# ARO-URI CENTER FOR OPTO-ELECTRONIC SYSTEMS RESEARCH

## FELLOWSHIP GRANT

## FINAL REPORT

## 1 OCTOBER 1986 - 30 JUNE 1993

## CONTRACT NO. DAAL03-86-G-0202



DECEMBER 1993



NICHOLAS GEORGE
PROGRAM DIRECTOR

THE INSTITUTE OF OPTICS
UNIVERSITY OF ROCHESTER
ROCHESTER, NEW YORK 14627



PREPARED FOR:

U.S. ARMY RESEARCH OFFICE
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RESEARCH TRIANGLE PARK, NC 27709-2211

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Dr. Nicholas George, Program Director and Wilson Professor of Electronic Imaging

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The Institute of Optics
University of Rochester
Rochester, NY 14627

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**13. ABSTRACT** *(Maximum 200 words)*

Through the establishment of the ARO-URI Center for Opto-Electronic Systems Research in The Institute of Optics of the University of Rochester and the subject grant, we have supported the fellowship program of 38 Ph.D. scholars. The key research interests have been in the areas of lasers, optical system design, signal processing, remote sensing, source analysis, integrated optics, and diffraction and propagation theory. The majority of these exceptional scholars have completed their Ph.D. research and have gone on to work in industry or academia. The few remaining students are completing their work and should be finished within one year. Included in this final report of the Fellowship Grant is a listing of the scholars who were supported along with their thesis title, advisor, and current place of employment. Finally, a listing of each of the thesis abstracts is given.

**14. SUBJECT TERMS**
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URI-ARO
Optoelectronics
Ph.D. Fellowship Program

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ARO-URI CENTER FOR
OPTO-ELECTRONIC SYSTEMS RESEARCH

# FELLOWSHIP GRANT

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# FELLOWSHIP GRANT

## 1. INTRODUCTION

The ARO-URI Center for Opto-Electronic Systems Research was established to contribute fundamental knowledge in the key technology areas of signal processing and image understanding, sources and sensors, and optical system design. A primary goal of the Center has been the education of outstanding graduate students, at both the Masters and Ph.D. levels, in these areas through its affiliation with The Institute of Optics. A large majority of the graduates from The Institute of Optics pursue their professional careers in American industry where they contribute significantly to that industry and to the national and international competitiveness in their respective fields. With the growing interest in optical technology, The Institute of Optics has been able to attract a large pool of applicants to its graduate program.

To achieve this goal, a fellowship program was established to provide funding through stipends to gifted graduate students and to attract the highest quality students to The Institute of Optics. During the course of the program, 38 Ph.D. scholars have been funded. Of those, 33 have completed their theses and five are in the process of finishing. The period of this program is from October 1986 to July 1993. The Director of the ARO-URI Center is Dr. Nicholas George, Wilson Professor of Electronic Imaging.

A listing of the faculty from The Institute of Optics who were involved in the Center is contained in Section 2 of this report. They are arranged according to their primary research interests.

Section 3 contains a listing of the Ph.D. fellows supported by the grant. The thesis title of their research is also given along with the faculty advisor, the year the thesis was completed or is expected to be completed, and the student's current location.

Section 4 contains the thesis abstract from the 33 students who have graduated from the program.

# FELLOWSHIP GRANT

## 2. LISTING OF FACULTY INVESTIGATORS

### SIGNAL PROCESSING & IMAGE UNDERSTANDING

| | |
|---|---|
| Optoelectronic Systems for Pattern Recognition and Remote Sensing | Nicholas George |
| Target Recognition Using Quantum Limited Images | G. Michael Morris |
| Spectral Effects in Two-Beam Interference, with Application to Aperture Synthesis | Emil Wolf |

### SOURCES AND SENSORS

| | |
|---|---|
| Nonlinear Optics | Robert R. Boyd |
| Integrated Optics and Optoelectronic Devices | Dennis G. Hall |
| Liquid Crystal Optics for Laser Applications | Stephen D. Jacobs |
| Coherence Properties of Nonlinear Optical Processes | Michael G. Raymer |
| Spatially Localized Electron Wave Packets and Nonlinear Laser Dynamics | Carlos R. Stroud |
| Electrically Pumped Color Center Lasers | Kenneth J. Teegarden |
| Ultrafast Nonlinear Optics | Ian A. Walmsley |
| Molecular Beam Epitaxial Growth of Materials for Visible Optoelectronic Applications | Gary W. Wicks |

### OPTICAL SYSTEMS DESIGN

| | |
|---|---|
| Advanced Optical Communication Systems | Govind P. Agrawal |
| Modeling and Optimization of Optical Systems | Gregory W. Forbes |
| Monolithic Integration of Waveguide Devices | Susan N. Houde-Walter |
| Gradient Index Optics | Duncan T. Moore |
| Tilted Component Optical Systems | John R. Rogers |

# Fellowship Grant

## 3. Listing of Ph.D. Fellows

| Title / Fellows / Advisor | Year | Current Address |
| --- | --- | --- |
| "Contributions to the theory of the electronic and optical properties of silicon-germanium(x)silicon(1-x) semiconductor superlattices"<br>**Carel Martijn de Sterke**<br>Dennis G. Hall, Advisor | 1987 | University of Sydney<br>Theoretical Physics Department<br>Sydney, Australia NSW 2006 |
| "Image recovery from partial Fresnel zone information"<br>**Robert John Rolleston**<br>Nicholas George, Advisor | 1988 | Xerox Corporation<br>Webster Research Center<br>800 Phillips Road, 0128-29E<br>Webster, NY 14580<br>(716) 422-3138 |
| "Laser speckle from thin and cascaded diffusers"<br>**Lyle Gordon Shirley**<br>Nicholas George, Advisor | 1988 | MIT<br>Lincoln Laboratory<br>P. O. Box 73-KB370<br>Lexington, MA 02173<br>(617) 981-0774 |
| "Optical phase conjugation enhanced by the Brillouin interaction"<br>**Mark Daniel Skeldon**<br>Robert Boyd, Advisor | 1988 | Laboratory for Laser Energetics<br>University of Rochester<br>Rochester, NY 14627<br>(716) 275-4781 |

## Listing of Ph.D. Fellows (continued)

| Title / Fellows / Advisor | Year | Current Address |
|---|---|---|
| "Diffraction theory for polygonal apertures"<br>**R. Edward English, Jr.**<br>Nicholas George, Advisor | 1988 | Lawrence Livermore National Laboratory<br>P. O. Box L-462<br>Livermore, CA 94550<br>(510) 422-3602 |
| "Two-beam coupling and phase conjugation by resonant nonlinear optical interactions"<br>**Mark T. Gruneisen**<br>Robert Boyd, Advisor | 1988 | U.S.A.F. Phillips Laboratory<br>PL/LITN<br>Kirtland Air Force Base<br>Albuquerque, NM 87117-6008<br>(505) 846-4730 |
| "Sol-gel method for making radial gradient-index glass"<br>**J. Brian Caldwell**<br>Duncan T. Moore, Advisor | 1989 | Enichem American, Inc.<br>2000 Princeton Park<br>Monmouth Junction, NJ 08852<br>(908) 422-0400 |
| "Instabilities and chaos of laser beams propagating through nonlinear optical media"<br>**Daniel J. Gauthier**<br>Robert Boyd, Advisor | 1989 | University of Oregon<br>Department of Physics<br>Eugene, OR 97402<br>(503) 346-4759 |
| "Classification techniques for quantum-limited and classical-intensity images"<br>**Miles N. Wernick**<br>G. Michael Morris, Advisor | 1989 | Frank Center for Imaging Analysis<br>University of Chicago<br>5841 S. Maryland Ave., MC 1037<br>Chicago, IL 60637<br>(312) 702-1293 |

## Listing of Ph.D. Fellows (continued)

| Title / Fellows / Advisor | Year | Current Address |
|---|---|---|
| "Dynamics and instabilities in homogeneously broadened laser systems"<br>**Karl William Koch, III**<br>Carlos Stroud, Advisor | 1989 | U.S.A.F. Phillips Laboratory<br>PL/LIDN<br>Kirtland Air Force Base<br>3550 Aberdeen Avenue, SE<br>Albuquerque, NM 87117-6008<br>(505) 846-4750 |
| "Interaction of atomic hydrogen with pico- and femtosecond laser pulses"<br>**Jonathan S. Parker**<br>Carlos Stroud, Advisor | 1989 | University of Maryland<br>NIST<br>College Park, MD<br>(301) 405-1000 |
| "Quantum-limited image recognition"<br>**Thomas Arthur Isberg**<br>G. Michael Morris, Advisor | 1989 | 3M Company<br>3M Center Bldg. 201-3E-03<br>St. Paul, MN 55144-1000<br>(612) 733-1110 |
| "Fabrication and testing of index gradients in fluoride materials"<br>**Michael Tad Houk**<br>Duncan T. Moore, Advisor | 1990 | Burleigh Instruments, Inc.<br>Burleigh Park<br>Fishers, NY 14453<br>(716) 924-9355 |
| "Optical emission from single-crystal silicon"<br>**Phillip Laurence Bradfield**<br>Dennis G. Hall, Advisor | 1990 | Seeking employment |

