

Optical Engineering

OpticalEngineering.SPIEDigitalLibrary.org

Polarization: Systems, Measurement, Analysis, and Remote Sensing

David B. Chenault
Dennis H. Goldstein
Michael W. Kudenov
Meredith Kupinski
J. Larry Pezzaniti
Joseph A. Shaw
Frans Snik
J. Scott Tyo
Christine L. Bradley

SPIE.

David B. Chenault, Dennis H. Goldstein, Michael W. Kudenov, Meredith Kupinski, J. Larry Pezzaniti, Joseph A. Shaw, Frans Snik, J. Scott Tyo, Christine L. Bradley, "Polarization: Systems, Measurement, Analysis, and Remote Sensing," *Opt. Eng.* **58**(8), 082401 (2019), doi: 10.1117/1.OE.58.8.082401.

Polarization: Systems, Measurement, Analysis, and Remote Sensing

David B. Chenault

Polaris Sensor Technologies, Inc.
Huntsville, Alabama, United States

Dennis H. Goldstein

Polaris Sensor Technologies, Inc.
Huntsville, Alabama, United States

Michael W. Kudenov

North Carolina State University
Raleigh, North Carolina, United States

Meredith Kupinski

University of Arizona
Tucson, Arizona, United States

J. Larry Pezzaniti

Polaris Sensor Technologies, Inc.
Huntsville, Alabama, United States

Joseph A. Shaw

Montana State University
Bozeman, Montana, United States

Frans Snik

Leiden University
Leiden, The Netherlands

J. Scott Tyo

Australian Defence Force Academy
Canberra, Australia

Christine L. Bradley

NASA Jet Propulsion Laboratory
Pasadena, California, United States

In the last 10 years, interest in polarization has exploded over previous time periods. From 1980 to 1989, 85 papers that referenced polarization as a keyword were published in *Optical Engineering*. From 1990-1999, this number increased substantially to 1240; 2000-2009 produced 1493 papers. In the 10 years to date, 2010 to 2019, over 2100 papers were published. The growth in the number of papers marks the increasingly diverse areas for devices, sensors, and applications in which polarization plays a primary or supporting role. This special section on polarization reflects that diversity and provides a good review of representative topics in polarization. In the nineteen papers presented here, we see continued improvements in devices, sensors, measurement approaches, and analytical techniques that address ever more real-world and practical applications, from displays to lithography to cancer. Improvements in modeling and analysis range from hybrid polarization and complex beams to optimization and understanding of the Mueller calculus. An examination of this special section will provide the reader a broad overview of polarization and its breadth of impact on the engineering of optical systems.

Included in the nineteen papers are two papers that provide an overview of different aspects of polarization. [Kruse et al.](#) describe visualization methods for presenting passive polarimetric images to the user in a meaningful way. It can be difficult to do this effectively and appropriately due to changing scene content. The authors provide recommendations based on the application and nature of the imagery. The second review paper by [Iglesias and Feller](#) provides a history of instrumentation for solar spectropolarimetry as well as descriptions of current and future instrumentation for this important field with wide-ranging impact. Improvements in devices and sensors are captured by seven papers. [Kramer and Baur](#) describe improved performance in achromatic retarders through the use of new materials. [Tauc et al.](#) analyze the impact of reflections on using a polarizer to characterize system performance and discuss their significance for polarimetric instruments. [Hagen et al.](#) provide a means for assessing the performance and noise characteristics of micro-grid polarization cameras and demonstrate the method on commercially available cameras. [Foreman and Goudail](#) show that three common metrics for optimizing other forms of Stokes polarimeters are frequently equivalent. [Pamet et al.](#) characterize statistical variations of an infrared active imaging polarimeter and how orthogonality breaking plays a role. [Toney et al.](#) describe material alternatives for LiNbO₃ waveguides and

show design, fabrication, and testing of the polarization mode conversion device with higher power capacity than previous materials. [Xu et al.](#) model high numerical aperture polarization aberrations in order to improve performance of lithographic projection lenses.

