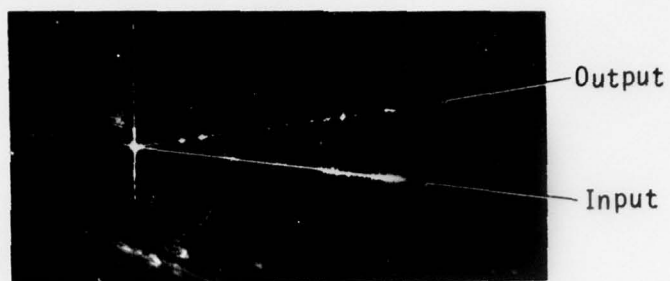


Figure 12B. Thin-Film Waveguide Reflector Using Cleaved Metallized Edge (Al) of 7059 Waveguide on Thermally-Grown  $\text{SiO}_2$  on Si.

APPENDIX C

INTEGRATED OPTICAL WAVEGUIDE AND  
CHARGE COUPLED DEVICE IMAGE ARRAY \*

J.T. Boyd and C.L. Chen  
Solid State Electronics Laboratory  
Department of Electrical and Computer Engineering  
University of Cincinnati  
Cincinnati, Ohio 45221  
(513) 475-4461

Abstract

The device structure and experimental operation of an integrated optical waveguide and charge coupled device (CCD) detector array are considered. The use of silicon as a substrate allows direct fabrication of the CCD detector array and a thermally oxidized layer of  $\text{SiO}_2$  forms an effective substrate for waveguide deposition. The detector array is composed of a two-phase, overlapping-gate CCD with first level polycrystalline silicon electrodes and second level aluminum electrodes connected in parallel by means of a series of gates to an array of photodiodes. In the photodiode region the  $\text{SiO}_2$  layer is tapered to a termination so that with minimal scatter, light is multiply-refracted into the detector region. The center-to-center detector element spacing of the device fabricated and successfully operated is 32  $\mu\text{m}$ . Optimum detector length is considered as a function of waveguide thickness. The integrated waveguide-CCD array is expected to become an integral part of various signal processing devices.

---

\* Research sponsored by the Air Force Office of Scientific Research, Air Force Systems Command, USAF, under Grant No. AFOSR-76-3032 and under a subcontract from Rockwell International as prime contractor for the Air Force Avionics Laboratory. The United States Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation hereon.

## I. INTRODUCTION

An integrated optical waveguide and charge-coupled device (CCD) linear imaging array have been fabricated and successfully operated. Such an integrated device is expected to find many applications in integrated optical signal processing device structures. Optical signal processing using an integrated optical format combines the advantages of parallel processing with those present in an efficient, compact, and economical device. Parallel processing occurs when information is imparted to the transverse spatial distribution of an optical wave. Appropriate modulation and processing techniques include highly-efficient and wide band acoustooptic deflection,<sup>1-4</sup> electrooptic deflection,<sup>5,6</sup> and one-dimensional spatial Fourier transformation performed by an optical waveguide lens.<sup>7</sup> For example, integrated optical acoustooptic deflection, optical waveguide lenses, and an integrated waveguide-detector such as described herein, can be used to perform wide band spectrum analysis of electronic signals.<sup>8</sup> In this and general integrated optical signal device configurations information carried by the light wave can be converted to electrical signals by means of a detector array. With the presence of a CCD in the detector array, transformation of the electrical signal from a parallel format into a serial format occurs in a natural and simple way. Information capacity of integrated optical signal processing devices will be limited by beam diffraction or array resolution and detector dynamic range. As the presence of optical scattering will reduce this capacity, integration of the array into the optical waveguide, and thereby minimizing scattering occurring in

waveguide-detector coupling, will allow superior performance as compared with the use of an external detector array.

The integrated waveguide-CCD detector array may find additional applications based on its inherent property of parallel entry of signal information into a CCD shift register. Optical injection of parallel signals into CCDs offers significant advantages over electrical injection techniques, in that for the latter sophisticated stabilized charge injection circuits are required for each entry tap.<sup>9</sup> Furthermore, capacitive coupling limits both the proximity of adjacent taps and the maximum usable signal frequency for parallel electrical injection. Parallel optical signal injection using bulk optical waves along with a mask to implement a fixed tap weight transversal filter has previously been demonstrated.<sup>10</sup> We anticipate that the use of integrated optical channel waveguide-detector structures would yield a device with greatly increased channel density and channel isolation. Parallel integrated optical signal injection into CCDs may also find application in multiplexing, programmable filtering, and memory devices.

The integrated waveguide-CCD detectors use silicon as a substrate. Besides allowing fabrication of a sophisticated detector array providing serial signal output, use of silicon allows fabrication of a variety of electronic circuitry on the same substrate. Furthermore, surface elastic waves can be excited efficiently on silicon using a ZnO film in the transducer region.<sup>11</sup> The thermally-oxidized SiO<sub>2</sub> layer, not being a deposited film, presents a very smooth, low refractive index surface for waveguide deposition. As the SiO<sub>2</sub>/Si surface is well-suited for the

formation of channel waveguides by preferential etching,<sup>12</sup> an array of channel waveguides with each waveguide coupled to an array element could provide increased spatial resolution and reduce the effects of optical scattering and spatial sampling.

## II. DEVICE STRUCTURE

The integrated optical waveguide and CCD linear image array are formed using a silicon substrate. Use of silicon allows the CCD detector array to be formed using the established processes of silicon device fabrication technology. The optical waveguide is formed on a layer of  $\text{SiO}_2$  thermally-grown on the silicon surface. This layer is sufficiently thick (typically  $1 \mu\text{m}$ .) so that evanescent coupling of light from the waveguide to silicon is negligible, except in the detector region.<sup>13</sup> In the detector region, the  $\text{SiO}_2$  layer tapers to zero thickness so that light in the waveguide is multiply-refracted into the silicon substrate. A taper which minimizes optical scatter is formed by allowing a carefully controlled amount of undercutting to occur during etching in device processing.<sup>14</sup> A profile of the integrated waveguide - CCD detector structure is shown in Figure 1.

The basis of CCDs is the metal-oxide-silicon (MOS) capacitor. In Figure 1 electrodes are formed from both aluminum (Al) and conducting polycrystalline silicon (polysilicon). Potential wells for minority charge are formed at or near the silicon surface under the electrodes of such capacitors upon application of an appropriate voltage. Charge representing a signal level can be stored in such a well for short periods of time. Charge transfer occurs by creating a deeper well beneath an adjacent capacitor by applying a larger voltage. By alternating capacitor voltages in either a two, three, or four phase manner, unidirectional charge transfer along an array of MOS capacitors can be effected.<sup>15</sup> A p-n junction is located at each end of the capacitor array for serial injection and collection of signal charge.

The detector array in Figure 1 consists of an array of photodiodes formed in n-type silicon connected in parallel by means of a series of gates to a CCD shift register.<sup>16,17</sup> One CCD unit cell corresponds to each photodiode. Channel isolation is maintained through the series of gates by the presence of channel stopping n+ regions. The detector array integrates the optical signal incident on the array of photodiodes as the potentials of the control and integration gates are adjusted so that charge excited by incident light collects underneath the integration gate. At the end of the integration period T, the transfer gate is turned on so that the collected charge is transferred into the shift register. This charge transfer occurs simultaneously for each array element. This parallel transfer of charge occurs in a time less than 1/2 of the CCD clock period so that the CCD is essentially stationary. Once this charge has transferred into the shift register, the transfer gate is turned off and the charge is shifted along the register to the end where a serial, discrete-time signal emerges representing the spatial light distribution. As soon as the transfer gate is turned off, the photosensors begin integrating charge and the cycle is repeated. The integration time is thus given as

$$T = N/f_c \quad , \quad (1)$$

where N is the number of CCD cells equal to the number of array elements and  $f_c$  is the CCD clock frequency. Because charge integration can occur while CCD readout takes place, sensing takes place essentially 100% of the time for reasonable values of N.<sup>18</sup>

The CCD shift register portion of the device is a two-phase, overlapping-gate structure consisting of one level of polysilicon electrodes insulated by an additional layer of  $\text{SiO}_2$  from a second level of overlapping aluminum electrodes.<sup>19</sup> Use of such an overlapping gate structure is superior to a single-level electrode in that such devices are characterized by greater stability and a higher charge transfer efficiency or, equivalently, a lower transfer inefficiency.<sup>20</sup> Dispersion of signal information is thus minimized.

For many applications of the integrated waveguide - CCD detector array, minimizing the array element center-to-center spacing allows the information handling capability to be maximized.<sup>8</sup> Such spacings will generally be limited by lithography considerations. Large aspect ratios of the rectangular photodiode region are generally undesirable. The question thus arises as to whether the extent of the photodiode in the direction of light propagation  $L$  can be chosen sufficiently large so that nearly all light incident can be multiply refracted into the detector region. To examine this question, we consider the decay of light intensity along the photodiode surface in the direction of light propagation  $I(z)$ , given as<sup>13</sup>

$$I(z) = I_0 e^{-\alpha_e z} \quad . \quad (2)$$

In (2)  $\alpha_e$  is an effective decay constant accounting for light coupled into the photodiode region given as

$$\alpha_e = \frac{1-R}{d \tan \theta} \quad , \quad (3)$$

where  $d$  is the waveguide thickness and  $\theta$  is the waveguide mode characteristic angle with respect the waveguide surface normal. For the case of

multiple refractive coupling (zero thickness SiO<sub>2</sub> layer in the photodiode region) R in (3) is the appropriate Fresnel reflection coefficient at the waveguide-silicon interface for the mode characteristic angle and polarization in question.<sup>21</sup> We will restrict our present discussion to the TE<sub>0</sub> mode. For a thin SiO<sub>2</sub> layer in the photodiode region evanescent wave coupling will occur causing the field in the waveguide to decay according to (2) and (3), but with R interpreted more generally as a composite reflection coefficient. As evanescent coupling is weaker than multiple refractive coupling, multiple refraction is preferred as it allows minimization of the photodiode length L required for efficient coupling. An analysis of photodiode quantum efficiency for the type of waveguide coupling described herein has shown that for a variety of situations the quantum efficiency increases with  $\alpha_e L$  until  $\alpha_e L \sim 3$ .<sup>14</sup> Since further increase of  $\alpha_e L$  causes no significant increase in quantum efficiency, an optimum value of detector length L<sub>0</sub> can be defined as

$$L_0 = 3/\alpha_e. \quad (4)$$

The magnitude of the device quantum efficiency for detector lengths greater than (4) saturates at a value determined by the silicon absorption coefficient at the wavelength of interest, depletion region depth, carrier diffusion lengths, and depth of the surface recombination region.

We have calculated the optimum detector length L<sub>0</sub> for the TE<sub>0</sub> mode as a function of waveguide thickness d for a waveguide refractive index of n<sub>g</sub> = 1.61. This refractive index is characteristic of the KPR photoresist waveguides used in the experiments described herein, as well as characteristic of 7059 sputtered glass waveguides. The result of the

calculation is shown in Figure 2 for  $\lambda = .9 \mu\text{m}$  and  $.6 \mu\text{m}$ . The portions of the curves to the left of the dotted vertical lines are the regions in which only a single TE mode can exist. In the single mode regions the optimum detector lengths would allow fabrication of efficient photodiodes with reasonable aspect ratios and with center-to-center spacings approaching photolithographic limits. However, for multimode waveguides the corresponding optimum detector lengths become quite long. It is fortunate that in many signal processing applications use of a single-mode waveguide is advantageous in view of other considerations.<sup>8</sup> In Fourier optical processing utilizing optical waveguide lenses the integrated waveguide-detector array described herein would find application in focal plane imaging. If  $L_0$  exceeds the depth of focus for such applications, then an array of channel waveguides, one passing directly over each photodiode would be required to preserve signal integrity.

Utilization of the integrated waveguide-detector arrays is limited by a maximum input optical power density  $S_{\text{max}}$  incident on each photodiode before dispersion of the discrete time signal emerging from the CCD occurs. The optically-induced charge must remain less than the maximum signal charge handling capability of the CCD  $Q_{\text{max}}$ , given approximately as

$$Q_{\text{max}} = C_{\text{ox}} A \Delta V, \quad (5)$$

where  $C_{\text{ox}}$  is the oxide capacitance per unit area,  $A$  is the area of each polysilicon electrode, and  $\Delta V$  is the difference between the maximum and minimum values of CCD clock voltage. The presence of  $\Delta V$  in (5) results from assuming two phase clock operation with pulse overlap. The maximum incident optical power density  $S_{\text{max}}$  is then just that value causing optically

induced charge in T seconds to be equal to  $Q_{\max}$ , i.e.

$$S_{\max} = \frac{h\nu C_{\text{ox}} A \Delta V}{ensdT} \quad (6)$$

where  $h\nu$  is incident photon energy,  $\eta$  is the device quantum efficiency,  $e$  is electron charge, and  $s$  is the width of the detector along the surface perpendicular to the direction of light propagation. For the actual fabricated device described in the next section  $C_{\text{ox}} = 2.95 \times 10^{-8}$  F/cm<sup>2</sup>,  $A = 1.56 \times 10^{-5}$  cm<sup>2</sup>,  $s = 25$   $\mu\text{m}$ , and  $L > L_0$  for  $d = 1$   $\mu\text{m}$ . Assuming typical or reasonable values of  $\eta = .1$ ,  $\Delta V = 10$  volts,  $T = 10^{-5}$  sec., and  $\lambda = .9$   $\mu\text{m}$ , we find from (6) that  $S_{\max} = 25$  W/cm<sup>2</sup>. This power density corresponds to a power of .25 mW for a 1 mm. diameter laser beam propagating in a 1  $\mu\text{m}$  thick optical thin-film waveguide.

### III. DEVICE OPERATION

The integrated waveguide-CCD detector array was fabricated using n type silicon having resistivity of 8 ohm-cm. and 100 orientation. The detector portion of the resulting device is shown in Figure 3. The presence of the photodiodes provides an electrode-free surface region for coupling light from the waveguide to the detector region by multiple refraction. This device contains 19 array elements with the photodiodes measuring 25  $\mu\text{m}$  x 115  $\mu\text{m}$  with 7  $\mu\text{m}$  of isolation between adjacent elements. In view of Figure 2, the photodiode length of 115  $\mu\text{m}$  is quite sufficient for effective coupling for the KPR photoresist waveguide employed in our experiments. However, this length would be somewhat long if we were to attempt to reduce the center-to-center spacing to the photolithographic limit. The two-phase overlapping gate CCD has a conventional charge collection diode for signal output and a charge injection diode for serial input. The latter allows for electronic evaluation of the CCD and for serial injection of bias charge.

A number of devices such as that shown in Figure 3 were fabricated on a single silicon wafer. After initial probe testing the wafer was segmented and individual arrays were mounted and bonded in dual-in-line packages. The packages employed were specifically altered so they accommodate a sufficiently large piece of silicon that would allow space for prism coupling of light into the waveguide and for waveguide propagation. Once packaged the devices could then be inserted in a socket attached to a standard prism coupling optical mount. A macroscopic view of HeNe laser light coupled into the optical waveguide is shown in Figure 4-a. The bright area on the left is a top view of the prism illuminated by scattered light, while the dark area in the center is the clamp pressing the prism against the surface. The streak of scattered light is approximately 125  $\mu\text{m}$  wide and corresponds to the light beam which had been externally focused propagating until it reaches the detector region. Bonding wire leading from bonding pads on silicon to connections on the package is illuminated by scattered light. The detector array is located between the termination of the streak of light and the bonding pads. Because the magnification in Figure 4-a is considerably less than that in Figure 3, details of the CCD detector array are not resolvable. Note that there is no visible indication of excess scatter occurring in waveguide-detector coupling. Figure 4-b is an oscilloscope trace of the signal emerging from the CCD corresponding to the laser excitation in Figure 4-a. Differential amplification of the signal was used to eliminate some of the pickup from the clock pulses.

The device was operated with a two-phase clock producing overlapping pulses in the 100 KHz frequency range. Counter circuitry synchronized to the clock was used to control pulsing of the transfer gate so that this gate was turned on only after charge in the CCD shift register had been completely shifted out. Counter circuitry was also employed to provide a suitable

electronic input for electronic evaluation of charge transfer efficiency. Charge transfer efficiency can be evaluated by serially injecting several low duty-cycle rectangular pulses with each separated by one clock period.<sup>20</sup> By carefully noting the degradation of the leading and trailing edges of the pulse train, information regarding transfer efficiency can be inferred. For the devices fabricated we determined a transfer efficiency of .993 per double transfer. Although this value is adequate for performance of our 19 stage device, higher values can be obtained. Good charge transfer efficiency requires very sharp lateral potential barriers.<sup>15</sup> Although the purpose of the channel stop diffused regions is to provide such barriers, the device processing sequence we employed involved a high temperature thick gate oxide growth step after the channel stop diffusion. Further diffusion thus would occur during the oxide growth, resulting in more gradual lateral barriers. Evidence that this was indeed occurring was obtained from the transfer efficiency measurements in that larger values of bias charge than usual were required to eliminate fixed transfer loss.<sup>20</sup> The problem can be overcome by using ion implantation for channel stop doping and altering the processing sequence.