## Listing of Ph.D. Fellows (continued)

| Title / Fellows / Advisor | Year | Current Address |
|---|---|---|
| "Effects and control of the correlation properties of light sources"<br>**Dean Faklis**<br>G. Michael Morris, Advisor | 1990 | Rochester Photonics<br>330 Clay Road<br>Rochester, NY 14623<br>(716) 272-3010 |
| "Nonlinear optical systems interacting with amplitude-modulated optical fields"<br>**Stephen Harry Chakmakjian**<br>Carlos Stroud, Advisor | 1990 | U.S.A.F. Phillips Laboratory<br>Nonlinear Optics Branch<br>Kirtland Air Force Base<br>Albuquerque, NM 87117-6008<br>(505) 822-7000 |
| "Serrated circular apertures: optical fourier transforms and fractal analysis"<br>**Madeleine Marie Beal**<br>Nicholas George, Advisor | 1990 | 3M Company<br>3M Center Bldg. 260-5A-11<br>St. Paul, MN 55144-1000<br>(612) 736-9287 |
| "Stochastic and deterministic fluctuations in stimulated brillouin scattering"<br>**Alexander Luis Gaeta**<br>Robert Boyd, Advisor | 1990 | Cornell University<br>Applied & Engineering Physics<br>Ithaca, NY 14853<br>(607) 255-9983 |
| "Radial gradient lenses for single-mode optical systems"<br>**John Paul Bowen**<br>Duncan T. Moore, Advisor | 1991 | Rochester Photonics<br>330 Clay Road<br>Rochester, NY 14623<br>(716) 272-3010 |

## Listing of Ph.D. Fellows (continued)

| Title / Fellows / Advisor | Year | Current Address |
|---|---|---|
| "Feedforward neural networks"<br>**Lennart Arnold Saaf**<br>G. Michael Morris, Advisor | 1992 | IBM<br>East Fishkill Facility<br>Fishkill, NY 12524<br>(914) 894-8554 |
| "Hamilton's methods applied to the design of asymmetric, optical systems"<br>**Bryan David Stone**<br>Gregory W. Forbes, Advisor | 1992 | University of Rochester<br>The Institute of Optics<br>Rochester, NY 14627<br>(716) 275-6205 |
| "Pulse shaping in colliding-pulse, mode-locked dye lasers"<br>**Mark Kevin Beck**<br>Ian A. Walmsley, Advisor | 1992 | University of Oregon<br>Department of Physics<br>Eugene, OR 97403<br>(503) 346-4751 |
| "Single point diamond turning of glass"<br>**Christian Gary Blough**<br>Duncan T. Moore, Advisor | 1992 | Rochester Photonics<br>330 Clay Road<br>Rochester, NY 14623<br>(716) 272-3010 |
| "Propagation, loss and free-carrier effects in silicon waveguide structures"<br>**Alan Frank Evans**<br>Dennis G. Hall, Advisor | 1992 | Corning Inc.<br>Sullivan Park, SP-FR-01-7<br>Corning, NY 14831<br>(607) 974-3947 |
| "Design methods for gradient-index optical systems"<br>**David Yih Hsing Wang**<br>Duncan T. Moore, Advisor | 1992 | Co. Breault Research<br>7820 East Broadway, Suite 207<br>Tucson, AZ 85710 |

## Listing of Ph.D. Fellows (continued)

| Title / Fellows / Advisor | Year | Current Address |
|---|---|---|
| | | (602) 721-0500 |
| "Global optimization in lens design"<br>**Andrew Ellicott Wistar Jones**<br>Gregory W. Forbes, Advisor | 1992 | Sinclair Optics Inc.<br>6780 Pittsford-Palmyra Road<br>Fairport, NY 14450<br>(716) 425-4380 |
| "An investigation of distributed coupling in a nonlinear semiconductor waveguide"<br>**David Floyd Prelewitz**<br>Thomas Brown, Advisor | 1992 | University of Rochester<br>The Institute of Optics<br>Rochester, NY 14627<br>(716) 275-8009 |
| "Recovery of particle size distributions from the far field scattering pattern"<br>**Scott D. Coston**<br>Nicholas George, Advisor | 1992 | Bio-Derm, Inc.<br>Clearwater, FL |
| "Wave guiding and grating coupling phenomena in silicon based integrated optics"<br>**Robert Milton Emmons**<br>Dennis G. Hall, Advisor | 1992 | NiOptics Corp<br>1801 Maple Avenue<br>Evanston, IL 60201<br>(708) 491-3196 |
| "Wavelength and roughness dependence of backscattering"<br>**Donald John Schertler**<br>Nicholas George, Advisor | 1993 | University of Rochester<br>The Institute of Optics<br>Rochester, NY 14627<br>(716) 275-5805 |

## Listing of Ph.D. Fellows (continued)

| Title / Fellows / Advisor | Year | Current Address |
|---|---|---|
| "Group III-vacancy mediated disordering of intrinsic and n-type AlGaAs/GaAs"<br>**Brian L. Olmsted**<br>Susan N. Houde-Walter, Advisor | 1993 | University of Georgia<br>Dept. Physics & Astronomy<br>Athens, GA 30602<br>(706) 542-2485 |
| "Optical absorption, emission, and modulation in III-V semi-conductor quantum well structures"<br>**Steven Mark Shank**<br>Gary W. Wicks, Advisor | 1993 | Cornell University<br>Applied & Engineering Physics<br>Ithaca, NY 14853<br>(607) 255-2000 |
| "Spatial optical transforms with applications"<br>**Keith Bryan Farr**<br>Nicholas George, Advisor | 1994 | Advanced Optical Systems, Inc.<br>3330 L&N Drive, Suite A<br>Huntsville, AL 35801<br>(205) 650-5960 |

## LISTING OF PH.D. FELLOWS (CONTINUED)

| TITLE / FELLOWS / ADVISOR | YEAR | CURRENT ADDRESS |
|---|---|---|
| "Dynamics of a molecular nuclear wave packet"<br>**Thomas Dunn**<br>Ian Walmsley, Advisor | (1994) | Anvik Corporation<br>250 Clearbrooke Road<br>Elmsford, NY 10523<br>(914) 345-2442 |
| "Semiclassical properties of Rydberg electron wave packets"<br>**Mark Mallalieu**<br>Carlos Stroud, Advisor | (1994) | The Institute of Optics<br>University of Rochester<br>Rochester, NY 14627<br>(716) 275-8006 |
| "A classical state of the atom: the Keplerian wave packet"<br>**Michael Noel**<br>Carlos Stroud, Advisor | (1994) | The Institute of Optics<br>University of Rochester<br>Rochester, NY 14627<br>(716) 275-8006 |
| "Image deblurring, coding, and compression for multiple point impluse responses"<br>**Bryan Stossel**<br>Nicholas George, Advisor | (1994) | The Institute of Optics<br>University of Rochester<br>Rochester, NY 14627<br>(716) 275-5805 |
| "Soliton generation in pulsed fiber lasers"<br>**Andrew Stentz**<br>Robert Boyd, Advisor | (1995) | The Institute of Optics<br>University of Rochester<br>Rochester, NY 14627<br>(716)175-5030 |

(        ) Means final examination is yet to be taken.

## FELLOWSHIP GRANT

## 4. ALPHABETICAL LISTING OF PH.D. THESES

**TITLE** **PAGE**

## ALPHABETICAL LISTING OF PH.D. THESES (CONTINUED)

## Alphabetical Listing of Ph.D. Theses (continued)

## Alphabetical Listing of Ph.D. Theses (continued)

UNIVERSITY MICROFILMS ORDER NUMBER ADG91-19454.

# SERRATED CIRCULAR APERTURES: OPTICAL FOURIER TRANSFORMS AND FRACTAL ANALYSIS

**Madeleine Marie Beal**

## Abstract

The optical transform of the transmission function of a serrated circular aperture is discussed, with particular emphasis on the relationship between the features in the transform and the parameters that describe the aperture serration. The transform is produced in a canonical optical processing system, where the scalar field distribution in the back focal plane of the lens is proportional to the two-dimensional spatial Fourier transform of the aperture transmission function. In the statistical diffraction theory, the quantity of interest is the two-point moment of the intensity, which is a fourth-order moment of this scalar field component.

A careful calculation of the diffracted field is performed. The two-point intensity moment is expanded in terms of second-order moments of the field. Due to the polar symmetry of the field, circularity does not hold and the two significant terms in the expansion are identical but for a $\pi$ rotation. From the detailed expression for the remaining second-order moment, interesting features of the optical transform are extracted. These features are ring fragmentation, the number of transform spikes, and spike appearance, which correspond to serration roughness, correlation angle, and correlation function, respectively. The results of computer simulations and optical experiments support the predicted relationships between the aperture parameters and transform features. Detailed study and modeling of the errors introduced during fabrication of apertures for use in the experiments show that very small errors (~2 μm) are easily seen in the optical Fourier transform.

The effects of the variations in the parameters of the serration on the fractal dimension of the aperture is also discussed. Geometric techniques are used to measure the fractal dimension of computer-designed apertures. The fractal dimension depends on the roughness $\sigma$ and correlation length $L$ of a serrated aperture or edge by way of the ratio $\sigma/L$ for a given correlation function shape. Changing the correlation function alters this dependence: the fractal dimension increases when the function is sharpened.

UNIVERSITY MICROFILMS ORDER NUMBER ADG92-31263.

