ARO-URI Center for Opto-Electronic Systems Research

Final Report

1 October 1986 - 31 May 1992

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We describe the research accomplishments of a five-year program in the ARO-URI Center for Opto-Electronic Systems Research. Research is included in materials, devices, and systems. Sixteen (16) faculty investigators participated in this effort. During this period, we published 229 papers in refereed journals. Four patents have been applied for. Thirty-eight (38) doctoral students have now completed their thesis research. More than 240 visits were made by faculty to DoD/Army laboratories, largely funded by the University. In addtion, faculty particpated in an extensive series of workshops held at Army laboratories on topics of relevance to the Army.

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ARO-URI CENTER FOR
OPTO-ELECTRONIC SYSTEMS RESEARCH

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We describe the research accomplishments of a five-year program in the ARO-URI Center for Opto-Electronic Systems Research. Research is included in materials, devices, and systems. Sixteen (16) faculty investigators participated in this effort. During this period, we published 229 papers in refereed journals. Four patents have been applied for. Thirty-eight (38) doctoral students have now completed their thesis research. More than 240 visits were made by faculty to DoD/Army laboratories, largely funded by the University. In addtion, faculty particpated in an extensive series of workshops held at Army laboratories on topics of relevance to the Army.

ARO-URI CENTER FOR
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1. INTRODUCTION

In this report we describe the activities and accomplishments of the ARO-URI Center for Opto-Electronic Systems Research. A brief historical statement is included in Appendix 7.1. As is described in this appended article, we have found it valuable to incorporate both the notion of a systems platform and a grouping of important themes in the planning and management of research. The central goal of the Center has been to make fundamental contributions to basic research in the critical technologies: signal processing and image processing and photonics.

In Sec. 2.1 we include a listing of faculty investigators who particpated in this program. This is followed with a listing of major themes and research topics being pursued.

In Sec. 3 we provide a cumulative listing of publications that have appeared largely in refereed journals. In all, 229 publications appeared with sponsorship by the Army Research Office. Separately in Sec. 4, we provide a publications listing by faculty investigator. These are cross-referenced with the cumulative listing as a convenience to the reader.

Section 5 contains a listing of patents pending and patents granted.

An important feature of this Center is its emphasis on research that is highly relevant to engineering systems and Army/DoD missions. This emphasis is important for two reasons. It recognizes the fact that the technological needs of the Department of Defense are often strongly systems-oriented. The Center actively relates the results of its research program to defense systems. In Sec. 6 we summarize this technology transfer in three separate listings:

6.1 Summary and cross-references

6.2 Faculty visits to DoD facilities, which were larged funded by the University of Rochester

6.3 Opto-Electronic Workshops

This report concludes with a listing (see Appendix 7.2) of Ph.D. scholars who were funded by the ARO-URI program. In all, we list 38 students who completed their doctoral thesis under this research program.

In site visits and strategic planning we have been guided by the review panel, listed below, that is drawn from a large number of Army laboratories. Their helpful guidance has contributed in large measure to our successes in technology transfer. The listing follows:

Review Panel

Rudolf G. Buser, Chairman of the Panel and Director, U.S. Army Night Vision and Electronic Sensors Directorate

Jefferson S. Bennett, Director, Research Directorate, U.S. Army Missile Command

Grant R. Gerhart, U.S. Army Tank-Automotive Technology Directorate

Gordon R. Griffin, U.S. Army Topographic Engineering Center

B. D. Guenther, Director, Physics Directorate, U.S. Army Research Office

Nicholas C. Kailos, Aviation Applied Technology Directorate

J. Michael Richey, Program Manager, Light Helicopter Program

Howard R. Schlossberg, Program Manager, Air Force Office of Scientific Research

Steven M. Shepard, U.S. Army Tank-Automotive Technology Directorate

2.1 Listing of Faculty Investigators

Govind P. Agrawal, Professor of Optics
Robert R. Boyd, Professor of Optics
Gregory W. Forbes, Associate Professor of Optics
Nicholas George, Director, Center for Opto-Electronic Systems Reseach, Wilson Professor of Electronic Imaging, Professor of Optics, and Professor of Electrical Engineering
Dennis G. Hall, Director, The Institute of Otpics and Professor of Optics
Susan N. Houde-Walter, Associate Professor of Optics
Stephen D. Jacobs, Senior Scientist in the Laboratory for Laser Energetics and Associate Professor of Optics
Duncan T. Moore, Rudolf and Hilda Kingslake Chair in Optical Engineering and Professor of Optics
G. Michael Morris, Professor of Optics
Michael G. Raymer, Associate Professor of Optics
John R. Rogers, Assistant Professor of Optics
Carlos R. Stroud, Professor of Optics
Kenneth J. Teegarden, Professor of Optics
Ian A. Walmsley, Associate Professor of Optics
Gary W. Wicks, Associate Professor of Optics
Emil Wolf, Wilson Professor of Optical Physics and Professor of Optics

2.2 MAJOR THEMES AND RESEARCH TOPICS

SIGNAL PROCESSING & IMAGE UNDERSTANDING	INVESTIGATOR	TIME PERIOD
Optoelectronic Systems for Pattern Recognition and Remote Sensing	Nicholas George	10/86 to 5/92
Target Recognition Using Quantum Limited Images	G. Michael Morris	10/86 to 5/92
Spectral Effects in Two-Beam Interference, with Application to Aperture Synthesis	Emil Wolf	10/86 to 5/92
SOURCES AND SENSORS		
Nonlinear Optics	Robert R. Boyd	10/86 to 5/92
Integrated Optics and Optoelectronic Devices	Dennis G. Hall	10/86 to 5/92
Liquid Crystal Optics for Laser Applications	Stephen D. Jacobs	10/86 to 5/92
Coherence Properties of Nonlinear Optical Processes	Michael G. Raymer	10/86 to 5/88
Spatially Localized Electron Wave Packets and Nonlinear Laser Dynamics	Carlos R. Stroud	10/86 to 5/92

Major Themes and Research Topics (continued)

Sources and Sensors (continued)	Investigator	Time Period
Electrically Pumped Color Center Lasers	Kenneth J. Teegarden	10/86 to 12/88
Ultrafast Nonlinear Optics	Ian A. Walmsley	9/88 to 5/92
Molecular Beam Epitaxial Growth of Materials for Visible Optoelectronic Applications	Gary W. Wicks	1/90 to 5/92

Optical Systems Design		
Advanced Optical Communication Systems	Govind P. Agrawal	1/90 to 5/92
Modeling and Optimization of Optical Systems	Gregory W. Forbes	10/86 to 5/92
Monolithic Integration of Waveguide Devices	Susan N. Houde-Walter	9/88 to 5/92
Gradient Index Optics	Duncan T. Moore	10/86 to 5/92
Tilted Component Optical Systems	John R. Rogers	10/86 to 4/88

3. CUMULATIVE PUBLICATION LISTING

OCTOBER 1986 THROUGH JUNE 1992

1. "The instantaneous cross-spectral density of non-stationary wavefields," Brian Cairns and Emil Wolf, Opt. Comm. **62**, 215-218 (1987).

