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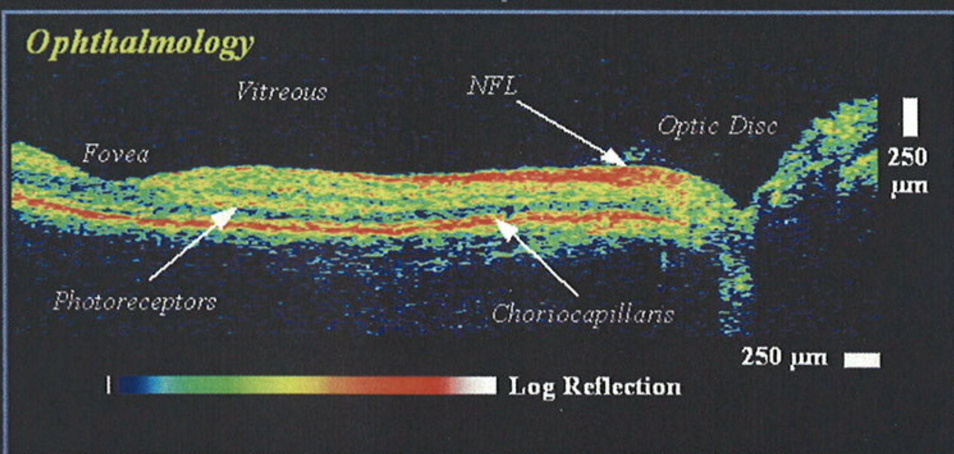
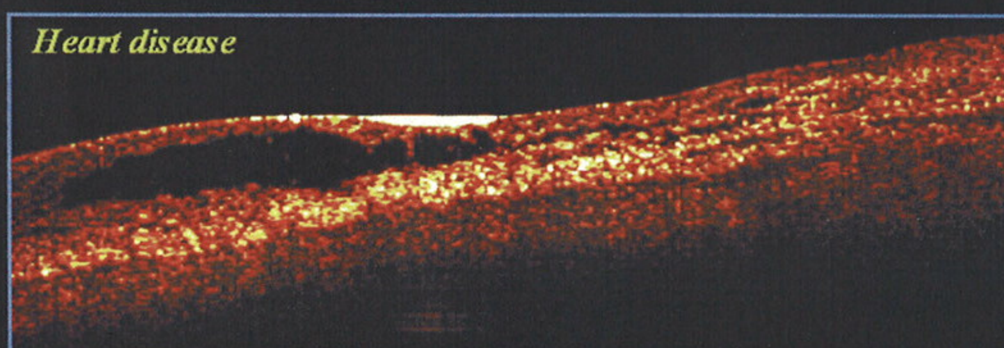
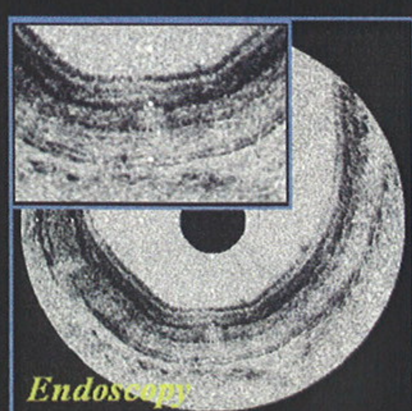
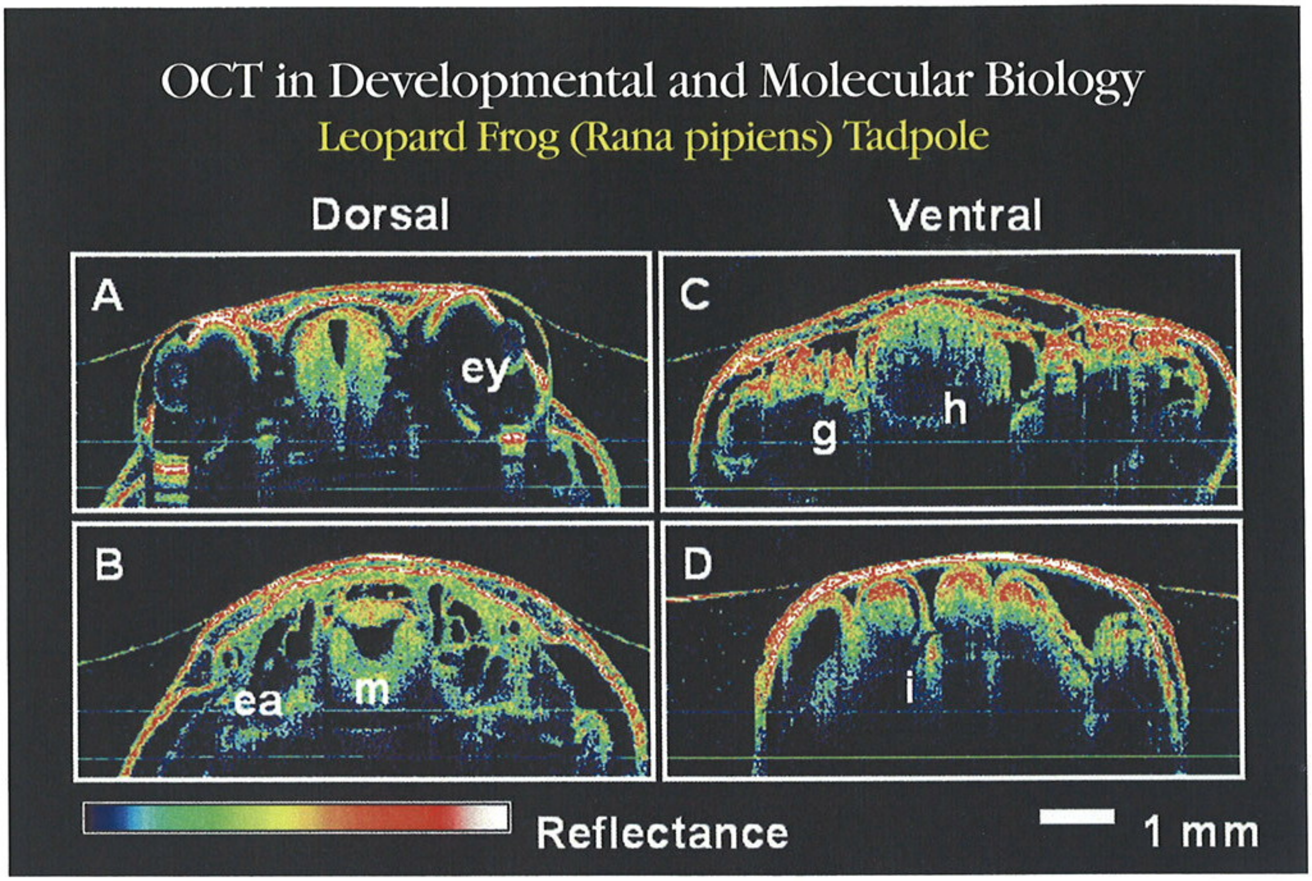



