

Plenary Speakers



Robert Boyd

Canada Excellence Research Chair in Quantum Nonlinear Optics, University of Ottawa

Professor of Optics and Professor of Physics, University of Rochester

Visiting Professor of School of Physics and Astronomy, University of Glasgow, Glasgow, Scotland, UK.

Dr. Robert W. Boyd was born in Buffalo, New York. He received the B.S. degree in physics from MIT and Ph.D. degree in physics from the University of California at Berkeley. His Ph.D. thesis was supervised by Charles Townes and involves the use of nonlinear optical techniques in infrared detection for astronomy. Professor Boyd joined the faculty of the University of Rochester in 1977, and in 2001 became the M. Parker Givens Professor of Optics and Professor of Physics. In 2010, he became Professor of Physics and Canada Excellence Research Chair in Quantum Nonlinear Optics at the University of Ottawa. His research interests include studies of “slow” and “fast” light propagation, quantum imaging techniques, nonlinear optical interactions, studies of the nonlinear optical properties of materials, and the development of photonic devices including photonic biosensors. Professor Boyd has written two books, co-edited two anthologies, published over 400 research papers ($\approx 46,000$ citations, Google h-index 93), and been awarded ten patents. He is a past chair of the Division of Laser Science of APS and has been a member of the Board of Directors of OSA. Professor Boyd has served as a member of the Board of Editors of Physical Review Letters and of the Board of Reviewing Editors of Science Magazine.

Quantum Radiometry and Quantum Aberration Correction

Quantum technologies have become sufficiently mature that they can now solve some problems that lie in the domain of traditional optical engineering. We have recently shown that we can make use of the correlations present in the light generated by spontaneous parametric down conversion to perform an absolute calibration of the response of a spectrophotometer. [A primary radiation standard based on quantum nonlinear optics, S. Lemieux, E. Giese, R. Fickler, M. V. Chekhova, and Robert W. Boyd, *Nature Physics* (2019)]. In a separate project, we are making use of quantum entanglement to perform nonlocal correction of optical aberrations [A.N. Black et al., in review]. Both of these approaches hold great promise for solving long-standing problems in optical engineering through use of quantum information approaches.



Bahaa E.A. Saleh

Dean of CREOL, The College of Optics and Photonics at the University of Central Florida

Dr. Bahaa E.A. Saleh has been Dean of CREOL, The College of Optics and Photonics at University of Central Florida, since 2009. He served as Chair of the ECE Department at Boston University (1994-2008) and at the University of Wisconsin-Madison (1990-1994). He received a Ph.D. degree from the Johns Hopkins University in 1971 and held faculty and research positions at the University of Santa Catarina in Brazil, Max Planck Institute in Germany, the University of California-Berkeley, the European Molecular Biology Laboratory, and Columbia University. Saleh's research areas include coherence and statistical optics, quantum optics, and image science. He has made significant contributions in these areas and his publications include more than 600 journal papers and conference proceedings, as well as 3 books: Photoelectron Statistics, (Springer, 1978); Fundamentals of Photonics (Wiley, 1991, 2007, 2019 with M. C. Teich), and Introduction to Subsurface Imaging (Cambridge, 2011). He served as editor-in-chief of the Journal of the Optical Society of America A (1991–1997) and founding editor of OSA's Advances in Optics and Photonics (2008–2013). Saleh is Fellow of IEEE, OSA, APS, SPIE, and the Guggenheim Foundation. He is the recipient of OSA's Beller Award, SPIE's BACUS award, Kuwait Prize, OSA's Distinguished Service Award, and OSA's C. K. Mees Medal.

Sensitivity and Resolution of Quantum-Enhanced Imaging: Decoherence, Coherence, and Ancillas

In classical imaging systems, sensitivity is limited by shot noise, and resolution is limited by diffraction. Light probes in nonclassical states, e.g., squeezed, sub-Poisson, or entangled, have been shown to offer super-sensitivity and/or super-resolution. However, these enhancements are often vulnerable to noise and decoherence. In two-photon interferometry, the slightest amount of decoherence can cause total loss of phase sensitivity at certain values of phase. I will show how this loss can be restored by use of an ancillary degree of freedom, such as polarization, entangled with the interferometer's path degree of freedom. Projective binary measurement with image-inversion interferometers can offer two-point resolution that avoids Rayleigh's curse. I will show that in the presence of the smallest level of *coherence* the curse resurges. Precision and resolution are not necessarily independent. I will demonstrate their relationship when measuring the phase gradient by use of single- and two-photon beams and both optimal quantum measurement and projective binary measurements in a scanning image-inversion interferometer.