2. "Sine-cosine cascade correlator with real-valued filters," Shen-ge Wang and Nicholas George. Opt. Lett. **12**, 383-385 (1987).

3. "Diffraction from a circular aperture: on-axis field strength," R. Edward English, Jr. and Nicholas George. Appl. Opt. **26,** 2360-2363 (1987).

4. "Interference pattern produced on reflection at a phase-conjugate mirror. Part I: Theory," E. Wolf, L. Mandel, R. W. Boyd, T. M. Habashy, and M. Nieto-Vesperinas, J. Opt. Soc. Am. B **4**, 1260-1265 (1987).

5. "Interference pattern produced on reflection at a phase-conjugate mirror. Part II: Experiment," Arturo A. Jacobs, Wayne R. Tompkin, Robert W. Boyd, and Emil Wolf, J. Opt. Soc. Am. B **4**, 1266-1268 (1987).

6. "Instabilities and chaos in the polarizations of counterpropagating light fields," Alexander L. Gaeta, Robert W. Boyd, Jay R. Ackerhalt, and Peter W. Milonni, Phys. Rev. Lett. **58**, 2432-2435 (1987).

7. "Optical emission from impurities within an epitaxial-silicon optical waveguide," T. G. Brown, P. L. Bradfield, D. G. Hall, and R. A. Soref, Opt. Lett. **12**, 753-755 (1987).

8. "Competition between four-wave mixing and amplified spontaneous emission," Michelle S. Malcuit, Daniel J. Gauthier, and Robert W. Boyd, Hyperfine Interactions, **37**, 125-139 (1987).

9. "Spectral shifts produced by source correlations," Dean Faklis and G. Michael Morris, Opt. Lett. **13**, 4-6 (1988).

10. "Optical waveguides in oxygen-implanted buried-oxide silicon-on-insulator structures," B. N. Kurdi and D. G. Hall, Opt. Lett. **13**, 175-177 (1988).

11. "Spectral modulation by control of source correlations," Avshalom Gamliel and Emil Wolf, Opt. Comm. **65**, 91-96 (1988).

12. "Diffraction from a small square aperture: approximate aperture fields," R. Edward English, Jr. and Nicholas George, J. Opt. Soc. Am. A **5**, 192-199 (1988).

13. "Instabilities of laser beams counterpropagating through a Brillouin-active medium," Paul Narum, Alexander L. Gaeta, Mark D. Skeldon, and Robert W. Boyd, J. Opt. Soc. Am. B **5**, 623-628 (1988).

14. "White light interferometry with an achromatic phase shifter," Nicholas George and Thomas Stone, Proc. Soc. Photo-Opt. Instr. Eng. **883**, 196-202 (1988).

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18. "Transients in the micromaser," C. R. Stroud, Jr., Proceedings of the Twelfth International Nathiagali Summer College on Physics and Contemporary Needs, Nathiagali, Pakistan, 18 June - 9 July 1987.

19. "Changes in the spectrum of a partially coherent light beam propagating in free space," Zagorka Dacic and Emil Wolf, J. Opt. Soc. Amer. A **5**, 1118-1126 (1988).

20. "Near-infrared dichroism of a mesogenic transition metal complex and its solubility in nematic hosts," K. L. Marshall and S. D. Jacobs, Mol. Cryst. Liq. Cryst. **159**, 181-196 (1988).

21. "Radial gradient-index eyepiece design," John P. Bowen, J. Brian Caldwell, Leo R. Gardner, Niels Haun, Michael T. Houk, Douglas S. Kindred, Duncan T. Moore, Masataka Shiba, and David Y. H. Wang, Appl. Opt. **27**, 3170-3176 (1988).

22. "Pattern recognition using photon-limited images," G. Michael Morris, in *Optical Computing and Processing*, edited by H. H. Arsenault and T. Szoplik (Academic Press, New York), (1989).

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25. "Above-threshold ionization with femtosecond pulses: a comparison of quantum and classical predictions," Jonathan Parker and C. R. Stroud, Jr., submitted to Physical Review Letters.

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28. "Amplitude-stabilized chaotic light," C. Radzewicz, Z. W. Li, and M. G. Raymer, Phys. Rev. **37**, 2039-2047 (1988).

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31. "Radiative decay of excitons bound to chalcogen-related isoelectronic impurity complexes in silicon," P. L. Bradfield, T. G. Brown, and D. G. Hall, Phys. Rev. B **38**, 3533-3536 (1988).

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35. "Observation of resonances at subharmonics of the Rabi frequency in the saturated absorption of a 100% amplitude-modulated laser beam," Stephen Chakmakjian, Karl Koch, and C. R. Stroud, Jr., J. Opt. Soc. Amer. B **5**, 2015-2020 (1988).

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40. "Maximum-likelihood image classification," Miles N. Wernick and G. Michael Morris, Proc. Soc. Photo-Opt. Instr. Eng. **938**, 317-321 (1988).

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64. "Real-time pattern recognition using photon-limited images," G. Michael Morris, Conference on Pattern Recognition for Advance Missile Systems, Huntsville, AL, November 14-15, 1988.

65. "A spectral equivalence theorem," Daniel F. V. James and Emil Wolf, Opt. Comm. **72**, 1-6 (1989).

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72. "Near threshold behavior of multimode CW dye lasers with an amplitude modulated pump," Stephen H. Chakmakjian, Stephanos Papademetriou, Karl Koch, Michael W. Noel, and C. R. Stroud, in *Coherence and Quantum Optics VI*, edited by J. Eberly, L. Mandel, and E. Wolf (Plenum Press, New York), pp. 137-141 (1990).