# The Pulse of Ultrafast Optics Research in RLE




# Pioneering New Applications for OCT Research




***Imaging in developmental and molecular biology.** Optical coherence tomography has applications to fundamental research, where it promises to become a powerful diagnostic imaging tool for developmental and molecular biology. OCT is well suited for developmental biology because it can image specimens noninvasively and in real time. The figure shows OCT imaging* in vivo *in a leopard frog (Rana pipiens) tadpole. The images demonstrate OCT's capability to perform high-resolution cross-sectional imaging of the tadpole's internal organs. The upper left image, taken through the head, shows the eyes and brain. Developmental and molecular biologists study animals such as the leopard frog tadpole to understand gene expression and organ development. Changes in genetic structure can be linked to changes in development, and abnormal development can be traced to its genetic origin.*

***Front cover illustration:** Optical coherence tomography (OCT) is a fundamentally new optical imaging modality. OCT performs high-resolution (1 to 15 micron), high-speed, cross-sectional tomographic imaging and has been applied to medical diagnostics, materials science, and microscopy. In medical diagnostics, the technology enables visualization of disease pathology in living organisms at resolutions approaching the cellular level. Because OCT can perform "optical biopsy" with a resolution approaching that of conventional biopsy, it promises to become a powerful diagnostic tool. In combination with small fiber-optic catheters, endoscopes, and other imaging devices, OCT imaging can be carried out at virtually any site in the body using noninvasive or minimally invasive procedures.*