Invited Speakers



Charles A. Bouman

Showalter Professor of Electrical and Computer Engineering and Biomedical Engineering, Purdue University

Dr. Charles A. Bouman is the Showalter Professor of Electrical and Computer Engineering and Biomedical Engineering at Purdue University. He received his B.S.E.E. degree from the University of Pennsylvania, M.S. degree from the University of California at Berkeley, and Ph.D. from Princeton University in 1989. Professor Bouman's research is in the fields of electronic and computational imaging in applications ranging from medical to scientific and consumer imaging. He is member of the National Academy of Inventors, a Fellow of the IEEE, AIMBE, IS&T, and SPIE, and was the 2014 recipient of the Electronic Imaging Scientist of the Year award. He has served as the IEEE Signal Processing Society's Vice President of Technical Directions, Editor-in-Chief of the IEEE Transactions on Image Processing, Vice President of Publications for the IS&T Society, and he led the creation of the IEEE Transactions on Computational Imaging.

The Magic of Intelligent Coherent Optical Processing

Coherent sensing of light has the potential to revolutionize optics in much the same way that coherent RF processing revolutionized communications and RADAR. The power of this approach is that once optical measurements are converted to digital form, they can be processed with advanced, nonlinear, intelligent algorithms that can far exceed the capabilities of analog optical devices.

In this talk, we present a case study in which digital-holographic (DH) imaging was used to solve a previously unsolved problem: single-shot imaging through deep turbulence. The key to our approach is the digital-holographic model-based iterative reconstruction (DH-MBIR) algorithm which is designed to solve the nonlinear inverse problem of recovering an image which has been distorted by anisoplanar or "deep" atmospheric turbulence. The DH-MBIR algorithm works through the integration of a physical sensing model, advanced algorithmic estimation techniques, and deep neural network data models. Together, these result in a fast algorithm for recovering both the images and atmospheric phase distortions from a single coherent measurement of the light field. The same algorithm is also shown to be applicable to the problem of synthetic aperture LIDAR (SAL). Results are shown for both synthetic and bench-top optical measurements.



Vivek Goyal

Associate Professor of Electrical and Computer Engineering, Boston University

Dr. Vivek Goyal received the M.S. and Ph.D. degrees in electrical engineering from the University of California, Berkeley, where he received the Eliahu Jury Award for outstanding achievement in systems, communications, control, or signal processing. He was a Member of Technical Staff at Bell Laboratories, a Senior Research Engineer for Digital Fountain, and the Esther and Harold E. Edgerton Associate Professor of Electrical Engineering at MIT. He was an adviser to 3dim Tech, winner of the 2013 MIT \$100K Entrepreneurship Competition Launch Contest Grand Prize, and consequently with Nest Labs 2014-2016. He is now an Associate Professor of Electrical and Computer Engineering at Boston University.

Dr. Goyal is a Fellow of the IEEE. He was awarded the 2002 IEEE Signal Processing Society (SPS) Magazine Award, the 2017 IEEE SPS Best Paper Award, an NSF CAREER Award, and the Best Paper Award at the 2014 IEEE Int. Conf. on Image Processing. Work he supervised won awards at the IEEE Data Compression Conf. in 2006 and 2011, the IEEE Sensor Array and Multichannel Signal Processing Workshop in 2012, the IEEE Int. Conf. on Imaging Processing in 2018, and the IEEE Int. Conf. Computational Photography in 2018, as well as five MIT thesis awards. He currently serves on the Editorial Board of Foundations and Trends and Signal Processing, the IEEE SPS Computational Imaging TC, and the IEEE SPS Industry DSP TC. He previously served on the Scientific Advisory Board of the Banff International Research Station for Mathematical Innovation and Discovery, as Technical Program Committee Co-chair of Sampling Theory and Applications 2015, and as Conference Co-chair of the SPIE Wavelets and Sparsity conference series 2006-2016. He is a co-author of Foundations of Signal Processing (Cambridge University Press, 2014).

