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PROCEEDINGS OF SPIE

Fifty Years of Optical Sciences at The University of Arizona

**Harrison H. Barrett
John E. Greivenkamp
Eustace L. Dereniak**
Chairs/Editors

**19–20 August 2014
San Diego, California, United States**

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John E. Greivenkamp, College of Optical Sciences, The University of Arizona (United States)

Eustace L. Dereniak, College of Optical Sciences, The University of Arizona (United States)

Session Chairs

- 1 History of OSC

Thomas L. Koch, College of Optical Sciences, The University of Arizona (United States)

- 2 Astronomical and Space Optics at OSC

Harrison H. Barrett, College of Optical Sciences, The University of Arizona (United States)

- 3 Optical Engineering at OSC

Russell A. Chipman, College of Optical Sciences, The University of Arizona (United States)

- 4 Quantum and Nonlinear Optics at OSC

Thomas D. Milster, College of Optical Sciences, The University of Arizona (United States)

- 5 Imaging at OSC

Eustace L. Dereniak, College of Optical Sciences, The University of Arizona (United States)

- 6 Optical Instrumentation at OSC

R. John Koshel, College of Optical Sciences, The University of Arizona (United States)

- 7 Photonics at OSC

John E. Greivenkamp, College of Optical Sciences, The University of Arizona (United States)

- 8 Optical Metrology at OSC

Stanley Pau, College of Optical Sciences, The University of Arizona (United States)

Introduction

This conference, held 19–20 August 2014 as part of the SPIE Optics + Photonics Symposium in San Diego, California, celebrated the 50th anniversary of the founding of the University of Arizona's Optical Sciences Center (OSC) by Aden Meinel. The conference surveyed the progression of OSC from a small group of talented faculty to its present status as a world renowned center of learning in optics and photonics.

Since its creation, the Center's primary purpose has been both education and cutting-edge research in the optics and photonics arenas. The College has already graduated over 700 PhD, 1200 MS and 500 BS students. Faculty members were recruited from among the nation's top talent in optical engineering, and this quickly spread to the fields of photonics, quantum optics and image science.

This conference and the papers contained in this book also provide a glimpse into the variety of research topics that our students are exposed to in these disciplines. A group of faculty and other individuals, each representing their affiliated specialty area, presented new research and breakthroughs in science and technology. The papers reflect the growth of the College and its tremendous impact on a variety of scientific fields in education and in research for industry, military and medical applications. Advances in the field of optics, developed at OSC, will significantly impact tomorrow's technology.

The conference sessions were divided into eight topics:

- 1: History of OSC
- 2: Astronomical and Space Optics at OSC
- 3: Optical Engineering at OSC
- 4: Quantum and Nonlinear Optics at OSC
- 5: Imaging at OSC
- 6: Optical Instrumentation at OSC
- 7: Photonics at OSC
- 8: Optical Metrology at OSC

History of OSC

OSC grew out of a national need for more highly trained engineers and physicists in the optical sciences. (Recall that the laser was developed in 1960.) Throughout its 50-year history, OSC has grown and evolved in response to the changing needs for trained optical scientists and engineers. The evolution of the core course education also evolved from topics that were of current interest in industrial and military applications. However from its very beginning, OSC was conceived to cover the full range from optical engineering and applied optics through optical

physics. Initially, only MS and PhD degrees were offered, but eventually, the Center grew to become a College within the University of Arizona, which now offers an ABET accredited BS degree in Optical Science and Engineering. In addition, a very successful distance learning program for graduate degrees has been established.

Astronomical and Space Optics at OSC

This session first reviews the contributions of OSC to space optics, most notably instrumentation for the Pioneer Saturn/Jupiter and Pioneer Venus missions. The earliest programs at OSC involve the fabrication and testing of large optics. The development of the Multiple Mirror Telescope in the 1970s revolutionized the design of astronomical telescopes. OSC and the Steward Observatory Mirror Laboratory continue their collaboration in the manufacture of large astronomical mirrors. The classic polishing techniques have given way to advanced computer controlled machines and highly engineered polishing laps. New measuring methods developed at OSC have enabled accurate metrology of steeply aspheric surfaces, both concave and convex, as well as off-axis segments of these aspheres.

