58. Photonics at The Institute of Optics

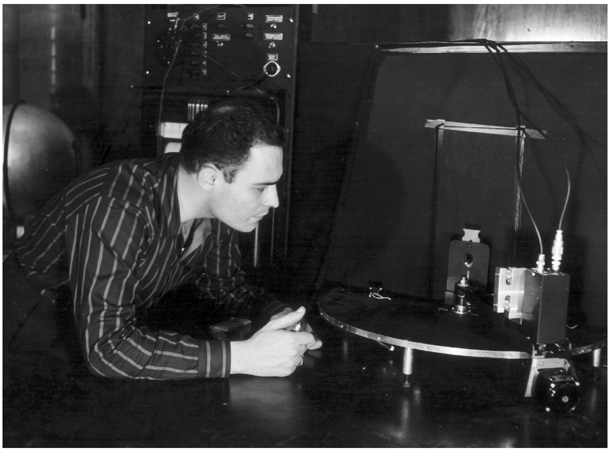
Dennis G. Hall

During the first century B.C., the Roman poet and satirist Horace observed that once a word has been allowed to escape, it cannot be recalled. And so it is that I find myself asked to write an essay about, of all things, photonics at The Institute of Optics. Such a request would have been unthinkable in the late 1980s, when some within the optics community were arguing that light was capable of ever so much more than an old-fashioned word like *optics* could communicate. The futuristic *photonics*, they admonished, projected a modern, exciting image that was big enough to convey both what the field had been and what it was destined to become. The broader field of photonics, they argued, would place the photon on an equal footing with the electron, to usher in a new era in technology.

Of course, if one already happened to have a great deal invested in the word *optics*, as did (and do) the members of the Optical Society of America (OSA) and the students, staff, faculty and alumni of The Institute of Optics, and if one already regarded *optics* as a field as big as all outdoors, then it was hard not to react to this upstart term *photonics* with some alarm. Where would this end? Would Emil Wolf be driven to change the title of Born & Wolf to *Principles of Photonics*? Would the University become the home of The Institute of Photonics? Inquiring minds in Rochester wanted to know! OSA members ended months of debate by voting in the fall of 1989 to retain the O in OSA, after which the entire issue receded into the background. OSA's members had considered patiently Shakespeare's advice in *Romeo and Juliet* that a rose by any other name would smell as sweet, but in the end had sided with Winston Churchill's (1952) more recent advice that "Short words are best and the old words when short are best of all."

Today, photonics has become a hopeful moniker for the subset of optical science and engineering that's associated with optical communication and information technologies, and especially, but not quite exclusively, with those involving optical waveguides. With that general landscape in mind, one might say that photonics at The Institute of Optics was foreshadowed by Brian O'Brien's suggestion in 1951 that surrounding each glass fiber in a fiber bundle with a lower refractive-index cladding would improve that bundle's performance as an image-transmission system.[1] Each fiber in such a bundle transmitted light by means of total internal reflection, with the lower-index cladding serving both to isolate each fiber from the others and to reduce surface scattering. Nearly a decade went by before Bob Potter completed, in 1960, the Institute's first Ph.D. dissertation in fiber optics,[2] a dissertation supervised by Bob Hopkins. Bear in mind that these contributions appeared very early indeed—T. H. Maiman's paper reporting the first laser[3] appeared in the latter half of 1960, almost simultaneously with Potter's dissertation.

Nineteen seventy was a defining year for photonics. Interest in optical-fiber waveguides as non-imaging transmission media became intense in late 1970 when researchers at the nearby Corning Glass Works demonstrated and reported glass fibers with transmission losses as low as 20 dB/km at wavelength $\lambda = 0.6328\,\mu m$.[4] That same year brought the first



Bob Potter (Ph.D., 1960) in the lab.

reported continuous-wave operation at room temperature of a III–V, AlGaAs/GaAs semiconductor laser. One year later, fiber transmission losses were down to 2 dB/km and the technology was off to the races. Soon every major corporation was gearing up to explore and exploit these and a host of related developments involving optical waveguide technologies.[5]

Nick George invited me to join the optics faculty in 1980 to teach and to build a research program in guided-wave optics. I remember commenting to Nick during a visit to the Institute in March 1980 that I had some reservations about Rochester's legendary winters. Without missing a beat, Nick, who himself had moved to Rochester from Caltech only a few years earlier, said, "Don't worry about that; you'll be too busy even to notice the weather." I can't say that I wasn't warned. The Institute's research infrastructure worried me a little at the beginning. Having spent the previous two years working on fiber-optics, integrated-optics and semiconductor-laser problems at McDonnell-Douglas Corp. in St. Louis, I knew only too well that The Institute of Optics of 1980 lacked the materials and processing laboratories that virtually everyone believed was needed to do publishable research on optical waveguide phenomena. I learned quickly, however, that the Institute had something far more precious than modern, solid-state laboratories. It had outstanding graduate students.