Computational Imaging with Few Photons or Electrons

Lidar systems use single-photon detectors to enable long-range reflectivity and depth imaging. By exploiting an inhomogeneous Poisson process observation model and the typical structure of natural scenes, first-photon imaging (FPI) demonstrates the possibility of accurate lidar with only 1 detected photon per pixel, where half of the detections are due to (uninformative) ambient light. While FPI has no quantum spookiness, it is highly unconventional just by virtue of exploiting probabilistic modeling of quanta of light. After explaining the simple ideas behind FPI, I will discuss other recent explorations of imaging under atypical acquisition models. This will include a discussion of interaction-free measurement in quantum electron microscopy that includes a spooky aspect.

Related paper identifiers:

10.1126/science.1246775

10.1038/ncomms12046

10.1038/s41586-018-0868-6

10.1109/TCI.2019.2913108

10.1109/TSP.2015.2453093

10.1109/TSP.2017.2706028

10.1103/PhysRevA.99.063809

arxiv:1906.03285

10.1364/OE.24.001873

10.1126/science.aat2298

10.1109/TSP.2019.2914891



Evgenii Narimanov

Professor of Electrical and Computer Engineering, Purdue University
Fellow of IEEE and OSA

Dr. Evgenii Narimanov is a professor of Electrical and Computer Engineering at Purdue University. He is a Fellow of IEEE and OSA. He received his Ph.D. in 1995, his M.S. (with highest honors) in 1991 and his B.S. (summa cum laude) in 1989 all from the Moscow Institute of Physics and Technology. His research interests focus on negative index (Meta) materials, optical systems with ray-chaotic dynamics, information-theoretical description of nonlinear fiber-optical systems, and non-linear dynamics.

Super-Resolution Imaging with Hyperbolic Materials

Optical imaging systems based on hyperbolic materials, offer the potential to combine subwavelength resolution with the advantage of an inherently label-free approach. In this talk, I review the recent developments in this field, in both direct imaging and structured illumination configurations.



Olivier Pfister

Professor of Physics, University of Virginia

Dr. Olivier Pfister received the B.S. in Physics from Université de Nice, France, in 1987, and the M.S. and the Ph.D. in Physics from Université Paris-Nord, France, in 1989 and 1993. In 1994, he was a lecturer at INM, Conservatoire National des Arts et Métiers, in Paris. He was then a research associate with John L. Hall at JILA, University of Colorado (1994-97) and with Daniel J. Gauthier at Duke University (1997-99). In 1999, he joined the faculty of the University of Virginia, where he is now a professor of physics. Olivier Pfister is a fellow of the American Physical Society and a member of the Optical Society of America. His current research interests are quantum computing with light and quantum measurements at the ultimate precision.

Engineering the quantum optical frequency comb: from spectral to spatial?

Our group has explored the nature of widely multidimensional quantum correlations and entanglement, both in Hilbert space and in the number of quantum subsystems. We have focused on the creation of the largest-to-date cluster states with simultaneously accessible (qu)modes, with 60 entangled fields confirmed, out of 10,000 probable. In this talk, I will describe these results and consider their possible translations to the spatial degrees of freedom for imaging.



Raphael C. Pooser

Research Scientist at Oak Ridge National Laboratory

Dr. Raphael C. Pooser is an expert in continuous variable quantum optics. He leads the quantum sensing team within the quantum information science group. His research interests include quantum computing, neuromorphic computing, and sensing. He currently leads the Quantum Computing Testbed project at ORNL, a large multi-institution collaboration. He has also developed a quantum sensing program from the ground up based on quantum networks over a number of years at ORNL. He has been working to demonstrate that continuous variable quantum optics, quantum noise reduction in particular, has important uses in the quantum information field. One of his goals is to show that the quantum control and error correction required in computing applications are directly applicable to quantum sensing efforts. He is also interested in highlighting the practicality of these systems, demonstrating their ease of use and broad applicability. His research model uses quantum sensors as a showcase for the technologies that will enable quantum computing. Dr. Pooser has over 16 years of quantum information science experience, having led the quantum sensing program at ORNL over the past eight. Dr. Pooser publishes in high impact journals, including in *Science*, *Nature*, and *Physical Review Letters*. He previously served as a distinguished Wigner Fellow. He also worked as a postdoctoral fellow in the Laser Cooling and Trapping Group at NIST after receiving his Ph.D. in Engineering Physics from the University of Virginia. He received a B.S. in Physics from New York University, graduating Cum Laude on an accelerated schedule. Dr. Pooser is active in the community, having served as a spokesperson for United Way and for the Boys & Girls Clubs of the TN Valley on many occasions in addition to volunteer work.