***Ophthalmology.** An OCT image of the human retina showing the region from the fovea to the optic nerve head.*

***Heart disease.** An OCT image of unstable atherosclerotic plaques in a human artery* in vitro. *OCT can image the internal structure of plaque on a micron scale and promises to have important applications in intravascular imaging.*

***Endoscopy.** An* in vivo *endoscopic image of a rabbit esophagus provides a view of structure with higher resolution than ultrasound. OCT imaging could have applications in endoscopy for the detection of early cancerous changes.*

***Nerve repair.** A three-dimensional view of a peripheral nerve constructed from eighty cross-sectional OCT images with 50-micron spacing. OCT can be used in a variety of*

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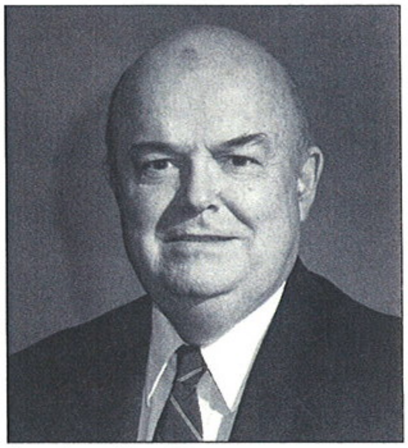
## Director's Message

Since the invention of the laser, there has been a major research effort in RLE to exploit nonlinear properties of optical materials and solid-state optics. Short optical pulses can be further shortened by pulse sharpening techniques based on these high-intensity pulses and their interaction with nonlinear materials. Extremely short pulses (measuring a few femtoseconds) can be obtained using the differential speed of the rising and falling edges of the pulse, which is then fed back through the apparatus to achieve further sharpening and pulse length shortening.



*Jonathan Allen, Director, Research Laboratory of Electronics*

The availability of these very short optical pulses has provided new means to probe electronic devices. These pulses can also be used to measure the size of very small structures noninvasively, forming the basis of new medical examination techniques. Fundamental understanding of optical processes is thus opening up new applications, including high-speed networking and perhaps even new coherent epochs for use in quantum computation. We look forward to a continuing flow of exciting new achievements in optics, as the basis of much new innovative technology.

# The Pulse of Ultrafast Optics Research in RLE

One of the greatest advances in science and technology during the last two decades has been the merging of optics and electronics. Coupled with this important evolution has been the rapid development of ultrafast optics and, in particular, the generation of ultrashort or femtosecond optical pulses that are 100,000 times shorter than a billionth of a second. Compact sources of ultrafast optical pulses near the 1.5-micron wavelength, as well as optical fibers and other fiber-optic components, are the key enabling technologies for creating new high-speed communication systems and for realizing bandwidth-intensive data transmissions. However, as the capacity of transmitting information continues to increase, our ability to manage it must increase as well, which in turn creates a constant demand for improved high-speed technology. In addition, as optical technologies achieve ultrahigh-data-rate transmission and greater sensitivity, the performance of fiber-optic devices and systems will begin to approach their fundamental physical limits. These critical issues must be addressed in order to reach a level of understanding needed to engineer future communication networks.