#### IV. SUMMARY

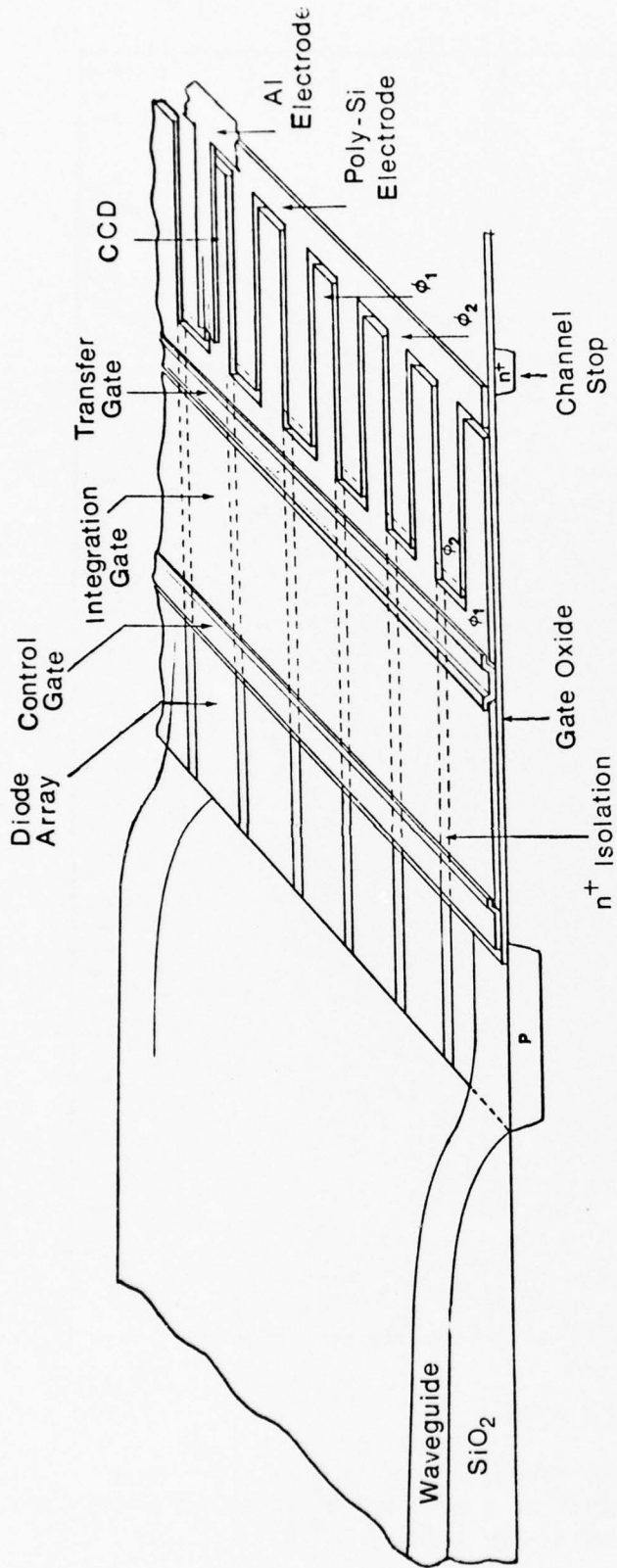
Successful fabrication and operation of a linear CCD image array integrated into an optical waveguide structure have been described. The integrated device is fabricated using silicon with a thick layer of thermally-oxidized  $\text{SiO}_2$  serving as the waveguide substrate. Data have been presented with regard to the optimum array element size required for the light wave to be efficiently coupled into the detector region. Minimal excessive scattering in the region where coupling of light from the waveguide to the detector occurs was observed. The integrated structure that has been described herein is expected to serve as a basic element in integrated optical signal processing devices and to provide a method for parallel entry of information into CCDs. In any such applications the use of silicon allows for integration of additional electronic circuitry and devices with the integrated waveguide-CCD detector array.

We would like to acknowledge J. T. Garrett for providing technical assistance and A. J. Van Velthoven of the NCR Microelectronics Division for supplying the device packages. Helpful discussions with D. B. Anderson are also appreciated.

## REFERENCES

1. L. Kuhn, M. L. Dakss, P. F. Heidrich, and B. A. Scott, "Deflection of an Optical Guided Wave by a Surface Acoustic Wave," *Appl. Phys. Lett.* Vol. 17, pp. 265-267, 1970.
2. C. S. Tsai, M. A. Alhaider, L. T. Nguyen, and B. Kim, "Wideband Guided-Wave Acoustooptic Bragg Diffraction and Devices Using Multiple Tilted Surface Acoustic Waves," *Proc. IEEE*, Vol. 64, pp 318-328, 1976.
3. B. Kim and C. S. Tsai, "High-Performance Guided-Wave Acoustooptic Scanning Devices Using Multiple Surface Acoustic Waves," *Proc. IEEE*, Vol. 64, pp 788-793, 1976.
4. E. G. H. Lean, J. M. White, and C. D. W. Wilkinson, "Thin-Film Acoustooptic Devices," *Proc. IEEE*, Vol. 64, pp 779-788, 1976.
5. D. P. Giarusso and J. H. Harris, "Electrooptic Modulation in a Thin Film Waveguide", *Appl. Opt.* Vol. 10, pp 2786-2788, 1971.
6. C. S. Tsai and P. Saunier, "Ultrafast Guided - Light Beam Deflection/ Switching and Modulation Using Simulated Electro-optic Prism Structures in  $\text{LiNbO}_3$  Waveguides," *Appl. Phys. Lett.* Vol. 27, pp 248-250, 1975.
7. R. Shubert and J. H. Harris, "Optical Guided Wave Focusing and Diffraction," *J. Opt. Soc. Amer.*, Vol. 61, pp 154-161, 1971.
8. D. B. Anderson, J. T. Boyd, M. C. Hamilton, and R. R. August, "Integrated Optics Approach to the Fourier Transform," to be published.
9. M. H. White, I. A. Mack, F. J. Kub, D. R. Lampe, and J. L. Fagan, "An Analog CCD Transversal Filter with Floating Clock Electrode Sensor and Variable Tap Gains," *Dig. of Tech. Papers, IEEE International Solid State Circuits Conference, Philadelphia, Pa.*, 1976.
10. M. A. Copeland, D. Roy, J. D. E. Beynon, and F. Y. K. Dea, "An Optical CCD Convolver," *IEEE Trans Electr. Dev.* Vol. ED-23, pp 152-155, 1976.
11. F. S. Hickernell, "Zinc Oxide Thin-Film Surface Wave Transducers," *Proc. IEEE*, Vol. 64, pp 631-635, 1976.
12. W. T. Tsang, C. C. Tseng, and S. Wang, "Optical Waveguides Fabricated by Preferential Etching," *Appl. Opt.* Vol. 14, pp 1200-1206, 1975.
13. P. K. Tien, and R. Ulrich, "Theory of Prism-Film Coupler and Thin Film Light Guides," *J. Opt. Soc. Am.* Vol. 60, pp 1325-1337, 1970.

14. J. T. Boyd and C. L. Chen, "Integrated Optical Silicon Photodiode Array," *Appl. Opt.* Vol. 15, pp 1389-1393, 1976.
15. C. H. Sequin and M. F. Tompsett, Charge Transfer Devices, Academic Press, 1975.
16. D. F. Barbe, "Imaging Devices Using the Charge Coupled Concept," *Proc. IEEE* Vol. 63, pp 38-67, 1975.
17. A. J. Steckl, R. D. Nelson, B. T. French, R. A. Gudmundsen, and D. Schechter, "Application of Charge Coupled Devices to Infrared Detection and Imaging," *Proc. IEEE* Vol. 63, pp 67-74, 1975.
18. M. F. Tompsett, G. F. Amelio, W. J. Bertram, R. R. Backley, W. J. McNamara, J. C. Mikkelsen, and D. A. Sealer, "Charge Coupled Imaging Devices: Experimental Results," *IEEE Trans. Electr. Dev.* Vol. ED-18, pp 992-996, 1971.
19. W. F. Kosonocky and J. E. Carnes, "Two Phase Charge-Coupled Devices with Overlapping Polysilicon and Aluminum Gates," *RCA Rev.* Vol. 34, pp 164-202, 1973.
20. R. W. Brodersen, D. D. Buss, and A. F. Tasch, "Experimental Characterization of Transfer Efficiency in Charge-Coupled Devices," *IEEE Trans. Electr. Dev.* Vol. ED-22, pp 40-46, 1975.
21. M. Born and E. Wolfe, Principles of Optics, Second Edition, Pergamon Press, 1964.



(100) n-type Silicon

Figure 1C. Integrated Optical Waveguide and CCD Detector Array.

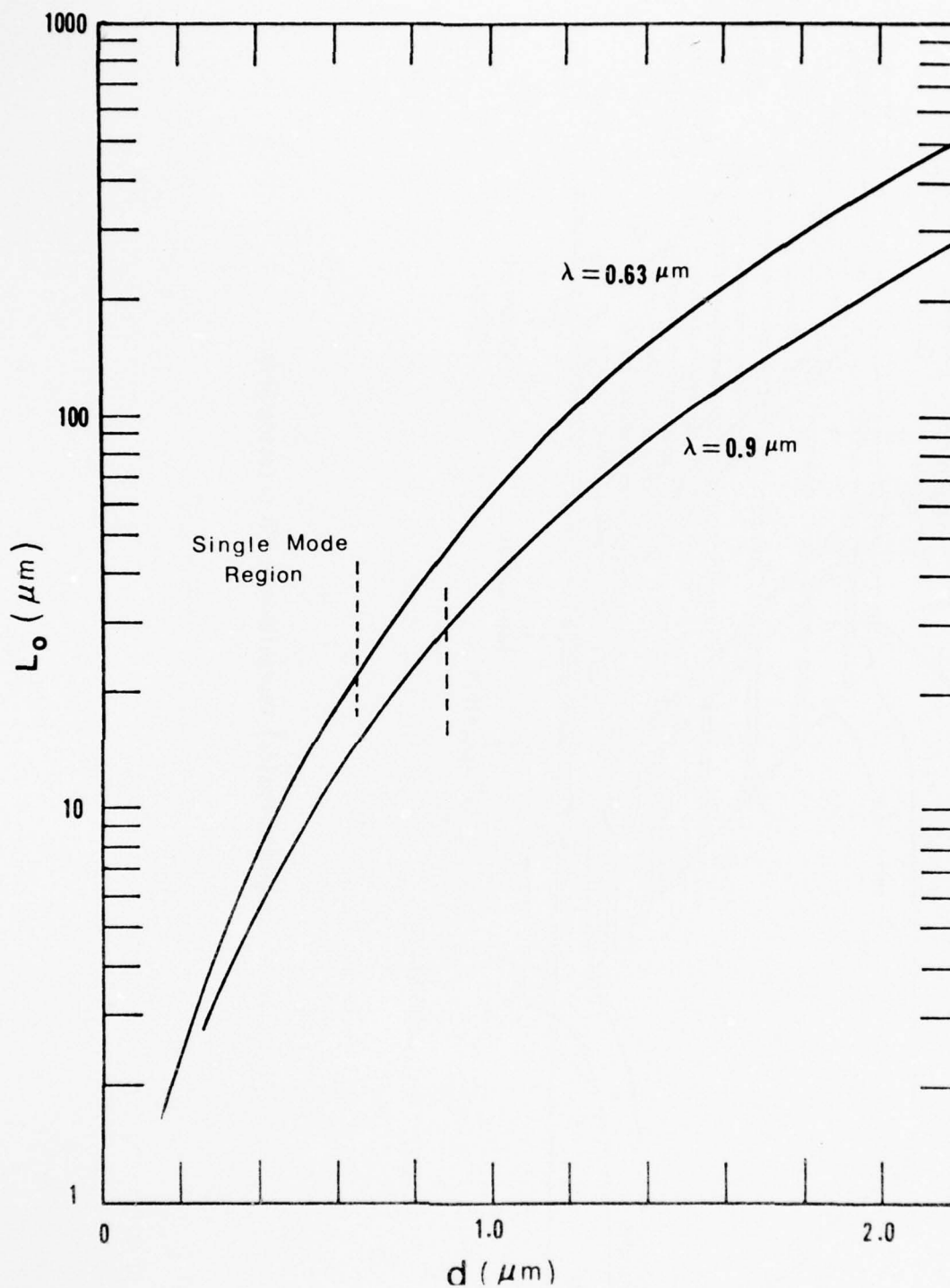


Figure 2C. Detector Length for Efficient Coupling of Light from Waveguide to Detector as a Function of Waveguide Thickness for a Waveguide Refractive Index  $n = 1.61$ .

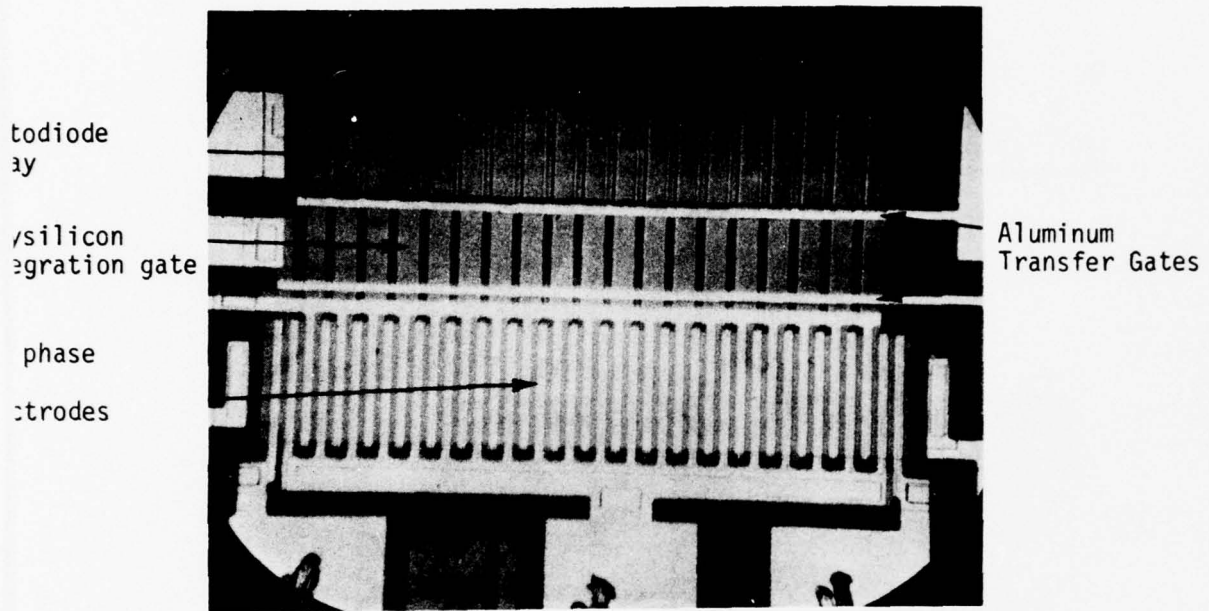
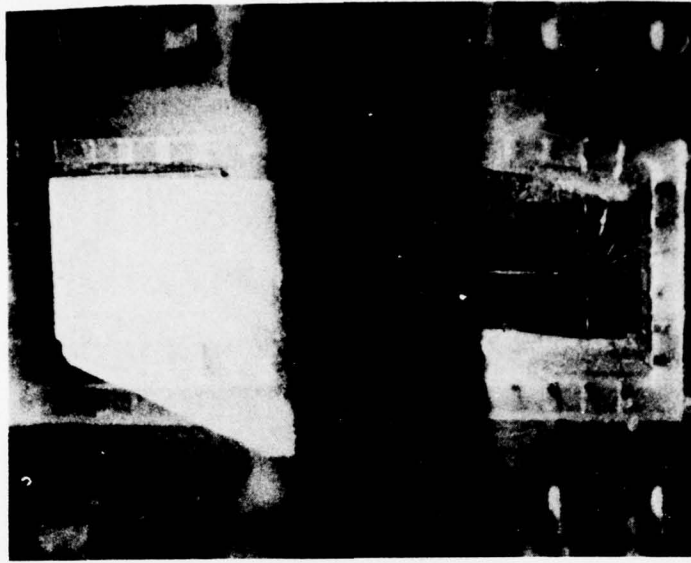
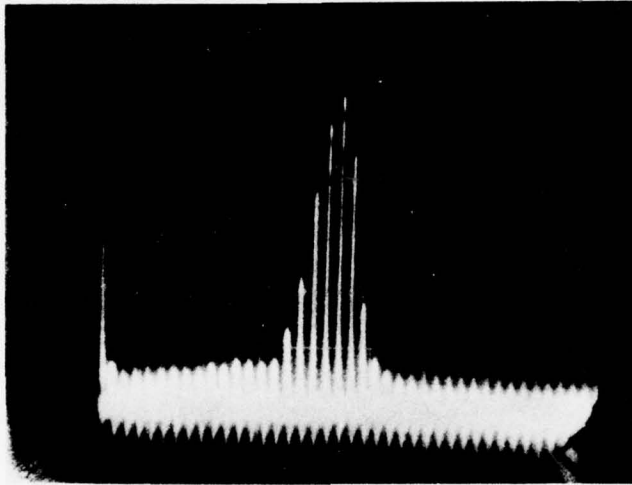


Figure 3C. Linear Photodiode Imaging Array Coupled to a Two-Phase, Overlapping Gate CCD.



(a)



(b)

Figure 4C. (a) Light Propagating in an Optical Waveguide from the Prism Coupler to the Integrated CCD Detector Array.  
(b) CCD Output Signal Corresponding to Illumination Shown in (a).

## APPENDIX D

### LINEAR CHARGE COUPLED DEVICE DETECTOR ARRAY FOR IMAGING LIGHT PROPAGATING IN AN INTEGRATED THIN-FILM OPTICAL WAVEGUIDE\*

C.L. Chen and J.T. Boyd  
Solid State Electronics Laboratory  
Department of Electrical and Computer Engineering  
University of Cincinnati  
Cincinnati, Ohio 45221  
(513) 475-4461

#### ABSTRACT

We will discuss device design, fabrication, and operation of a linear charge coupled device (CCD) detector array integrated with a thin-film optical waveguide and applications of this structure to integrated optical signal processing and fiber optical communications. A two-phase, overlapping-gate CCD is connected in parallel by means of a series of gates to an array of photodiodes. The photodiode provides an electrode-free surface region so that a highly-efficient waveguide-detector coupling technique can be implemented. A thermally-oxidized layer of SiO<sub>2</sub> forms an effective substrate for the optical waveguide.

#### I. INTRODUCTION

A CCD linear imaging array integrated with an optical waveguide structure has been fabricated and successfully operated. In this integrated device guided optical waves propagate along the wafer surface entering the imaging device laterally as opposed to from the top or bottom of the device as in conventional imaging devices. Light can be confined in a thin-film in the transverse dimension perpendicular to the film surface by having a film thickness on the order of the optical wavelength and a refractive index greater than that of the substrate. As a thick layer of SiO<sub>2</sub> having refractive index  $n = 1.46$  serves as the effective substrate for the thin-film waveguide, a wide variety of thin films having a larger refractive index can be utilized to form optical waveguides. If the film is uniform along the direction parallel to the axis of the detector array, a slab waveguide exists and the function of the CCD linear detector array is to image light in this transverse direction. This light variation could be the result of parallel optical signal processing performed at another location in the optical waveguide. Alternatively, a number of parallel channel waveguides could be defined photolithographically with each channel waveguide coupling to a single array element. Although both types of structures are expected to find applications in signal processing and optical communications, the present discussion will generally be confined to the slab waveguide structure.