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75. "Spectral changes in light propagation from a class of partially coherent sources," Avshalom Gamliel (E. Wolf, Faculty Investigator), in *Coherence and Quantum Optics VI*, edited by J. Eberly, L. Mandel, and E. Wolf (Plenum Press, New York), pp. 361-365 (1990).

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77. "Neural networks applied to diffraction pattern sampling," Nicholas George and Shen-ge Wang, Appl. Opt. **33**, 3127-3134 (1994).

78. "Measurement of the electrically-induced refractive index change in silicon wavelength $\lambda = 1.3\ \mu m$ using a Schottkey diode," A. F. Evans and D. G. Hall, Appl. Phys. Lett. **56**, 212-214 (1990).

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80. Coherence properties of light propagating in a one-dimensional Lorentz medium," WeiJian Wang and Emil Wolf, in *Coherence and Quantum Optics VI*, edited by J. Eberly, L. Mandel, and E. Wolf (Plenum Press, New York), pp. 1207-1212 (1990).

81. "The spectrum of radiation from a moving source of any state of coherence," Daniel F. V. James (E. Wolf, Faculty Investigator), in *Coherence and Quantum Optics VI*, edited by J. Eberly, L. Mandel, and E. Wolf (Plenum Press, New York), pp. 553-557 (1990).

82. "Scattering of electromagnetic fields of any state of coherence from fluctuating media," John T. Foley and Emil Wolf, in *Coherence and Quantum Optics VI*, edited by J. Eberly, L. Mandel, and E. Wolf (Plenum Press, New York), pp. 309-314 (1990).

83. "Purification of thermotropic liquid-crystalline siloxane oligomer with supercritical carbon dioxide," Sushil Krishnamurthy and Shaw H. Chen (S. Jacobs, Faculty Investigator), Makromol. Chem. **190**, 1407-1412 (1989).

84. "Polarization properties of optical phase conjugation by two-photon resonant degenerate four-wave mixing," Martti Kauranen, Daniel J. Gauthier, Michelle S. Malcuit, and Robert W. Boyd, Phys. Rev. A **40**, 1908-1917 (1989).

85. "Optimal interpolants for Runge-Kutta ray tracing in inhomogeneous media," Bryan D. Stone and G. W. Forbes, J. Opt. Soc. Am. A **7**, 248-254 (1990). **(85)**

86. "Aluminum-nitrogen isoelectronic trap in silicon," R. A. Modavis and D. G. Hall, J. Appl. Physics **67**, 545-547 (1990).

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89. "Anomalies in optical harmonic generation using high-intensity laser radiation," Michelle S. Malcuit, Robert W. Boyd, William V. Davis, and Kazimierz Rzazewski, Phys. Rev. A **41**, 3822-3825 (1990).

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91. "Polarization bistability of counterpropagating laser beams," Daniel J. Gauthier, Michelle S. Malcuit, Alexander L. Gaeta, and Robert W. Boyd, Phys. Rev. Lett. **64**, 1721-1724 (1990).

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5. PATENTS

INVENTIONS DISCLOSURES

1. "Optimal mask design for the evaporation of aspheric surfaces," John R. Rogers and John D. Martin, April 1988.

2. Systems for upconversion of broadband infrared images," Edward A. Watson and G. Michael Morris, July 1988.

3. "A system for amplifying ultrashort laser pulses at high repetition rates without cavity locking of the source and amplifier," R. J. D. Miller, I. A. Walmsley, and S. A. Letzring, February 1989.

PATENTS GRANTED

1. "Broad-spectrum achromatic phase shifters, phase modulators, frequency shifters, and frequency modulators," Thomas W. Stone and Nicholas George, U.S. Patent No. 4,786,124, filed November 22, 1988.

6.1 Summary of Technology Transfer Activities

Faculty Investigators	**16**
(see Sec. 2 for details)	
Publications	**229**
(see Secs. 3 and 4 for details)	
Inventions	
Disclosures	3
Patents	1
(see Sec. 5 for details)	
Faculty Visits	**242**
(see Sec. 6.2 for details)	
NVESD Workshops	**27**
(see Sec. 6.3 for details)	
Army Summer School (person-weeks)	**114**
Ph.D. Fellows	
Graduated	35
Completing	3
(see App. 7.2 for details)	

6.2 SUMMARY OF FACULTY VISITS TO DoD

Night Vision and Electronic Sensors Division	162
Missile Command, Redstone Arsenal	16
Army Research Office	8
Army ResearchLaboratory, Adelphi	10
Topographic Engineering Center	3
Jet Propulsion Laboratories	2
West Point Military Academy	4
Natick RD&E Center	1
MICOM Physical Sciences Directorate	3
Strategic Defense Command	1
Electronic Technology & Devices Laboratory	1
Photonics Center, Rome Laboratories	1
Letterman Army Institute	3
Tank & Automotive Command	4
Material Systems Analysis Activity, Aberdeen	2
Ballistic Research Laboratoires, Aberdeen	4
Aviation Technology Division, Ft. Eustis	3
MIT Media Laboratory	1
Armament RD&E Center, Picatinny Arsenal	1
Armament R&D Center, Dover	1
Air Force Weapons Laboratory, Kirtland	1
Elgin Air Force Base, Florida	1
Other	9
TOTAL	**242**

6.3 Listing of NVESD Workshops

The U.S. Army Night Vision and Electronic Sensors Division

is hosting a series of

OPTOELECTRONIC WORKSHOPS

jointly with the

ARO-URI Center for Opto-Electronic Systems Research

The Institute of Optics
University of Rochester
Rochester, NY 14627

March 1988 through February 1991

These workshops are held at CCNVEO, Ft. Belvoir, for the purpose of establishing intensive interaction on topics of importance to DoD. They are being coordinated by Dr. Nicholas George at the University of Rochester, Rochester, New York, (716) 275-2417.