# PULSE SHAPING IN COLLIDING-PULSE MODE-LOCKED DYE LASERS

**Mark Kevin Beck**

## Abstract

An investigation into the pulse shaping mechanisms in colliding-pulse, mode-locked (CPM) dye lasers is performed. First, a technique is outlined for measuring the group velocity dispersion (GVD) of optical elements with very high precision. This is important because the pulses of interest in this thesis have very large bandwidths, and consequently are easily distorted by dispersive elements. By measuring this dispersion, these distortions can be compensated for. Next, the intensity and phase of the ultrashort pulses produced by a CPM laser are measured using the frequency domain phase measurement technique. These pulses are approximately 60 fs in duration, and are found to be asymmetric, with a sharper rising than falling edge. The pulses are found to have a negative chirp. Lastly, a numerical model of the laser behavior is implemented. The measured pulses are compared with the pulses calculated using the model in order to help determine what physical effects are important in determining the pulse shape and chirp. It is found, not surprisingly, that amplitude shaping due to saturable gain and absorption play a major role in the pulse shaping. It is also found, possibly more surprisingly, that slow self-phase modulation (SPM) due to off resonant saturation of the gain and absorption, in combination with GVD are the main sources of phase shaping of the pulses. This phase shaping is what causes the measured asymmetry and downchirp of the pulses, but is not believed to be a major factor in determining their duration. No evidence is found that fast SPM due to the Kerr effect is playing a significant role in shaping the 60 fs pulses measured in the experiments. The reasons for this are twofold: pulses produced by a laser which has independently adjustable fast SPM are not found to be any shorter than those produced by the normal laser, and addition of fast SPM to the model for reasonable laser parameters causes an instability in the pulses before it produces a reduction of the pulse duration. If the parameters of the model are adjusted to a more "ideal" case, it is found that phase effects can significantly reduce the pulse duration, but only if the amplitude shaping is sufficiently weak that nearly bandwidth limited pulses cannot be obtained from amplitude shaping alone.

UNIVERSITY MICROFILMS ORDER NUMBER ADG92-31264.

# SINGLE POINT DIAMOND TURNING OF GLASS

**Christian Gary Blough**

## Abstract

The feasibility of single point diamond turning optical quality glass surfaces has been experimentally studied. The main objective of the research is to study the ductile removal process of glass and identify the important parameters. By investigating several optical glasses and varying different machining variables, a matrix of the important parameters has been generated.

A precision lathe capable of ductile machining glass has been assembled by adding a nano-positioning toolholder to an existing machine. The toolholder enables the structural loop between the tool and workpiece to be effectively closed. Using a proximity sensor and analog electronics, a feedback loop has been constructed that increases the rigidity, thermal stability, and tool positioning accuracy of the existing machine. With the closed loop system, the tool positioning resolution is 15 nm and the effective structural loop stiffness is $1.75 \times 10^3$ N/µm. The closed loop system has been verified by machining a circular grating in germanium to within 3 nm of its theoretical form.

The ductile machining of glass was limited by one key variable, tool edge wear. For every glass investigated, except FCD1, there was nearly instantaneous catastrophic loss of the cutting edge due to oxidation and/or graphitization of the diamond.

UNIVERSITY MICROFILMS ORDER NUMBER ADG91-28745.

## RADIAL GRADIENT LENSES FOR SINGLE-MODE OPTICAL SYSTEMS

**John Paul Bowen**

### Abstract

Methods of design and analysis of radial gradient lenses fabricated by a chemical vapor deposition process are developed.

Radial gradient microlenses are useful for a variety of applications, especially those involving microoptics and coupling light between single-mode optical systems. A methodology for combining commercial lens design software and the calculation of single-mode coupling efficiency is presented. This offers the ability to analyze completely general optical systems for single-mode coupling efficiency.

Microoptics manufactured by the modified chemical vapor deposition (MCVD) process have refractive index profiles that may have perturbations, among them a layer structure. The beam propagation method is used to investigate the effects of such perturbations of the refractive index profile on the performance of the lenses.

A facility was constructed in order to perform chemical vapor deposition. The facility used a horizontal pulling process in order to produce 0.5 mm. diameter lenses from the collapsed preforms.

A measurement system based on the refracted near-field method has been designed and built to measure the refractive index profile of samples fabricated by MCVD. In addition, a system for measuring the effect of the lenses on a Gaussian beam input has also been constructed. These two measurements systems are used to confirm effects predicted by the beam propagation method.

UNIVERSITY MICROFILMS ORDER NUMBER ADG90-32734.

# OPTICAL EMISSION FROM SINGLE-CRYSTAL SILICON

**Philip Laurence Bradfield**

## Abstract

The thought of merging integrated optics and electronics on a silicon medium is a very attractive idea because it is easy to imagine building upon the already established electronics industry. In general, integrated optical devices are not constructed from silicon because some of its inherent properties are not conducive to certain needs of integrated optics. A medium that can act as a light source as well as a waveguide would meet two of the more important needs. The problem with silicon is that it has an indirect band-gap and this prevents it from being an intrinsic light emitter except at very low temperatures. One method of overcoming this obstacle is with impurities that create energy levels in the band-gap where radiative transitions can occur. Isoeletronic centers are one type of impurity complex that do this, and four isoelectronic complexes, including a newly discovered one, are studied in this thesis. Both photo- and electroluminescence (PL & EL) experiments were performed as well as measurements to determine radiative lifetimes, external quantum efficiencies, thermal properties of the luminescence, chemical make-up of a center, and optimization of annealing procedures used to create the Be-related isoelectronic impurity.

Specifically, an investigation of the dependence of the sulfur-related PL on the concentration of sulfur is presented. Concentration quenching of the sulfur-related PL is observed and new conclusions about the chemical make-up of the sulfur-related complex are discussed. The newly discovered selenium-related complex that exhibits luminescence at temperatures greater than 80 K is characterized and the striking similarities between it and sulfur suggests that they are closely related. The belief that other chalcogens will not display similar behavior is also presented. Further, it is shown that these centers can act as sources in waveguide structures, being excited either optically or electrically, and a silicon LED (in a waveguide structure) with 0.2-0.5% efficiency at $T \cong 60$ K is demonstrated. Also, evidence that oxygen plays a significant role in the indium-related complex is presented.

UNIVERSITY MICROFILMS ORDER NUMBER ADG89-26028.

## SOL-GEL METHODS FOR MAKING RADIAL GRADIENT-INDEX GLASS.

**J. Brian Caldwell**

### Abstract

Various sol-gel methods for making radial gradient-index (GRIN) glass are investigated. The method of wet gel leaching with metal alkoxide dopants is shown to be particularly successful in producing optical quality material. This method is used to make GRIN glass in high silica $TiO_2$-$SiO_2$ and $ZrO_2$-$SiO_2$ based systems in which $B_2O_3$, $Al_2O_3$, or $GeO_2$ are added to optimize one or more of the processing steps. The resulting glasses have very high melting points and low coefficients of thermal expansion. A wide variety of index profile shapes can be produced with this method. Theoretical approaches to modeling the sol-gel process are discussed.

An immersion method for measuring the absolute index of refraction at the center of a radial gradient sample is presented. This method is simple and inexpensive to implement, and it is accurate to at least $\pm 0.001$.

Several new lens designs are presented which consist of one, two, or three Wood lenses (flat-surfaced radial gradient-index lenses). These designs demonstrate that it is possible to design highly corrected systems using rather simple Wood lenses which have either parabolic or shallow index profiles. Color correction is discussed, as is the use of infrared transmitting materials.

UNIVERSITY MICROFILMS ORDER NUMBER ADG91-11484.

# NONLINEAR OPTICAL SYSTEMS INTERACTING WITH AMPLITUDE-MODULATED OPTICAL FIELDS

**Stephen Harry Chakmakjian**

## Asbstract

This thesis is concerned with the interaction of amplitude-modulated (AM) optical fields with various nonlinear systems. An experimental and theoretical analysis of three distinct nonlinear systems is treated: two-level atoms interacting with a 100% AM field: four-level laser amplifier with an AM pump intensity: a multimode dye laser with an AM pump intensity.

A 100% AM field is the limiting case of strong modulation in which the energy at the carrier frequency is completely supressed, and only the modulation sidebands remain. The interaction of such an optical field with an ensemble of radiatively broadened two-level atoms (an optically-pumped sodium atomic beam is used) yields a complicated series of parametric resonances when both the Rabi frequency and the modulation frequency are large compared with the atomic-transition linewidth. The time-averaged fluorescence, and therefore, the absorption of energy exhibits *parametric-resonant enhancement* whenever the modulation frequency is equal to a subharmonic of the Rabi frequency.

Population oscillations in a multilevel laser amplifier are studied using weak amplitude-modulation spectroscopy. Two laser fields are applied to a four level laser amplifier (alexandrite is used as the amplifier). The intensity of the laser tuned to the pump-transition frequency is weakly modulated, while the modulated gain experienced by a second laser, tuned to the inverted transition, is measured. Amplitude-modulation spectroscopy is used to determine the temperature increase due to thermal relaxations within the crystal.

The near-threshold behavior of multimode cw dye lasers with an AM pump intensity is studied for several dye-laser cavity configurations. The intensity of the argon pump beam is weakly modulated and the modulation spectrum of the laser intensity is studied. Critical slowing down of the response of the laser intensity is observed. The behavior of multimode lasers are compared with the predictions of single-mode four-level laser theory. Also, the modulation spectrum of the fluorescent intensity is studied. The phenomenon of non-adiabatic gain clamping is discussed in relation to the results. Furthermore, the absorption spectrum of the modulation in the intensity of the argon pump beam is studied to complete a modulation-energy-balance analysis.

UNIVERSITY MICROFILMS ORDER NUMBER ADG92-31275.

# RECOVERY OF PARTICLE SIZE DISTRIBUTIONS FROM THE FAR FIELD SCATTERING PATTERN

**Scott D. Coston**

## Abstract

Methods of sorting or counting particles from light-scattering patterns are presented. In the first method, characteristics in the scattered field magnitude and phase are used to distinguish between two classes of particles: metal and dielectric spheres of equivalent size. These observations led to the conclusion that characteristics in the forward-scattered field are not suitable for sorting between the two particle classes. In fact, in the forward-scattering region, both particles exhibit intensity patterns indistinguishable from the optical transform intensity for a disc or an aperture. On the other hand, the backscattered fields are excellent for identifying the two particles. In another method, a matched filter is used to sort between the two particles. Discrimination of the particles can be made by noting differences in the intensity pattern at the correlation plane.