#### II. DEVICE STRUCTURE AND OPERATION

The integrated optical waveguide and CCD linear image array are formed on a common silicon substrate with the optical waveguide being formed

on a layer of SiO<sub>2</sub>. This layer is sufficiently thick (typically 2  $\mu\text{m}$ .) so that evanescent coupling of light from the waveguide to silicon is negligible, except in the detector region. In the detector region, the SiO<sub>2</sub> layer tapers to zero thickness so that light in the waveguide is coupled into the silicon substrate.<sup>1</sup> A taper which minimizes optical scatter is formed by allowing a carefully controlled amount of undercutting to occur during etching in device processing. A profile of the integrated waveguide - CCD detector structure is shown in Figure 1. Note in Figure 1 that the waveguide is continuous along the diode region instead of directed and terminated onto this region. Such a configuration causes the light reflected from the waveguide-silicon interface to be totally internally reflected from the waveguide surface and incident again on the waveguide-silicon interface. Since the waveguide continues along the detector region, this process repeats itself many times. The resulting multiple refraction of light into the detector minimizes detector loss due to reflection.

The detector array in Figure 1 consists of an array of photodiodes formed in *n*-type silicon connected in parallel by means of a series of gates to a CCD shift register. The charge transfer portion of the device utilizes a two-phase, overlapping-gate structure consisting of one level of polysilicon electrodes insulated by an additional layer of SiO<sub>2</sub> from a second level of overlapping aluminum electrodes.<sup>2</sup> One CCD unit cell corresponds to each photodiode. Channel isolation is maintained through the series of gates by the presence of channel stopping *n*<sup>+</sup> regions. The detector array integrates the optical signal incident on the array of photodiodes as the potentials of the control and integration gates are adjusted so that charge excited by incident light collects underneath the integration gate. At the end of the integration period *T*, the transfer gate is turned on so that the collected charge is transferred into the shift register. This charge transfer occurs simultaneously for each array element and in a time less than 1/2 of the CCD clock period. Once this charge has transferred into the shift register, the transfer gate is turned off and the charge is shifted along the register to the end where a serial, discrete-time signal emerges representing the spatial light distribution. As soon as the transfer gate is turned off, the photosensors begin integrating

\* Research sponsored by the Air Force Office of Scientific Research, Air Force Systems Command, USAF, under Grant No. AFOSR-76-3032 and under a subcontract from Rockwell International as prime contractor for the Air Force Avionics Laboratory. The United States Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation hereon.

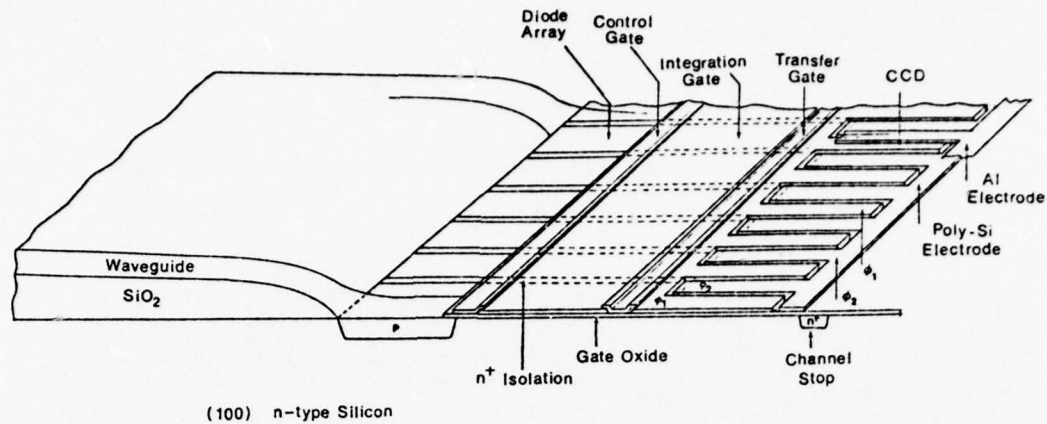


Figure 1. Integrated optical waveguide and CCD detector array.

charge and the cycle is repeated. The integration time is thus  $N$  times the lock period where  $N$  is the number of CCD cells equal to the number of array elements. Because charge integration can occur while CCD readout takes place, sensing takes place essentially 100% of the time.<sup>3</sup> For many applications of the integrated waveguide - CCD detector array, minimizing the array element center-to-center spacing allows the information handling capability to be maximized.<sup>4</sup> Such spacings will generally be limited by lithography considerations. Large aspect ratios of the rectangular photodiode region are generally undesirable. The question thus arises as to whether the extent of the photodiode in the direction of light propagation  $L$  can be chosen sufficiently large so that nearly all light incident can be multiply refracted into the detector region. To examine this question, we consider the decay of light intensity along the photodiode surface in the direction of light propagation  $I(z)$ , given as

$$I(z) = I_0 e^{-\alpha_e z} \quad (1)$$

In (1)  $\alpha_e$  is an effective decay constant accounting for light coupled into the photodiode region given as

$$\alpha_e = \frac{1-R}{d \tan \theta} \quad (2)$$

where  $d$  is the waveguide thickness and  $\theta$  is the waveguide mode characteristic angle with respect to the waveguide surface normal.  $R$  in (2) is the appropriate Fresnel reflection coefficient at the waveguide-silicon interface for the mode characteristic angle and polarization in question.<sup>6</sup> We will restrict our present discussion to the  $TE_0$  mode. For a thin  $SiO_2$  layer in the photodiode region evanescent wave coupling will occur causing the field in the waveguide to decay according to (1) and (2), but with  $R$  interpreted more generally as a composite reflection coefficient. As evanescent coupling is weaker than multiple re-

fractive coupling, multiple refraction is preferred as it allows minimization of the photodiode length  $L$  required for efficient coupling. An analysis of photodiode quantum efficiency for the type of waveguide coupling described herein has shown that for a variety of situations the quantum efficiency increases with  $\alpha_e L$  until  $\alpha_e L \sim 3$ .<sup>1</sup> Since further increase of  $\alpha_e L$  causes no significant increase in quantum efficiency, an optimum value of detector length  $L_0$  can be defined as

$$L_0 = 3/\alpha_e \quad (3)$$

The magnitude of the device quantum efficiency for detector lengths greater than (3) saturates at a value determined by the silicon absorption coefficient at the wavelength of interest, depletion region depth, carrier diffusion lengths, and depth of the surface recombination region.

We have calculated the optimum detector length  $L_0$  for the  $TE_0$  mode as a function of waveguide thickness  $d$  for a waveguide refractive index of  $n_g = 1.61$ . This refractive index is characteristic of the KPR photoresist waveguides used in the experiments described herein, as well as characteristic of 7059 sputtered glass waveguides. The result of the calculation is shown in Figure 2 for  $\lambda = 0.9 \mu m$  and  $0.6 \mu m$ . The portions of the curves to the left of the dotted vertical lines are the regions in which only a single  $TE$  mode can exist. In the single mode regions the optimum detector lengths would allow fabrication of efficient photodiodes with reasonable aspect ratios and with center-to-center spacings approaching photolithographic limits. However, for multimode waveguides the corresponding optimum detector lengths become quite long. It is fortunate that in many signal processing applications use of a single-mode waveguide is advantageous in view of other considerations.<sup>4</sup> In Fourier optical processing utilizing optical waveguide lenses the integrated waveguide-detector array described herein would find application in focal imaging. If  $L_0$  exceeds

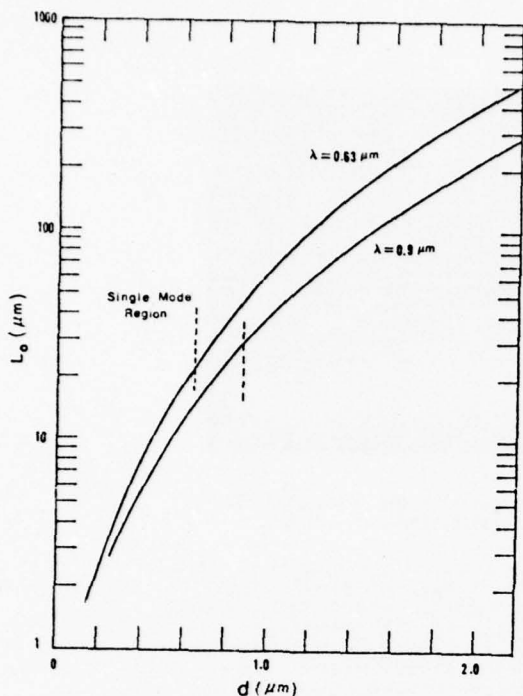


Figure 2. Detector length for efficient coupling of light from waveguide to detector as a function of waveguide thickness for a waveguide refractive index  $n = 1.61$ .

the depth of focus for such applications, then an array of channel waveguides, one passing directly over each photodiode would be required to preserve signal integrity.

The integrated waveguide-CCD detector array configuration shown in Figure 1 was fabricated using  $n$  type silicon having resistivity of 8 ohm-cm. and 100 orientation. The detector portion of the resulting device is shown in Figure 3. This device contains 19 array elements with the photodiodes measuring  $25 \mu\text{m} \times 115 \mu\text{m}$  with  $7 \mu\text{m}$  of isolation between adjacent elements. In view of Figure 2, the photodiode length of  $115 \mu\text{m}$  is quite sufficient for effective coupling for the KPR photoresist waveguide employed in our experiments. However, this length would be somewhat long if we were to attempt to reduce the center-to-center spacing to the photolithographic limit. The two-phase overlapping gate CCD has a conventional charge collection diode for signal output and a charge injection diode for serial input. The latter allows for electronic evaluation of the CCD and for serial injection of bias charge.

After initial probe testing of fabricated devices, individual arrays were mounted and bonded in dual-in-line packages. The packages employed were specifically altered so they could accommodate a sufficiently large piece of silicon that would allow space for prism coupling of light into the waveguide and for waveguide propagation. Once packaged the devices could then be inserted in a

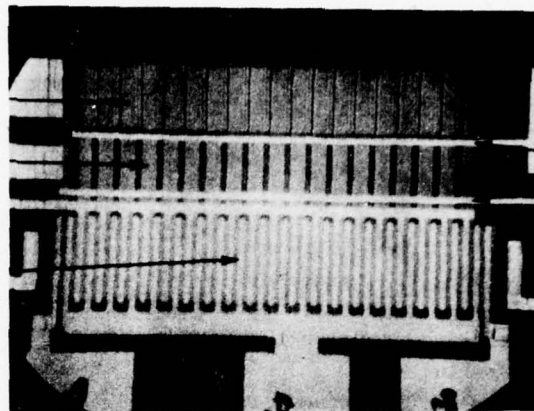


Figure 3. Linear photodiode imaging array coupled to a two phase, overlapping gate CCD.

socket attached to a standard prism coupling optical mount. A macroscopic view of HeNe laser light coupled into the optical waveguide through a prism coupler<sup>5</sup> is shown in Figure 4-a. The bright area on the left is a top view of the prism illuminated by scattered light, while the dark area in the center is a clamp pressing the prism against the surface. The streak of scattered light is approximately  $125 \mu\text{m}$  wide and corresponds to the light beam which had been externally focused propagating until it reaches the detector region. Bonding wire leading from bonding pads on silicon to connections on the package is illuminated by scattered light. The detector array is located between the termination of the streak of light and the bonding pads. Because the magnification in Figure 4-a is considerably less than that in Figure 3, details of the CCD detector array are not resolvable. Note that there is no visible indication of excess scatter occurring in waveguide-detector coupling. Figure 4-b is an oscilloscope trace of the signal emerging from the CCD corresponding to the laser excitation in Figure 4-a. Differential amplification of the signal was used to eliminate some of the pickup from the clock pulses.

The device was operated with a two-phase clock producing overlapping pulses in the 100 KHz frequency range. Counter circuitry synchronized to the clock was used to control pulsing of the transfer gate so that this gate was turned on only after charge in the CCD shift register had been completely shifted out. Counter circuitry was also employed to provide a suitable electronic input for electronic evaluation of charge transfer efficiency. Charge transfer efficiency can be evaluated by serially injecting several low duty-cycle rectangular pulses with each separated by one clock period.<sup>7</sup> By carefully noting the degradation of the leading and trailing edges of the pulse train, information regarding transfer efficiency can be inferred. For the devices fabricated we determined a transfer efficiency of .993 per double transfer. Although this value is adequate for performance of our 19 stage device, higher values can be obtained. Good charge transfer efficiency requires very sharp lateral potential barriers.<sup>8</sup> Although the purpose of the channel stop diffused regions is to provide such

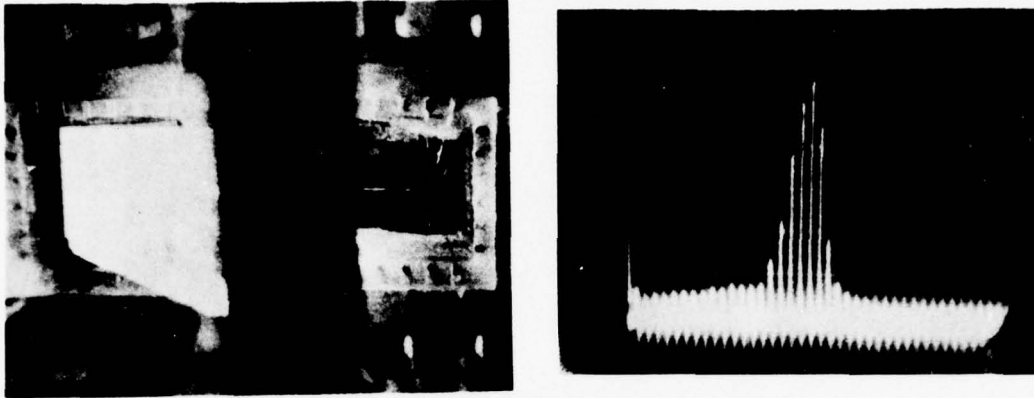


Figure 4. (a) Light propagating in an optical waveguide from the prism coupler to the integrated CCD detector array. (b) CCD output signal corresponding to illumination shown in (a).

$n^+$  barriers, the device processing sequence we employed involved a high temperature thick gate oxide growth step after the channel stop diffusion. Further diffusion thus would occur during the oxide growth, resulting in more gradual lateral barriers. Evidence that this was indeed occurring was obtained from the transfer efficiency measurements in that larger values of bias charge than usual were required to eliminate fixed transfer loss.<sup>7</sup> The problem can be overcome by using ion implantation for channel stop doping and altering the processing sequence.

### III. APPLICATIONS

The integrated optical waveguide and charge-coupled device (CCD) linear imaging array structure is expected to find many applications in integrated optical signal processing device structures.

Optical signal processing using an integrated optical format combines the advantages of parallel processing with those present in an efficient, compact, and economical device. Parallel processing occurs when information is imparted to the transverse spatial distribution of an optical wave. Appropriate modulation and processing techniques include highly-efficient and wide band acoustooptic deflection,<sup>9</sup> electrooptic deflection,<sup>10</sup> and one-dimensional spatial Fourier transformation performed by an optical waveguide lens.<sup>11</sup>

For example, integrated optical acoustooptic deflection, optical waveguide lenses, and an integrated waveguide-detector such as described herein can be used to perform wide band spectrum analysis of electronic signals by employing the configuration shown in Figure 5.<sup>4</sup>

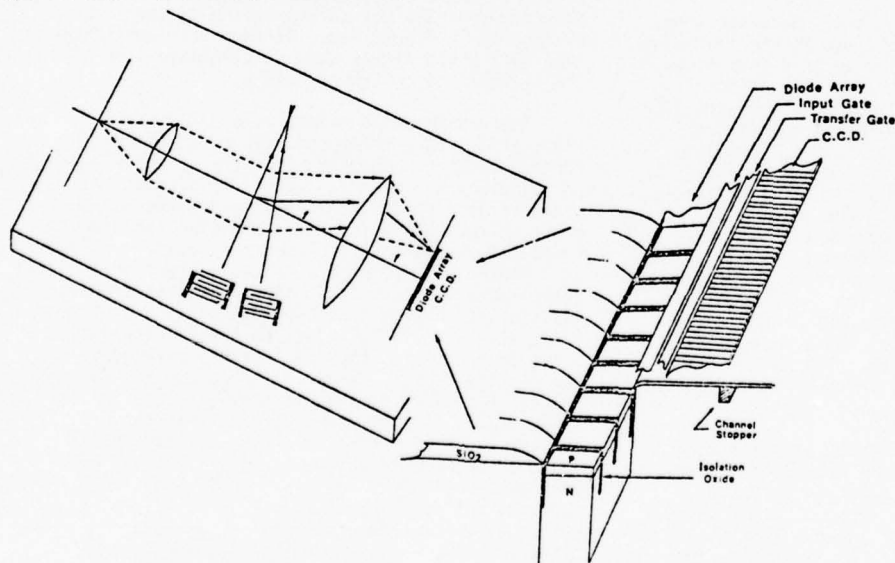


Figure 5. Integrated optical spectrum analyzer configuration.

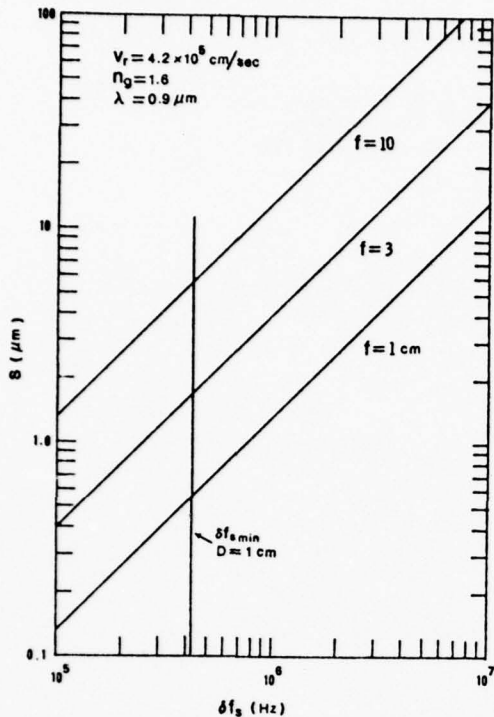


Figure 6. Detector array center-to-center spacing as a function of spectrum analyzer frequency resolution.