Optical Engineering at OSC

These presentations review OSC's valuable accomplishments in both teaching and research in optical engineering, covering the spectrum from the infrared to visible engineering applications. Particular attention is paid to the significant contributions in optical design and aberration theory. Presentations included the development of key mathematical formulism that take the understanding of optical aberration theory in entirely new directions. Computer-based optical design and optimization is followed from the overnight runs on the University mainframe computer to today's PC and laptop environment allowing a fast and flexible design process.

Quantum and Nonlinear Optics at OSC

This session traces the development of quantum optics, from the vibrant theory community founded by Scully and Lamb to more recent advances in single- and multi-atom quantum control, and their integration into a novel atom-light quantum interface. The semiconductor quantum optics group discusses the work being done with planar micro-cavities, including VCSELs, photonic crystal cavities, and other III-V material structures. Other recent research is being conducted on the effects of intense, ultrafast interactions of light with media, encompassing extreme nonlinear effects ranging from the creation of light filaments to many-body interactions between electronic carriers.

Imaging at OSC

This session covers many aspects of the historical development of imaging and image science at OSC as well as selected current research topics. Several themes emerge. One is the close relation between OSC and the Department of Radiology,

and how it drove new programs, new grants and new faculty hires. A second, and rather obvious theme, is the dramatic impact of computer technology on imaging. Through the mid-1980s, many students and faculty at OSC developed clever analog computers to overcome the limitation of digital computers of the day, but then OSC began leading the development of parallel computers and their application to imaging. In papers at this session we heard how modern computer power can be integrated into systems for molecular imaging and compressive sensing.

A very early development at OSC was methods for measuring and predicting image quality in terms of the scientific or medical goals of the imaging. This made possible a true science of imaging, with established experimental methods and theories with testable predictive power. Today, Image Science is one of four tracks in the PhD program at the College of Optical Sciences, and approximately twenty graduate courses are offered in this area.

Optical Instrumentation at OSC

Over the past 50 years, a large number of optical instruments have been developed at OSC for a myriad of applications. This session reviews a sampling of different instruments developed in recent years, including imaging spectrometers and polarimeters, optics for soft x-rays, as well as wearable augmented reality displays.

Photonics at OSC

The photonics program at OSC began in 1984, focusing on the development of femtosecond laser sources and their use in investigating semiconductor carrier dynamics. The program later expanded into organic photonics, fiber lasers, vertical cavity surface emitting lasers, nonlinear photonics, and optical communications, among other areas. Photonics has been critical to the growth of the Internet, which currently carries tens of exabytes per month via optical fiber. The future growth of information technology, including the transmission and processing of vast amounts of data (thousands of exabytes per month over optical fiber), will require a new class of photonic devices that readily integrate directly with semiconductor circuits and processors. Nanophotonic materials and devices, such as nanophotonic polymer materials and electro-optic polymer/silicon nanowire modulators, will enable us to meet these extraordinary requirements.

Optical Metrology at OSC

Every science requires a metric to establish quality, and this session discusses various methods developed at OSC to measure surface quality and optical properties, essential components of the applied optics. A major thrust of this work is the development of the technology of phase-shifting interferometry. The development of the Shack-Hartmann wavefront sensor had a tremendous influence on

ophthalmic optics. Scattering measurements and scattering properties of optical surfaces and materials were discussed in terms of developments being made at OSC. Finally, recent work in the use of interferometry to characterize ophthalmic components and the human eye are reviewed.

The College of Optical Sciences thanks SPIE for the gracious support provided in hosting the conference and making possible the publication of this special Proceedings volume.

Harrison H. Barrett
John E. Greivenkamp
Eustace L. Dereniak

Tenured and Tenure-Track Faculty of the Optical Sciences Center and the College of Optical Sciences

1964-2014

Brian P. Anderson
Amit Ashok
Clarence L. Babcock
Harrison H. Barrett
Peter H. Bartels
Rolf Binder
Nicolaas Bloembergen
Jim H. Burge
James J. Burke
Russell A. Chipman
Milorad Cvijetic
Eustace L. Dereniak
Michael Descour
James A. Eyer
Charles M. Falco
Mahmoud Fallahi
B. Roy Frieden
Jack D. Gaskill
Hyatt M. Gibbs
John E. Greivenkamp
Hong Hua
Stephen F. Jacobs
Poul Jessen
R. Jason Jones
Galina Khitrova
Khanh Kieu
Miroslav Kolesik
Chris L. Koliopoulos
R. John Koshel
Katherine Creath
Franko Kueppers
Matthew A. Kupinski
Willis E. Lamb Jr.