By 1980, the required, senior-level undergraduate laboratory (Optics 256) already had two fiber-optics experiments, one that used a fast oscilloscope to compare the optical-pulse delays introduced by step-index and gradient-index multimode fibers, and another that used an electro-optic modulator to transmit a television signal through a few meters of optical fiber. It was via the former experiment that students learned in a personal way how much care it takes to inject the invisible, near-IR output of a tiny semiconductor laser into something even as large as a 50-μm-core-diameter multimode fiber. Some found it so challenging that they were certain that there was something wrong with the experiment, but most felt pretty good when they finally mastered it. A few faculty had small fiber-optics side-projects underway in 1980. For example, Duncan Moore had an interest in rays propagating in gradient-index fibers and in the use of gradient-index lenses to facilitate coupling light into fibers, and another, Ken Teegarden, was helping a local Rochester company

Hall research group luncheon meeting.

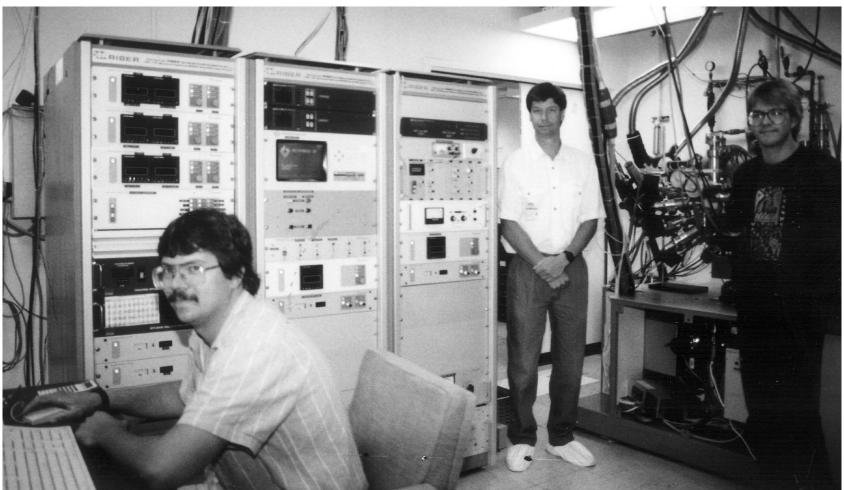
explore an idea for a fiber-optic pressure sensor. My appointment to the faculty reflected the Institute's decision to make optical waveguide phenomena part of its teaching and research core.

I developed a new graduate course titled guided-wave optics and taught it for the first time as a special-topics course in the spring of 1981. The next year it was assigned a regular course number, Optics 468. The course covered the basics of planar optical waveguides, coupled-mode theory, elementary waveguide devices such as Bragg reflectors and directional couplers, propagation and pulse-broadening in optical fibers, and an introduction to the band-theory of solids and semiconductor lasers. There was no single book at that time that covered all of this material, so I taught the course entirely from my own lecture notes. The course catered primarily to first- and second-year graduate students, but it was open to adventurous undergraduate seniors, too. I taught that course each spring for six years before turning it over to others.

Major help with laboratory development arrived on the scene when, thanks to a proposal effort led by Ken Teegarden, the Institute was designated in 1982 as the home of the New York State Center for Advanced Optical Technology (known as the CAT program). Several such centers were created throughout the state in a number of different technical fields as part of New York's master plan for economic development. With its long and distinguished history in optics, the University was the natural site for the state's CAT program in optics. The CAT program brought to the Institute two million dollars per year in combined state and industrial funding targeted for five technologically important areas, one of which was guided-wave optics. That infusion of funds made it possible to build a clean room and a photolithography laboratory, to purchase a variety of vacuum deposition systems and other specialized equipment needed to fabricate thin-film structures, and to hire a laboratory engineer (Oliver King, then a new optics M.S. graduate) to help keep the equipment working and to work with graduate students to develop the solid-state fabrication and processing techniques required for their research.