The remainder of the investigation involves recovering the particle-size distribution from the incoherently added optical transform intensity of discs or apertures. Since the optical transform intensity for a disc or an aperture approximates the forward-scattering intensity for a sphere, the application of the method to spheres is straight forward. We begin by giving the necessary conditions to be able to record the incoherently added intensity pattern from a collection of discs or apertures. (The incoherently added intensity pattern is simply an integral over the particle size distribution multiplied by the intensity of a single particle). Then, using Bessel integral identities and Abel transforms, an expression giving the particle-size distribution as an integral over the intensity, multiplied by a kernel is derived. Numerous computer calculations and experiments using the inversion formula are presented. Recovery of single size, multiple discrete size, and continuous-size distributions are performed with excellent results compared to known values. Recovery of the distribution function was also shown to be unaffected by relatively large amounts of noise added to the intensity data.

A careful examination of the sensitivity of the inversion formula to small changes in the particle size distribution is also discussed. We show that differences in particle sizes of a few percent are easily identified. Recovery of fine-scale structure in the distribution is also studied. We show that the smallest structure that can be recovered is inversely proportional to the largest scattering angle used to evaluate the inversion integral.

UNIVERSITY MICROFILMS ORDER NUMBER ADG88-11941.

# CONTRIBUTIONS TO THE THEORY OF THE ELECTRONIC AND OPTICAL PROPERTIES OF SILICON-GERMANIUM(X)SILICON(1-X) SEMICONDUCTOR SUPERLATTICES.

**Carel Martijn de Sterke**

## Abstract

This thesis describes theoretical investigations into the properties Si-$Ge_xSi_{1-x}$ strained layer superlattices. The optical properties are emphasized in order to assess the possibilities of improving the usefulness of silicon for optical applications. In the bulk material this is limited because of the indirect nature of the band gap, which precludes direct optical transitions between the band extrema.

Knowledge of the optical properties of a solid requires a knowledge of the band structure. In the first major part of this work, therefore, the structure of conduction and valence band in Si-$Ge_xSi_{1-x}$ superlattices are calculated. The Effective Mass Approximation is used in these calculations, so that the superlattice wavefunctions are written as a superposition of wavefunctions of the constituent bulk materials. The conduction band calculations focus on the influence of the multi-valley structure of this energy band. It was shown that this influence is very small, but that it increases for decreasing superlattice period. The valence band calculations emphasize the degeneracy of the top of this band. This degeneracy lowers the symmetry compared to that of non-degenerate bands and causes the energy bands of the superlattice to lose their cylindrical symmetry. An investigation of this phenomenon includes a critical evaluation of the axial approximation, in which this loss of symmetry is averaged out.

The last part of this thesis describes some of the optical properties of Si-$Ge_xSi_{1-x}$ superlattices. The first topic is direct band-to-band transitions over the energy gap. These transitions, which are strictly forbidden in the bulk material are symmetry allowed in the superlattice environment. The associated oscillator strength, however, is too small for any practical purposes, except for superlattices with very small periods. After this, transitions among the conduction minibands in these structures are considered. A preliminary conclusion is that these transitions, which have typical wavelengths of several micrometers, can have appreciable oscillator strengths. The final topic concerns indirect transitions in silicon doping superlattices. Specifically, the absorption due to indirect transitions in these superlattices is compared to that in bulk silicon. The conclusion is that the absorption in the superlattice increases for a certain range of energies. The actual absorption coefficient in this energy region, however, is too small for practical purposes.

UNIVERSITY MICROFILMS ORDER NUMBER ADG93-04765.

## WAVE GUIDING AND GRATING COUPLING PHENOMENA IN SILICON-BASED INTEGRATED OPTICS

**Robert Milton Emmons**

### Abstract

This thesis reports on a study of the properties of various waveguides and grating couplers that have possible applications in integrated optics. The focus is on the properties that are important for applications in silicon related systems. The first part of the thesis develops a general computer model that is used to analyze these types of structures. The model is applied to waveguide and grating structures of current interest. Optimization tools are incorporated into the computer model. These tools are shown to be of great utility in producing improved designs for a broad range of waveguide-grating systems.

The silicon-on-insulator (SOI) system considered is one in which a leaky guided-wave can exist in a device-grade silicon layer. Analysis shows that these waves can be low loss and that the leaky nature of the guide results in large mode loss discriminations even for reasonably thick silicon guiding layers. Strong interface reflections which occur during grating coupling cause strong variations in coupling length and efficiency when system parameters are changed. Results show that the correct design approach can result in efficient couplers with cover coupling efficiencies above 60%. The SOI system is shown to exhibit polarization dependent coupling efficiencies which make the TM mode cover coupling efficiencies much larger than the TE counterparts.

The interference and polarization effects observed theoretically in SOI are compared with those observed in couplers based on glass, gallium arsenide, and silicon nitride systems. The importance of these effects is shown to vary widely. The effect of design strategies on efficiency and tolerancing is considered. A glass based waveguide system is used to investigate the polarization dependent coupling efficiency in the laboratory.

Results of the study highlight the importance of a good design approach during grating coupler synthesis. The design approach is applied to a silicon based ARROW waveguide to further illustrate the importance of the technique. The large mode size of ARROW modes generally makes coupling lengths in this system very long. Results show that an efficiency of above 50% into an aperture of 1 mm is possible when the correct design strategy is applied and the structure is explicitly optimized.

UNIVERSITY MICROFILMS ORDER NUMBER ADG89-07463.

# DIFFRACTION THEORY FOR POLYGONAL APERTURES

**R. Edward English, Jr.**

## Abstract

We explain and describe diffraction from polygonal apertures over a wide range of sizes and observation distances. In the first case considered, a small square aperture ($2a \times 2a$, $ka \lesssim 1$, where $k = 2\pi/\lambda$ is the wavenumber) in a perfectly conducting plane screen of vanishing thickness diffracts a normally incident, linear polarized, monochromatic plane wave. Within the vector framework of Maxwell's equations, we hypothesize a solution for the dominant component of the electric field. Subsequently, by means of an integro-differential equation formulation of the diffraction problem applied to small apertures, we substantiate the solution. The solution represents the first three terms in a more general expansion for the aperture field. Physical intuition and the solutions for circular apertures and slits motivate us to propose this expansion. Numerical calculations validate the solution over most of the aperture except in the close vicinity of the corners of the aperture. This limited expansion does not achieve an accurate description of the field near the corners.

In the remainder of the investigation we treat diffraction within the realm of Fourier optics. We develop a Gaussian beam expansion and use it to describe diffraction from a plane-screen corner of arbitrary angle. Two intersecting, coplanar half-plane screens form this corner. For Gaussian illumination of the corner, we consider several opening angles and explain computer-generated plots of the diffracted intensities. In addition we compute the optical transform of a uniformly illuminated triangular aperture and a sector of a circular aperture. Both of these aperture are plane-screen corners, but they have different bounding edges.

The triangular aperture transform solution constitutes a basis for describing diffraction by a polygonal aperture. A suitable combination of rotated, elemental triangular apertures can represent the polygon. Hence, the diffraction pattern for the polygon comprises the diffraction patterns of these elemental triangles. A similar decomposition procedure is the key to writing a simple closed-form solution for diffraction by nested polygonal apertures. We present results for the particular case of a regular pentagon; here, the elemental building blocks are isosceles triangles with a grating-like structure. The diffraction patterns of these nested apertures contain interesting, low-intensity features: nested polygons are traced out in the diffraction pattern. Numerical calculations and careful measurements confirm them.

UNIVERSITY MICROFILMS ORDER NUMBER ADG92-31277.

# PROPAGATION, LOSS AND FREE-CARRIER EFFECTS IN SILICON WAVEGUIDE STRUCTURES

**Alan Frank Evans**

**Abstract**

This research explores silicon as an integrated optical material. A variety of material systems have been investigated for integrated optic applications, including lithium niobate, GaAs, glass, and polymers. However, silicon, the backbone of the microelectronics industry, has largely been ignored. Yet, silicon's role as the dominant electronic material can be taken advantage of for integrated optics, particularly optoelectronic applications. Low-loss optical waveguides and optical modulators are the two important components of integrated optical circuits investigated for silicon in this thesis.

Attention is directed towards silicon-on-insulator (SOI) material, currently generating excitement for submicron VLSI electronic integration due to its numerous advantages and processing compatibility. Not only could SOI material lead the push towards next generation microelectronic circuits, but it can also act as an optical waveguide. SOI waveguiding properties are fully studied and characterized. Specifically, optical attenuation measurements are presented on SOI material formed by the SIMOX (Separation by **IM**plantation of **OX**ygen) and BESOI (**B**ond-and-**E**tchback **S**ilicon-**O**n-**I**nsulator) processes using a fiber-optic scanning technique. In addition, waveguiding parameters (silicon refractive index, thickness, and grating depth) are determined and grating input coupling efficiency is addressed.

First-order perturbative scattering theories are extended and applied to investigate the source of the measured optical attenuation in SOI waveguides. A separation of the measured optical loss due to scattering from interface roughness and refractive index fluctuations is possible by interpretating the dependence of loss on the mode number ($TE_0$ and $TE_1$). Both scattering components play a role in the observed attentuation. The scattering theory is further used to model the physical surface and volume irregularities. Moreover, interesting interference effects are predicted in the calculated loss as a function of waveguide thickness as well as a strong sensitivity of SOI waveguides to surface roughness and refractive-index inhomogeneities compared with other semiconductor waveguides.

Integrated optical modulators find application in optical communication and signal processing. To determine the electrically-induced, free-carrier, refractive-index changes possible in silicon, a silicon Schottky diode structure supporting a surface plasmon mode is employed. The strong overlap of the injected free carriers and optical mode provide a useful change in the refractive index of silicon at a very low current density. The interplay of free-carrier and thermal effects is also examined.