George N. Lawrence
Rongguang Liang
H. Angus Macleod
Masud Mansuripur
Arvind S. Marathay
Dean B. McKenney
Tom D. Milster
Robert H. Noble
Robert A. Norwood
Stanley Pau
Leilei Peng
Nasser Peyghambarian
Murray Sargent III
Dror Sarid
José Sasián
Jim Schwiegerling
Marlan O. Scully
Bernhard O. Seraphin
Roland V. Shack
Robert R. Shannon
Richard L. Shoemaker
Glenn T. Sincerbox
Philip N. Slater
Orestes N. Stavroudis
George I. Stegeman
Grover Swartzlander
William Swindell
Yuzuru Takashima
Kurtis J. Thome
J. Scott Tyo
William L. Wolfe Jr.
Ewan M. Wright
James C. Wyant

Any listing of faculty is by necessity incomplete. It does not recognize the significant contributions of the many Joint-Appointment Faculty, Research Faculty and Adjunct Faculty that have served the Optical Sciences Center and the College of Optical Sciences.

Graduates of the Optical Sciences Center and the College of Optical Sciences

1964-August, 2014

Doctor of Philosophy

Abdeq M. Abdi 2005	Louri Beregovskii 1999
Chiayu Ai 1987	Jill D. Berger 1997
Hazim Younis Al-Abawi 1982	Justin Philip Bergfield 2010
Andrew Alexander 1994	Bruce Edward Bernacki 1992
Kais Al-Marzouk 1982	John W. Berthold 1976
Joseph Ambrose 1994	Jacob Lee Beverage 2003
Douglas W. Amlin 1982	Stuart F. Biggar 1990
Douglas W. Anderson 1978	Gabriel Carlisle Birch 2012
Blake Anderton 2014	Wiley T. Black 2014
Ronald L. Antos 1981	Denise Marie Blanchard 1997
Ismail Emre Araci 2010	Alan R. Bleier 1984
Miena Magdi Hakeem Armanious 2010	Richard P. Bocker 1975
Paul D. Atcheson 1985	Eric L. Bogatin 1980
Riley W. Aumiller 2013	Deepak Boggavarapu 1993
Jason M. Auxier 2006	William Bomberger 1980
David J. Aziz 1995	Garret T. Bonnema 2008
Brett Edward Bagwell 2006	Donald C. Booth 1980
Lu Bai 1998	Glenn D. Boreman 1984
Dave Paul Baiocchi 2004	Brent J. Bos 2002
Kunjithapatham Balasubramanian 1988	Robert Boye 2000
William C. Banyai 1988	Robert P. Breault 1979
Christoph James Baranec 2007	James B. Breckinridge 1976
Noah Bareket 1979	Peter I. Brick 2001
Sergio Barraza-Felix 2002	Lawrence D. Brooks 1982
Frederick O. Bartell 1978	Francois Brown de Colstoun 1994
Brian J. Batdorf 1991	Michael P. Browne 1991
Allen Keith Bates 1994	Stephen D. Browning 1983
James M. Battiato 1998	Thomas J. Bruegge 1985
Daniel R. Bauer 2012	Richard A. Buchroeder 1976
Brian Jeffrey Bauman 2003	James H. Burge 1993
Neil Anthony Beaudry 2003	James J. Burke 1972
Robert G. Bedford 2003	Guillaume Pascal Nicolas Butel 2013
Bernard W. Bell 1985	Dale M. Byrne 1978
Eduardo A. Bendek 2012	Wenrui Cai 2013