r: 3/1/91

Faculty Organizer	CCNVEO Organizer

I. PHASE CONJUGATION / STRONGLY DRIVEN ATOMIC SYSTEMS

March 22, 1988

Robert Boyd 716-275-2329	Richard Utano 703-664-4127

II. AUTOMATIC PATTERN RECOGNITION

April 7, 1988

Nicholas George 716-275-2417	Mark C. Norton 703-664-1039

III. OPTO-ELECTRONICS IN III-V SEMICONDUCTORS— MATERIALS AND DEVICES

May 3, 1988

Gary Wicks 716-275-4857	L. N. Durvasula 703-664-1900

IV. LIQUID CRYSTALS FOR LASER APPLICATIONS

May 11, 1988

Stephen Jacobs 716-275-4837	Juergen L. Pohlmann 703-664-5364

Faculty Organizer	CCNVEO Organizer

V. MODERN COHERENCE THEORY

May 18-19, 1988

Emil Wolf 716-275-4397	C. Ward Trussell 703-664-5310

VI. TESTING / FABRICATION / GRADIENT INDEX OPTICS AND COMPUTER AIDED MANUFACTURE OF OPTICS

May 24, 1988

Duncan T. Moore 716-275-5248	Robert A. Spande 703-664-6665

VII. ADVANCED TECHNOLOGY FOR RADIOMETRY AND THE DETECTION OF OPTICAL RADIATION

June 14, 1988

Robert Boyd 716-275-2329	John H. Pollard 703-664-5780 Mark C. Norton 703-664-1039

VIII. QUANTUM LIMITED IMAGING AND IMAGE PROCESSING

July 12, 1988

G. Michael Morris 716-275-5140	Lynn E. Garn 703-664-6066

Faculty Organizer	CCNVEO Organizer

IX. DYNAMICAL INSTABILITIES IN HOMOGENEOUSLY BROADENED LASERS

August 23, 1988

Carlos Stroud 716-275-2598	Albert Pinto 703-664-4766

X. FEMTOSECOND TIME-RESOLVED SPECTROSCOPY

November 8, 1988

Ian Walmsley 716-275-0312	Edward Sharp 703-664-5767

XI. SUPERLATTICE DISORDERING

December 7, 1988

Susan Houde-Walter 716-275-7629	John Pollard 703-664-5780

XII. RYDBERG ATOMS AS SOURCES AND DETECTORS OF FAR INFRARED AND MICROWAVES

January 25, 1989

Carlos Stroud 716-275-2598	John Malamas 703-664-1121

Faculty Organizer	CCNVEO Organizer

XIII. LASER RADARS, SPECKLE, AND REMOTE SENSING

February 7, 1989

Nicholas George 716-275-2417	Jay Fox 703-664-4287

XIV. LIQUID CRYSTAL SHUTTER / CHOPPER FOR MID INFRARED

February 21, 1989

Stephen Jacobs 716-275-4837	James Miller 703-664-1585

XV. CRITICAL ISSUES IN OPTICAL MATERIALS

May 11, 1989

Dennis Hall 703-664-2134	Bucky Freeman 703-664-5508

XVI. DIFFRACTIVE OPTICAL ELEMENTS

June 21, 1989

G. Michael Morris 716-275-5140 Thomas Stone 716-275-7834	Mark C. Norton 703-664-1039

Faculty Organizer	CCNVEO Organizer

XVII. INVERSE PROBLEMS AND TOMOGRAPHY

September 14, 1989

Emil Wolf 716-275-4397 Warren Smith 716-275-2323	Rudolf Buser James Ratches 703-664-5151

XVIII. CCNVEO VISIONICS DIVISION OVERVIEW

October 11, 1989

Ronald Antos 716-275-4179	Luanne Obert 703-664-5845

XIX. STABILITY OF NONLINEAR OPTICAL INTERACTIONS

November 13, 1989

Robert Boyd 716-275-2329	Gary Wood 703-664-1431

XX. CCNVEO TECHNICAL PANEL ON NIGHT VISION GOGGLE SYSTEMS

April 26, 1990

Ronald Antos 716-275-4179	Rudolf Buser 703-664-5151

Faculty Organizer | CCNVEO Organizer

XXI. CCNVEO INFRARED TECHNOLOGY DIVISION REVIEW

May 8, 1990

Ronald Antos
716-275-4179

Rudolf Buser
703-664-5151

XXII. CCNVEO IMAGE AND SIGNAL PROCESSING DIVISION REVIEW

May 15, 1990

Ronald Antos
716-275-4179

Joseph Swistak
Terry Jones
703-664-6436

XXIII. OPTICAL SYSTEM ASSESSMENT FOR DESIGN AND SIMULATED ANNEALING

August 2, 1990

Gregory Forbes
716-275-7227

Robert Spande
703-664-6665

XXIV. NONIMAGING CONCENTRATORS FOR HIGH-POWER DIODE-PUMPED SOLID-STATE LASER SYSTEMS

November 27, 1990

Ian Walmsley
716-275-0312

C. Ward Trussell
704-664-5310

Faculty Organizer | CCNVEO Organizer

XXV. LIQUID CRYSTAL MATERIALS AND DEVICES FOR OPTO-ELECTRONIC APPLICATIONS

December 5, 1990

K. L. Marshall
716-275-5151

James E. Miller
703-664-1585

XXVI. OVERVIEW OF ARO-URI COESR RESEARCH IN SEMICONDUCTOR MATERIALS, SEMICONDUCTOR DEVICES, AND DIFFRACTIVE OPTICS

December 13, 1990

Ronald Antos
716-275-4179

Wayne Grant
703-664-4956

XXVII. SEMICONDUCTOR LASERS AND THEIR APPLICATIONS

December 17, 1990

Govind Agrawal
716-275-4846

C. Ward Trussell
703-664-5310

A Case Study...

DUAL-USE TECHNOLOGIES AND UNIVERSITY RESEARCH INITIATIVES

By Dr. Nicholas George, Dr. B.D. Guenther and Dr. Vincent Piarulli

Introduction

Since its founding in 1951, the U.S. Army Research Office has been actively sponsoring basic research that has led to technological advancements of direct use to the missions of the U.S. Army. This article illustrates, by a case study, how this research has also led to the development of dual-use technology in the areas of optoelectronics and imaging important to both military and civilian sectors.

The subject of this case study is a partnership involving DOD, the university community, and industrial corporations. The case study is authored by participants in the partnership from the Physics Division of the U.S. Army Research Office, the Center for Opto-Electronic Systems Research at the University of Rochester, and the Commercial and Government Systems Division of the Eastman Kodak Company.

We trace this case history of an ongoing experiment to optimize dual-use technology starting with the description of a successful University Research Initiative (URI) program in Opto-Electronic Systems Research at the Institute of Optics of the University of Rochester, and describe the challenge to expand it to a dual-use activity that led to the formation of the Center for Electronic Imaging Systems. We conclude with a discussion of the technologies included in this highly innovative cooperative research and development effort that involves government, university, and corporate members in a new partnership.