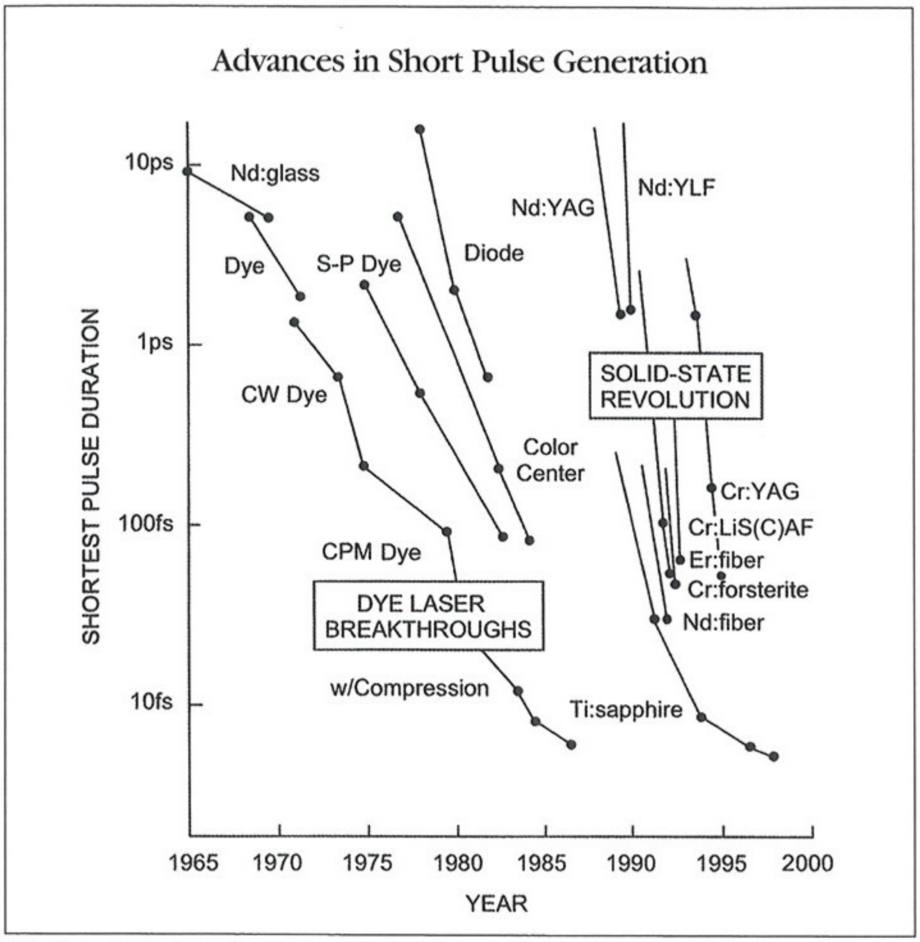
An essential component in the development of high-bit-rate optical systems is the ability to generate ultrashort optical pulses using lasers. Over long distances, optical fiber transmission systems have the ability to carry bandwidths and data rates many orders of magnitude greater than those permitted by traditional electronic or microwave technologies. Ultrashort pulses provide one way to exploit this capability. The shorter the pulses, the greater the bit rate can be in a single fiber-optic wavelength channel.

In ultrafast science, record-breaking optical pulses and the ability to extend them to new wavelengths have been critical developments. The shorter a pulse is made, the broader its bandwidth becomes, which can be an important factor in many scientific applications. With modest pulse energy, extremely high peak powers can be achieved with ultrashort pulses. Thus, damage to materials can be avoided, in some applications. In basic research, these pulses have allowed investigators to control the dynamics of molecular systems in ways never before possible, and have helped scientists to understand a broad range of natural phenomena on short time scales. The high time resolution possible with ultrashort pulses is important for studies of electronic as well as chemical and biochemical kinetics. They can also be used to create and reconstruct specific quantum states, which may ultimately provide a means to control various chemical reactions and to synthesize complex molecules.

The use of ultrafast pulses as innovative tools in biomedical imaging, surgical procedures, micromachining, and the spectroscopic investigation of fundamental processes is rapidly expanding. In addition, emerging applications for ultrafast optical pulses in communications and industry have underscored the need to develop new techniques capable of measuring the electric field of these events, which are typically measured in femtoseconds or $10^{-15}$ seconds.

### Quantum Optics and Electronics

The broad fields of quantum optics and electronics encompass the study of lasers, nonlinear and solid-state optics, ultrafast optical phenomena, and laser materials processing. Major advances in




*This plot, which shows the shortest obtainable optical pulse duration versus year, also serves to illustrate the development of the laser technologies used to generate them. Much of the early pioneering work in this field was carried out with molecular dye lasers. In the 1990s, the advent of techniques for modelocking solid-state lasers has permitted researchers to push investigations to the limits of optics.*

these areas have depended on the realization of more robust and practical sources of coherent radiation. After the development of the first lasers in the early 1960s, other novel, coherent light sources were discovered: ion and excimer lasers, molecular lasers, tunable dye lasers, semiconductor and solid-state lasers, and light sources based on nonlinear techniques. New coherent light sources have enabled innovative research within frequency and time regimes that had been beyond the capabilities of previous optical devices. Generally, once a new light source is realized, research focuses on improving the source's frequency purity or towards short-pulse generation for diagnostic or communication applications.