Quantum Imaging for Advanced Characterization

In this talk, I will outline quantum-enhanced sensing modalities for nanoscale imaging. Typical atomic force microscopes use optical readout of the cantilever displacement in order to provide an imaging signal. New imaging modalities that focus on ultrasonic measurements have brought the shot noise of the optical field into play when measuring away from resonance, allowing for shot noise limited measurements even at room temperature. However, state of the art approaches to AFM to date have been unable to leverage the lower noise floor away from the mechanical resonance frequency because minimum resolvable signals fall below the noise floor off-resonance. As a result, AFM techniques can only probe the RF response of materials at discrete mechanical frequencies, with slow measurements associated with micromechanical ringdown times that are highly susceptible to nonlinear dynamics. In the shot noise limited regime, far below the back-action limit, these devices are good candidates for quantum imaging, where quantum effects like entanglement are used to enhance the readout of optical beam displacements, revealing signals that were previously buried in the noise. The ability to lower the noise floor beyond current classical limits enables broadband materials characterization critical to describing electronic dynamics in complex materials with orders of magnitude faster acquisition times than are currently available. I will compare and contrast two common imaging techniques, with added quantum enhancement: direct detection readout and interferometric readout. I will outline a new scheme that relies on squeezed light and nonlinear interferometry to scale nanoscale imaging and characterization below the shot noise limit.



Ali Shakouri

Mary Jo and Robert L. Kirk Director of the Birck Nanotechnology Center
Professor of Electrical and Computer Engineering, Purdue University

Dr. Ali Shakouri is the Mary Jo and Robert L. Kirk director of the Birck Nanotechnology Center and professor of electrical and computer engineering at Purdue University. He received his doctoral degree from the California Institute of Technology in 1995 and his bachelor's degree in engineering from Telecom ParisTech in France in 1990. He was a faculty member at the University of California, Santa Cruz from 1998 to 2011, where he directed a multi university research center focused on direct conversion of heat into electricity. He also initiated a sustainability curriculum and a California-Denmark summer program in renewable energies in collaboration with colleagues in sociology, political science and environmental studies.

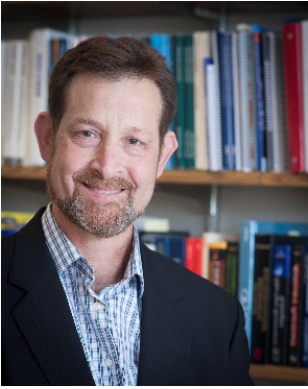
Ali's major initiative at the Birck Nanotechnology Center focuses on nanomanufacturing and printing smart films. The goal is to develop low cost devices and internet of things (IoT) sensor networks to enable digital agriculture, smart food packaging, wearables for healthcare monitoring and smart infrastructure. This involves two dozen faculty from colleges of engineering, science, agriculture and pharmacy.

Ali received a Packard Fellowship in Science and Engineering in 1999, an NSF CAREER Award in 2000 and the Thermi Award in 2014.

Ali Shakouri and Amirkoushyar Ziabari

Lock-in imaging below diffraction limit

Lock-in thermoreflectance imaging of active electronic and optoelectronic devices with 800ps time and 10mK temperature resolution is demonstrated. An image deconvolution technique is used to achieve spatial resolution below diffraction limit extracting the temperature of nanoheater lines with dimensions in 100-200nm range. Indication of hydrodynamic heat flow in thin film silicon at room temperature is presented. Finally, the impact of signal-to-noise ratio on sub-diffraction imaging is briefly discussed.