The decision to establish this Center for Opto-Electronic Systems Research was in recognition of the key role played by optoelectronics in providing the Army the capability of target acquisition. As noted in Figure 1, the program is organized around a canonical optoelectronics and imaging system. This figure serves as a basic definition for an optoelectronics system. The faculty research spans materials, devices, and systems and is organized to promote technology transfer of a generalized system nature to the Army. Dr. Nicholas George directs this ARO-URI at the university. The Army Advisory Board for this URI program is chaired by Dr. Rudolf Buser, director of the Night Vision and Electronic Sensors Directorate at Fort Belvoir. Dr. Buser deserves credit for many management innovations that have allowed the development of meaningful interactions between university and Army research organizations.

Need for Optoelectronics

In 1987 the Institute of Optics of the University of Rochester was designated as a center-of-excellence in optoelectronics. Funding was provided under the University Research Initiative program after an intensive competition involving 40 universities. The Center for Opto-Electronic Systems Research was established with the goals of: contributing basic scientific knowledge in the critical technology areas of signal and image processing and photonics, and participating in technology interactions with Army laboratories.

After five years of operation and a new competition, URI support for this center was continued for the period of 1992 to 1997. There are currently 10 faculty and 10 doctoral scholars participating in the URI program. Each faculty participant makes four trips a year to Army laboratories. The center's research topics are kept relevant through a review process that involves ratings by two advisory boards: the Technology Advisory Board and the Executive Advisory Board.

A number of examples of relevant research topics at the center that have led to technology transfer are: laser locator, optimization software for lens design, surface emitting circular laser beam from semiconductor lasers, theoretical limits of focusing laser beams, resolving subwavelength features in scanning systems, and classification of images independent of scale and angle of orientation. Five of the six listed technology transfers have dual-use applications. For example, the optimization software is now available in two commercial programs: *CODE V* and *Oslo*. Of particular interest to the Army is the effort in Automatic Target Recognition (ATR) that led to the sixth technology transfer.

Automatic Target Recognition

Vision, one of the seemingly simplest of all human activities, is still far beyond the reach of computer builders. Although the new generation of supercomputers performs

billions of arithmetic operations a second, the current machine vision systems perform much less efficiently than the human visual system. Since so much of human activity is associated with vision, research on robotic vision has great allure. The military needs vision machines to help guide land vehicles and planes and to provide ATR to the soldier.

An ATR system is the connection of an optoelectronic system to a computer which, in combination, have some facsimile of the attributes of the human visual system. The long-term objective is for the ATR system to be capable of making operator-independent decisions about scene content. In short, an ATR system must be able to receive the incoming imagery, process it for information content, and present the critical decision.

An important Army ATR mission is to locate targets by a helicopter in a pop-up mode. Breakthroughs in ATR research offer great potential for changing the scope of industry and defense. At the Institute of Optics, significant accomplishments have been made in ATR such as the classification of images independent of scale and angle of orientation. This remains an important system goal in the URI Center.

Imaging in the Information Age

Stimulated by the activities at the Army URI Center in ATR, the Rochester Imaging Consortium was formed three years ago by faculty from the University of Rochester (UR) and the Rochester Institute of Technology (RIT). It was formed as a special interest (working) group to concentrate on imaging in the information age. At first, the emphasis was to accomplish jointly some worthwhile research in electronic imaging and to experiment on some management strategies that would promote technology transfer, as we viewed it, at the bench-level across universities and corporate boundaries. Initially, two companies, Xerox and Eastman Kodak, were very responsive and contributed knowledge, technology, and funding. The initial effort was kept small and we concentrated our research on digital half toning and image quality. From this working group we developed the concept of the research triplet (Figure 2), grouping a faculty member with a corporate engineering-scientist and postdoctoral scholar or Ph.D. student.

Since faculty conducting research generally work in an autonomous and independent fashion, it seems natural to build in the technology transfer at the working group level. This innovative organizational plan has worked well and was used as the basis for the next step in technology transfer. One reason for its success is that each triplet is autonomous and failure of one does not jeopardize others. Also, this structure minimizes the need for middle-level managers.

Center for Electronic Imaging Systems

Both in the Rochester community and in major laboratories of the Army, leaders have expressed the need for leveraging of RD&A activities for a number of years. Dr. Gerald Iafrate, the director of ARO, suggested that efforts to leverage the ARO-URI research by obtaining the support of the industrial leaders in electronic imaging would create incredible possibilities. Spurred on by this encouragement, we began in earnest to seek corporate, New York State, and national support.

This work led to the creation of a major Center for Electronic Imaging Systems in Rochester by joining the university community—the University of Rochester and the Rochester Institute of Technology—with industrial leaders in electronic imaging—the Xerox Corporation, the Eastman Kodak Company, 3M, Harris' RF Communications, and a rapidly increasing number of other companies in New York State. Major funding has been obtained from a National Science Foundation (NSF) grant under the Industry University Cooperative Research Centers Program (IUCRC) that also includes funding from the New York State Science and Technology Foundation (NYSSTF), ARO, and the Night Vision and Electronic Sensors Directorate of the Army Communications-Electronics Command. In March 1993, we were designated by NYSSTF as the Center of Advanced Technology in Electronic Imaging Systems (CAT-EIS).

Our long-term vision is to establish and maintain a national center for all phases of electronic imaging systems with an impact that attracts national attention and provides a national service. As stated by Dr. Steven