UNIVERSITY MICROFILMS ORDER NUMBER ADG90-32744.

# EFFECTS AND CONTROL OF THE CORRELATION PROPERTIES OF LIGHT SOURCES

**Dean Faklis**

## Abstract

Several topics associated with the influence and control of the statistical properties of light are investigated. One topic that is considered is the modification of the observed spectrum by the correlation properties of a partially coherent secondary source. It is demonstrated experimentally that source correlations that violate a certain scaling condition give rise to a normalized spectrum in the far zone that is different from the normalized spectrum of the light at the source.

Statistical correlations can also give rise to frequency shifts in the spectrum observed in the far field if the correlation function of the emitted radiation does not satisfy the scaling condition. A Fourier achromat is used to generate a secondary source in which the degree of spatial coherence is independent of wavelength; i.e., it violates the scaling condition. The spectrum detected in the far zone of the secondary source is found to be displaced in frequency and distorted relative to the spectrum measured at the secondary source. The displacement is found to be toward the higher frequencies or the lower frequencies depending on the direction of observation.

The use of a new method to generate partially coherent sources with controllable correlation is also investigated. Experiments are described in which the feasibility of synthesizing source correlations for use in spectral modulation applications is tested. The secondary source with controlled correlation is generated using an interferometric optical system that is designed and constructed around a general spectral filter. The degree of spectral coherence is shown to be directly related to the passband of the filter.

The final topic that is considered is the calculation of the correlation properties of synchrotron radiation. The second-order statistical properties of synchrotron radiation resulting from a three-dimensional relativistic electron bunch in a storage ring are calculated. The theory is extended, using a formalism in the space-frequency domain, to allow for electrons in a 3-D bunch to have a distribution of velocities.

UNIVERSITY MICROFILMS ORDER NUMBER ADG94-To be assigned.

## SPATIAL OPTICAL TRANSFORMS WITH APPLICATIONS

**Keith Bryan Farr**

**Abstract**

Two-dimensional transforms of objects under natural illumination are considered. An optoelectronic hybrid system is used to acquire the spatial transform. The optical portion of the system consists of a twin-imaging interferometer cascaded with a lens system that achromatizes the interference fringes. The interference fringes are detected by a CCD array, and postdetection processing is done by a digital computer.

A generalized model for optical spatial transforms is introduced, which in its most general form consists of two independent imaging systems that share common object and exit-pupil planes. The spatial transform is detected in the exit-pupil plane. The radial shear and rotational shear interferometers are presented as examples.

Two methods of improving the optical portion of the spatial-transform system are explored. The first is the use of a wavelength tunable laser as a diagnostic tool. With this tool a technique for constructing a beamsplitter cube that has extremely well-balanced paths is developed. The second approach to improving the optical system is the development of a design procedure for the lenses. A three-element design is presented that has length $320\,mm$ and is capable of resolving over $10^6$ pixels with an operating spectral bandwidth of $100\,nm$.

In some spatial transforms presented, a tunable laser source and a moving diffuser are used to form a spatially incoherent narrow-band source. In order to verify the spatial coherence of these sources a technique for measuring spatial coherence is developed using the inverse relationship between the angular spread of light and the coherence length of the source. Coherence measurements using both white-light and laser sources are presented.

A catalog of object-transform pairs is assembled and grouped into three series. In the first series, relationships between object features and transform features are explored including the inverse nature of the object and transform widths, the replication effect of gratings, and the edge-angle relationship. In the second series, features that are unique to the cosine and sine transforms are emphasized. Object position sensitivity and symmetry properties of the cosine and sine transforms are examined. The orientation ambiguity of the cosine transform is demonstrated along with a simple method of removing that ambiguity. In the third series the general cosinusoidal transform is demonstrated. The transform is shown to progress from cosine transform to Hartley transform to sine transform with the changing reference angle in the interferometer.

UNIVERSITY MICROFILMS ORDER NUMBER ADG91-19464.

# STOCHASTIC AND DETERMINISTIC FLUCTUATIONS IN STIMULATED BRILLOUIN SCATTERING

**Alexander Luis Gaeta**


## Abstract

The dynamical behavior of stimulated Brillouin scattering (SBS) under a variety of conditions is investigated both theoretically and experimentally. Under conditions of a single continuous-wave laser field, the initiation of the SBS process is treated by including the thermal fluctuations of the material density which lead to spontaneous Brillouin scattering. Predictions are made for the threshold of SBS, for the output Stokes spectrum, and for the temporal behavior of the Stokes light. The spectrum of the output Stokes light is predicted to exhibit gain-narrowing as the input laser intensity is increased. Under certain conditions, the Stokes output intensity is expected to exhibit nearly 100% fluctuations even far above the threshold for SBS. Experiments performed in a single-mode optical fiber verify many of the predictions of the theory.

Due to the high gain that can be achieved for the Stokes wave, a small amount of feedback from both interfaces of the interaction region is found to dramatically modify the characteristics of the output Stokes light. The system is found to undergo a transition from stochastic to deterministic behavior. Theoretical analysis demonstrates that the threshold for Brillouin oscillation can be much lower than the threshold for single-beam SBS, and the spectrum is shown to be nearly monochromatic. The temporal behavior of the Stokes light above threshold is found to exhibit both stable and periodic output. Experiments utilizing a single-mode optical fiber with feedback from the endfaces confirmed many of the theoretical predictions.

Stimulated Brillouin scattering in the presence of two counterpropagating laser beams is studied. Under these conditions, the laser beams become temporally unstable to the growth of Stokes and anti-Stokes light. For the case when the input intensities of the two waves are comparable, the threshold for instability can be significantly lower than the threshold for usual single-beam SBS and, for the case of a broad Brillouin line, the system can show a period-doubling route to chaos. This Brillouin instability was observed experimentally using carbon disulfide as the Brillouin-active material.

UNIVERSITY MICROFILMS ORDER NUMBER ADG89-26037.

# INSTABILITIES AND CHAOS OF LASER BEAMS PROPAGATING THROUGH NONLINEAR OPTICAL MEDIA

**Daniel Joseph Gauthier**

## Abstract

The interaction of two strong laser beams propagating through a nonlinear optical medium is studied theoretically and experimentally. It is shown that this interaction is unstable in that new, intense fields can be generated. An experiment has been performed to investigate the stability characteristics of near-resonant laser beams counterpropagating in a sodium vapor. It is found that the states of polarization of the transmitted waves change abruptly to a value different than the input polarizations when the intensities of the waves are above a well-defined threshold. This result demonstrates that multistability can occur in a cavity-less, nonlinear optical system.

When the intensities of the counterpropagating waves are far above the threshold for multistability there are no stable states of the system and the fields fluctuate chaotically in time. This result shows that an optical system can be dynamically unstable due solely to the effects of the nonlinear interaction and the effects of propagation. The attractors describing the dynamical evolution of the system are constructed in phase space and the fractal dimensions and entropies characterizing the attractors are determined. The boundary of the region of instability is measured and is found to depend on the detuning of the laser frequency from the sodium $3S_{1/2} \rightarrow 3P_{1/2}$ resonance, on the intensities and polarizations of the input beams, on the atomic number density, and on the buffer gas pressure.

The results are in good qualitative agreement with the predictions of a theory that models the nonlinear optical response in terms of the optical Kerr effect. Quantitative agreement is obtained through use of a more detailed model based on the solutions to the density-matrix equations of motion for the atomic system.

UNIVERSITY MICROFILMS ORDER NUMBER ADG89-13571.

# TWO-BEAM COUPLING AND PHASE CONJUGATION BY RESONANT NONLINEAR OPTICAL INTERACTIONS.

**Mark Tyree Gruneisen**

## Abstract

Two-beam-coupling and degenerate-four-wave-mixing interactions are studied for the case of near-resonance excitation of a system of two-level atoms. First, a theoretical and experimental study is made of the gain and absorption experienced by a weak probe beam propagating through a sodium vapor in the presence of an intense pump field that is nearly resonant with the $3^2S_{1/2} \rightarrow 3^2P_{3/2}$ atomic transition. The probe-transmission spectrum includes three distinct resonances that result from the modification of the atomic-level structure by the ac-Stark effect. Two of these resonances can lead to amplification of the probe wave. The larger gain was measured at the Rabi-sideband resonance and corresponds to a 38-fold increase in the probe intensity, while a somewhat smaller gain, leading to a 4-fold increase, was measured at the Rayleigh resonance.

For probe-field intensities comparable to the pump-field intensity, a theoretical calculation predicts a vast number of Rabi-subharmonic resonances. However, the highest coupling efficiencies occur at the Rayleigh resonance and persist even when the effects of atomic motion and propagation are included. An experiment was carried out with beams of equal energies using a pulsed alexandrite laser turned near the $4^2S_{1/2} \rightarrow 4^2P_{3/2}$ transition in potassium vapor. The transmitted probe wave was observed to contain 85% of total input energy.

Finally, a theory of degenerate four-wave mixing is presented that includes the effects of pump-wave propagation in the weak-probe limit. An analytic solution for the intensity distribution of the two counterpropagating pump fields is derived and used to calculate the spatial variation of the nonlinear absorption and coupling coefficients that appear in the coupled-amplitude equations for the probe and conjugate waves. The couples-amplitude equations are then solved numerically to obtain the phase-conjugate reflectivity. A study is made of the effects of laser intensity, absorption path length, and detuning on the phase-conjugate reflectivity. The conditions required to achieve unit reflectivity and oscillation are discussed.

UNIVERSITY MICROFILMS ORDER NUMBER ADG90-32755.