Coherent laser light propagating in a thin-film waveguide is expanded and collimated prior to being incident on a surface elastic wave which has been excited by the incoming signal. Surface elastic waves can be excited efficiently on silicon using a ZnO film in the transducer region.<sup>12</sup> Diffraction of light by the surface elastic wave occurs in such a way that light is diffracted at different angles corresponding to different signal frequency components. The signal frequency range of the spectrum analyzer corresponds to the bandwidth of the surface elastic wave transducer configuration. For a range of signal frequencies and wave intensities, the deflection angle is linearly proportional to the signal frequency and the diffracted light amplitude is linearly proportional to the signal surface elastic wave amplitude. A waveguide lens is then positioned so as to perform a one-dimensional Fourier transform. Signal spectral information which is represented by the angular composition of light emerging from the surface elastic wave region then becomes represented by the transverse spatial variation of light in the Fourier transform plane. The intensity of the light spatial distribution in the transform plane corresponds to the signal power density spectrum and can then be converted to an electrical signal by means of a detector array. With the presence of a CCD in the detector array, transformation of the electrical signal from a parallel format into a serial format occurs in a natural and simple way.

Information capacity of integrated optical

signal processing devices will be limited by beam diffraction or array resolution and detector dynamic range.<sup>4</sup> In particular, the nature of acoustooptic deflection and of the Fourier transform property of lenses causes the optical diffraction pattern in the lens transform plane to be displaced by a distance  $s$  for a signal frequency deviation  $\delta f_s$ , where<sup>4</sup>

$$s = \frac{f\lambda}{n_e v_r} \delta f_s \quad (4)$$

In (4)  $f$  is the lens focal length,  $\lambda$  is the optical wavelength,  $n_e$  is the waveguide mode effective refractive index, and  $v_r$  is the Rayleigh wave velocity. If the detector array in Figure 5 is spacing of  $s$ , then  $\lambda f_s$  is the frequency difference which can be resolved by the spectrum analyzer. The relationship between center-to-center spacing and frequency resolution is illustrated in Figure 6 for several focal lengths and typical parameters. As expected, smaller center-to-center spacings are required to resolve smaller frequency differences. The vertical line in Figure 6 corresponds to the diffraction-limited frequency resolution for a 1 cm. aperture. Once this asymptote has been reached, further reduction in detector center-to-center spacing cannot improve frequency resolution. As the presence of optical scattering will reduce both spectrum analyzer frequency resolution and dynamic range, integration of the array into the optical waveguide, and thereby minimizing scattering occurring in waveguide-detector coupling, will allow superior performance as compared with the use of an external detector array.

The integrated waveguide-CCD detector array may find additional applications based on its inherent property of parallel entry of signal information into a CCD shift register. Optical injection of parallel signals into CCDs offers significant advantages over electrical injection techniques, in that for the latter sophisticated stabilized charge injection circuits would likely be required for each entry tap. Furthermore, capacitive coupling limits both the proximity of adjacent taps and the maximum usable signal frequency for parallel electrical injection. Parallel optical signal injection using bulk optical waves along with a mask to implement a fixed tap weight transversal filter has previously been demonstrated.<sup>13</sup> We anticipate that the use of integrated optical channel waveguide-detector structures could yield a programmable device with potentially a large channel density and almost complete channel isolation. Parallel integrated optical signal injection into CCDs may also find application in multiplexing, other types of programmable filtering, and memory devices.

#### IV. SUMMARY

Successful fabrication and operation of a linear CCD image array integrated into an optical waveguide structure have been described. Data have been presented with regard to the optimum array element size required for the light wave to be efficiently coupled into the detector region. Minimal excessive scattering in the region where

coupling of light from the waveguide to the detector occurs was observed. The integrated structure that has been described herein is expected to serve as a basic element in integrated optical signal processing devices and to provide a method for parallel entry of information into CCDs.

We would like to acknowledge J. T. Garrett for providing technical assistance, S. G. Garg for performing the polysilicon deposition, and A. J. Van Velthoven of the NCR Microelectronics Division for supplying the device packages. Helpful discussions with D. B. Anderson and M. C. Hamilton are also appreciated.

#### REFERENCES

1. J. T. Boyd and C. L. Chen, "Integrated Optical Silicon Photodiode Array," *Appl. Opt.* Vol. 15, pp 1389-1393, 1976.
2. W. F. Kosonocky and J. E. Carnes, "Two Phase Charge-Coupled Devices with Overlapping Polysilicon and Aluminum Gates," *RCA Rev.* Vol. 34, pp 164-202, 1973.
3. M. F. Tompsett, G. F. Amelio, W. J. Bertram, R. R. Backley, W. J. McNamara, J. C. Mikkelsen, and D. A. Sealer, "Charge Coupled Imaging Devices: Experimental Results," *IEEE Trans. Electr. Dev.* Vol. ED-18, pp 992-996, 1971.
4. D. B. Anderson, J. T. Boyd, M. C. Hamilton, and R. R. August, "Integrated Optics Approach to the Fourier Transform," to be published.
5. P. K. Tien, and R. Ulrich, "Theory of Prism-Film Coupler and Thin Film Light Guides," *J. Opt. Soc. Am.* Vol. 60, pp 1325-1337, 1970.
6. M. Born and E. Wolfe, Principles of Optics, Second Edition, Pergamon Press, 1964.
7. R. W. Brodersen, D. D. Buss, and A. F. Tasch, "Experimental Characterization of Transfer Efficiency in Charge-Coupled Devices," *IEEE Trans. Electr. Dev.* Vol. ED-22, pp 40-46, 1975.
8. C. H. Sequin and M. F. Tompsett, Charge Transfer Devices, Academic Press, 1975.
9. C. S. Tsai, M. A. Alhaider, L. T. Nguyen, and B. Kim, "Wideband Guided-Wave Acoustooptic Bragg Diffraction and Devices Using Multiple Tilted Surface Acoustic Waves," *Proc. IEEE*, Vol. 64, pp 318-328, 1976.
10. C. S. Tsai and P. Saunier, "Ultrafast Guided-Light Beam Deflection/Switching and Modulation Using Simulated Electro-optic Prism Structures in  $\text{LiNbO}_3$  Waveguides," *Appl. Phys. Lett.* Vol. 27, pp 248-250, 1975.
11. R. Shubert and J. H. Harris, "Optical Guided Wave Focusing and Diffraction," *J. Opt. Soc. Amer.*, Vol. 61, pp 154-161, 1971.
12. F. S. Hickernell, "Zinc Oxide Thin-Film Surface Wave Transducers," *Proc. IEEE*, Vol. 64, pp 631-635, 1976.
13. M. A. Copeland, D. Roy, J. D. E. Beynon, and F. Y. K. Dea, "An Optical CCD Convolver," *IEEE Trans Electr. Dev.* Vol. ED-23, pp 152-155, 1976.

## APPENDIX E

### Inhomogeneous optical waveguide lens analysis\*

W. H. Southwell  
Electronics Research Division  
Rockwell International  
Anaheim, California 92803

#### Abstract

Gradient-index ray-tracing techniques are used to evaluate performance of inhomogeneous optical waveguide lenses. Using the thin-film waveguide parameters including the lens thickness profile, the phase error and diffraction pattern are derived. The procedure is applied to a classical Luneburg index profile for which exact results are known. The results indicate that better than diffraction-limited accuracy is achievable with reasonable computer running times. A second example demonstrates the procedure on lens profiles approximating generalized Luneburg lenses (focal length  $>$  diameter).

---

\*This work was supported by the Air Force Avionics Laboratory.

## INTRODUCTION

The optical waveguide lens technology<sup>1</sup> is being developed with the expectation of performing signal processing functions using the transform properties of lenses in an integrated optics format. From an optical design consideration, the problem presents new degrees of freedom as well as some constraints. Aside from dealing with one-dimensional apertures, perhaps the most significant difference results from the ability to create inhomogeneous refractors using homogeneous materials in the thin-film integrated optics format. Furthermore, these lenses function in an immersed region of nonunity index. Thus, it becomes possible to utilize the perfect imaging properties of the Luneburg lenses which have been known for many years.<sup>2</sup>

The basic techniques involving the focusing properties of gradient-index media have been known and utilized in the microwave antenna art. Achieving the diffraction-limited potential of planar waveguide lenses in the optical region, however, may not be an easy task in practice. Thus, it is necessary as in the case of standard optical design to have an analysis and design capability. The present paper addresses this issue.

Using the differential equation for ray paths in inhomogeneous media, a waveguide lens ray-trace algorithm is derived from which the optical imaging quality may be ascertained from given or measured waveguide thickness profiles. The associated phase errors are derived using Hamilton's angular characteristic function, from which the image diffraction pattern is calculated. Various numerical techniques employed are described, and some numerical examples illustrating the procedure are included.

## WAVE PROPAGATION IN LAYERED MEDIA

The basis of the effective index for optical propagation is contained in a consideration of the electric field modes in the dielectric waveguide layers.<sup>3</sup> In particular, we will consider the four-layer structure shown in Fig. 1. The layers shown represent a planar structure with optical propagation to the right. The propagating modes are the solutions to Maxwell's equations subject to the appropriate boundary conditions. We present here the results for the case  $n_2 > n_3 > n_1, n_4$ .

Application of the boundary conditions yields the following equations:

$$\tan(hkt + \phi) = -h/p \quad (1)$$

$$\tan\phi = (h/\ell) \tan \gamma \quad (2)$$

$$\tan(-\ell kd + \gamma) = \ell/q \quad , \quad (3)$$

where  $k = 2\pi/\lambda$  and

$$p = \sqrt{n_e^2 - n_1^2} \quad (4)$$

$$h = \sqrt{n_2^2 - n_e^2} \quad (5)$$

$$q = \sqrt{n_e^2 - n_4^2} \quad (6)$$

$$\ell = \begin{cases} \sqrt{n_3^2 - n_e^2} & n_e < n_3 \\ \sqrt{n_e^2 - n_3^2} & n_e \geq n_3 \end{cases} \quad , \quad (7)$$

where  $n_e$  is the effective index for the optical propagation mode.

Using various trigonometric identities, the boundary conditions (1), (2) and (3) may be combined into the following transcendental equation:

$$F(n_e) = \frac{[1 - \frac{\ell}{q} \tan(\ell kd)] \tan(hkt) + \frac{h}{\ell} [\frac{\ell}{q} + \tan(\ell kd)]}{1 - \frac{\ell}{q} \tan(\ell kd) - \frac{h}{\ell} [\frac{\ell}{q} + \tan(\ell kd)] \tan(hkt)} + \frac{h}{p} \quad n_e < n_3,$$

or

$$F(n_e) = \frac{\left[ ([q + \ell] e^{2\ell kd} + q - \ell) \tan(hkt) + \frac{h}{\ell} ([q + \ell] e^{2\ell kd} - q + \ell) \right]}{[q + \ell] e^{2\ell kd} + q - \ell - \frac{h}{\ell} \tan(hkt) ([q + \ell] e^{2\ell kd} - q + \ell)} + \frac{h}{p} \quad (8)$$

$$n_e \geq n_3.$$

The solution  $n_e$  of the equation  $F(n_e) = 0$  is the desired effective index. The numerical solution may be obtained by iteration from a starting value  $n_e^0$  using Newton's method,

$$n_e^{i+1} = n_e^i - \frac{F(n_e^i)}{\frac{dF}{dn}}, \quad (9)$$

where the derivation  $dF/dn$  is also evaluated at  $n_e^i$ . Although an analytical expression may be derived for  $dF/dn$  using implicit differentiation, it is computationally more efficient to obtain a numerical derivative. The numerical derivative requires only one additional evaluation of  $F(n_e)$ , whereas the analytical derivative appears to be much more complicated.

We have thus established a means to evaluate the effective index  $n_e$  in terms of the waveguide parameters and the overlay thickness  $t$ , shown in Fig. 1. Due to the possibility of higher order modes in the waveguide, multiple solutions for  $n_e$  may result. Care should be taken to assure that the initial starting value for  $n_e$  in Eq. (9) is close to the desired solution. Generally, when "stepping" through a changing overlay profile, the previous solution may be used as a starting point for the next adjacent step. This provides rapid convergence and propagation follows the same mode. All of the analysis in this paper assumes a single mode propagation.

Having established the means to provide the effective index, we are now in a position to outline the procedure for tracing a ray through a

reguide region of changing overlayer thickness. For regions of uniform overlayer, the effective index is uniform and propagation follows a straight line. In one step the optical path is described using conventional geometrical optics for these regions having no index changes.

As the ray encounters a region of a gradient index, the ray will begin to execute a curved path. We next address the problem of determining this curved path.

#### GRADIENT-INDEX RAY TRACE

We restrict our interest in this paper to waveguide profiles (and consequently index profiles) having circular symmetry. Consider the ray path shown in Fig. 2. The position vector  $r$  is described in a coordinate system with its origin at the center of symmetry of the index profile. The position of the ray is described by the components of  $r$ . The direction of the ray  $s$  is given by the instantaneous tangent to the curve,

$$r = x \hat{i} + y \hat{j}$$

$$s = \lim_{\Delta s \rightarrow 0} \frac{\Delta r}{\Delta s} = \alpha \hat{i} + \beta \hat{j} .$$

The quantities  $\alpha$  and  $\beta$  are also called the direction cosines of the ray. The ray tracing procedure described here follows, with some modifications, that published by L. Montagnino.<sup>4</sup>

Suppose we know the initial ray position  $(x_0, y_0)$  and direction  $(\alpha_0, \beta_0)$  at one point in space. To find the position in a close neighborhood, we expand  $r(s)$  in a Taylor's series about the known point. The argument  $s$  is the scalar distance along the path. The vector  $s$  is a unit vector in the direction of the tangent.

$$r(s_0 + \Delta s) = r(s_0) + \left. \frac{dr}{ds} \right|_{s=s_0} \Delta s + \frac{1}{2!} \left. \frac{d^2 r}{ds^2} \right|_{s=s_0} (\Delta s)^2 + \frac{1}{3!} \left. \frac{d^3 r}{ds^3} \right|_{s=s_0} (\Delta s)^3 + \dots \quad (10)$$

The first derivative  $dr/ds$  is the ray vector  $s$ , and the second derivative is the curvature vector  $K = d^2 r/ds^2 = ds/ds$ . Thus, the ray vector obeys the expansion

$$s(s_0 + \Delta s) = s(s_0) + K(\Delta s) + \frac{1}{2} \frac{dK}{ds} (\Delta s)^2 + \dots \quad (11)$$

The required derivatives are obtained from the differential equation for the ray position in a gradient index medium,

$$\frac{d}{ds} \left[ n \frac{dr}{ds} \right] = \nabla n, \quad (12)$$

where  $\nabla n$  is the index gradient

$$\nabla n = \frac{\partial n}{\partial x} \hat{i} + \frac{\partial n}{\partial y} \hat{j} \quad (13)$$

Expanding Eq. (12), we obtain the curvature vector

$$K = \frac{1}{n} [\Delta n - (\nabla n \cdot s) s] \quad (14)$$

Before obtaining the last required derivative  $dK/ds$ , we rewrite Eq. (14), making use of the symmetry in  $n$

$$K = f(r) [r - (r \cdot s) s], \quad (15)$$

where

$$f(r) = \frac{1}{nr} \frac{dn}{dr} \quad (16)$$

Differentiating Eq. (15), we have

$$\frac{dK}{ds} = \frac{1}{r} \frac{df}{dr} (s \cdot r) [r - (r \cdot s) s] - f[(r \cdot K)s + (r \cdot s)K], \quad (17)$$

where we have used the general relationships,

$$\frac{dg}{ds} = s \cdot \nabla g, \quad \nabla g(r) = \frac{1}{r} \frac{dg}{dr} r \quad (18)$$

The ray tracing algorithm, therefore, is as follows:

- (1) From the known position and directions  $(x_0, y_0, \alpha_0, \beta_0)$  and index gradient, evaluate the curvature  $K$  and its derivative, Eqs. (14) and (17) at that point.
- (2) Select an incremental step size  $\Delta s$  and evaluate the new position and angle from Eqs. (10) and (11).
- (3) Considering our new position and angle as known, go back to Step (1) and repeat the sequence until the exit surface is reached or until the region is encountered when the index gradient vanishes.

We note that this algorithm requires the index, the gradient  $dn/dr$ , and the second derivative  $d^2n/dr^2$  at each point. It is necessary to discuss how these are obtained.

The assumption is that the only known quantities are the waveguide parameters of Fig. 1, including the outerlayer profile. This thickness profile is either taken from measurements or otherwise specified.

The previous section describes how the index is evaluated as a function of the planar position of the ray. The required index derivatives are perhaps most easily provided using numerical derivative approximations,

$$\frac{dn}{dr} = \frac{1}{2\Delta t} [n(t + \Delta t) - n(t - \Delta t)] \quad (19)$$

$$\frac{d^2n}{dr^2} = \frac{1}{(\Delta t)^2} [n(t + \Delta t) - 2n(t) + n(t - \Delta t)] \quad (20)$$

where  $t = t(r)$  is the given thickness profile.

## EXIT BOUNDARY LOCATION

It is necessary to consider the problem of precisely locating the ray position as it exits the lens region. For computational efficiency, the step size  $\Delta s$  is large compared to the required ray tracing tolerances. Thus, an interpolation is required once the ray has stepped outside the lens.

The procedure we take for locating the edge is as follows. We first define the function  $F$

$$F = r_0^2 - r^2, \quad (21)$$

where  $r_0$  is the lens radius and  $r^2 = x^2 + y^2$  as determined by the ray position. By considering the last point inside the lens as the base point, we see that  $r$  becomes a function of the step size  $\Delta s$ . The function  $F$  then may be considered a function of  $\Delta s$ ,  $F = F(\Delta s)$ . The problem of locating the edge is then solved by finding the root  $\Delta s$  that makes  $F(\Delta s) = 0$ . This may be done using Newton's method

$$(\Delta s)_e = (\Delta s)_0 - \frac{F/dF}{d(\Delta s)} \Big|_{\Delta s = \Delta s_0}. \quad (22)$$

Since the functional dependence of  $F$  on  $\Delta s$  is given through Eq.(10), we have

$$\frac{\partial F}{\partial(\Delta s)} = -2r \cdot \frac{dr}{d(\Delta s)} = -2r \cdot s. \quad (23)$$

Initially  $(\Delta s)_0 = 0$  at our base point inside the lens and the derivative in Eq. (22) has already been evaluated. It is thus a simple matter to apply Eq. (22) until  $|F| < 10^{-8}$  or some prescribed small quantity.