## Light and its Properties

Under various conditions, light possesses different properties. It can behave as a stream of particles or as a series of waves. Scientists describe light as being made of photons that form waves. Ordinary light is characterized by various wavelengths (the distance between the amplitude peaks of the waves), amplitudes (the top-to-bottom distance of each wave), and frequencies (the number of peak excursions in one second). As witnessed through a prism, normal light is polychromatic and is of lower intensity than laser light. It also emerges from a transparent medium with the same wavelength it had before it passed through the medium.

Laser light, however, consists of highly concentrated photons traveling in a narrow beam. Light waves from an unmodulated laser can be almost all of the same frequency and, hence, are monochromatic. High-intensity laser light has the ability to change the optical properties of various media (such as molecules, materials, surfaces, and condensed matter) and can cause intense beams with new wavelengths to be generated. Ordinary light waves can be compared to a scrambling football team or a teeming mob of people moving in different directions. In contrast, the properties of laser light resemble that of a precision marching band or soldiers marching in step. This characteristic is called *coherence,* in which the laser light vibrates in a synchronous phase.

Novel sources of light, particularly the various forms of laser light, are the driving forces behind modern optical science and technology. In its simplest sense, a laser is composed of a resonator with mirrors at both ends that contains a lasing material. The material may be, for example, a ruby, crystal,

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semiconductor, carbon dioxide gas, or various chemicals. A source of energy, such as light or electricity, "pumps" or excites the atoms in the lasing material. As the excited atoms return to their normal or ground state, photons are released at a specific frequency, which results in amplification. The released photons bounce back and forth between the mirrored ends of the resonator, travel through the lasing medium, and experience amplification by stimulating the emission of other photons. A chain reaction is created by this stimulated emission of radiation. A partially transmitting mirror on one end of the laser resonator allows a fraction of the photons to escape. This results in an emerging laser beam of coherent light.

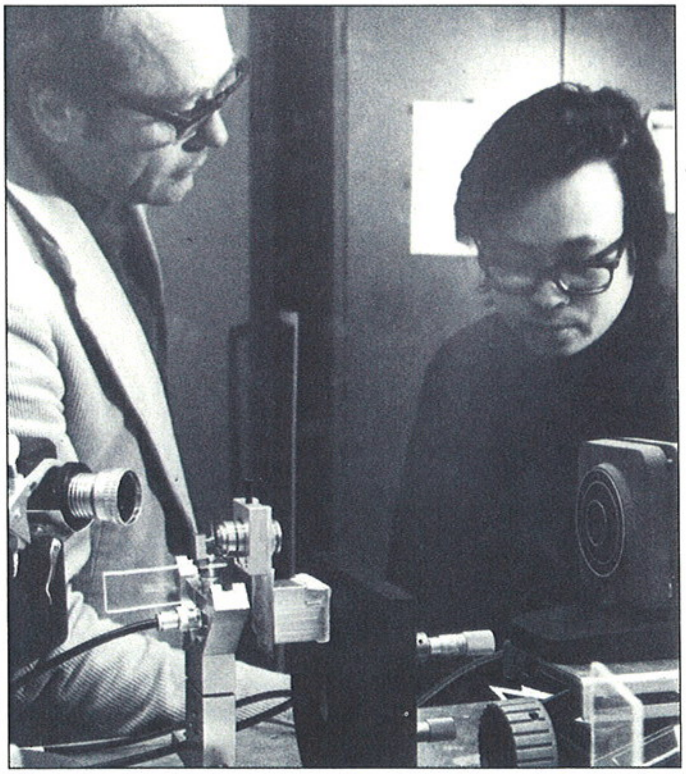
## Laser Technology

Solid-state and semiconductor diode lasers are found in a wide range of functions: from low-power domestic uses such as compact-disc players and computer printers to high-power uses in industrial, medical, and military applications. For their active media, solid-state lasers use transparent substances, such as crystal or glass, that are *doped* (injected with impurity elements) to provide the necessary energy states for lasing. The optical pumping mechanism is fur-

# The Importance of Being Ultrashort

In the June 1988 edition of ***RLE currents,*** Institute Professor Hermann A. Haus was asked: "What is the goal of producing the shortest, fastest pulses?" This was his response:

You can use those pulses to build switches that have wonderful optical properties to check electronic circuits. Electronic circuits have switching times of 10 or 15 picoseconds, so you can look at them electronically. But, if you tried to look at a pulse of that speed on a scope, you would have to load the circuit enormously, and the circuit won't respond the way it does when it's not loaded. Optically, you can send pulses and look at that circuit without loading it. Now you can find out what is going on. The diagnostics that you have enable you to look at electronic circuits and make them perform faster.