The mid-1980s was a boom time for the Institute. External support for research reached unprecedented levels. The success of winning CAT designation from the state of New York was matched by winning a multi-million-dollar, multi-year program from the Department of Defense, the University Research Initiative (URI) program in optoelectronics and optoelectronic systems, thanks to a proposal effort led by Nick George. Photonics proved to be such a broad and fertile field for research and became so visible internationally that many more outstanding Ph.D. students were drawn to it than could be accommodated by a single faculty member. The Institute responded in 1987 by hiring two of its own Ph.D. graduates as new assistant professors, Thomas G. Brown, who had completed his Ph.D. in my research group, and Susan N. Houde-Walter, who had completed her Ph.D. in Duncan Moore's group, *and* a new associate professor, Gary W. Wicks, all three of whom had strong interests in optical waveguides, optical materials, semiconductor lasers and related subjects.

Tom Brown had carried out research on coherent fiber-optic communications at GTE laboratories before taking up graduate studies in the Institute, where his dissertation research had centered on radiative impurity complexes in single-crystal silicon. Susan Houde-Walter's intellectual journey had taken her from an undergraduate degree in studio arts from Sarah Lawrence College all the way through a Ph.D. from The Institute of Optics, where her research had focused on forming refractive-index gradients in glass by means of an ion-exchange process. Both Tom and Susan had cut their teeth on guided-wave optics as graduate students by taking Optics 468. Susan went on to teach that course after she joined the faculty. Gary Wicks had earned his undergraduate and Ph.D. degrees in applied and engineering physics from Cornell University, where he had remained for another six years as a research associate to help Les Eastman lead his large semiconductor research group. By 1987, Gary had already made a name for himself as a specialist in the growth of III–V semiconductor layers and layered structures by the method known as molecular-beam epitaxy (MBE), a sophisticated crystal-growth technique carried out in an ultrahigh-vacuum chamber, referred to (sometimes with affection) as a "mega-buck evaporator." Immediately

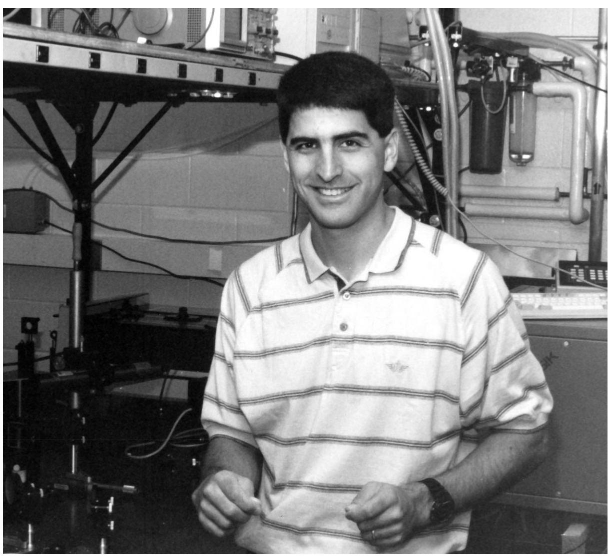


Gary Wick and Mike Koch operate the MBE facility.

upon his arrival, Gary developed and taught a new course, Optics 421, optical properties of semiconductors.

The Institute's decision to hire Gary Wicks, to purchase an MBE system and to establish a well-equipped III–V MBE laboratory and research effort recognized that advances in modern optical technologies depend heavily upon specialized materials growth and processing. One high-energy physicist at the University criticized this hiring decision, arguing that the Institute had strayed from its charter, demonstrating that high-energy physics might not be the best lens through which to view the field of optics. Advances in optical science and engineering have always been intimately connected with advances in materials science. That optics was undergoing another historic change, one that made the semiconductor an important *optical* material, was an established fact in the off-campus world. The Institute of Optics faced a clear choice: Either change and help lead, or be left behind. A decision between two such alternatives can be made very quickly.

Two years later, in 1989, the Institute seized the opportunity to add to its faculty Bell Labs scientist Govind Agrawal, already a highly visible theoretician in the field of optical communications, recognized for his work on semiconductor lasers and nonlinear effects in optical fibers. Govind created a new course titled optical communications (Optics 428) as soon as he arrived, and over the course of the next three years developed his course notes into a book, *Fiber-Optics Communication Systems*, now in its third edition and used throughout the world.[6] Since joining the Institute's faculty, Govind has published four additional books on related subjects. In 1994, the Institute hired another of its Ph.D. alumni, Turan Erdogan, to carry out research in fiber optics. After completing his Ph.D. in my research group in 1992 by demonstrating and investigating the properties of a novel semiconductor laser, Turan accepted a postdoctoral position at Bell Labs, where he explored the use of ultraviolet laser emission to write Bragg gratings directly into the core region of an optical fiber. That work proved so successful that it made it possible for fiber Bragg gratings to be



Turan Erdogan returned to the Institute after a postdoctoral position at Bell Labs.

incorporated into practical fiber-optic communication systems. Turan declined a permanent position at Bell Labs in order to accept an appointment as an assistant professor in the Institute. Professors Brown, Houde-Walter, Wicks, Agrawal, and Erdogan all established vigorous, productive research programs in photonics very quickly after their respective arrivals.