Andrew M. Weiner

Scifres Family Distinguished Professor of Electrical and Computer Engineering, Purdue University

Dr. Andrew M. Weiner, the Scifres Family Distinguished Professor of Electrical and Computer Engineering at Purdue University, is best known for pioneering work on programmable femtosecond pulse shaping and ultrafast signal processing. His recent work concerns optical frequency combs as well as multi-frequency and time-frequency quantum optics, including integrated photonics quantum sources. Weiner is a member of the National Academy of Engineering and National Academy of Inventors, was selected as a Department of Defense National Security Science and Engineering Faculty Fellow, and has received the OSA Wood Prize and the IEEE Photonics Society Quantum Electronics Award, among others. He is author of the textbook *Ultrafast Optics* and recently concluded a six-year term as Editor-in-Chief of *Optics Express*.

Broadband Photonic Signal Processing for Time-Frequency Quantum Optics – and Imaging?

Entanglement is a key resource for quantum information processing. Photons have proven to be an indispensable tool for investigation of entanglement and its applications; they also have a long history in (classical) imaging. Over the last several years, my group has worked with broadband photons that are entangled in discrete frequency bins or in continuous time-frequency degrees of freedom. In this talk, I will review our efforts to adapt tools from the fields of classical ultrafast optics and high-speed photonics (pulse shapers, phase modulators, dispersion) to expand our ability to manipulate broadband photon entanglement and speculate on potential connections to imaging problems.

Organizing Committee



Ali Shakouri

Mary Jo and Robert L. Kirk Director of the Birck Nanotechnology Center
Professor of Electrical and Computer Engineering, Purdue University

Dr. Ali Shakouri is the Mary Jo and Robert L. Kirk director of the Birck Nanotechnology Center and Professor of Electrical and Computer Engineering at Purdue University. He received his doctoral degree from the California Institute of Technology in 1995 and his bachelor's degree in engineering from Telecom ParisTech in France in 1990. He was a faculty member at the University of California, Santa Cruz from 1998 to 2011, where he directed a multi university research center focused on direct conversion of heat into electricity. He also initiated a sustainability curriculum and a California-Denmark summer program in renewable energies in collaboration with colleagues in sociology, political science and environmental studies.

Ali's major initiative at the Birck Nanotechnology Center focuses on nanomanufacturing and printing smart films. The goal is to develop low cost devices and internet of things (IoT) sensor networks to enable digital agriculture, smart food packaging, wearables for healthcare monitoring and smart infrastructure. This involves two dozen faculty from colleges of engineering, science, agriculture and pharmacy.

Ali received a Packard Fellowship in Science and Engineering in 1999, an NSF CAREER Award in 2000 and the Thermi Award in 2014.



Yong P. Chen

Director, Purdue Quantum Science and Engineering Institute
Karl Lark-Horovitz Professor of Physics and Astronomy
Professor of Electrical and Computer Engineering, Purdue University

Yong P. Chen leads the “Quantum Matter and Devices Laboratory” that makes, measures and manipulates diverse quantum matter ranging from 2D/topological/hybrid quantum materials to atomic quantum gases, with potential applications such as energy, sensing, and quantum technologies. He received a B.S. and M.S. in mathematics from Xi’an Jiaotong University and MIT, respectively, a Ph.D. in electrical engineering from Princeton University, and did a physics postdoc at Rice University. He joined the Purdue faculty in 2007 and is currently the Karl Lark-Horvitz Professor of Physics and Astronomy and Professor of Electrical & Computer Engineering as well as the Inaugural Director of the Purdue Quantum Science and Engineering Institute (PQSEI). He is a recipient of (young) faculty awards from NSF, DOD, ACS, IBM and Horiba Award, a Fellow of the American Physical Society, a principal investigator in WPI-AIMR International Materials Research Center in Japan, and selected as a Villum Investigator in Denmark.



Mahdi Hosseini

Assistant Professor of Electrical and Computer Engineering
Assistant Professor of Physics (by courtesy), Purdue University

Dr. Mahdi Hosseini is currently an Assistant Professor of Electrical and Computer Engineering at Purdue University, where he works on quantum photonics and atom-optics for applications in quantum communication and sensing. He received his Ph.D. in 2012 from Australian National University working on developing atomic quantum memories using atomic gasses. As a postdoc at MIT, he studied cavity quantum electrodynamics interactions between photons and an ensemble of atoms in the group of Vladan Vuletic. Since 2016, Mahdi has been a faculty in Electrical and Computer Engineering and Physics (by courtesy). His research interest is the study of novel regimes of light-matter interactions for applications ranging from quantum information to bio-sensing.