We have now established the general procedure for ray tracing through the waveguide lens. But we have not, as yet, specified a value for the step size  $\Delta s$ . To do this, let us return to a discussion of the convergence properties of the above ray tracing algorithm.

## CONVERGENCE AND AN EXTRAPOLATION TECHNIQUE

There are two factors to be considered when determining a value for the step size  $\Delta s$ . They are computing time and accuracy. It is important to know the accuracy of the ray heights as they leave the lenses. If the rays are being plotted and visual accuracy is sufficient, then the step size is easily determined. The ray trace may be repeated, each time reducing the step size a factor of 2, until no changes are visible on the plot.

However, when tracing diffraction-limited systems, it is necessary to have confidence that the ray trace will provide an exit height accurate to some fraction of a wavelength. This may require extremely small step size and, consequently, long computing time. We, therefore, suggest the following extrapolation technique for achieving the desired accuracy with reasonable step sizes.

For simplicity, let  $h = \Delta s$  be the step size. Consider the ray exit height  $y$  as a function of the (small) step size  $h$ ,  $y = y(h)$ . The problem is to estimate the value of  $y$  for the limit as  $h$  approaches zero. This suggests a Taylor's expansion.

$$y(h) = y(0) + \frac{dy}{dh} h + \frac{1}{2} \frac{d^2y}{dh^2} h^2 + \dots \quad (24)$$

If we assume  $h$  is small enough that the first three terms of the expansion suffice, then we may pick an  $h$ , trace the ray and determine  $y(h) = y_1$ . But there are three unknowns in Eq. (24). Thus, we perform two more ray traces, each time reducing  $h$  by a factor of 2, to give us  $y_2$  and  $y_3$ . This gives us the set of linear equations:

$$\begin{aligned} y_1 &= a_1 + a_2h + a_3h^2 \\ y_2 &= a_1 + a_2h/2 + a_3h^2/4 \\ y_3 &= a_1 + a_2h/4 + a_3h^2/16 \end{aligned} \quad (25)$$

In matrix notation,

$$y = H a , \quad (26)$$

which has a solution

$$a = H^{-1} y, \quad (27)$$

where the matrix H is

$$H = \begin{pmatrix} 1 & h & h^2 \\ 1 & h/2 & h^2/4 \\ 1 & h/4 & h^2/16 \end{pmatrix} . \quad (28)$$

If we choose  $h = 0.025$ , then

$$H^{-1} = \begin{pmatrix} 1/3 & -2 & 8/3 \\ -80 & 400 & -320 \\ 4266.7 & -12800 & 8533.3 \end{pmatrix} . \quad (29)$$

The solution for  $a_1$ , which is the desired estimate  $y(0)$ , is

$$y = y_1/3 - 2y_2 + 8y_3/3 . \quad (30)$$

Equation (30) is the extrapolation formula. Notice that it is a weighted mean of three ray-traced values and that the sum of the weights is unity. Furthermore, it turns out that these weighting factors are the same for any value of  $h$  used to trace  $y_1$ . The validity of Eq. (30), of course, depends on  $h$  being small enough such that the expansion (24) is valid.

To demonstrate the gradient index algorithm and illustrate the extrapolation technique, a classical Luneburg<sup>2</sup> lens index profile was traced. The index profile is given by

$$n = n_0 \sqrt{2 - (r/r_0)^2} , \quad (31)$$

where  $r_0$  is the lens radius and  $n_0$  is the immersion index. The example was chosen because all parallel rays incident on the left are known to come to perfect focus on the optical axis at the edge of the lens. Also, the index gradients are higher than those encountered with longer focal length lenses. Figure 3 shows six rays traced through this classical Luneburg lens.

We next investigated the ray exit height for the lower ray shown in Fig. 3. In this case, this exit height also represents the ray trace error since the true height should be zero. Figure 4 is a plot of the ray trace error as a function of the ray trace step size for a Luneburg lens with a radius of 2 cm (the computation of all the work reported in this paper was performed on a Hewlett Packard 9830A calculator). The tabulation in Table I shows the results of the first three ray traces of that ray.

TABLE I. Exit height  $y$  for various step sizes  $h$

$h(\text{cm})$	$y(\text{cm})$
0.1	$8.65078 \times 10^{-3}$
0.05	$4.18073 \times 10^{-3}$
0.025	$2.05583 \times 10^{-3}$

Using the extrapolation (30), we obtain  $y = 4.3466 \times 10^{-6}$  cm. This result is well within diffraction-limited ray trace accuracy.

Being satisfied that the numerical ray trace procedure is capable of diffraction-limited accuracies, we next proceed to determine the diffraction patterns in the image surface.

## WAVEFRONT ERROR

For systems which are near diffraction limited, the spot diagrams determined by ray tracing are not adequate for comparisons to actual measured image patterns. This occurs because the ray trace itself does not account for diffraction effects. We surmount this problem by employing a technique to determine the phase errors from the ray trace data. These phase errors are then expressed in a pupil function (which is a function of the pupil coordinates). The pupil function is then Fourier transformed and squared to form the image diffraction pattern.

To derive the wavefront errors from ray trace intercept data, we draw upon the theory of Hamilton's angle characteristic function.<sup>5</sup> The angular characteristic function  $T(\beta)$  represents the optical path length along the path through the system described by the entrance height  $y_0$ . This function is also expressed as a function of the exit angle  $\beta$ . The theory states that the ray intercept error  $y$  in the image plane is given by

$$y = - \frac{\partial T}{\partial \beta} . \quad (32)$$

To utilize this theory, we assume that the optical path length may be expressed as a power series in the exit angle coordinate  $\beta$ ,

$$T = c_1\beta^2 + c_2\beta^4 + c_3\beta^6 + \dots \quad (33)$$

Since we are dealing with symmetric systems we consider only even powers of  $\beta$  (the coefficients in this expansion are related to the usual aberrations; that is, the quadratic error,  $c_1$  corresponds to defocus and the other coefficients are related to various orders of spherical aberration).

To determine these coefficients, we trace a number of rays and record the intercepts and the exit angles  $y_j, \beta_j$ . These data points are then fit in a least-squares fashion to the function

$$\frac{\partial T}{\partial \beta} = (2c_1\beta + 4c_2\beta^3 + 6c_3\beta^5 + \dots) . \quad (34)$$

This procedure determines the  $c$  coefficients for the optical path length in Eq. (33).

Prior to fitting the intercept data to the expression (34), it is convenient to first normalize the  $\beta$ 's. By doing this, the wavefront error function (33) is then automatically expressed in terms of normalized aperture coordinates. The preceding statement is valid strictly for systems with a linear relationship between aperture and exit angle. Although this is only approximately true, it is sufficiently close for our case

The phase error is  $2\pi/\lambda$  times the optical path error. Figure 5 is a plot of the phase error of the Luneburg lens of Fig. 3 using the extrapolation Eq. (30) on the rays with  $\Delta s = 0.1$  cm for the initial step size. Since we expect zero phase error, the amount shown represents the residual ray tracing error. We note that it is considerably less than  $\pi/4$  and consequently represents a diffraction-limited wavefront.

The pupil function is given by the expression

$$P = \exp[i2\pi T(y/y_0)/\lambda], \quad (35)$$

where the function  $T$  is expressed in terms of aperture position  $y$ .

It may be shown<sup>6</sup> that the square of the Fourier transform of  $P$  yields the irradiance diffraction pattern in the image plane. This is performed using the discrete fast Fourier transform algorithm. Figure 6 is the diffraction pattern for the Luneburg lens as traced in Figs. 3 and 5.

To further test the system, we moved the detector plane slightly away from the edge of the lens and repeated the evaluation. The corresponding phase error is shown in Fig. 7 and its diffraction pattern in Fig. 8.

## EXAMPLE OF THE GENERAL PROCEDURE ON A WAVEGUIDE PROFILE

We conclude by presenting an example of how this ray trace technique may be used to illustrate the effects of various waveguide profiles on image quality.

Suppose we have a profile described by the relationship  $t=t_0 \cos^{.18} (\pi r/2r_0)$  as shown in Fig. 9. This profile yields an approximation to the index distribution for the generalized Luneburg lens given by Morgan.<sup>7</sup> The exact solution would give a perfect focus in an image surface outside of the lens boundary. Using the techniques described in this paper and the waveguide parameters shown in the figure caption, a number of rays were traced through the system. Figure 10(a) is a plot of these rays. We next alter the lens profile to follow a  $\cos^{.25} (\pi r/2r_0)$  dependence. The results of the trace are plotted in Fig. 10(b). We see how the effects of the shape of the knee of the lens profile affect the spherical aberration. Finally, we plot the lens profile with a  $\cos^{.211} (\pi r/2r_0)$  dependence shown in Fig. 11(c).

## CONCLUSIONS

The above example demonstrates the potential of this analysis technique in designing and fabricating waveguide lenses. When used in conjunction with laboratory measurements, the skill in producing waveguide lenses with desired properties is greatly enhanced. Both the input quantities (the lens profiles) and the output quantities (ray plots and image diffraction patterns) are in terms of measured quantities.

The algorithms presented are designed to be computationally efficient and have diffraction-limited accuracy.

## REFERENCES

1. D. B. Anderson, R. L. Davis, J. T. Boyd and R. R. August, "Comparison of Optical Waveguide Lens Technologies," to be published in J. Quantum Electronics, Special Issue Integrated Optics, April 1977.
2. R. K. Luneburg, Mathematical Theory of Optics (University of California Press, Berkeley, 1966), p. 187.
3. P. K. Tien, "Light Waves in Thin Films and Integrated Optics," Appl. Opt. 10, 2395 (1971).
4. L. Montagnino, "Ray Tracing in Inhomogeneous Media," J. Opt. Soc. Amer. 58, 1667 (1968).
5. M. Born and E. Wolf, Principles of Optics (Pergamon Press, Ltd., London, 1970), p. 137.
6. J. W. Goodman, Introduction to Fourier Optics (McGraw-Hill, New York, 1968), p. 61.
7. S. P. Morgan, "General Solution of the Luneburg Lens Problem," J. Appl. Phys. 29, 1358 (1958). The exact overlayer profiles yielding Morgan's solutions for the generalized Luneburg lens will be published in a forthcoming paper by Southwell.

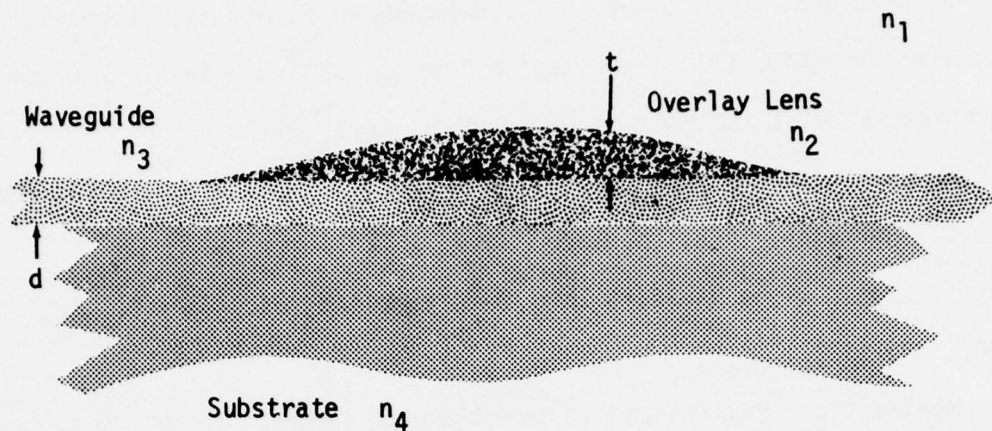


Figure 1E. Cross-Section of Multilayer Planar Dielectric Waveguide. Optical propagation is from left to right.

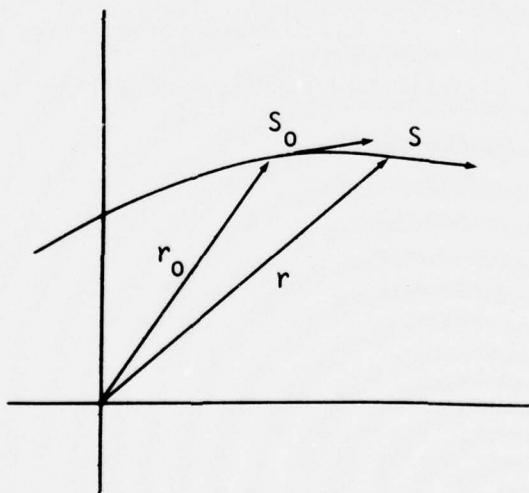


Figure 2E. Ray Path Geometry Showing Ray Position Vector  $r$  and the Ray Vector  $s$ . The Scalar  $s$  is the distance Along the Path and the Vector  $s$  is a Unit Vector Tangent to the Path.

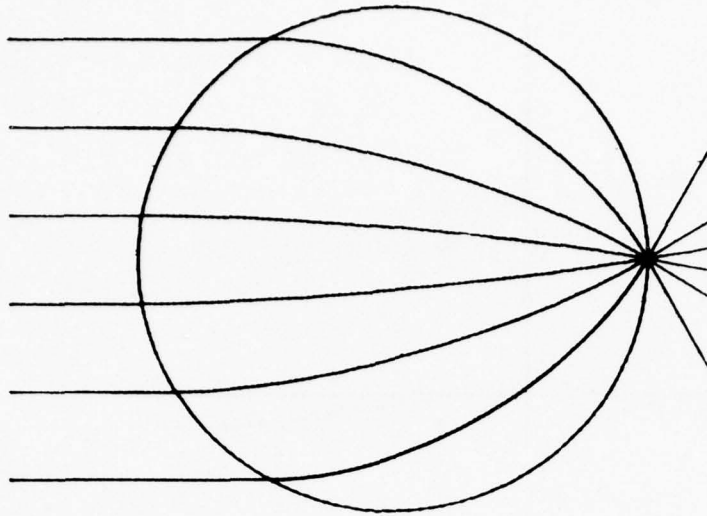


Figure 3E. Plot of the Ray Paths Traced Through the Classical Luneburg Lens Described by Eq. (31).

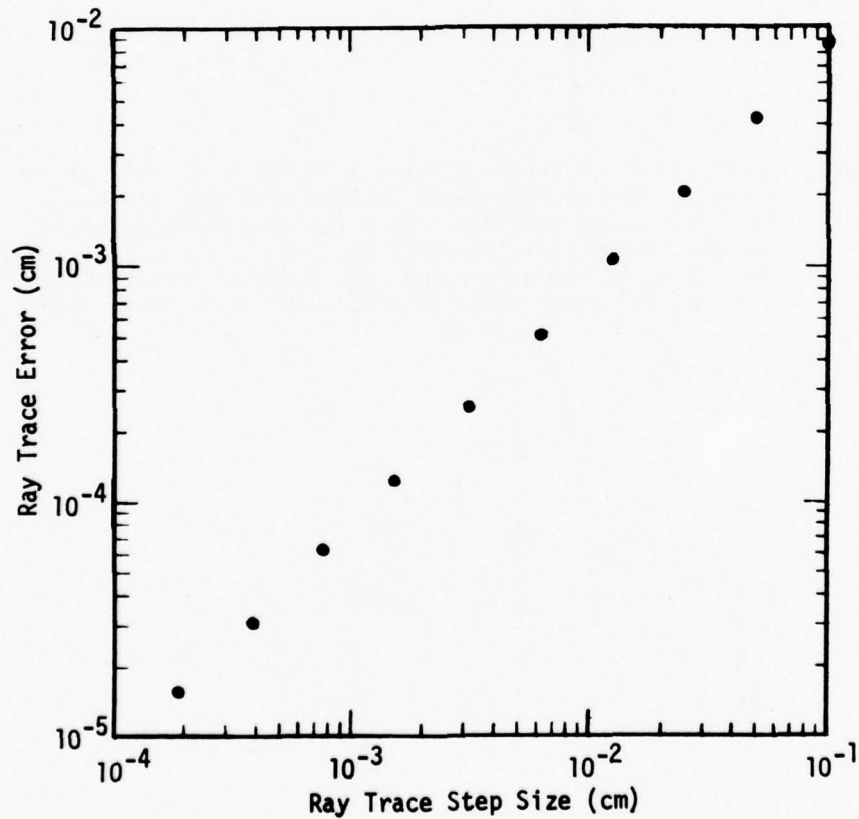


Figure 4E. Plot of the Ray Trace Error as a Function of the Step Size  $\Delta s$  for a 2 cm Radius Classical Luneburg Lens Shown in Fig. 3E. It is Shown that Extrapolation Techniques can Yield Required Accuracy without Using Extremely Small Step Size.

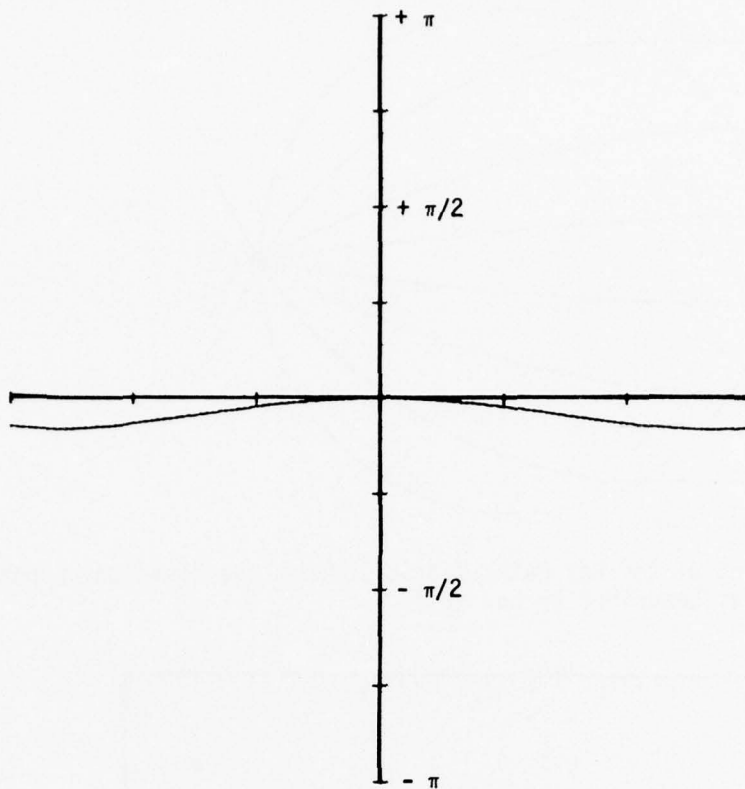


Figure 5E. Wavefront Phase Error in Radians in the Exit Pupil of the Luneburg Lens of Fig. 3E as Derived from the Ray-Trace Technique Using  $\lambda=0.633\mu$ . This residual phase error is due to the numerical ray-tracing, but may be made as small as desired at the expense of more computer running time. However, the error shown is within the diffraction limit.