Advancing the understanding of physical exploitation and manipulation of polarization in diffractive optical elements, addressable computer-generated holograms, and amplitude modulators are described in papers by [Karpeev et al.](#), [Davis et al.](#), and [Chen, Zhang, and Zahn](#). Interesting applications exploiting polarization are presented by [Smith](#), who presents a quantum lidar that uses quantum entanglement in polarization, and by [Malik et al.](#), who show that fluorescence polarization may be a viable discriminant for cancer in renal biopsies.

An advancement in understanding experimental Mueller matrices and the nondepolarizing component is given by [Ossikovski and Arteaga](#) while [Zhdanov et al.](#) develop and demonstrate ray tracing of scenes with anisotropic media.

Finally, two papers advance the understanding of remote sensing and scattering in remote sensing applications. [Kupinski et al.](#) improve modeling of scattering of surfaces through the addition of a volume scattering term to produce a Mueller matrix bidirectional reflectance distribution function and, in a separate paper, [the same authors](#) demonstrate realistic rendering of scenes of JPL's GroundMSPI instrument. [Eshelman and Shaw](#) describe and show transformation between three reference frames for sky polarization and demonstrate it in a sunrise-to-sunset sequence of image frames.

Polarization conferences continue to show the diversity shown here and support the new generation of researchers, new approaches to sensors and modeling, and new applications. SPIE has supported polarization conferences since 1988 and continues to in the present year. This year marks the twenty-first year in a row that an SPIE polarization conference has been held. Over the last fifteen years, the polarization conferences have alternated between SPIE symposia with a defense focus at conferences in the even years and with a remote sensing focus in the odd years.

The special section editors would like to thank Karen Klokkevold, Karolyn Labes, and Eric Lochridge at SPIE and Michael Eismann, editor-in-chief of *Optical Engineering*, for their hard work in preparing these papers and supporting the guest editors, and for their diligence and patience with the peer-review process.

David B. Chenault is currently president of Polaris Sensor Technologies Inc., where he is leading a team of engineers and scientists developing next generation sensors including a suite of one-of-a-kind polarization imaging systems. He and his team support federal government programs and commercial customers for defense, intelligence, safety, and environmental applications. He received his BS in physics from Vanderbilt University and his MS and PhD in physics from the University of Alabama in Huntsville. He pursued research and development in a variety of optical systems with several defense contractors before founding Polaris. He has developed an infrared spectropolarimeter, imaging polarimeters in the visible, and throughout the infrared along with the data reduction and calibration routines to support them and overseen development of many others. He was co-editor for *Optical Engineering* special sections on polarization in 1995 and 2002 and for an *Applied Optics* feature issue in 2006. He has regularly co-chaired SPIE conferences on polarization since 1999. He is an SPIE Fellow, Class of 2008, and is a member of OSA and IEEE.

Dennis H. Goldstein performs research in polarized light. He is a Fellow of SPIE and AFRL. He served as a topical editor for *Applied Optics* for six years and regularly reviews manuscripts for five technical journals and two publishing companies. He has been involved in organizing and chairing conferences in polarimetry since 1989. He is a member of SPIE, the Optical Society of America, the American Physical Society, and Sigma Pi Sigma.

Michael W. Kudenov is an associate professor of electrical and computer engineering at North Carolina State University in Raleigh, North Carolina. He graduated in 2005 from the University of Alaska Fairbanks with a BS in electrical engineering and in 2009 from the University of Arizona with a PhD in optical sciences. His research focuses on the development, calibration, and validation of new spectral and polarimetric imaging systems for wavelengths spanning the UV to the thermal IR, including high speed and snapshot imaging spectrometers, polarimeters, cross-correlation spectrometers, and spectropolarimeters. Applications include space situational awareness, chemical imaging, quality control, optical modeling and calibration, agriculture, and phenotyping.

Meredith Kupinski is a research professor of the College of Optical Sciences at the University of Arizona. She received her MS and PhD degrees in optical science from University of Arizona in 2003 and 2008, respectively. Her research interests include task-relevant metrics for imaging system design, estimation/detection theory, and stochastic systems analysis and information quantitation. She is a recipient of the NSF Fellowship for Science, Engineering, and Education for Sustainability and a Jean d'Alembert Visiting Scholar award.