## FABRICATION AND TESTING OF INDEX GRADIENTS IN FLUORIDE MATERIALS

**Michael Tad Houk**

### Abstract

The feasibility of manufacturing and measuring gradient-index (GRIN) fluoride materials that transmit ultraviolet light is demonstrated. Conventional Czochralski crystal growing equipment is modified to allow controlled doping of the melt during the growth of a mixed crystal. This doping produces a composition that varies along the axis of the crystal in a predictable manner. Mixed barium fluoride and calcium fluoride crystals that transmit optical wavelengths to 210 nm are grown. The theory of crystal growth in conjunction with active doping is discussed and the appropriate equations governing the index profile as a function of growth parameters are derived. This method is of a general nature and is applicable to the production of controlled index gradients in a wide variety of materials whose phase properties include a solid solution.

In order to measure the index profiles in the ultraviolet region of the spectrum an achromatic moire deflectometer is designed and built. To provide accurate phase information an automated phase retrieval scheme is implemented using a personal computer and the harmonic phase modulation method. The diffraction theory for the operation of the deflectometer is presented along with the theory of harmonic phase modulation that is used to extract phase information from the fringe pattern. An analysis of the effects of non-ideal phase modulation is also presented. Measurements of the index profiles of several GRIN materials are made at wavelengths from the visible to the UV and the results are presented with a discussion of possible sources of error and their removal or compensation. Calculation of the dispersion number of GRIN materials is carried out for two different types of materials and the results are compared with the theoretical predictions.

A highly non-linear gradient dispersion in the ultraviolet region of the spectrum presents difficulties when correcting chromatic aberrations. The use of a chromatic coordinate representation of the index of refraction is shown to be adaptable for GRIN materials and its use in designing achromatic singlets is demonstrated using Robb's graphical method.

UNIVERSITY MICROFILMS ORDER NUMBER ADG90-21091.

# QUANTUM-LIMITED IMAGE RECOGNITION

**Thomas Arthur Isberg**

## Abstract

Correlation-based methods for automatic image recognition are implemented using a position-sensitive, photon-counting detection system. It is demonstrated that the information provided by a small number of detected photoevents can be used to accurately estimate the cross correlation between a classical-intensity input scene and a reference (or filter) function stored in computer memory. A theoretical formalism is developed that describes the behavior of the quantum-limited correlation signal for complex filter functions. The theoretical predictions are verified experimentally using a position-sensitive photon-counting detection system. The speed at which the detection system operates makes this an effective technique for implementing correlation based methods for image recognition in real time, even when there is an abundance of input illumination.

First, image correlation at low light levels is investigated. When the reference function that is stored in computer memory is a digitized version of the classical-intensity input object, the correlation output corresponds to that of a conventional matched filter. It is demonstrated that as few as 1000 detected photoevents provide sufficient information to discriminate accurately among a set of engraved portrait images.

Rotation-invariant image recognition using a rotation-invariant circular-harmonic filter is also implemented using photon-counting techniques. In addition, a new method is demonstrated for normalizing the correlation output in real time using the positional information from the detected photoevents. This new normalization may allow rotation-invariant circular-harmonic filters to be utilized in a cluttered environment.

The estimation of moment invariants for image recognition is also considered. Experiments are performed that demonstrate that the information provided by a few thousand detected photoevents is sufficient to estimate moment invariants that remain unchanged when segmented input images are scaled, change in position, or undergo inplane rotations.

Finally, the automatic recognition of images from within a cluttered environment is considered. The photon-counting detection system is used to implement a two-stage template matching algorithm to locate objects of interest from within cluttered scenes. Both two-stage matched filtering, and two-stage rotation-invariant filtering is considered.

UNIVERSITY MICROFILMS ORDER NUMBER ADG93-04777.

## GLOBAL OPTIMIZATION IN LENS DESIGN

**Andrew Ellicott Wistar Jones**

### Abstract

The demand for lens systems of unconventional forms, coupled with the increased computing power available to most lens designers, has motivated the development of global optimization algorithms for lens design. The successful implementation of such an algorithm requires both a well designed global optimization scheme and an understanding of the special requirements posed by lens design problems. The "simulated annealing" algorithm for global optimization has attracted considerable attention from lens designers; existing variants of simulated annealing, however, lack the desired invariance under linear transformations of the coordinates or of the objective function, and typically require the specification of several hand-picked, problem-specific parameters. Success in applying these methods to lens design problems has therefore been limited.

A new variant of simulated annealing—*Adaptive Simulated Annealing* (ASA)—is presented here in the general context of global optimization over continuous variables subject to constraints. In ASA, fixed temperature schedules and step generation routines have been replaced with heuristic-based algorithms that require minimal user-specified information and that are invariant under linear transformations of either the coordinates or the objective function. A parallel-processing implementation of ASA that provides increased efficiency is presented and applied to two standard problems for illustration and comparison.

The application of ASA to lens design is examined. It is found that the lens design problem as typically posed—the "canonical" lens design problem—is not suited to efficient optimization with ASA. Modifications for optimization with ASA that raise efficiency—in particular, nonlinear inequality constraints and non-linear coordinate transformations—are introduced. The effectiveness of ASA in lens design is then demonstrated through application to several standard lens design problems.

UNIVERSITY MICROFILMS ORDER NUMBER ADG90-21093.

## DYNAMICS AND INSTABILITIES IN HOMOGENEOUSLY BROADENED LASERS

**Karl William Koch, III**

### Abstract

This thesis describes theoretical and experimental studies of a homogeneously broadened ring dye laser. The thesis is particularly concerned with the two-frequency instability in which a bichromatic field emerges from the laser above the instability threshold. The interaction of a bichromatic field with an isolated atomic resonance is examined. The time-averaged inversion and the saturated gain exhibit structure in the form of a series of subharmonic resonances. The stability of a strong bichromatic laser field to the growth of a subharmonic probe field is examined. The gain of the subharmonic bichromatic probe field in the presence of the strong bichromatic laser field is calculated. The strong bichromatic field is stable to the growth of the subharmonic fields when the modulation frequency of the strong field coincides with the Rabi frequency of the lasing transition.

The existence of chaos in a strongly driven nonlinear system *is experimentally investigated* in a multimode ring dye laser. A dye laser is pumped with a modulated pump source. The response of the dye laser to commensurate and incommensurate modulations is reported. We find that for commensurate modulations, the dye laser responds in a periodic fashion and the rf spectrum of the dye laser is composed of a series of harmonics. For incommensurate modulations, the dye laser responds in a quasiperiodic fashion with a broadband rf spectrum.

The two-frequency instability in a multimode cw-pumped ring dye laser is shown to occur in a number of cavity configurations. The two-frequency instability is shown to exhibit a sensitive dependence on the cavity detuning.

The recently proposed band model of the laser is examined and theoretical predictions of the model are experimentally analyzed. Experimental evidence is presented which illustrates that conventional theories for two-, three-, and four-level lasers are inadequate to describe the excited state population dynamics of a cw dye laser. Modulation spectroscopy is used in a new signal-limited technique to measure an upper bound on the decay time of the lower levels in a rhodamine-6G dye molecule.

UNIVERSITY MICROFILMS ORDER NUMBER ADG94-05876.

## GROUP III-VACANCY MEDIATED DISORDERING OF INTRINSIC AND N-TYPE ALUMINUM GALLIUM ARSENIDE/GALLIUM ARSENIDE SUPERLATTICES

**Brian Lewis Olmsted**

### Abstract

The mechanisms of superlattice disordering, a useful technique for optoelectronic device fabrication and integration, have been investigated. Al-Ga interdiffusion coefficients in AlGaAs/GaAs superlattices were determined using photo- luminescence spectroscopy (PLS) and secondary ion mass spectrometry (SIMS). Al-Ga interdiffusion in intrinsic AlGaAs heterostructures is mediated by second nearest-neighbor hopping of group III vacancies throughout the 700 to 1050 °C range and in both Ga- and As-rich annealing ambients. The predicted increase of two orders of magnitude in the Al-Ga interdiffusion coefficient with As pressure between the Ga- and As-rich solidus limits was observed. The depth profiles of Al-Ga interdiffusion are consistent with group III-vacancy diffusion between the crystal surface and bulk, and yielded a single, reasonable vacancy diffusion coefficient. The activation energy of interdiffusion agreed with that predicted for second nearest-neighbor hopping of vacancies based on theoretical estimates of vacancy formation and migration energies. Additionally, the annealing of silicon nitride encapsulated superlattices indicated very limited Al-Ga interdiffusion even with an As overpressure. This is attributed to the lack of group III vacancies. Conversely, silicon dioxide caps appeared to be very permeable.

A quantitative test of the Fermi-level effect on Al-Ga interdiffusion in n-type superlattices was performed using PLS, SIMS, and C-V profiling. A significant variation was observed in the enhancement with annealing ambient in quantum wells that were Si-doped during growth. This attributed to electrical compensation and the As overpressure's effect on group III-vacancy formation at the crystal surface. The predicted Fermi-level enhancement of a factor of forty was observed only when neither excess Ga or As were included. Disordering by the indiffusion of a variety of group IV and VI donors was also investigated. An enhancement in Al-Ga interdiffusion was observed in each case with the disordering being attributed to group III vacancies. However, important differences have been observed in the interdiffusion characteristics induced by Si or Ge, and that by S or Se. Additionally, the depth profiles of deep levels associated with group III vacancy—donor complexes were obtained using cathodoluminescence.

UNIVERSITY MICROFILMS ORDER NUMBER ADG90-22629.