Lonnie K. Calmes 1998	Brian Comaskey 1982
Eugene W. Campbell 1994	Thomas Wright Cooley 1995
Sawyer Duane Campbell 2013	Curtis A. Corum 2005
Barbara A. Capron 1986	Jasmin Cote 1996
Ellen B. Cargill 1990	Marie Cote 1995
James T. Carriere 2004	Blake M. Coughenour 2014
Timothy J. Carty 1989	Karlton Crabtree 2010
Gary E. Carver 1980	Alan E. Craig 1984
Kenneth R. Castle 1985	Cameron James Craigie 1993
Luca Caucci 2012	Katherine Creath 1985
Miguel A. Cervantes-Monto 1982	Blake G. Crowther 1997
Elizabeth Chain 1983	Jeffrey S. Czapla-Myers 2006
Matthew T. Chang 1998	Joseph C. Dagher 2006
Ming-Wen Chang 1975	Saurav Das 1998
Rong-Seng Chang 1980	Carolyn Marie Conner Davenport 1992
Yu-Chun Chang 1999	Thomas L. Davenport 2002
Karl Chao 1989	Martha W. Dawsey 2013
Hacene M. Chaouch 2011	Eugenio Manuel De La Rosa Rivera 2004
Sangam Chatterjee 2003	Brian J. DeBoo 2004
Souma Chaudhury 2008	Merritt N. Deeter 1988
Arturo Chavez-Pirson 1989	Richard Dekany 1994
Patrick S. Cheatham 1976	Imelda DeLarue 2003
Ching-Tai Chen 1982	Erich E. De leon 2012
Chungte Bill Chen 1978	Kenneth W. DeLong 1990
Jyhcheng Chen 1995	Eustace L. Dereniak 1976
Liyang Chen 2004	Christopher T. DeRose 2009
Tao Chen 2006	Matthew W. Derstine 1985
Yi-Chun Chen 2006	Lewis F. DeSandre 1989
Lu Cheng 1997	Michael R. Descour 1994
Yeou-Yen Cheng 1985	Scott L. Devore 1988
Kit-Iu Cheong 2007	Jeremy Todd Dobler 2005
Shuchung Chiao 1996	Oscar L. Doellner 1991
Matthew D. Chidley 2005	Michael E. Donovan 2000
Russell A. Chipman 1987	Dennis Douglas 2014
Ming-Yee Chiu 1980	Christian Y. Drouet d'Aubigny 2003
Taeyoung Choi 2008	Matthew B. Dubin 2002
Chien Chou 1978	Heather L. Durko 2014
Chih-Li Chuang 1991	Roger L. Easton 1986
George Cipperly 1992	Stephen K. Eckhardt 1990
Stephan R. Clark 2000	Jeffrey E. Ehrlich 1989
Andrew Franklin Clements 2012	Elliot Gene Eichen 1982
Eugene R. Cochran III 1988	James T. Eickmann 1998
Donald K. Cohen 1987	Rania Abd El-Maksoud 2009
Christopher Coleman 1998	Erin Marie Elliott 2002
D'nardo Colucci 1993	Kenneth Scott Ellis 1999

