McCoy Distinguished Lecture

David D. Nolte

Professor of Physics, Purdue University

"Light Interactions"

From Holographic Semiconductors to Your State of Health

Friday, October 21, 2005

3:30 p.m. Lecture

Fowler Hall, Stewart Center

4:30 p.m. Reception

Stewart Art Gallery

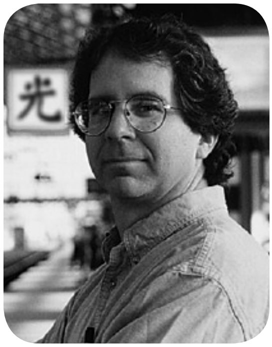
PURDUE
UNIVERSITY

Herbert Newby McCoy Award

The Herbert Newby McCoy Award was established in 1964 by Mrs. Ethel Terry McCoy in honor of her husband, a distinguished Purdue alumnus. A native of Indiana, Herbert Newby McCoy studied chemistry at Purdue University, earning a BS degree in 1892 and an MS degree in 1893. He received his PhD at the University of Chicago in 1898. McCoy spend the early part of his career as a professor of chemistry, teaching at North Dakota State University, the University of Utah, and the University of Chicago. During the latter part of his career, he was president of Carnotite Reduction Company in Chicago and vice president of Lindsay Light and Chemical Company, also in Chicago. He died in 1945 in Los Angeles, California.

To celebrate her husband's lifelong interest in science, Mrs. McCoy requested that this annual award be made to a student or faculty member in the science departments of Purdue University making the greatest contribution of the year to science. Since the first award was conferred in the spring of 1965, it has remained the most prestigious research award given by the University in the area of science. Nominations are invited from all faculty members, and the recipient is selected by representatives of the science faculties and the president of the University.

The McCoy Distinguished Lecture Series has been established to honor the Herbert Newby McCoy Award winner and to present to the Purdue community the nature of the research and its contribution to the field of science.



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“Light Interactions”

From Holographic Semiconductors to Your State of Health

David D. Nolte, professor of physics, has been a member of the Purdue University faculty since 1989. A native of northern Ohio, he attended Cornell University in Ithaca, New York where he worked summers at the Cornell electron storage ring (CESR) helping build and analyze data from the CLEO particle detector just after CLEO began operating in 1980. He was deeply influenced by professors Al Sievers and Kurt Gottfried and future Nobel prize winners David Lee and Robert Richardson. He graduated Phi Beta Kappa in 1981 with a BA from the School of Arts and Sciences.

After Cornell, with the help of Gottfried and David Cassel, he received a summer fellowship from the German Academic Exchange Program (DAAD) to work at the German electron synchrotron (DESY) on the PETRA ring outside of Hamburg. He worked with Prof. Hermann Fischer's group from the University of Bonn on two-photon events that occur when an electron and positron each emit a photon under low-angle scattering. The photons are so energetic that they collide and generate a particle-antiparticle pair. These interacting photon events interestingly presaged his later work in nonlinear optics where photons interact with photons inside crystals but with energies a billion times smaller.

After Hamburg, Nolte entered graduate school in physics at the University of California at Berkeley and took his first research position under Prof. Paul Richards helping build a rocket-borne infrared spectrometer to study the cosmic background radiation left over from the Big Bang. While working in Richard's infrared lab, he was attracted to the research of students working for Prof. Eugene Haller on defect states in semiconductors. In 1983, he switched research fields to work in solid state physics under the direction of Haller and Prof. Leo Falicov. He graduated from Berkeley with his PhD in 1988.

Nolte took a post-doctoral position at AT&T Bell Laboratories in Holmdel, New Jersey under the direction of Alastair Glass. There he was introduced to the field of laser physics and quantum electronics, and in particular to a nonlinear optical process known as the photorefractive effect in which photons interact with other photons under extremely low light conditions. While working with Glass, Wayne Knox and Daniel Chemla, Nolte demonstrated the first photorefractive quantum well (PRQW) structures in the summer of 1989.

In the fall of 1989, Nolte took a position as an assistant professor in the physics department at Purdue University where he continued working on photorefractive effects in semiconductors and established a new record in 1990 with the PRQW devices for the highest-sensitivity dynamic holographic effects in any material system. Through the 1990s Nolte's group explored the origins of the high sensitivity, uncovering novel nonlinear transport effects in highly-compensated semiconductor quantum structures. During this time Nolte also explored quantum confinement effects in quantum structures, performed the first magneto-optic time-reversal experiments, studied femtosecond optical interactions using holography, and began applying the sensitive holographic devices to applications such as adaptive interferometry, femtosecond pulse manipulation, and biomedical applications, including the invention and demonstration of the BioCD.