# INTERACTION OF ATOMIC HYDROGEN WITH PICO- AND FEMTOSECOND LASER PULSES

**Jonathan S. Parker**

**Abstract**

This thesis presents a theoretical study of the interaction of atomic hydrogen with coherent laser pulses in the 5 femtosecond to 10 picosecond range, in the weak-field limit, and in intense fields. We approach the problem in the weak-field limit by studying the relationship between the Fourier relation of the laser pulse ($\Delta\omega\Delta t$) and the $\Delta E\Delta t$ relation of the atomic Rydberg wave packet generated by the laser pulse. A derivation of the wave packet based on the WKB approximation is given, permitting the quantity $\Delta t$ to be derived for the quantum state, with the conclusion that under certain circumstances a transform-limited laser pulse (satisfying $\Delta\omega\Delta t = 1/2$) can generate a transform-limited electron (satisfying $\Delta E\Delta t/h = 1/2$).

The interaction of hydrogen with femtosecond pulses is studied at field intensities as high as $2.2 \bullet 10^{14}$W/cm$^2$. The full three-dimensional Schrodinger equation is numerically integrated at intensities of this order as a guide to the development of theory. In terms of the Fermi golden rule (FGR) formulation of ionization, the results may be summarized as follows: just about every approximation employed in the derivation of FGR breaks down at $10^{14}$W/cm$^2$. Nevertheless, it was possible to provide straightforward non-perturbative methods to replace the approximations and perturbative methods employed FGR.

A population-trapping effect is found numerically and modeled theoretically. Despite the high field intensities, population representing the excited electron is recaptured from the ionization continuum by bound states during the excitation. Population returns to the atom with just the right phase to strongly inhibit ionization. A theory is presented that models this effect for a variety of laser pulse shapes, with and without the rotating-wave approximation.

The numerical integration reveals that a certain amount of above-threshold ionization (ATI) occurs. A theory similar to the Keldysh-type theories of ATI is developed. The theory differs from the Keldysh theories in that, like Schrodinger's equation, it is invariant under certain gauge transformations. The proposed theory gives far superior agreement with the numerical integration than Keldysh theory.

Classical ionization at $2.2 \bullet 10^{14}$W/cm$^2$ is studied by numerically integrating Newton's equation on a Monte Carlo ensemble constructed to correspond to the above examples.

UNIVERSITY MICROFILMS ORDER NUMBER ADG93-13879.

## AN INVESTIGATION OF DISTRIBUTED COUPLING IN A NONLINEAR SEMICONDUCTOR WAVEGUIDE

**David Floyd Prelewitz**

### Abstract

In this thesis, we theoretically and experimentally analyze the nonlinear coupling properties of a model waveguide-grating structure. A planar Si-on-insulator (SOI) structure with a periodic distributed grating coupler is used as the model system. Unlike other optoelectronic materials, Si does not possess a direct band gap or a linear electrooptic effect. However, it may be possible to utilize silicon's large free carrier effect in optoelectronic devices. It may also be possible to integrate Si optical structures with Si based electronic circuits on monolithic substrates.

In our experimental study of the SOI structure, a distributed grating input coupler is used to transfer light from a Nd:YAG Q-switched laser ($\lambda_0$ =1.064 μm=23 nsec) into the guiding region by exciting $TE_0$ modes. Temporal changes in the waveguide mode pulse profiles are then measured with a digital sampling oscilloscope (DSO). Linear and nonlinear coupling measurements are made using various input conditions in an attempt to characterize the structure. From our observations, power dependent optical limiting and damped oscillations are evident in the pulse profiles.

By numerically modeling the structure, we attribute the temporal fluctuations in the mode profile to intensity dependent changes in the refractive index of the Si guiding layer. Contributions to the refractive index from both free carrier and thermal changes are considered. Rapid index variations causes the propagation wavevector in the interaction region to be power dependent. As a result, the coherent optical coupling properties of the structure are altered. We have determined that spatial changes in the resonance condition of the coupling structure accounts for most of the limiting effects. Damped oscillations observed in the temporal pulse profile are attributed to interference effects induced by a nonlinear phase shift in the guided mode.

The numerical computations indicate that the nonlinear coupling process is dominated by free carrier effects. However, competition between electronic and thermal processes becomes more acute with higher energies. By fully modeling the two dimensional carrier and thermal dynamics, we are able to fully characterize the nonlinear coupling process due to the material and geometric constraints.

UNIVERSITY MICROFILMS ORDER NUMBER ADG88-17091.

## IMAGE RECOVERY FROM PARTIAL FRESNEL ZONE INFORMATION

**Robert John Rolleston**

### Abstract

The problem of reconstructing an unknown image from partial data in the Fresnel zone region is discussed. The Fresnel region of a coherent optical processing system is used as a basis for the definition of a Fresnel zone transform pair. An iterative method of reconstructing an unknown image located in the object domain, from either the phase-only or magnitude-only date in the transform domain, is investigated.

The Fresnel zone transform is implemented digitally using a fast Fourier transform routine. The number of Fresnel zones, which is a measure of how far out of the Fourier transform plane one is located, is limited by certain sampling considerations. From the Fourier transform plane through the Fresnel region, it is demonstrated that the phase-only information in the transform allows for a very good reconstruction in just a few iterations of the reconstruction algorithm.

Phase-only information in the Fresnel zone transform leads to very good reconstructions throughout the Fresnel zone region. For a given number of iterations, there is a slight degradation in the quality of the reconstructed image as the number of Fresnel zones is increased. The phase of the Fresnel zone transform preserves the structure of the sharp edges in the image.

A degradation in the reconstructed image results if noise is present in the given data. The probability density functions of the magnitude and phase of a signal in the presence of coherently additive noise are derived. The effects of both signal independent and signal dependent noise are investigated.

In reconstructing an image from either the phase-only or magnitude-only data of the Fresnel zone transform, the iterative reconstruction algorithms which are used are shown to be stable both in the presence of noise and in an error in the number of Fresnel Zones. In addition, while there is only a slight degradation in the quality of the reconstruction from phase-only data, there is a dramatic improvement in the quality of the magnitude-only reconstruction as one moves out of the Fourier transform plane and into the Fresnel region. (Abstract shortened with permission of author.)

UNIVERSITY MICROFILMS ORDER NUMBER ADG92-31312.

## FEEDFORWARD NEURAL NETWORKS FOR IMAGE CLASSIFICATION

**Lennart Arnold Saaf**

**Abstract**

The application of artificial neural networks to image classification is investigated. A particular network architecture is considered: the three-level feedforward neural network. A specific configuration for image classification is described, in which each artificial neuron or unit in an input level of the network represents a pixel of a two-dimensional image. The concept of optimum binary coding is introduced, in which the classification of an image is coded in the units of a hidden level. This coding is shown to greatly reduce the computation required to run the network compared to a comparable two-level network. Computer simulations demonstrating the ability of three-level feedforward neuron networks to classify printed characters are reported.

A new optical implementation of a feedforward neural network is described, in which the interconnection strengths between the input and hidden units of a three-level network are stored holographically. This approach benefits from the powerful abilities of optics to perform computational tasks on two-dimensional images quickly and in parallel. The classification of printed characters using a hybrid system, consisting of an optical processor and digital electronics, is reported.

A new application of neural networks is reported: the classification of photon-limited images. The statistics of photon-limited images are analyzed, and a method of calculating the expected classification performance of a network is described. The theoretical results make it possible to predict the number of photoevents needed in a photon-limited image to achieve a given level of confidence in the classification. A photon-counting camera is used to acquire photon-limited images for input to a three-level feedforward neural network implemented in a microcomputer. Experimental results for the classification of printed characters are presented that agree with the theoretical predictions.

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## WAVELENGTH AND ROUGHNESS DEPENDENCE OF BACKSCATTERING

**Donald John Schertler**

### Abstract

The variation of scattered light with surface roughness and illuminating wavelength is analyzed with a particular emphasis on remotely sensing the surface structure and height profile of the scattering object. The wavelength variation is used to determine the height distribution of the scattering surface and is compared to the stretched envelope of a pulse echo system. Remarkable consistency is found between the processed complex field amplitude and the stretched pulse envelope.

The autocorrelation of the intensity scattered from a surface measured as a function of the illuminating frequency is shown to be proportional to the square of the first order characteristic function associated with the surface height distribution. Experiments, supported by computer simulations, are conducted for imaging and far-zone scattering systems in which roughnesses ranging from 1 mm to 1mm can be determined in a noncontact method.

In studying the effects of surface roughness on the scattered intensity, a useful quantity to calculate is the scattering cross section. The cross section depends only on the characteristics of the surface and the incident and scattering angles. It is found by reducing the two point correlation of the field scattered from the surface or disc. The field correlation requires an intricate calculation of the ensemble average of several surface height and slope terms that become dominant for large roughnesses and for large incident angles. Two surface types are considered and the important effect of shadowing is included. In the backscatter direction, the Gaussian surface has a cross section which falls off rapidly with increasing incident angle. The exponential surface, however, has a cross section that actually increases with incident angle for certain roughness conditions. Experimental measurements support these calculations.

The backscattering cross section calculation for the tilted disc is extended to curved or shaped objects, specifically a sphere. The increase in cross section of the disc at large incident angles would imply that a sphere with a similarly rough surface would exhibit a halo from its outer regions. This is confirmed in the calculations but has yet to be observed experimentally.

UNIVERSITY MICROFILMS ORDER NUMBER ADG94-05883.

# OPTICAL ABSORPTION, EMISSION, AND MODULATION IN III-V SEMICONDUCTOR QUANTUM WELL STRUCTURES

**Steven Marc Shank**

## Abstract

An experimental study of topics relating to optical absorption, emission, and modulation in III-V semiconductor GaAs/AlGaAs quantum well structures is presented. Several novel quantum well structures are examined and evaluated for use in electrooptic modulators, laser diodes, and monolithically integrated laser diodes and passive waveguides. The design of the epitaxial structures, the molecular beam epitaxy growth, the optical characterization of the wafers, the fabrication of the wafers into basic optoelectronic devices (electrooptic waveguides, laser diodes, and segmented laser diodes), and the characterization of these devices are described.