Amirkoushyar Ziabari

Postdoctoral Research Associate at Oak Ridge National Laboratory

Dr. Amirkoushyar Ziabari is a Postdoctoral Research Associate in the Imaging, Signals and Machine learning (IS&ML) group at the Electrical and Electronics Systems Research Division (EESRD) at Oak Ridge National Laboratory (ORNL). Before joining ORNL, Dr. Ziabari was a Postdoc at Integrated Imaging group at the Department of Electrical and Computer Engineering (ECE) at Purdue University. He also received his Ph.D. from the department of ECE at Purdue University in August 2016. His research interests have been at the intersection of physics, signal processing and machine learning, where he has used image/signal processing and machine learning ideas to explore multiscale experimental physics phenomena. He is currently working on data analytic, data driven and physics-based image reconstruction and segmentation for advanced manufacturing in order to improve the state-of-the-art in real time monitoring of the process.

Ali Shakouri and Amirkoushyar Ziabari

Lock-in imaging below diffraction limit

Abstract: Lock-in thermoreflectance imaging of active electronic and optoelectronic devices with 800ps time and 10mK temperature resolution is demonstrated. An image deconvolution technique is used to achieve spatial resolution below diffraction limit extracting the temperature of nanoheater lines with dimensions in 100-200nm range. Indication of hydrodynamic heat flow in thin film silicon at room temperature is presented. Finally, the impact of signal-to-noise ratio on sub-diffraction imaging is briefly discussed.

Thank you to the following sponsors:



Tomás Díaz de la Rubia

Chief Scientific Officer

Senior Vice President for Strategic Initiatives, Purdue University

Dr. Tomás Díaz de la Rubia is Purdue University's Chief Scientific Officer and Senior Vice President for Strategic Initiatives in **Discovery Park**. In this position, his responsibilities include building upon Discovery Park's foundation of excellence which has enabled high-impact research that crosses traditional academic boundaries. He works closely with the faculty and deans to help catalyze Purdue's many strengths and build on its legacy of interdisciplinary research with global impact. He is also a professor of Materials Science, and of Strategic Management (by courtesy) in the Krannert School of Management.

Before coming to Purdue, Díaz de la Rubia served as innovation leader and a director in Deloitte's energy and resources industry practice in Washington, D.C., working with Fortune 500 energy and manufacturing companies to identify and capitalize on business opportunities arising from potentially disruptive, innovative new technologies.

Prior to joining Deloitte, Tomás was the chief research officer and deputy laboratory director for science and technology at the Lawrence Livermore National Laboratory (LLNL) in California, where he was responsible for the long-term health of the science and technology foundations of the laboratory's \$1.6 billion research program. In this capacity, he oversaw a \$300M program of basic and applied research, and was responsible for the Laboratory's industrial partnerships and technology commercialization. From 2002-2009, he was an associate director at LLNL, leading its chemistry, materials science, life sciences, and energy and environmental sciences organizations, as well as its \$60 million basic materials science, chemistry and biology programs with the Department of Energy's Office of Science.

Tomás is a member of the National Academies of Sciences, Engineering and Medicine Intelligence Community Studies Board, which discusses science and technology issues of importance to the nations' intelligence community. Tomás also serves as a member of the Board of Directors of the Civilian Research and Development Foundation (CRDF Global), a non-profit organization dedicated to promoting peace and prosperity through international scientific collaboration, and as a member of the Editorial Board of Applied Physics Reviews. Among his hobbies, he is a member of the Confrerie des Chevaliers du Tastevin, a worldwide group dedicated to promoting the virtues of the wines and foods of Burgundy.

Díaz de la Rubia has published more than 150 peer-reviewed articles and has co-edited several books and conference proceedings. He is a fellow of the American Physical Society and of the American Association for the Advancement of Science and served as an elected member of the board of directors of the Materials Research Society, and vice-chair of the division of computational physics of the American Physical Society. He holds a bachelor's degree (summa cum laude) and a doctorate in physics from The State University of New York, Albany.



Birck Nanotechnology Center
DISCOVERY PARK



Electrical and Computer Engineering
COLLEGE OF ENGINEERING



Physics and Astronomy
COLLEGE OF SCIENCE



Purdue Quantum Science and Engineering Institute
DISCOVERY PARK