Nolte is co-author or author of more than 140 publications and holds six patents in optoelectronic materials and interferometry. He has written numerous book chapters and encyclopedia articles, has been editor of four volumes and is the author of the book *Mind at Light Speed: A New Kind of Intelligence* (Simon&Schuster, 2001). He is a fellow of the American Physical Society (APS) and the Optical Society of America (OSA). He was a Presidential Young Investigator (PYI) of the National Science Foundation and a research fellow of the Alfred P. Sloan Foundation, and is a Purdue University Faculty Scholar. He is a dedicated teacher and received the Ruth and Joel Spira Award for best undergraduate teacher in physics. His past and present outside activities include serving as member of the board of advisors for Nankai University in Tianjin, China, technical founder and member of the scientific board of the Lafayette-based company QuadraSpec Inc., NATO science consultant, chairman of the 8th International Conference on Photorefractive Effects and Materials, and he has served for numerous years on the technical committee of the conference on lasers and electro-optics (CLEO).

Abstract of Lecture:

A long-term goal of photonic research is the control of light by light inside nonlinear optical materials just like electrons control electrons inside transistors. However, unlike charged electrons that interact and repel strongly, light does not naturally interact with itself. Indeed, one of the great advantages of using light for communications is that light beams pass entirely through each other without any effect at all. But inside nonlinear optical crystals, light uses the electronic properties of the intervening material to mediate an indirect interaction between photons. While this secondary interaction is usually extremely weak and requires laser intensities brighter than the surface of the sun, our research group in the Department of Physics has developed a material, based on quantum effects in semiconductors, that allows photons effectively to bounce off of other photons with 40 percent efficiency using light that is as dim as the light in a darkened room.

With this extraordinarily sensitive material, fashioned into devices called photorefractive quantum wells (PRQW), we recently achieved the long-standing goal of holographic imaging into living tissue. Proposed over 40 years ago, shortly after the invention of the laser, we were the first to image inside living tissue, observing morphological structure inside osteogenic cancer tumors and tracking the time course of a toxin affecting mitochondrial electron transport by measuring sub-cellular motility in the form of shimmering laser speckle.

Perhaps the most ubiquitous application of the holographic films is in adaptive interferometry, which we have applied to ultrasound detection, with potential for non-contact biomedical imaging. More recently, we have applied it to the detection of proteins on spinning disks called BioCDs. The BioCD uses concepts borrowed from music compact discs (CDs), but we modify them to sense proteins in samples with high sensitivity and at high speed. The rim of the BioCD spins at velocities up to 60 mph making protein measurements at a rate of up to a million per second. The high-capacity potential of the BioCD may one day make it possible to track concentrations of thousands of proteins in blood to define a molecular state of health that is like a trajectory through a high-dimensional "health" space.

Research:

Dynamic holography uses light to control light, just like transistors use electrons to control other electrons. In dynamic holographic mixing, two laser beams form mutual interactions in a nonlinear medium that allows the light beams to self-diffract off each other. The world's most sensitive dynamic holographic material is the photorefractive quantum well (PRQW) developed by Nolte at Purdue in collaboration with Prof. Michael Melloch of the School of Electrical Engineering. The special importance of the PRQW devices is the unusually low light levels that can still accomplish this self-scattering of light off light. Fully developed holograms can be recorded in the PRQW devices using laser light as dim as the light of a darkened room.

The superior properties of these advanced optoelectronic materials are based on unexpected physics of electronic transport that, in effect, put electrons in suspended animation inside semiconductor crystals under high electric field. Dielectric relaxation, which normally limits charge accumulation in semiconductors, is disabled under high electric fields in these highly compensated materials, thus allowing low light intensities to drive large charge redistribution. This nonlinear electron transport gives the materials exquisite sensitivity to record extremely weak light fluxes.

Nolte's group has recently achieved a landmark accomplishment that spans the fields of holography and biomedical imaging by using these media to record the first depth-resolved holograms of biological tissue, imaging into rat osteogenic sarcoma tumor spheroids and mouse corneas. In this application, dynamic holography acts as coherent "sun glasses" that eliminate the glare of scattered light that normally makes it impossible to see into skin and tissue. With this adaptive optics approach, it is now possible to peer directly inside translucent media using neither ionizing radiation nor computed reconstruction. This work represents a paradigm shift both in the fields of holography and in biomedical imaging — the first time such weak holograms have been recorded in fast dynamic media, and the first time it has been possible to use light to see directly inside tissue.