The quantum confined Stark effect and its influence on the electrooptic properties of quantum wells are described. In particular, electroabsorption and electrobirefringence in (111)B quantum wells are investigated. This quantum well system is chosen due to the larger heavy hole effective mass compared to standard (100) quantum wells. It is demonstrated that electroabsorption and electrobirefringence are enhanced in (111)B quantum wells, which agrees with theoretical predictions based on the heavy hole mass anisotropy.

Computer simulations of the quantum confined Stark effect in asymmetric quantum well structures are described. It is demonstrated that asymmetric quantum wells can exhibit enhanced red shifts of the absorption edge, and blue shifts of the absorption edge under an applied reverse bias. An experimental investigation of laser diodes with asymmetric quantum well active regions is described. An evaluation of the blue shift effect on the interband absorption at the laser wavelength is made and related to the efficiency of these structures for monolithic integration with passive waveguides.

The optical properties of n-type modulation doped quantum wells are described. It is shown that the interband absorption at the spontaneous emission peak can be greatly reduced compared to undoped quantum wells. N-type modulation doped quantum wells are utilized as the active regions for separate confinement heterostructure laser diodes. It is demonstrated that transparency current and threshold current is reduced for modulation doped active regions due to reduced interband absorption. Segmented lasers are fabricated and the loss of the passive segment is determined for undoped and modulation doped active regions.

UNIVERSITY MICROFILMS ORDER NUMBER ADG88-17094.

## LASER SPECKLE FROM THIN AND CASCADED DIFFUSERS

**Lyle Gordon Shirley**

### Abstract

The scattering of laser light from a single diffuser and from a cascade of two diffusers is analyzed with particular emphasis on remote sensing. It is shown that diffuser surface properties and the spacing between diffuser planes can be determined remotely. Conceptually, one measures the angular distribution of the radiation pattern or the decorrelation of the far-zone speckle pattern with respect to changes in the wavelength or the angle of incidence of an input plane wave.

Models for the transmission of light through single diffusers are presented that contain a dependence on the angle of illumination. The validity of a simplified transmission function for single diffusers that does not depend on angle is examined, and it is found that the simple transmission function is adequate for treating the individual diffusers in a cascade. This is important, since the simpler transmission function leads to manageable overall expressions for the cascade.

A general expression is derived for the two-state correlation function of far-zone complex amplitude from a cascade of two diffusers, where the two states are the initial and final values of the wavelength, angle of incidence, angle of observation, and spacing. This function is then related to the two-state correlation function of intensity, which is a measure of the correlation between the initial and final speckle patterns. The two-state correlation function of intensity is evaluated for various double diffuser combinations.

The effect of surface height models on the radiation pattern is studied. Of particular interest are strong diffusers that have a normally distributed height profile and whose surface height autocorrelation functions are paraboloidal or conical for small spatial offsets. Excellent agreement is obtained between theoretical radiation patterns calculated with conical and paraboloidal autocorrelation functions and experimental radiation patterns measured from ground-glass and acid-etched diffusers, respectively.

UNIVERSITY MICROFILMS ORDER NUMBER ADG88-16881.

# OPTICAL PHASE CONJUGATION ENHANCED BY THE BRILLOUIN INTERACTION

**Mark Daniel Skeldon**

## Abstract

This thesis provides an in-depth study of the Brillouin interaction and how it can be exploited to enhance other nonlinear optical processes. The work begins with a detailed derivation of the equations of motion describing the stimulated Brillouin scattering (SBS) process. The derivation applies the principles of conservation of momentum and energy to a fluid particle in the medium, and evolves into a complete mathematical description of the SBS process including optical absorption and thermal effects. Predictions of the important parameters for this process, such as the SBS gain and reflectivity are given for the cases of a single and multimode laser. When using a multimode laser it is shown under what conditions the SBS gain and reflectivity are unaffected by the number of modes in the pump laser. Experiments carried out in this limit confirm the theoretical predictions.

The novel scheme for combining SBS and conventional four-wave mixing into what is called Brillouin-enhanced four-wave mixing is discussed both theoretically and experimentally. This new geometry for producing a phase-conjugate signal is capable of combining the good feature of both the SBS and four-wave mixing processes, while eliminating the undesirable features of these processes. This Brillouin-enhanced four-wave mixing process produces a phase-conjugate mirror with reflectivities greater than 100%, with no frequency shift on reflection, and produces a high-fidelity phase-conjugate signal even when using aberrated pump waves. Experimental verification of all these features is demonstrated.

A phase-conjugate oscillator consisting of a conventional mirror and a phase-conjugate mirror based on Brillouin-enhanced four-wave mixing has been constructed. The beam divergence and near-field spot size of this oscillator has been measured for various cavity lengths and radii of curvature of the conventional mirror. A theoretical analysis of the mode structure of this oscillator has been performed assuming a Gaussian reflectivity profile for the phase-conjugate mirror. The beam-parameter measurements made on the experimental phase-conjugate oscillators are in good agreement with our theoretical analysis.

UNIVERSITY MICROFILMS ORDER NUMBER ADG92-31321.

# HAMILTON'S METHODS APPLIED TO THE DESIGN OF ASYMMETRIC OPTICAL SYSTEMS

**Bryan David Stone**

## Abstract

Given an asymmetric optical system and a specific ray near the center of the bundle of rays passed by the system (the so-called base ray) any of Hamilton's characteristic functions generally can be expanded in a Taylor series about that ray. Specifying the coefficients of the terms of second degree in this Taylor series is equivalent to specifying a system's first-order imaging properties. Methods are described here that can be used to constrain the configuration of an asymmetric system to ensure the coefficients of the terms through second degree are of a form that yield desired first order imaging properties. With this approach to the first-order layout of an asymmetric system, it is necessary to know the form of the characteristic function associated with the desired imaging properties. The requisite forms associated with a variety of imaging properties are also discussed here.

There are, however, essential aspects of asymmetric system design that do not fall within the realm of first-order optics. In particular, asymmetric systems do not generally form the sharpest image with object and image planes perpendicular to the base ray, but first-order optics says nothing about optimal orientations of the object and image. At a minimum, second-order optics must be considered. This observation motivated the study of second-order optics for asymmetric systems. The foundations of a method for configuring asymmetric systems, along with the object and image planes, to ensure sharp imagery through second order are also described.

The methods mentioned above can be used to guarantee that only those systems possessing desired first- and second-order imaging properties are considered in the initial phase of design, thereby significantly reducing the dimensionality of the configuration space. This is illustrated through a number of examples. Such procedures simplify any subsequent exploration and increase the likelihood that the optimal solution will be found.

UNIVERSITY MICROFILMS ORDER NUMBER ADG92-31326.

**DESIGN METHODS FOR GRADIENT-INDEX OPTICAL SYSTEMS**

**David Yih Hsing Wang**

**Abstract**

Methods for designing axial and radial gradient-index (GRIN) optical systems are developed and analyzed.

A set of simple analytic expressions that describe a weak-powered GRIN lens' Seidel aberration contributions is presented. The proposed equations enable direct analysis of a GRIN lens' Seidel aberration contributions.

A set of simple analytic expressions that describe a weak-powered GRIN lens' paraxial chromatic aberration contributions is introduced. The proposed equations provide the requirements for designing achromatic axial GRIN singlets.

The use of the simulated annealing algorithm for locating suitable starting solutions for a GRIN optical system is demonstrated.

A systematic design study of five-element axial and radial GRIN zoom lenses for 35 mm photography with zoom ratio of 1.6 is presented. The design study yields a large number of highly effective GRIN designs. This study finds that the presence of a single gradient introduces a significant improvement to a five-element zoom lens' optical performance.

Finally, a systematic design study of axial, shallow radial, and radial GRIN seven-element zoom lenses for 35 mm photography with zoom ratio of 2.0 is presented. This design study also generates a large number of highly effective GRIN designs. This study finds that the presence of two axial or radial gradients provides a significant enhancement to a seven-element zoom lens' optical performance.

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# CLASSIFICATION TECHNIQUES FOR QUANTUM-LIMITED AND CLASSICAL-INTENSITY IMAGES

**Miles N. Wernick**

## Abstract

Automatic classification of both quantum-limited and classical-intensity images is considered. A new discriminant vector for classical-intensity images is proposed which can also be applied to general pattern recognition problems. The proposed discriminant vector, based on convex analysis, is shown in all cases to correctly distinguish two image classes if that is, indeed, possible with a linear discriminant. Further, it is shown to be the discriminant vector that maximizes the minimum separation of the values obtained by forming the inner products between it and the input images. Experiments are reported in which the discriminant vector is used to successfully distinguish first two classes, then eight classes of images.

The classification problem is also considered for the case of quantum-limited input images. Quantum-limited images arise as a matter of course in applications such as night vision, low-dose electron microscopy, and radiological imaging. It can also be shown, however, that for reasons of computational efficiency it may be advantageous to use a quantum-limited imaging system as the input to the classifier. The inner product between a quantum-limited image and a discriminant vector is shown to be a Monte Carlo estimator of the corresponding high-light-level inner product. In principle, therefore, any linear classifier can be implemented using the quantum-limited system. In addition, however, new solutions, specifically designed for quantum-limited images are derived using statistical decision theory. These solutions are shown experimentally to provide excellent results. The method is then extended to permit classification of quantum-limited images despite in-plane rotations, and the result is demonstrated experimentally. Finally, the application of the low-light-level solutions to high-light-level situations is considered.