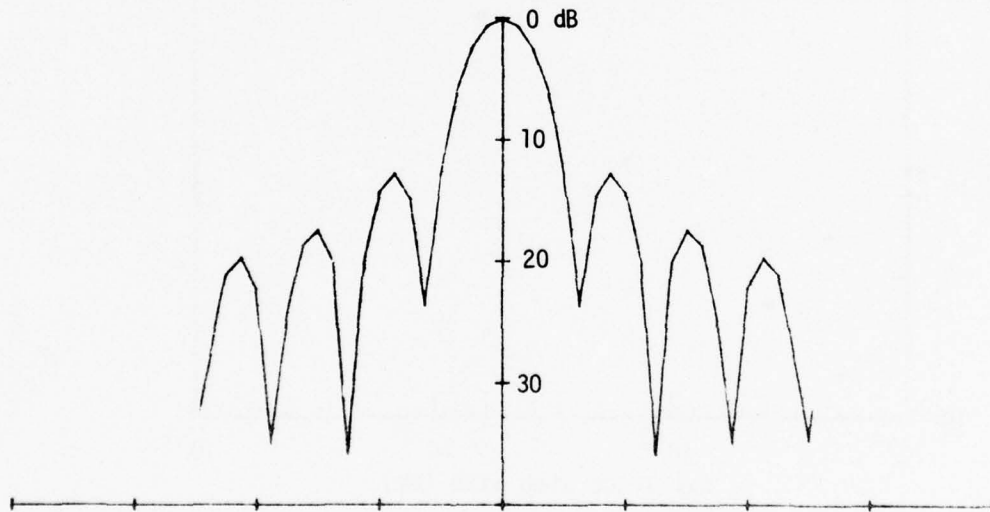


Figure 6E. Diffraction Pattern Showing the Log of the Intensity in the Image Surface for the Luneburg Lens of Figs. 3E and 5E. This pattern agrees with the sinc function squared.

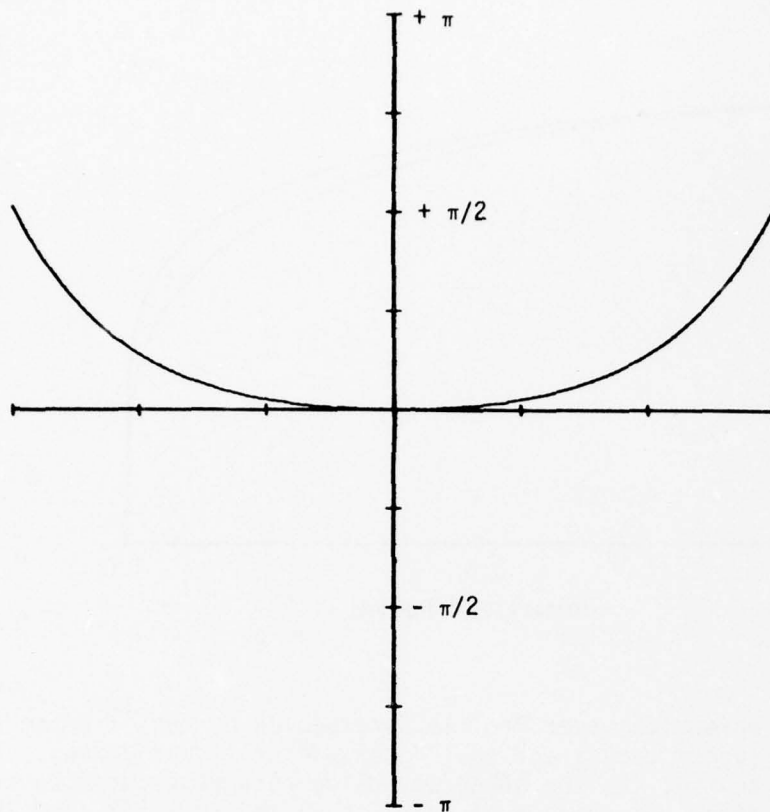


Figure 7E. Phase Error of the Luneburg Lens of Fig. 3E Defocused by  $0.5\mu$ .

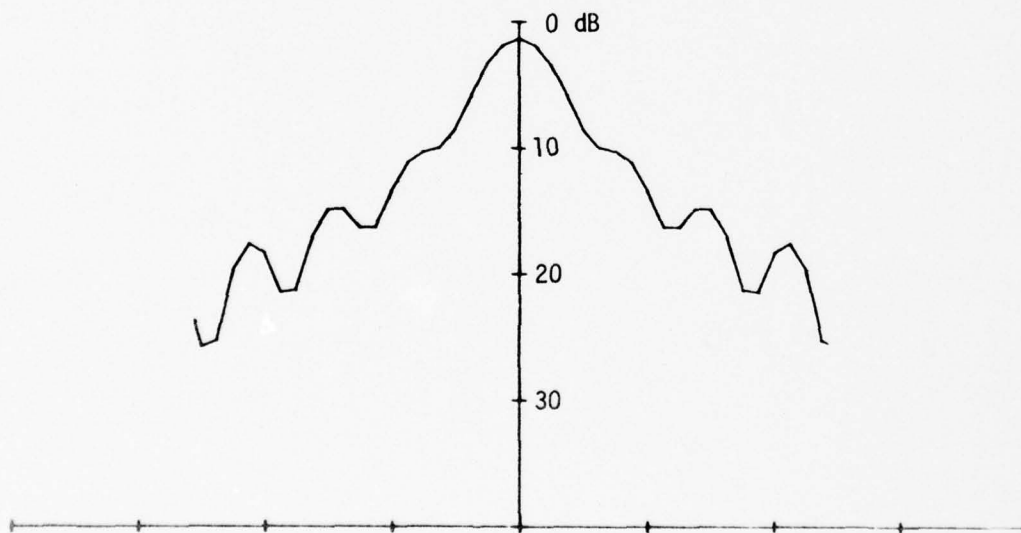


Figure 8E. Diffraction Pattern Resulting from Defocused Luneburg Lens Shown in Fig. 7E. A 64-point fast Fourier transform algorithm was used to generate this pattern.

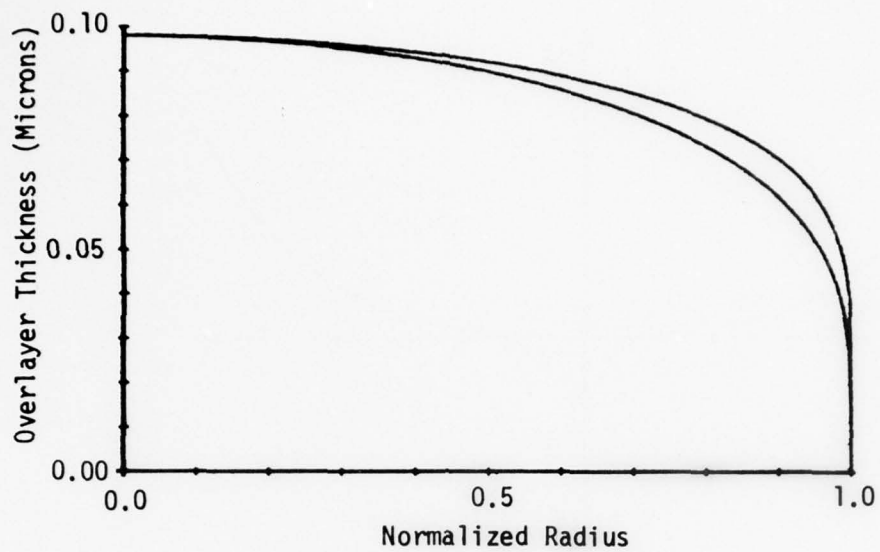


Figure 9E. Waveguide Layer Profile, Represented by  $\cos^{.18}$  Dependence (upper curve) and  $\cos^{.25}$  Dependence (lower curve). Referring to Fig. 1E, the other waveguide parameters used to trace this lens are:  $n_1=1$ ,  $n_2=2$ ,  $n_3=1.565$ ,  $n_4=1.47$ ,  $d=0.75\mu$ , and  $\lambda=0.633\mu$ .

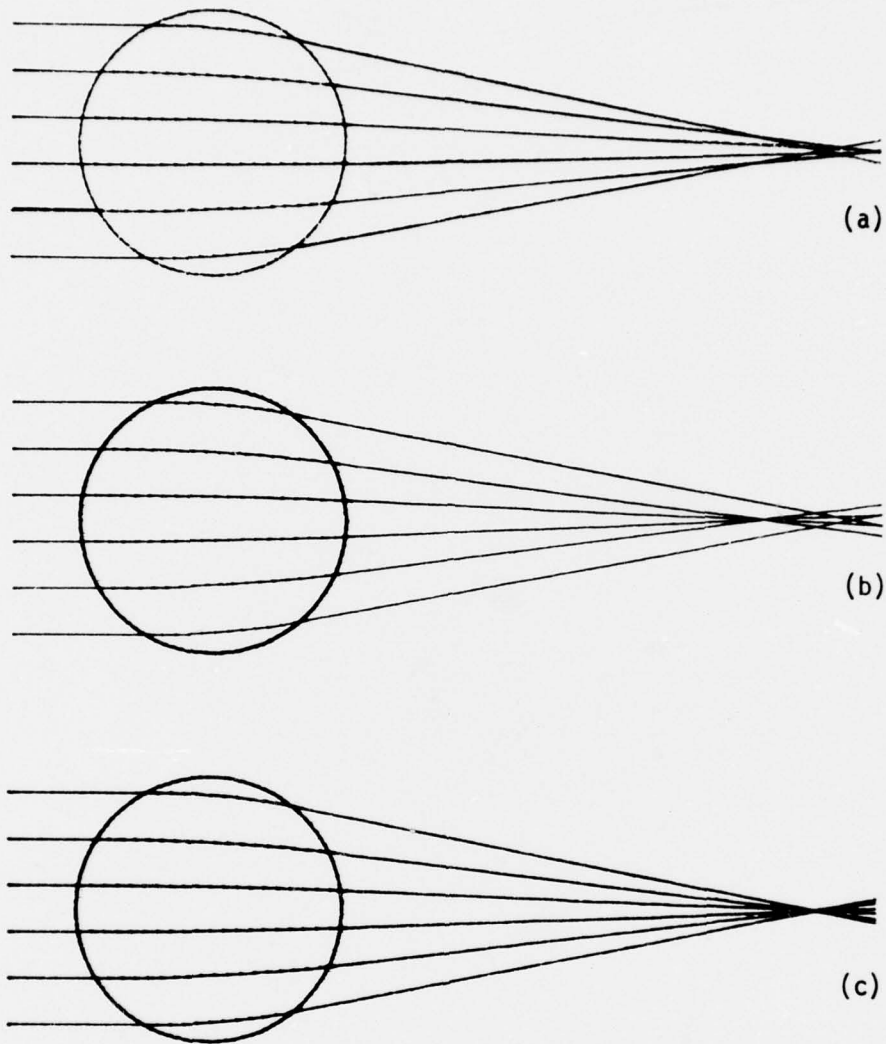


Figure 10E. Ray Plots of Waveguide Lens Described in Fig. 9E: (a) with  $\cos^{.18}$  dependence profile; (b) with  $\cos^{.25}$  dependence profile; (c) with  $\cos^{.211}$  dependence profile.

APPENDIX F

Index and waveguide thickness profiles  
for  
generalized Luneburg lenses\*

W. H. Southwell  
Electronics Research Division  
Rockwell International  
Anaheim, California 92803

ABSTRACT

An analytical approximation is derived which provides a transcendental relationship for the spherically symmetric inhomogeneous index distribution which perfectly focuses infinite objects. Using this expression, the index profiles (called generalized Luneburg lenses) were calculated for lenses having f-numbers down to  $f/1$ . It is shown through a ray-tracing example that these profiles have sufficient accuracy to provide diffraction-limited performance in the optical wavelength region. An expression is also derived for the lens overlay film thickness profile on an optical waveguide in terms of these generalized Luneburg lens index profiles.

---

\* This work was supported by the Air Force Avionics Laboratory.

## INTRODUCTION

In general<sup>1</sup>, a Luneburg lens is a variable-index, spherically symmetric refracting structure which will form perfect geometrical images of two given concentric spheres on each other. One of the spheres may be of infinite radius, in which case the lens will perfectly focus a parallel beam of rays. Luneburg<sup>2</sup> derived an integral equation for these symmetric index profiles. He then solved it explicitly for the case of focusing a parallel beam to an image surface coincident with the edge of the lens. We refer to this well-known refractive index distribution,  $n = \sqrt{2-r^2}$ , where both  $n$  and  $r$  are normalized to unity at the edge of the lens radius, as the "classical" Luneburg lens. By "generalized" Luneburg lenses, we refer to those having image surfaces located at distances greater than one lens radius from the center of the lens.

Morgan<sup>1</sup> formalized the problem more generally than Luneburg by allowing index discontinuities. His solutions are also expressed in terms of integral equations.

Interest in these generalized Luneburg lenses has arisen in integrated optics for application to Fourier transform signal processing functions<sup>3,4</sup>. Zernike<sup>5</sup> demonstrated a classical Luneburg lens on an optical waveguide. Variations in waveguide overlay thickness result in changes in the effective refractive index for optical propagation in the waveguide. Such thickness changes provide the index gradients required for the thin-film Luneburg lenses. This is, in effect, a means of obtaining the rather large index inhomogeneities needed using a homogeneous optical medium. Generalized Luneburg lenses have been demonstrated as waveguide beam expansion systems and as Fourier transform lenses.<sup>4,5</sup>

The problem which we address in this paper is to specify the Luneburg lens index profile and, subsequently, to specify the corresponding overlay waveguide thickness profile. Figure 1 illustrates the optical waveguide parameters.

We report in this paper an analytical approximation for Luneburg's integral equation from which the index profile for the generalized Luneburg lens may be extracted to sufficient accuracy to ray-trace optical wavelengths to diffraction-limited performance. This expression was derived as an expansion based on a consideration of known behavior at certain limits. The expression consists of five parameters which depend on the focal length. Two of these parameters may be determined from the "boundary" limits and the others are determined using a least-squares procedure. This analytical expression provides a convenient means for obtaining the index at any  $r$  for ray-tracing purposes. It also provides a means of conveniently determining integrated optics Luneburg lens thickness profiles.

Plots and tabulated values for Luneburg lens index and waveguide overlay thickness profiles are presented. Using a ray-trace procedure described in another paper,<sup>6</sup> the example herein demonstrates that the phase errors resulting from these index profiles are less than diffraction limited.

#### NUMERICAL INTEGRATION OF THE INTEGRAL EQUATION FOR GENERALIZED LUNEBURG LENSES

A spherically symmetric index distribution  $n(r)$  which gives a perfect image of an infinite object satisfies<sup>2</sup> the integral equation

$$n = \exp[\omega(\rho, s)], \quad (1)$$

where  $\rho = rn$  and

$$\omega(\rho, s) = \frac{1}{\pi} \int_{\rho}^1 \frac{\sin^{-1}(x/s)}{(x^2 - \rho^2)^{1/2}} dx \quad (2)$$

It is assumed that  $r$  is normalized with respect to the radius of the lens region such that  $0 \leq r \leq 1$ . It is also assumed that the lens is immersed in a homogeneous waveguide medium of  $n_0$  and that  $n$  above is normalized with respect to  $n_0$  such that  $1 \leq n$ . The quantity  $s$  is the image distance as measured from the center of the lens, so that  $1 \leq s$ . The full aperture f-number for these lenses turns out to be  $s/2$  for  $2 \leq s$ .

For the case  $s=1$ , where the image surface is located at the edge of the lens itself, the above integral may be evaluated in closed form. This yields the "classical" Luneburg lens

$$n = \sqrt{2-r^2} \quad (3)$$

For generalized Luneburg lenses (longer focal lengths), we must deal with the integral in Eq. (2) directly. To do this, we first perform a change of variables,

$$\omega(\rho, s) = \frac{1}{\pi} \int_0^{1-\rho} \frac{\sin^{-1}\left(\frac{y+\rho}{s}\right)}{(y+2\rho)^{1/2} y^{1/2}} dy \quad (4)$$

We may now remove the  $y^{-1/2}$  singularity by performing an integration by parts,

$$\omega(\rho, s) = \frac{1}{\pi} \left[ 2 \sin^{-1} \left( \frac{1}{s} \right) \frac{(1-\rho)^{1/2}}{(1+\rho)^{1/2}} - \int_0^{1-\rho} \left( \left[ s^2 - (y+\rho)^2 \right]^{-1/2} \right. \right. \\ \left. \left. - \frac{\sin^{-1} \left( \frac{y+\rho}{s} \right)}{(y+2\rho)} \right) \frac{y^{1/2} dy}{(y+2\rho)^{1/2}} \right] \quad (5)$$

Although Eq. (5) appears more complicated, it is actually "well-behaved" and may be easily evaluated numerically. Table I is a tabulation of the quantity  $\omega(\rho, s)$  for various values of  $\rho$  and  $s$ . The integration was performed by dividing the interval into four equal regions and using a 32-point Gaussian quadrature<sup>7</sup> on each region. The numbers given are believed accurate to better than one part in the sixth decimal place.

#### AN ANALYTICAL APPROXIMATION FOR $\omega(\rho, s)$

At this point, we observe that performing an extremely accurate numerical integration to evaluate  $\omega(\rho, s)$  is cumbersome. Furthermore, the quantity obtained is not the index as a function of radial position  $r$ , but is a function of  $\rho = rn$ . Thus, the desired index distribution is still imbedded.