Yasufumi Enami 2003	Paul A. Gohman 1998
Muhsin Eralp 2007	Lewis J. Golden 1974
Victor C. Esch 1990	Elena V. Goldstein 1996
Joshua Eskin 1997	Goldie L. Goldstein 2013
Alan Eskovitz 1987	Dathon R. Golish 2008
Li Fan 2006	Qian Gong 1990
Qiang Fang 2012	Douglas S. Goodman 1979
Janet S. Fender 1981	Timothy D. Goodman 1996
Felix E. Fernandez 1987	Eric P. Goodwin 2007
Eric Carl Fest 2008	Joshua A. Gordon 2008
Robert D. Fiete 1987	Scott K. Gordon 1977
Donis G. Flagello 1993	Thorsten Graeve 1994
Laurence M. Flath 1994	Jeffrey Wayne Grantham 1991
Brian D. Fluegel 1992	David J. Graser 2000
Bridget K. Ford 2002	Robert Terry Gray 1983
Marsha Jane Fox 1993	John E. Greivenkamp 1980
Jerome B. Franck 1989	Devon W. Griffin 1990
Jesse A. Frantz 2004	Daniel F. Grogan 1990
Klaus Freischlad 1986	Kevin A. Gross 2006
Fred F. Froehlich 1996	Carter L. Grotbeck 1994
Tao-Yi Fu 1984	Ranjan Grover 2006
Canek Fuentes-Hernandez 2004	Paulo T. Guerreiro 1997
Allan H. Gabel 1988	Krishna Mohan Gundu 2008
Mark Gallagher 1993	Anurag Gupta 2002
Haiyong Gan 2008	Thomas R. Gurski 1974
Robert O. Gappinger 2002	Joshua N. Haddock 2005
Kevin Jay Garcia 1999	Nathan A. L. Hagen 2007
Keith Gardner 1980	Charles W. Haggans 1992
Joseph Geary 1984	Robert Edward Hahn 1976
Anoop George 2011	Walter Hahn 1992
James D. George 2001	Roger A. Hajjar 1992
Ronie George 2013	Heidi Hall 2001
James A. Georges 2003	Jarel B. Hambenne 1975
Ronald E. Gerber 1995	Roy A. Hamil 1980
Wayne M. Gibbons 1987	Chien-Wei Han 1995
Harald W. Giessen 1995	Jed J. Hancock 2012
Edward L. Gieselmann 1972	Akiko Harasaki 2000
George W. Gigioli 1988	Paul A. Harten 1992
C Lee Giles 1981	John P. Hartke 2005
Michael K. Giles 1976	Neal E. Hartsough 1994
Gene R. Gindi 1982	James E. Harvey 1976
Boris L. Glebov 2010	Eric G. Hawman 1981
Anthony D. Gleckler 1994	John B. Hayes 1984
Timothy M. Gleeson 1998	Mark S. Hayworth 1988
Arthur Gmitro 1982	Duanfeng He 1991

Sami Hendow 1982	Julia Craven Jones 2011
Joshua R. Hendrickson 2010	Matthew E. Jungwirth 2012
Jon A. Herlocker 2000	Aditya Kalavagunta 2004
Gregory Scott Herman 2013	Dong-Yel Kang 2009
Ronald S. Hershel 1971	Joshua L. Kann 1995
Chris A. Hessenius 2013	Angelique L. Kano 2009
Jacob Yost Hesterman 2007	David L. Kaplan 1988
Robert K. Hickernell 1987	Chris Karaguleff 1985
Thomas S. Hickernell 1988	Georgios Kastis 2002
Carolyn Frances Hickey 1987	Carol Jane Kastner 1985
Paul Dallas Hillman 1984	Keith J. Kasunic 1997
Marc D. Himel 1988	Patrick A. Kearney 1994
Roland Himmelhuber 2014	James Lewis Keef 2008
Van Arlen Hodgkin 1994	Paul E. Keller 1991
Jeffrey M. Hoffman 1993	Shanalyn Kemme 1998
Peter Hofmann 2012	Chandler Kennedy 1972
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Hongbo Li 2006	Anna-Britt Mahler 2006
Li Li 2003	Cornelius M. Mahoney 1972
Ming De Li 1987	Houssine Makhoul 2007
Qian Li 2011	Alejandro V. Maldonado 2013
Ying Li 1999	Proteep C.V. Mallik 2003
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Eric K. Lindmark 1994	Chadwick B. Martin 2004
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Tao Liu 2003	Oscar Alberto Martinez 2013
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Ann M. Locke 2001	Eric Anders Mason 2013
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Yuan Luo 2007	Brian P. McGinnis 1986
Amy G. Lusk 1987	William G. McKinley 1975
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Christopher J. MacGahan 2012	Edward S. Meinel 1980
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Nathan Daniel Meraz 2008	Brian W Myer 2008
Romeo L. Mercado 1971	Catherine D. Myers 2005
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Thomas D. Milster 1984	Kevin E. Newman 2014
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Jeremiah J. Montoya 2009	Gerald T. O'Connor 1981
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David J. Perry 1984	Logan L. Richardson 2013
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Jeff Jonathan Persoff 1981	Tyson J. Ririe 2010
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Nicolas Coracides 2004	Jose Florez 2006
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Chris Yarbrough 1999
Julius Yellowhair 1996
Wente Yin 2014
Will Yokubaitis 2003
Samir D. Youssef 2013
Bryan Yurs 2004
Livia Zarnescu 2010
Melissa Zaverton 2009
Christopher Zimmer 2006
Peter Zinsli 2005
Leonard Zugby 2006