J. Larry Pezzaniti received his physics BS in physics from the University of Florida and his MS and PhD also in physics with an optics emphasis from the University of Alabama in Huntsville. After his PhD, he worked for almost 5 years at Abbott Laboratories in Chicago, Illinois, developing medical instrumentation. He then worked at MEMS Optical in Huntsville, Alabama, developing wafer level micro-optical devices, primarily for the telecom industry. In 2003, he joined Polaris Sensor Technologies as chief technical officer. The thrust of his work at Polaris has been in leading development efforts for polarimetric, multi- and hyperspectral imaging systems in the visible to long wave infrared spectrum. He has over 100 publications and holds over 23 patents.

Joseph A. Shaw is director of the Optical Technology Center and professor of optics and photonics and electrical engineering at Montana State University in Bozeman, Montana, USA. He earned a PhD and MS in optical sciences from the University of Arizona, an MS in electrical engineering from the University of Utah, and a BS in electrical engineering from the University of Alaska Fairbanks. For three decades, he has developed passive and active optical remote sensing instruments and methods, with a strong emphasis on polarimetric sensing systems. Since 2003 he has been the co-chair of the SPIE Polarization Science and Remote Sensing conference. He is a Fellow of SPIE and OSA, is the author of the 2017 SPIE book *Optics in the Air: Observing Optical Phenomena through Airplane Windows* and is the 2019 recipient of the SPIE G.G. Stokes Award for optical polarization.

Frans Snik is a staff researcher at Leiden Observatory (Leiden University, the Netherlands), where he leads a research group on optical instrumentation for astronomy and remote sensing. He specializes in polarimetric and polarization-based optics. His main research line focuses on the development of astronomical instrumentation to directly image and characterize planets around other stars than the sun. Versions of his polarization-based vector-APP coronagraph are currently being installed at many of the large ground-based telescopes around the world to enable the direct observations of such exoplanets. In addition, he and his group are developing polarimetric techniques to detect signs of life in the light from habitable exoplanets. He is co-inventor of the spectral polarization modulation technique that forms the core of a range of SPEX instruments that perform high-angle multi-angle spectropolarimetric measurements of atmospheric aerosols, to understand their effects on our climate and our health. This technology has now been selected to fly onboard

NASA's PACE satellite as part of the SPEXone instrument. He led the iSPEX citizen science project for which he developed low-cost smartphone add-ons based on the SPEX technology, that enabled thousands of participants to measure air pollution.

J. Scott Tyo is a professor of electrical engineering and the head of the School of Engineering and IT at UNSW Canberra. He has been a faculty member at the US Naval Postgraduate School, the University of New Mexico, and the College of Optical Sciences at the University of Arizona. His research group studies advanced optical sensing, focusing in polarimetry. He was the 2014 recipient of the SPIE GG Stokes award for his work on modulated polarimeters.

Christine L. Bradley received her BS and PhD degrees in optical science and engineering from the College of Optical Sciences, The University of Arizona, Tucson, Arizona, USA, in 2011 and 2017,

respectively. She is an optical engineer at the Jet Propulsion Laboratory (JPL), California Institute of Technology, Pasadena, California, USA. Since joining JPL, she has contributed to polarized light reflection and diffraction models of roughened optical edges for the Starshade project, supported cubesat development for an imaging spectrometer, and operated the GroundMSPI (Ground-based Multiangle Spectro-Polarimetric Imager) and PRISM (Portable Remote Imaging Spectrometer) instruments for Earth measurement campaigns. Currently, she is the optics lead for an imaging spectrometer for an Earth Ventures Instrument (EVI-4) Mission called Earth Surface Mineral Dust Source Investigation (EMIT) that operates in the visible to short-wave infrared to map the Earth's surface mineralogy of arid dust regions from the vantage point of the International Space Station. Her interests lie in the development of instrumentation for Earth science applications and polarimetry.