It is desirable to derive an analytical expression to represent or approximate the function  $\omega(\rho, s)$  to the required accuracy. To gain some insight into the functional form of such an expression, we investigate the limiting behavior of Eq. (5) as  $\rho \rightarrow 1$ , which is near the edge of the lens. The integrand in the integral of Eq. (5) approaches zero as  $y^{1/2} \rightarrow 0$ , thus the integral portion behaves as  $(1-\rho)^{3/2}$ . But this is a higher order term compared to the first term on the right side of Eq. (5). Thus, in the limit as  $\rho \rightarrow 1$ ,  $\omega(\rho, s)$  behaves as

$$\omega(\rho, s) = \frac{\sqrt{2}}{\pi} \sin^{-1}\left(\frac{1}{s}\right) (1-\rho)^{1/2} \quad \rho \rightarrow 1 \quad (6)$$

Furthermore, we are led to believe that the next order term will have a  $(1-\rho)^{3/2}$  behavior which suggests the form

$$\omega(\rho, s) = p_1(1-\rho)^{1/2} + p_2(1-\rho)^{3/2} + p_3(1-\rho)^{5/2} + p_4(1-\rho)^{7/2} + p_5(1-\rho)^{9/2} \quad (7)$$

We have already established that

$$p_1 = \frac{\sqrt{2}}{\pi} \sin^{-1}\left(\frac{1}{s}\right) \quad (8)$$

Another constraint is that the function must reduce to the correct value at  $\rho=0$ . From Eq. (4), this value is

$$\omega(0, s) = \frac{1}{\pi} \int_0^{1/s} \frac{\sin^{-1}x}{x} dx, \quad (9)$$

where we have applied another change of variables. The inverse sine in Eq. (9) may be expanded in a series and the integration performed term by term. This leads to

$$\omega(0, s) = \frac{1}{\pi} \left[ s^{-1} + \frac{1}{2 \cdot 3 \cdot 3} s^{-3} + \frac{1 \cdot 3 s^{-5}}{2 \cdot 4 \cdot 5 \cdot 5} + \frac{1 \cdot 3 \cdot 5 s^{-7}}{2 \cdot 4 \cdot 6 \cdot 7 \cdot 7} + \dots \right] \quad (10)$$

The function  $\omega(0, s)$  also determines the value of the index at the center of the lens through the relation  $n = \exp[\omega(0, s)]$  which is also its maximum value. Table II is a tabulation of  $\omega(0, s)$  using Eq. (10) and the maximum index values.

We note that the values of  $\omega(0,s)$  using Eq. (10) agree with the values obtained by numerical integration of Eq. (5) as listed in the  $\rho=0$  row of Table I.

Returning to Eq. (7), we see that  $\omega(0,s)$  equals the sum of the coefficients. Thus, we may specify

$$p_5 = \omega(0,s) - p_1 - p_2 - p_3 - p_4 \quad (11)$$

With Eqs. (8) and (11), only three of the  $p$  coefficients are as yet unspecified. To determine these remaining coefficients, we fit the data given in Table I to the function  $\omega(\rho,s)$  given by Eq. (7). The problem is a linear least-squares curve-fit and the solution is readily obtained. Notice that more points are included near the  $\rho=1$  region in order to more heavily weight the region when the greatest change is occurring. Table III is a tabulation of the results of the curve-fit for the 29 "data" points determined from the numerical integration of Eq. (5). In performing the curve-fit,  $p_1$  was also allowed to vary in order to economize the fit. We note, however, that the best-fit value for  $p_1$  agrees very well with the value predicted by Eq. (8).

#### GENERALIZED LUNEBURG LENS INDEX PROFILES

Having an analytical expression for  $\omega(\rho,s)$ , we are now in a position to extract  $n(r)$  numerically for any specified value of  $r$ . To do this, we define a function  $F$ ,

$$F(n) = \exp[\omega(\rho,s)] - n. \quad (12)$$

For a given  $r$ , we extract the value of  $n$  that makes  $F(n)$  vanish using Newton's iterative method. A tabulation of results is given in Table IV. Plots of

these profiles are shown in Fig. 2.

The ability to provide a numerical value of  $n$  for a given  $r$  is useful for ray tracing these generalized Luneburg lenses. In addition to a numerical value of  $n$ , the ray-trace algorithms<sup>6</sup> also require values for  $dn/dr$  and  $d^2n/dr^2$ . Even though the above procedure provides only a numerical value for  $n(r)$ , we are able to derive analytical expressions for  $dn/dr$  and  $d^2n/dr^2$  in terms of  $r$  and the numerical value for  $n$ . This is done using implicit differentiation of Eq. (12) using Eq. (7) for  $\omega(\rho,s)$ . The results are

$$\frac{dn}{dr} = \frac{-n^2 G}{2(1-rn)^{1/2} + nrG}, \quad (13)$$

$$\frac{d^2n}{dr^2} = \frac{2n^3 [G^2(1-rn)^{1/2} + H]}{[2(1-rn)^{1/2} + nrG]^2} + \frac{2}{n} \left( \frac{dn}{dr} \right)^2, \quad (14)$$

where

$$G = p_1 + 3p_2(1-rn) + 5p_3(1-rn)^2 + 7p_4(1-rn)^3 + 9p_5(1-rn)^4, \quad (15)$$

and

$$H = -p_1 + 3p_2(1-rn) + 15p_3(1-rn)^2 + 35p_4(1-rn)^3 + 63p_5(1-rn)^4. \quad (16)$$

#### WAVEGUIDE LENS THICKNESS PROFILES

The equations<sup>6</sup> governing the relationship between the effective index of refraction  $n$  for the TE mode and the lens overlay thickness  $t$  (see Fig. 1) on

an integrated optics planar waveguide are,

$$-\frac{h}{p} = \begin{cases} \frac{\left[1 - \frac{\ell}{q} \tan(\ell kd)\right] \tan(hkt) + \frac{h}{\ell} \left[\frac{\ell}{q} + \tan(\ell kd)\right]}{\left[1 - \frac{\ell}{q} \tan(\ell kd)\right] - \frac{h}{\ell} \left[\frac{\ell}{q} + \tan(\ell kd)\right] \tan(hkt)} n < n_3 \\ \frac{\left[(q+\ell)e^{2\ell kd} + q-\ell\right] \tan(hkt) + \frac{h}{\ell} \left[(q+\ell)e^{2\ell kd} - q+\ell\right]}{\left[(q+\ell)e^{2\ell kd} + q-\ell\right] - \frac{h}{\ell} \tan(hkt) \left[(q+\ell)e^{2\ell kd} - q+\ell\right]}, n \geq n_3 \end{cases} \quad (17)$$

where  $k = 2\pi/\lambda$ ,  $d$  is the waveguide thickness, and

$$\begin{aligned} p &= \sqrt{n^2 - n_1^2} \\ h &= \sqrt{n_2^2 - n^2} \\ q &= \sqrt{n^2 - n_4^2} \\ \ell &= \begin{cases} \sqrt{n_3^2 - n^2} & n < n_3 \\ \sqrt{n^2 - n_3^2} & n \geq n_3 \end{cases} \end{aligned} \quad (18)$$

The indices used in Eq. (18) are as follows:

$n_1$  is the outer index ( $n_1 = 1$ , usually air),  $n_2$  is the bulk index of the lens overlay material,  $n_3$  is the bulk index of the waveguide material, and  $n_4$  is the substrate index.

Although Eq. (17) is a transcendental equation when determining  $n$  for a given  $t$ , it may be solved explicitly for  $t$  as a function of  $n$ ,

$$t = \begin{cases} \tan^{-1} \left[ \frac{h \left[ 1 - \frac{\ell}{q} \tan(\ell kd) \right] + \frac{ph}{\ell} \left[ \frac{\ell}{q} - \tan(\ell kd) \right]}{\frac{h^2}{\ell} \left[ \frac{\ell}{q} - \tan(\ell kd) \right] - p \left[ 1 - \frac{\ell}{q} \tan(\ell kd) \right]} \right] & n < n_3 \\ \tan^{-1} \left[ \frac{h \left[ (q + \ell) e^{2\ell kd} + q - \ell \right] + \frac{ph}{\ell} \left[ (q + \ell) e^{2\ell kd} - q + \ell \right]}{\frac{h^2}{\ell} \left[ (q + \ell) e^{2\ell kd} - q + \ell \right] - p \left[ (q + \ell) e^{2\ell kd} + q - \ell \right]} \right] & n \geq n_3. \end{cases} \quad (19)$$

Consequently, with the above numerical determination of  $n(r)$ , the lens thickness profile is given by Eq. (19). Table V is a tabulation of the overlay thickness for the waveguide parameters shown. The refractive indices in decreasing value are representative of  $Ta_2O_5$ , Corning 7059 glass and  $SiO_2$ . Figure 3 is a plot of these profiles.

#### DISCUSSION

From an examination of the sum of the residual errors for the best-fit parameters as shown in Table III, we see that better fits are obtained for the larger values of  $s$ . This means that fewer terms in the expansion in Eq. (7) could be used and still provide adequate accuracy for the larger  $s$  values.

It also appears that it may be possible to parameterize all the  $p$ -coefficients as functions of  $s$ . This may be done by either considering higher order terms in the expansion of Eq. (5) or by a curve-fitting process of the best-fit parameters.

We have not pursued the above suggestions for further simplifications. The parameter formulation and the technique for determining their values have proven to be quite satisfactory.

To test the accuracy of the approximation of Eq. (7), we ray-traced the  $s=2$  case using a recently developed procedure<sup>6</sup> that provides phase errors

and image diffraction patterns. Figure 4 is a plot showing six rays traced through the lens. Nineteen rays were traced and the resulting pupil phase error at  $\lambda = 0.9\mu$  was determined. The result is shown in Fig. 5. The corresponding intensity diffraction pattern is shown on a logarithmic scale in Fig. 6. We note that the index as derived from Eq. (7) produces diffraction-limited results. The phase errors for the higher values of  $s$  are even less.

#### ACKNOWLEDGMENT

The author wishes to express appreciation to D. B. Anderson for introducing him to the interesting problem of waveguide lens design and for helpful discussions in the preparation of this paper.

## REFERENCES

1. S. P. Morgan, "General Solution of the Luneburg Lens Problem," J. Appl. Phys. 29, 1358 (1958).
2. R. K. Luneburg, Mathematical Theory of Optics (University of California Press, Berkeley, 1966), p. 187.
3. M. C. Hamilton, D. A. Wille, and W. J. Miceli, "An Integrated Optical RF Spectrum Analyzer," IEEE 1976 Ultrasonic Symposium Proceedings, Annapolis, MD.
4. D. B. Anderson, R. L. Davis, J. T. Boyd and R. R. August, "Comparison of Optical Waveguide Lens Technologies," to be published in J. Quantum Electronics, Special Issue Integrated Optics, April 1977.
5. F. Zernike, "Luneburg Lens for Optical Waveguide Use," Optics Commun., Vol. 12, pp 379-381, 1974.
6. W. H. Southwell, "Inhomogeneous optical waveguide lens analysis," J. Opt. Soc. Am.
7. V. J. Krylov, Approximate Calculation of Integrals (Macmillan, New York 1962) pp 100-111 and 337-340.

TABLE I. THE FUNCTION  $\omega(\rho, s)$  USING NUMERICAL INTEGRATION OF EQ. (5)

$\rho = nr$	Focal Length (from center of lens)			
	$s=2$	$s=3$	$s=5$	$s=9$
0	0.161532974	0.106778890	0.063805003	0.035392104
0.05	0.161342261	0.106648497	0.063725803	0.035347899
0.10	0.160769336	0.106256851	0.063487944	0.035215145
0.15	0.159808733	0.105600483	0.060389404	0.034992731
0.20	0.158451834	0.104673946	0.062527016	0.034678922
0.25	0.156686071	0.103469292	0.061796158	0.034271183
0.30	0.154494419	0.101975755	0.060890568	0.033766077
0.35	0.151854652	0.100179276	0.059802058	0.033159113
0.40	0.148738270	0.098061820	0.058520124	0.032444524
0.45	0.145108972	0.095600405	0.057031366	0.031614952
0.50	0.140920465	0.092765706	0.055318671	0.030660993
0.55	0.136113226	0.089519984	0.053359994	0.029570529
0.60	0.130609596	0.085813951	0.051126507	0.028327704
0.65	0.124306009	0.081581790	0.048579670	0.026911308
0.70	0.117060059	0.076732851	0.045666328	0.025292067
0.75	0.108667412	0.071136813	0.042309951	0.023427811
0.80	0.098816687	0.064594618	0.038393469	0.021253986
0.85	0.086989077	0.056773724	0.033720994	0.018662513
0.90	0.072186077	0.047032184	0.027913781	0.015444290
0.91	0.068702784	0.044746660	0.026553125	0.014690614
0.92	0.064982368	0.042308139	0.025102071	0.013887006
0.93	0.060981056	0.039688340	0.023543894	0.013024222
0.94	0.056638918	0.036848515	0.021855673	0.012089597
0.95	0.051869952	0.033733031	0.020004490	0.011064939
0.96	0.046542594	0.030256728	0.017939945	0.009922388
0.97	0.040436101	0.026276641	0.015577406	0.008615163
0.98	0.033121510	0.021514796	0.012752276	0.007052273
0.99	0.023495253	0.015255661	0.009040778	0.004999423
1.00	0	0	0	0

TABLE II. THE FUNCTION  $\omega(o,s)$  USING EQ. (10)  $n_{\max} = \exp[\omega(o,s)]$

s	$\omega(o,s)$	$n_{\max}(r=0)$
2	0.161532974	1.17531121
3	0.106778890	1.11268820
4	0.0798585731	1.08313387
5	0.0638050027	1.06588453
6	0.0531341389	1.05457109
7	0.0455246840	1.04657684
8	0.0398234213	1.04062701
9	0.0353921041	1.03602586
10	0.0318487205	1.03236132
17	0.0187277137	1.01890418

TABLE III. RESULTS OF FITTING EQ. (7) TO THE DATA IN TABLE I.

The values listed for SUM are the sum of the squares of the errors for the 29 points.  $p_5$  was determined by Eq. (11).

	s=2	s=3	s=5	s=9
SUM	$3.9101 \times 10^{-11}$	$5.8134 \times 10^{-12}$	$1.7893 \times 10^{-12}$	$5.3512 \times 10^{-13}$
$p_1$	0.235687835	0.152976535	.0906399959	.0501194645
$p_2$	$-7.47500358 \times 10^{-2}$	$-4.22494061 \times 10^{-2}$	$-2.34300068 \times 10^{-2}$	$-1.26356394 \times 10^{-2}$
$p_3$	$6.72894476 \times 10^{-3}$	$-1.93175172 \times 10^{-3}$	$-2.51100017 \times 10^{-3}$	$-1.63934418 \times 10^{-3}$
$p_4$	$-5.14447054 \times 10^{-3}$	$-8.25244897 \times 10^{-4}$	$-1.49192458 \times 10^{-4}$	$-4.07947091 \times 10^{-5}$
$p_5$	$-9.89299661 \times 10^{-4}$	$-1.19124255 \times 10^{-3}$	$-7.44793717 \times 10^{-4}$	$-4.11582122 \times 10^{-4}$

TABLE IV. NORMALIZED REFRACTIVE INDEX PROFILES FOR GENERALIZED LUNEBURG LENSES

r	s=2	s=3	s=5	s=9
0	1.175311212	1.112688200	1.065884534	1.036025859
0.05	1.174999407	1.112507930	1.065788087	1.035976411
0.10	1.174071705	1.111969546	1.065500332	1.035828873
0.15	1.172521576	1.111069129	1.065018948	1.035581965
0.20	1.170340993	1.109801290	1.064340603	1.035233817
0.25	1.167519780	1.108158811	1.063460759	1.034781859
0.30	1.164044879	1.106132212	1.062373426	1.034222692
0.35	1.159899514	1.103709214	1.061070836	1.033551908
0.40	1.155062156	1.100874045	1.059543028	1.032763858
0.45	1.149505212	1.097606509	1.057777265	1.031851324
0.50	1.143193243	1.093880684	1.055757219	1.030805062
0.55	1.136080437	1.089663045	1.053461790	1.029613132
0.60	1.128106836	1.084909633	1.050863316	1.028259883
0.65	1.119192434	1.079561599	1.047924746	1.026724355
0.70	1.109227400	1.073537799	1.044594938	1.024977603
0.75	1.098054844	1.066721643	1.040800259	1.022977928
0.80	1.085437716	1.058935566	1.036428193	1.020661529
0.85	1.070987513	1.049884988	1.031290974	1.017921692
0.90	1.053981685	1.039009952	1.025027636	1.014552365
0.91	1.050159236	1.036524794	1.023580201	1.013768729
0.92	1.046155078	1.033902395	1.022045349	1.012935510
0.93	1.041942017	1.031119755	1.020407545	1.012043672
0.94	1.037484456	1.028146025	1.018645667	1.011080865
0.95	1.032734249	1.024938133	1.016729693	1.010029408
0.96	1.027623448	1.021432662	1.014614324	1.008862349
0.97	1.022050589	1.017529080	1.012225136	1.007534739
0.98	1.015851602	1.013049431	1.009422596	1.005960167
0.99	1.008726930	1.007614146	1.005874179	1.003921693
1.00	1	1	1	1

TABLE V. OVERLAY THICKNESS IN MICRONS FOR OPTICAL WAVEGUIDE LUNEBURG LENSES  
 The waveguide parameters are  $n_1=1$ ,  $n_2=2.1$ ,  $n_3=1.565$ ,  $n_4=1.47$ ,  $d=1.0665\mu$ , and  $\lambda=0.9\mu$

r (cm)	s=2	s=3	s=5	s=9
0	0.2191	0.1591	0.1223	0.0979
0.05	0.2187	0.1590	0.1222	0.0979
0.10	0.2177	0.1585	0.1220	0.0978
0.15	0.2160	0.1578	0.1216	0.0975
0.20	0.2135	0.1567	0.1211	0.0972
0.25	0.2105	0.1554	0.1204	0.0968
0.30	0.2068	0.1537	0.1196	0.0963
0.35	0.2024	0.1518	0.1186	0.0957
0.40	0.1975	0.1495	0.1174	0.0949
0.45	0.1920	0.1469	0.1160	0.0940
0.50	0.1860	0.1440	0.1141	0.0930
0.55	0.1794	0.1406	0.1126	0.0918
0.60	0.1722	0.1370	0.1105	0.0905
0.65	0.1646	0.1328	0.1081	0.0888
0.70	0.1563	0.1282	0.1054	0.0869
0.75	0.1472	0.1229	0.1022	0.0846
0.80	0.1374	0.1169	0.0983	0.0817
0.85	0.1262	0.1097	0.0935	0.0780
0.90	0.1130	0.1006	0.0870	0.0727
0.91	0.1099	0.0984	0.0853	0.0713
0.92	0.1067	0.0960	0.0835	0.0697
0.93	0.1031	0.0933	0.0814	0.0679
0.94	0.0993	0.0903	0.0790	0.0657
0.95	0.0949	0.0869	0.0762	0.0632
0.96	0.0898	0.0827	0.0728	0.0601
0.97	0.0835	0.0774	0.0682	0.0559
0.98	0.0749	0.0699	0.0616	0.0499
0.99	0.0597	0.0562	0.0496	0.0395
1.00	0	0	0	0

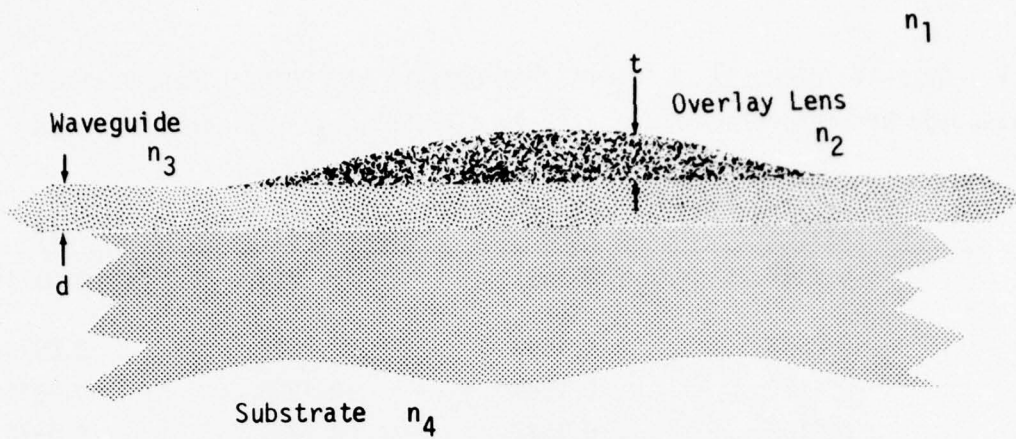


Figure 1F. Cross-Section of Multilayer Planar Dielectric Waveguide.