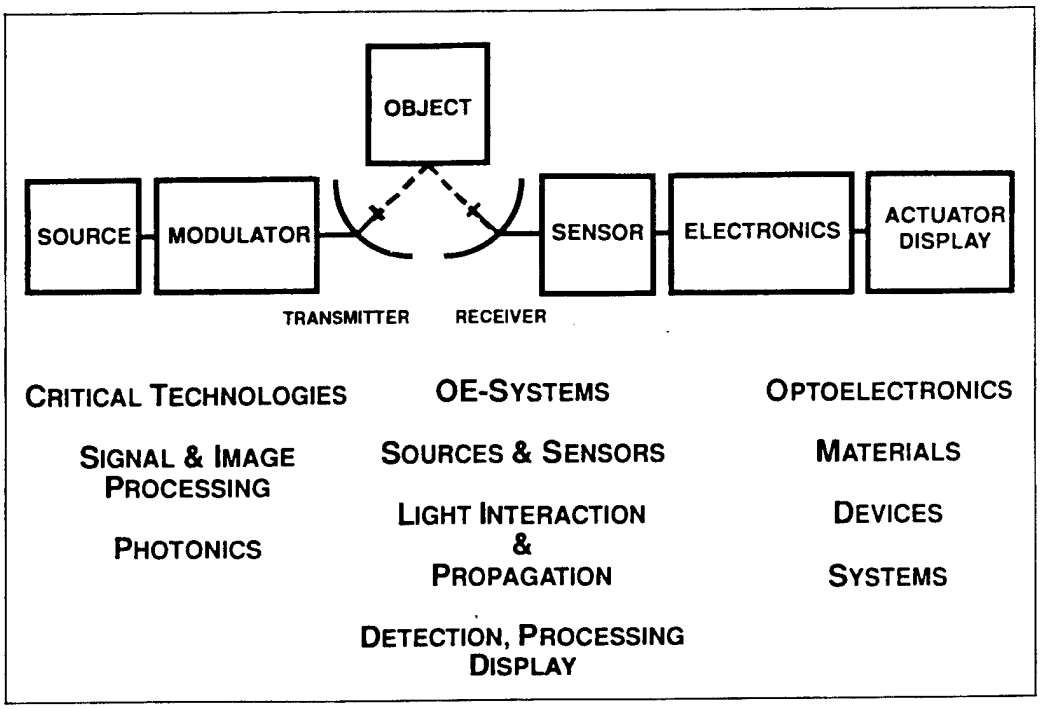

Figure 1.
Canonical opto-electronic system.

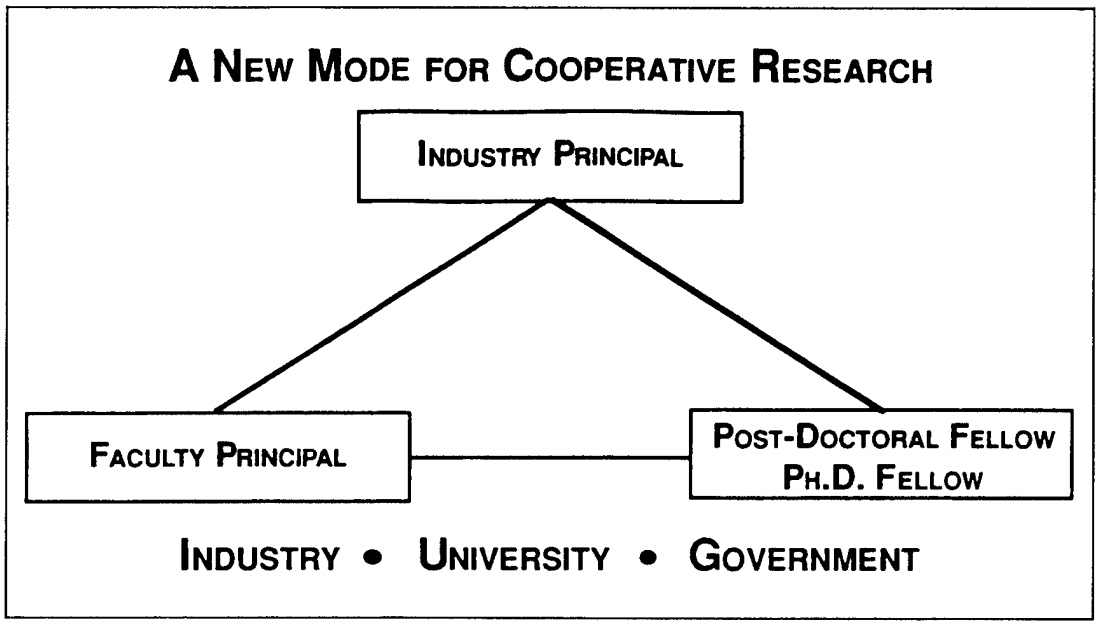

Figure 2.
Research project triplets.

B. Bolte, manager of the Webster Research Center, vice president, Xerox: "The University serves as the common meeting ground for corporations, and it is a natural place for pre-competitive research conducted cooperatively by faculty and company personnel."

An electronic imaging system can be approached from several viewpoints. The development engineer thinks in terms of the imaging chain: acquisition, capture, processing, storage, retrieval, transmission, display, editing, and printing. This is the same generic optoelectronic system (Figure 1), being used as the systems platform in guiding the research of the original Army URI Center.

For the systems planner, the strategic planner, or the CEO, it is useful to think in terms of program themes or systems goals. Hence, we have added to the generic imaging system eight major themes that serve as a framework around which we organize, report, and evaluate our research projects in our new CAT-EIS: Electronic Imaging Systems, Sequences of Images, Image Quality, Image Processing, Color, Imaging Through Turbulence, Automatic Pattern Recognition, and Visualization and 3-D Display.

In setting up the CAT-EIS as a joint venture between many organizations having different goals and perspectives, we found it useful to adhere closely to five requirements for successful alliances (described in the study "When Giants Learn to Dance" by Rosabeth Kantor). These points are paraphrased as follows:

• CEO Approval. For a successful alliance, the senior management of all

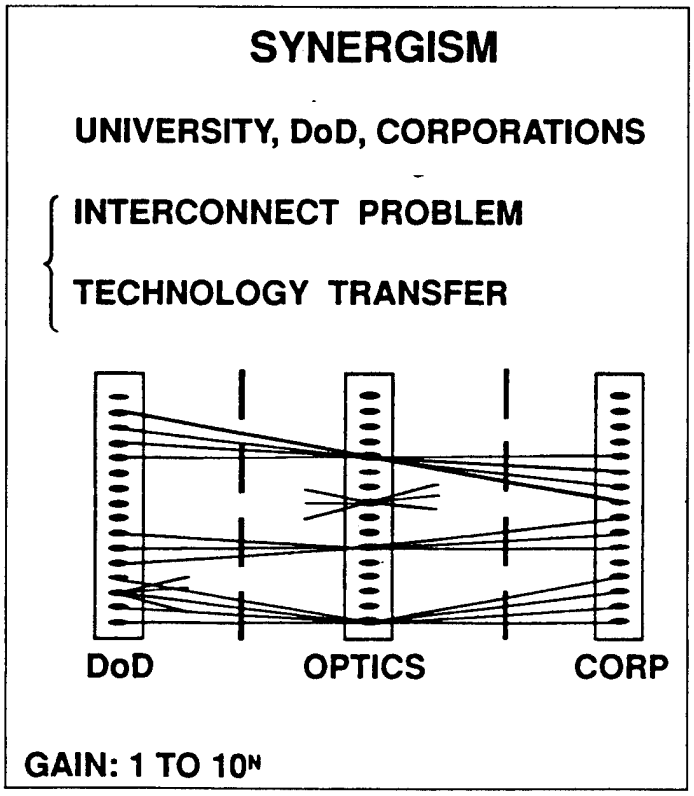

Figure 3.
Neural model.