During most of the 1980s and 1990s, The Institute of Optics had fourteen full-time, tenured or tenure-track faculty. That six of the fourteen faculty worked principally in what today might be called photonics demonstrates how important that specialty had become by the end of the twentieth century. Those six faculty made their interests felt both in the curriculum and in research. It would take more space than is available in this essay to describe the many research accomplishments that have emerged from those six groups, but let me offer a snapshot.

Gary Wicks's research program in III–V semiconductors produced advances of its own and provided fuel for the ideas and efforts of others. For example, he and his students, along with MBE laboratory engineer Mike Koch, developed a solid-phase phosphorus source that made it possible to use MBE to grow phosphorus-containing semiconductor layers without using dangerous gases.[7] That source is now used universally to grow phosphide compounds via MBE. Gary's group used that technique at the Institute to fabricate and demonstrate, for instance, low-threshold InAsP/GaInAsP semiconductor lasers that emit light at wavelength $\lambda = 1.3\,\mu\text{m}$.[8] Without the local control over the growth process that Gary's effort made possible, and without his advice about semiconductor subtleties, it would have been much more difficult, and perhaps impossible, for (then) graduate student Turan Erdogan, working in my research group, to complete so successfully his dissertation project, the creation of a novel concentric-circle grating, surface-emitting AlGaAs/GaAs semiconductor laser.[9] Turan was awarded OSA's 1995 Adolph Lomb Medal for that achievement. Many other faculty and graduate students both within and outside of the Institute benefited from the capabilities and advances within the MBE group.

III–V semiconductors are not the answer to every question, however. Tom Brown and graduate student N. Darius Sankey turned heads by becoming the first to observe all-optical switching in a nonlinear, periodic, Bragg-resonant medium, and they did so using a *silicon*-based optical waveguide system.[10] All-optical switching is, in some sense, a holy grail of nonlinear optics. The idea of controlling light with light summons images of optical logic elements, all-optical switching networks, and even all-optical computing. Theoretical predictions about switching in nonlinear Bragg structures began appearing in the mid to late 1980s, but no physical system that exhibited such switching could be found. Tom and Darius were able to show that a silicon-on-insulator optical waveguide configured with a surface grating *does* exhibit (non-thermal) all-optical switching.

Susan Houde-Walter's work has investigated the relationship between atomic-level properties and the resulting macroscopic optical properties of both glass and III–V semiconductors, but she and her students have also developed a strong presence in the theoretical analysis and design of optical waveguide systems. As an example of the former, she and her students have used various accelerator facilities in the United States and Europe to apply the EXAFS (extended x-ray absorption fine structure) technique to developing a microscopic understanding of the properties of optical glasses.[11] Her work in the latter area has included investigations of how the optical mode changes as light passes from one component to the next in multi-component, integrated-optical devices. That work included the development of new tools to track down such modes as layer configurations and refractive-index profiles vary and become complicated.[12] Beginning in 2005, Susan will take up her duties as president of the Optical Society of America.

Govind Agrawal and his students have contributed mightily to the quantitative understanding of many phenomena that occur in optical fibers and semiconductor lasers. One prominent example is identifying the root cause of the so-called filamentation that occurs in broad-area semiconductor lasers, something that had been observed for at least two decades.[13] Other examples include analyses of soliton propagation and other nonlinear effects in optical fibers, the properties of vertical-cavity, surface-emitting semiconductor lasers, optical effects in semiconductor laser amplifiers, and the behavior of fiber Bragg gratings. At the time of this writing, Govind's publication list includes some three hundred entries.

It deserves mention that other members of the faculty made occasional forays into photonics. For instance, Robert Boyd's research program in nonlinear optics has included the study of soliton-propagation effects in optical fibers.[14] Indeed, optical-waveguide phenomena became so widespread during the 1980s and the 1990s that it touched the research of most or all of the optics faculty at one time or another. By the year 2000, *photonics* (a.k.a. guided-wave optics, optoelectronics, etc.) had become one of the pillars of research and teaching in The Institute of Optics.

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Scanning electron microscope image of the circular grating formed in the surface of an AlGaAs epitaxial wafer grown onto a GaAs substrate by molecular beam epitaxy (MBE). The circular pattern, with period 250 nanometers, was created using electron-beam lithography. When pumped, the structure emitted a narrow-bandwidth beam of light with a circular cross-section propagating in a direction perpendicular to the corrugated surface.