The idea of using light to image into biological tissue has a long history motivated by its benign nature compared to potentially hazardous X-rays, and its high spatial resolution compared to MRI technology. While a vigorous community of optical biomedical imaging has emerged, none of the standard optical techniques had allowed direct depth-resolved imaging, requiring instead computed tomography, model-based signal inversion, diffusing photons, or point-by-point scanning. Within the holography community, many attempts had been made, with some success, to see through tissue, essentially by shadow-casting to generate 2D projections. But none had been able to record holograms in reflection, from selected depths, allowing full 3D viewing. First proposed in 1963, only three years after the invention of the laser, volumetric holographic imaging into living tissue was an unfulfilled dream for almost 40 years. This is because light scattered from deep inside biological tissue is exceedingly weak, dimmer by up to eight orders of magnitude relative to background intensities (the glare that keeps us from seeing into our skin). Only by the unique sensitivity of the PRQW materials is it possible to record holograms of such weak signals, thereby establishing the Purdue group of David Nolte, in collaboration with Prof. John Turek of the Veterinary School of Medicine, as the first to accomplish the goal of direct holographic biomedical imaging.

There is an unusual breadth to Nolte's research activities. Tangential to the biomedical imaging research, he has studied the physics and applications of optical time reversal. He was the first to explore the fundamental physics of time-reversed light in the presence of magnetic fields, with the help of Prof. Ramdas and Dr. Miotkowski of the physics department, and the first to apply femtosecond spectral interferometry, in collaboration with Prof. Andrew Weiner of the School of Electrical Engineering, to cause photons to jump forwards and backwards through time. He also has an active collaboration in geophysics with Prof. Laura Pyrak-Nolte of the physics department, making contributions to seismic imaging of fractures, and participates in fundamental explorations of the physics of fluids in micron-scale porous media.

Nolte has built one of the world's most sensitive adaptive interferometers. It uses adaptive holography to compensate mechanical variations and optical aberrations that plague all current conventional interferometers. The mirrors of the adaptive interferometer can move by tens of microns, yet the interferometer has achieved surface displacement sensitivity to less than a picometer. The ability to perform vibration-free interferometry is a powerful and widely applicable resource for the field of sensing and metrology. His group is now applying this concept to their newly-developed BioCD, a biochip implemented as a spinning-disk interferometer that detects molecular recognition of antibody-antigen binding. The BioCD has been licensed by Purdue University to QuadraSpec Inc. of Indiana, which recently won the prestigious Krannert-sponsored 2004 Burton T. Morgan Entrepreneurial Competition based on Nolte's technology and his collaboration with Prof. Fred Regnier of the chemistry department. The BioCDs have the potential for high-speed high-throughput molecular assays with applications in diagnostic medicine and drug discovery.

Past McCoy Award Winners

2004 Stanton B. Gelvin, Biological Sciences
2003 Philip L. Fuchs, Chemistry
2002 Roberto Colella, Physics
2002 Alexandre Eremenko, Mathematics
2001 Janet L. Smith, Biological Sciences
2000 Nicholas A. Peppas, Chemical Engineering, Biomedical Engineering.
1999 Ray A. Bressan, Horticulture
1998 Ei-ichi Negishi, Chemistry
1997 Gregory B. Martin, Agronomy
1996 Ben S. Freiser, Chemistry
1996 Timothy S. Baker, Biological Sciences
1995 John H. Cushman, Agronomy and Mathematics
1994 Anant K. Ramdas and Sergio Rodriguez, Physics
1993 Philip S. Low, Chemistry
1992 Nicholas J. Giordano, Physics
1991 William J. Ray, Jr., Biological Sciences
1990 R. Graham Cooks, Chemistry
1989 Thomas K. Hodges, Botany and Plant Pathology
1988 William A. Cramer, Biological Sciences
1987 Austen Angell, Chemistry
1986 Stanley A. Barber, Agronomy
1985 Louis de Branges, Mathematics
1985 Rolf P. Scharenberg, Physics
1984 Laszlo J. Gutay, Physics
1983 Dale W. Margerum, Chemistry
1982 William L. Pak, Biological Sciences
1981 Heinz G. Floss, Medicinal Chemistry
1980 Philip F. Low, Agronomy
1979 Leonard E. Mortenson, Biological Sciences
1978 Albert W. Overhauser, Physics
1977 R. Stuart Tobias, Chemistry
1976 King Sun Fu, Electrical Engineering
1975 Michael Laskowski, Jr., Chemistry
1974 Michael G. Rossmann, Biological Sciences
1973 Shreeram S. Abhankar, Mathematics
1972 Hubert M. James, Physics
1972 Robert A. Benkeser, Chemistry
1971 John B. Bancroft, Botany and Plant Pathology
1970 H. Edwin Umbarger, Biological Sciences
1969 Hsu Y. Fan, Physics
1968 Harry Beevers, Biological Sciences
1967 Edwin T. Mertz, Biochemistry
1967 Oliver E. Nelson, Botany and Plant Pathology
1966 Herbert C. Brown, Chemistry
1965 Seymour Benzer, Biophysics

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