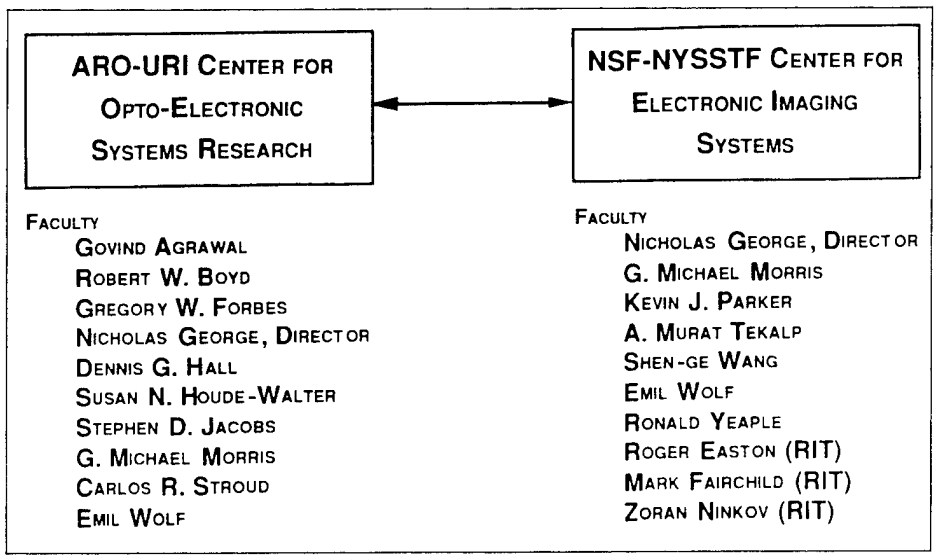

Figure 4.
Defense technology conversion.

participating organizations must agree on and support the goals. Hence, it is important to keep senior managers of all participating companies and agencies properly informed.

- Formal agreements to define the rewards for all participants.
- Continuing interdependence is needed among all participants.
- The consortium must insure that information flows between participants. For this we have expanded the working model of research triplets described earlier. It is a useful management technique for ensuring technology transfer and for optimizing the communication between industrial, government, and university laboratories.
- Informal association is necessary in order to build understanding and trust.

Both in the ARO-URI and for the CAT-EIS, technology transfer across 25 or more research disciplines is required. Putting the faculty investigator in charge has been effective for stimulating interaction. We have developed a neural network model in which individual faculty are shown as the "hidden layer" in Figure 3. Management establishes as many random, but reasonable, interconnects as possible with engineering personnel in governmental and corporate laboratories. After a learning period, we expect some of the interconnects will flourish for each faculty member. This neural model also shows management that the complex resulting interconnects are as hard to evaluate and count as are research publications. On the other hand, contributions to major themes are much easier to evaluate in simple terms.

Dual-Use Technologies

Both imaging and optoelectronics are central to DOD missions and to industrial applications. With the presence of the ARO-URI Center for Opto-Electronic Systems Research and NSF-NYSSTF-CAT-EIS at the University of Rochester, it is clear that a centralized management can effectively develop a strategic plan that maximizes dual-use technology by the various research triplets. Consider the faculty active on the two programs (see Figure 4). The approximate 30 percent overlap between the two programs promotes the creation of dual-use technology. Clearly, the two groups span a research spectrum that is considerably broader than that by either group alone.

By the addition of Eastman Kodak, Xerox and others to the university-based research effort, clearly the technological capability of the group has been enhanced in all aspects of imaging. We will illustrate this by a few examples associated with automatic pattern recognition, an important element of ATR.

Eastman Kodak has recently released a series of Kodak Photo CD products that allow intelligently managed storage, processing, and retrieval of enormous data bases of pictorial images. A high volume image conversion workstation is shown in Figure 5. Several person years of R&D effort have already gone into the establishment of a document reader for printed alphanumerics and for handwritten characters on Internal Revenue Service documents.

Working on research triplet plans with the Commercial and Government Systems Division of Eastman Kodak (V. Piarulli and A. Mirzaoff), we have formulated specific topics on automatic pattern recognition, as follows: Document recognition, Vehicular recognition (also involving NAC-TACOM), Facial recognition, Fingerprint recognition, and Image quality recognition.

In these areas, the university-based research funded by the Army has developed high-speed algorithms that are independent of scale and orientation. The ability to acquire and digitize images or transforms at high speed has been added by Eastman Kodak with their capability in image recording, processing, and retrieval.

State-of-the-Art in Facial Recognition

As a specific example of automatic pattern recognition, we will present one

Figure 5.
Eastman Kodak workstation for intelligent managed storage and retrieval.

recent experiment on facial recognition by Shen-ge Wang and Nicholas George. The question posed is whether one can train a computer using faces at a forward and a 60 degree view and thereafter recognize the face when it is seen at a 30 degree view. Of course the simpler problem of recognizing the face at the forward look and the 60 degree view has already been answered affirmatively.

Figure 6 shows the faces and Figure 7 shows the results of the experiment in a tabular form. We have used 10 photos at 0 degrees and 10 photos at 60 degrees to learn each of the six different faces, for persons A through F. Then, using data based both on the input image and its spatial transform, we are able to recognize the faces perfectly when they are seen at 30 degrees.

For each person A through F, we test the automatic recognition using 10 separate photographs of each face at 30 degrees. This explains the 10's in the diagonal of Figure 7. We emphasize that the computer was not trained on any of the faces at 30 degrees. We see the remarkable result that the computer has learned to sense that it is looking at the same face but at a different angle. Of course there are many variations possible in this experiment and these are currently being pursued under the ARO-URI Center for Opto-Electronic Systems Research.

Conclusion

The Army made a long-term investment in optoelectronics and imaging at The Institute of Optics beginning in 1987. That investment resulted not only in technology of use to the Army but also in dual-use technology for commercial applications. The research accomplishments attracted investments of both people and money by commercial firms into the resource created by the Army. These joint research activities are stimulating the interest of scientists from these commercial firms in Army problems such as ATR. New management techniques have been developed to insure that this new cooperative venture will develop ideas that are rapidly transferred into both commercial and military applications.