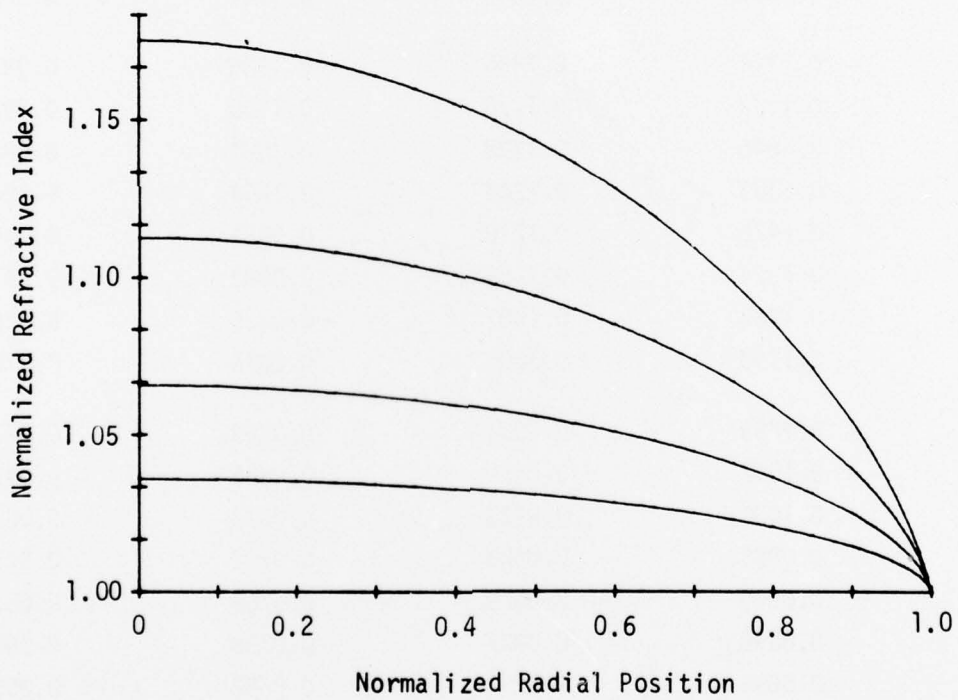


Figure 2F. Index Profiles for Generalized Luneburg Lenses. From top to bottom, the lenses have full aperture f-numbers of  $f/1$ ,  $f/1.5$ ,  $f/2.5$ , and  $f/4.5$ .

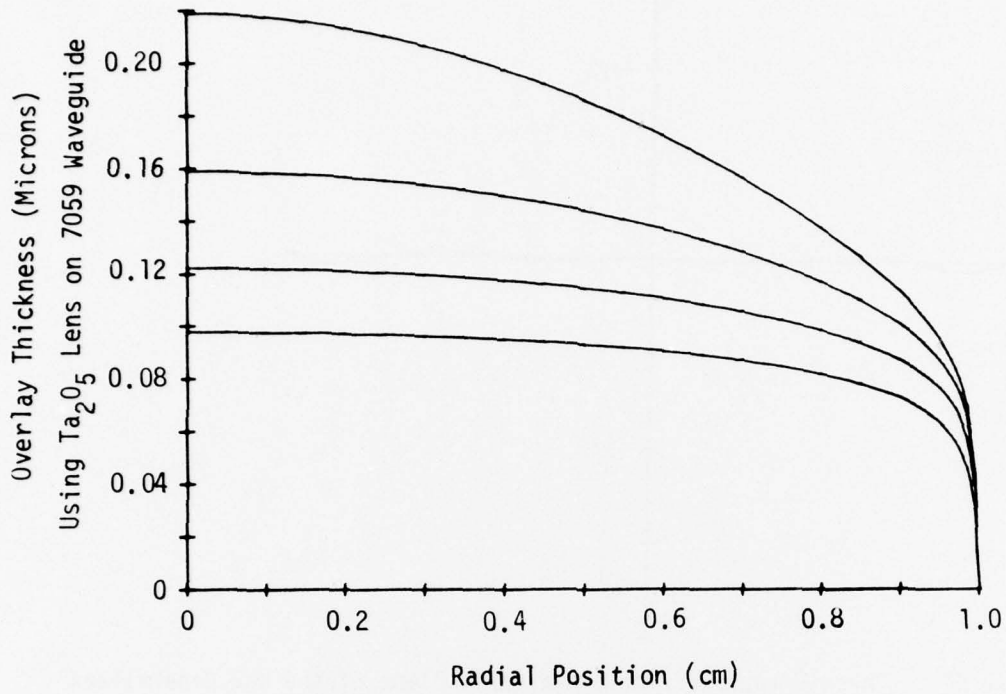


Figure 3F. Waveguide Overlay Thickness Profiles for the Generalized Luneburg Lens Profiles Shown in Fig. 2F for the Waveguide Parameters Listed in Table V.

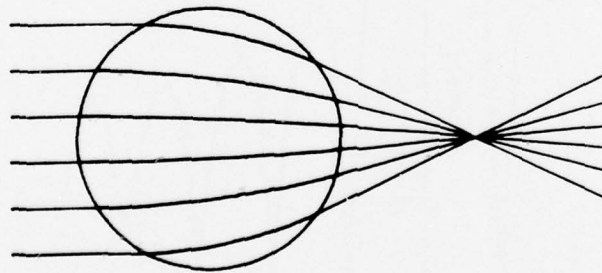


Figure 4F. Ray Trace of the  $s=2$  Generalized Luneburg Lens Using the Index Profile Derived from Eq. (7).

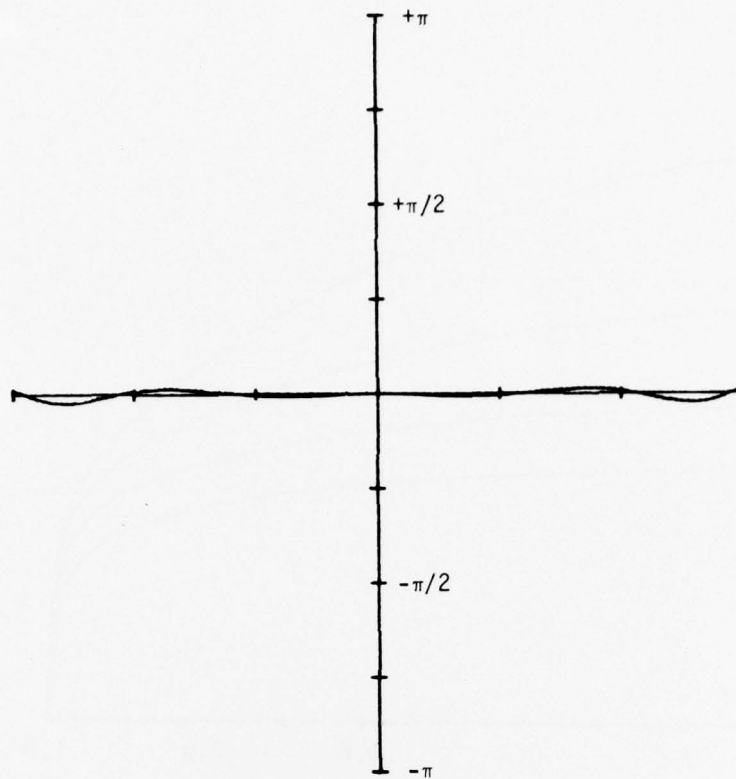


Figure 5F. Phase Error Profile in the Pupil Plane of the  $s=2$  Generalized Luneburg Lens Using the Approximation Eq. (7) to Derive the Index Profile.

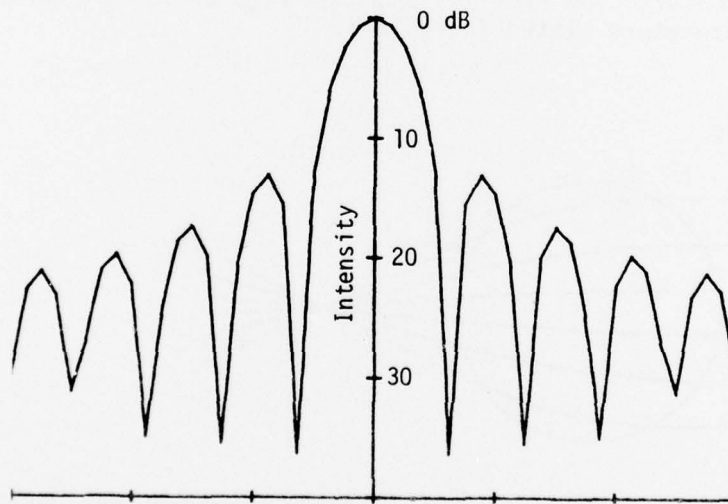


Figure 6F. Intensity Diffraction Pattern Using Logarithmic Scale in the Image Surface for the Luneburg Lens of Figs. 4F and 5F. (Note that this coincides with a diffraction-limited distribution).

#### IV. REFERENCES

1. M. C. Hamilton and D. A. Wille, "Acousto-Optic Diffraction in Optical Waveguides," Digest of Technical Papers, Topical Meeting on Integrated Optics, New Orleans, Louisiana, January 21-24, 1974.
2. M. C. Hamilton, D. A. Wille, and W. J. Miceli, "An Integrated Optical RF Spectrum Analyzer," IEEE 1976 Ultrasonic Symposium Proceedings, Annapolis, Maryland.
3. L. J. Cutrona, E. N. Leith, C. J. Palermo and J. J. Porcello, "Optical Data Processing and Filtering," IRE IT-6, 386 (1960).
4. J. T. Tippett, D. A. Berkowitz, L. C. Clapp, C. J. Koester and A. Vanderburgh, Editors, Optical and Electro-Optical Information Processing, MIT Press 1965.
5. K. Preston, Jr., Coherent Optical Computers, McGraw-Hill 1972.
6. D. B. Anderson, et al, "Thin Film Light Sources for Integrated Optics," Final Technical Report, AFAL Contract F33615-73-C-1041, Rockwell International Report C73-292.23/501, November 1974.
7. D. B. Anderson, R. R. August and J. E. Coker, "Distributed-Feedback Double-Heterostructure GaAs Injection Laser with Fundamental Grating," Appl. Opt. 13, 2742 (1974).
8. R. G. Hunsperger, "Optimized Thin Film Light Sources," Final Report on Contract F33615-75-C-1024, August 1976.
9. D. A. Wille and M. C. Hamilton, "Acousto-Optic Deflection in Ta<sub>2</sub>O<sub>5</sub> Waveguides," Appl. Phys. Lett. 24, 159 (1974).
10. E. G. H. Lean, J. M. White, and C. D. W. Wilkinson, "Thin-Film Acousto-Optic Devices," Proc. IEEE, Vol. 64, 779 (1976).
11. Y. Omachi, "Acousto-Optical Light Diffraction in Thin Films," J. Appl. Phys. 44, 3928 (1973).
12. C. S. Tsai, M. A. Alkaidar, L. T. Nguyen, and B. Kim, "Wideband Guided-Wave Acousto-Optic Bragg Diffraction and Devices Using Multiple Tilted Surface Acoustic Waves," Proc. IEEE 64, 318 (1976).

13. T. G. Giallorenzi and A. F. Milton, "Light Deflection in Multimode Waveguides Using the Acousto-optic Interaction," J. Appl. Phys., Vol. 45, pp 1762-1774, 1974.
14. W. S. C. Chang, "Acoustooptical Deflection in Thin Films," IEEE J. Quant. Electron., Vol. QE-7, pp 167-170, 1971.
15. J. T. Boyd and C. L. Chen, "Integrated Optical Silicon Photodiode Array," Appl. Opt., Vol. 15, pp 1389-1393, 1976.
16. D. B. Anderson, R. L. Davis, J. T. Boyd, R. R. August, and R. E. Eisile, "Optical Waveguide Lenses I," Final Report on Contract F33615-75-C-1017, AFAL-TR-76-54, Mar. 1976.
17. F. S. Hickernell "Zinc-Oxide Thin-Film Surface-Wave Transducers," Proc. IEEE Vol. 64, pp 631-635, 1976.
18. F. S. Hickernell, "The Acoustic Properties of Oxide Films and Their Application to Acoustic Surface Wave Devices," J. Sol. St. Chem. Vol. 12, pp 225-231, 1975.
19. F. S. Hickernell, "DC Triode Sputtered Zinc Oxide Surface Elastic Wave Transducers," J. Appl. Phys. Vol. 44, pp 1061-1071, 1973.
20. N. Chubachi, J. Kushibiki, and Y. Kikuchi, "Monolithically Integrated Bragg Deflector for an Optical Guided Wave Made of Zinc-Oxide Film," Elec. Lett. Vol. 9, pp 193-194, 1973.
21. K. W. Loh, W. S. C. Chang, W. R. Smith, and T. Grudkowski, "Bragg Coupling Efficiency for Guided Acoustooptic Interaction in GaAs," Appl. Opt. Vol. 15, pp 156-166, 1976.
22. G. S. Kino and R. S. Wagers, "Theory of Interdigital Couplers on Nonpiezoelectric Substrates," J. Appl. Phys. Vol. 44, pp 1480-1488, 1973.
23. J. W. Goodman, Introduction to Fourier Optics, McGraw-Hill 1968.
24. L. D. Dickson, "Characteristics of a Propagating Gaussian Beam," Appl. Phys., Vol. 9, pp 1854, 1970.

25. E. G. H. Lean, "Interaction of Light and Acoustic Surface Waves," in Progress in Optics, E. Wolf, Ed., Vol. 11, pp 123-166, North Holland, 1973.
26. N. Uchida and N. Niizeki, "Acousto-optic Deflection Materials and Techniques," Proc. IEEE, Vol. 61, pp 1073-1092, 1973.
27. B. Kim and C. S. Tsai, "High-Performance Guided-Wave Acousto-optic Scanning Devices Using Multiple Surface Acoustic Waves," Proc. IEEE, Vol. 64, pp 788-793, 1976.
28. R. V. Schmidt, "Acoustooptic Interactions Between Guided Optical Waves and Acoustic Surface Wave," IEEE Trans. Son. and Ultrason., Vol. SU-23, pp 22-32, 1976.
29. E. I. Gordon, "A Review of Acoustooptical Deflection and Modulation Devices," Proc. IEEE, Vol. 54, pp 1391-1401, 1966.
30. C. L. Chen, "Thin Film Optical Waveguide and Integrated Photodetector," MS Thesis, Department of EE, Univ. of Cincinnati, 1975.
31. D. H. Hensler, J. D. Cuthbert, R. J. Martin, and P. K. Tien, "Optical Propagation in Sheet and Pattern Generated Films of  $Ta_2O_5$ ," Appl. Opt., Vol. 10, pp 1037-1042, 1971.
32. P. K. Tien, R. J. Martin, and G. Smolinsky, "Formation of Light-Guiding Interconnections in an Integrated Optical Circuit by Composite Tapered-Film Coupling," Appl. Opt., Vol. 12, pp 1909-1916, 1973.
33. P. K. Tien, G. Smolinsky, and R. J. Martin, "Radiation Fields of a Tapered Film and a Novel Film-to-Fiber Coupler," IEEE Trans. Vol. MIT-23, pp 79-85, 1975.
34. T. Tamir Ed., Integrated Optics, Springer-Verlag (1975)(Chapter 2).
35. F. Zernike, "Luneburg Lens for Optical Waveguide Use," Optics Commun., Vol. 12, pp 379-381, 1974.
36. M. Born and E. Wolfe, Principles of Optics, Pergamon Press, New York (1964).
37. R. K. Luneburg, The Mathematical Theory of Optics, University of California Press, Berkeley, California (1954).

38. S. P. Morgan, "General Solution of the Luneburg Lens Problem," J. Appl. Phys., Vol. 29, pp 1358-1369, 1958.
39. O. N. Stavroudis, The Optics of Rays, Wavefronts and Caustics, Academic Press, New York (1972) p 118.
40. H. Jasik, "Fundamentals of Antennas," Antenna Engineering Handbook, McGraw Hill, Chapter 2, 2-1 (1961).
41. W. T. Welford, Aberrations of the Symmetrical Optical System, Academic Press, Chapter 11, (1974).
42. E. H. Linfoot, Sc.D., Fourier Methods in Optical Image Evaluation, The Focal Press (1964).
43. W. F. Kosonocky and J. E. Carnes, "Two Phase Charge-Coupled Devices with Overlapping Polysilicon and Aluminum Gates," RCA Rev. Vol. 34, pp 164-202, 1973.