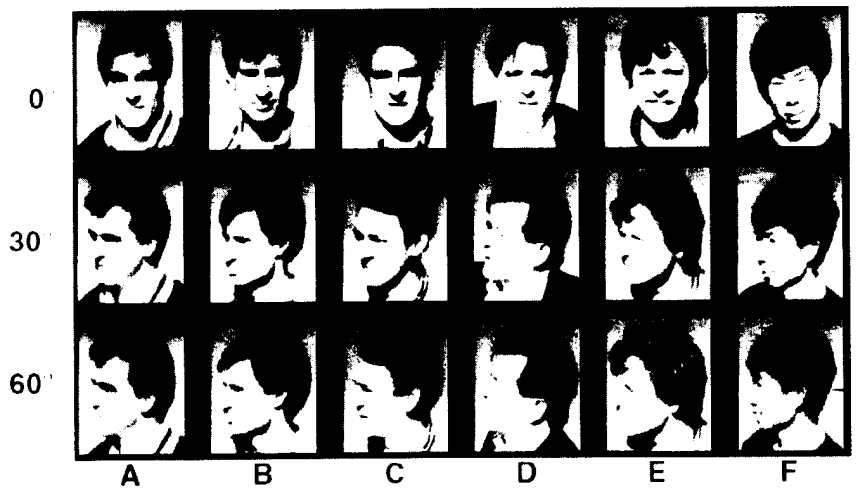

Figure 6. Facial Recognition - Image Database

INPUT		DESIRED OUTPUT																	
		A			B			C			D			E			F		
		0°	30°	60°	0°	30°	60°	0°	30°	60°	0°	30°	60°	0°	30°	60°	0°	30°	60°
A	0°	L																	
	30°		10																
	60°			L															
B	0°				L														
	30°					10													
	60°						L												
C	0°							L											
	30°								10										
	60°									L									
D	0°										L								
	30°											10							
	60°												L						
E	0°													L					
	30°														10				
	60°															L			
F	0°																L		
	30°																	10	
	60°																		L

Figure 7. 0° & 60°: Learning, 30°: Testing Combined Optical Transform and Image Data

DR. NICHOLAS GEORGE is associate dean for research in the College of Engineering and Applied Science and also a professor of optics at the University of Rochester. He is the founding director of both the ARO-URI Center for Opto-Electronic Systems Research and the NSF-NYSSTF-CAT: Electronic Imaging Systems.

DR. B.D. GUENTHER is director of the Physics Division of the Army Research Office. He received his undergraduate degree from Baylor and his graduate degrees from the University of Missouri in condensed matter physics. He has published extensively in optics and solid state physics and is the author of an optics textbook.

DR. VINCENT PIARULLI is the technology coordinator for Kodak's Commercial and Government Systems Group. He is actively involved with development and dual-use transfer activities in many of Kodak's imaging technologies. He holds a Ph.D. degree in mechanical and aerospace science from the University of Rochester where he was a NASA Fellow.

APPENDIX 7.2

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

†The Ph.D. Fellows listed above were associated with this URI program under a separate grant, DAAL03-86-G-0202. Further details can be found in the Final Report, December 1993.

Listing of Ph.D. Fellows (continued)

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

Listing of Ph.D. Fellows (continued)

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

Listing of Ph.D. Fellows (continued)

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

Listing of Ph.D. Fellows (continued)

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

Listing of Ph.D. Fellows (continued)

Title / Fellows / Advisor	Year	Current Address
		(602) 721-0500
"Global optimization in lens design" **Andrew Ellicott Wistar Jones** Gregory W. Forbes, Advisor	1992	Sinclair Optics Inc. 6780 Pittsford-Palmyra Road Fairport, NY 14450 (716) 425-4380
"An investigation of distributed coupling in a nonlinear semiconductor waveguide" **David Floyd Prelewitz** Thomas Brown, Advisor	1992	University of Rochester The Institute of Optics Rochester, NY 14627 (716) 275-8009
"Recovery of particle size distributions from the far field scattering pattern" **Scott D. Coston** Nicholas George, Advisor	1992	Bio-Derm, Inc. Clearwater, FL
"Wave guiding and grating coupling phenomena in silicon based integrated optics" **Robert Milton Emmons** Dennis G. Hall, Advisor	1992	NiOptics Corp 1801 Maple Avenue Evanston, IL 60201 (708) 491-3196
"Wavelength and roughness dependence of backscattering" **Donald John Schertler** Nicholas George, Advisor	1993	University of Rochester The Institute of Optics Rochester, NY 14627 (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" **Brian L. Olmsted** Susan N. Houde-Walter, Advisor	1993	University of Georgia Dept. Physics & Astronomy Athens, GA 30602 (706) 542-2485
"Optical absorption, emission, and modulation in III-V semi-conductor quantum well structures" **Steven Mark Shank** Gary W. Wicks, Advisor	1993	Cornell University Applied & Engineering Physics Ithaca, NY 14853 (607) 255-2000
"Spatial optical transforms with applications" **Keith Bryan Farr** Nicholas George, Advisor	1994	Advanced Optical Systems, Inc. 3330 L&N Drive, Suite A Huntsville, AL 35801 (205) 650-5960
"Dynamics of a molecular nuclear wave packet" **Thomas Dunn** Ian Walmsley, Advisor	1994	Anvik Corporation 250 Clearbrooke Road Elmsford, NY 10523 (914) 345-2442
"Semiclassical properties of Rydberg electron wave packets" **Mark Mallalieu** Carlos Stroud, Advisor	1994	Consultant

Listing of Ph.D. Fellows (continued)

Title / Fellows / Advisor	Year	Current Address
"A classical state of the atom: the Keplerian wave packet" **Michael Noel** Carlos Stroud, Advisor	(1994)	The Institute of Optics University of Rochester Rochester, NY 14627 (716) 275-8006
"Image deblurring, coding, and compression for multiple point impluse responses" **Bryan Stossel** Nicholas George, Advisor	(1994)	The Institute of Optics University of Rochester Rochester, NY 14627 (716) 275-5805
"Soliton generation in pulsed fiber lasers" **Andrew Stentz** Robert Boyd, Advisor	(1995)	The Institute of Optics University of Rochester Rochester, NY 14627 (716)175-5030

( ) Means final examination is yet to be taken.