*Above: In 1978, the world's shortest pulses from a semiconductor device were achieved by Professor Hermann A. Haus (left) and graduate student Ping-Tong Ho. This was the first demonstration of modelocking in semiconductor lasers. Here, they examine the operation of a gallium-arsenide diode laser in an external resonator.* *(Photo courtesy MIT Electrical Engineering and Computer Science Department)*

From the optical viewpoint, if you want to look at some interesting optical properties, it's usually important to disturb the medium, and then watch the disturbance (by exciting carriers or electrons in the medium). Or, you can excite the atoms in the medium and watch them. The wonderful thing is that the excitation can be made quite large since you can have enormous intensities but small images. If you make the pulse half as long and twice as intense, the energy stays the same. So, with femtosecond pulses you can achieve extremely high intensities and very nonlinear responses of the medium that you can study.

You can study processes of duration longer than the duration of the pulse. Anything slower than the pulse will give you very nice results. Here is an analogy: You know those beautiful photographs of bullets by Edgerton? He stopped bullets at microseconds (a microsecond is $10^{-6}$). Now, you can open the laser's shutters to fifty femtoseconds. Fifty femtoseconds is another factor of twenty. That's six orders of magnitude. So, it's twenty multiplied by $10^6$ times faster than Edgerton's camera. Of course, nothing microscopic moves that fast. No one can stop individual electrons because you can't see them. But, you can observe clusters of electrons in action and you can stop the smallest particles.

nished by radiation from a powerful light source, such as a flash lamp. Semiconductor diode lasers are excited by the current through the diode.

Devices enabled by high-power near-infrared diodes, such as fiber lasers, can now produce outputs greater than 10 watts. Fiber lasers have become useful sources of ultrashort pulses because of their compact size and compatibility with fiber-optic components and systems. The lasing medium in a fiber laser is an optical fiber doped with low levels of rare-earth halide elements that make it capable of amplifying light. Its output is tunable over a broad range of wavelengths and may be broadband. Currently, many research efforts are concentrating on high-repetition-rate modelocked erbium-doped fiber lasers as reliable and compact sources for network transmitters in the 1550-nanometer spectral region. The wide optical bandwidth generated by a single modelocked laser pulse can be partitioned into many channels for wavelength division multiplexing applications, an approach that may be more economical than a large bank of individually selected continuous-wave sources.

Femtosecond lasers can generate pulses so short (less than $10 \times 10^{-15}$ seconds) that they can be used to create and study excitations on a time scale shorter than that of fast internal relaxation phenomena. The nonequilibrium states produced by femtosecond lasers permit dynamical processes in matter that can be studied in regimes not previously accessible. Recent advances in femtosecond laser technology have extended the use of these experiments and their applications to scientists in other fields. The discovery of new types of nonlinear optical interactions are anticipated as well as the creation of new photochemical and photophysical techniques for materials processing.

To reduce the size and cost of lasers, a recent emphasis in ultrafast laser science has been to develop compact, robust, and ultrafast sources. These include semiconductor multiple quantum well lasers and diode-pumped solid-state lasers. Diode-pumped solid-state lasers converted by frequency doubling to multiwatt green and blue sources have extended operation into the ultraviolet spectral range and into the infrared regime using parametric oscillation. This technique enables the generation of a frequency-tunable coherent beam of light from an intense laser beam of fixed frequency. The union of laser and nonlinear optics technologies also extends to ultrafast sources such as all-solid-state femtosecond systems. Ongoing research on solid-state lasers continues to pursue the generation of new wavelengths or the use of these lasers as drivers for nonlinear optical converters, such as optical parametric oscillators. Some of the most exciting advances have been realized in the areas of high-power fiber laser sources (averaging tens of watts), mid-infrared semiconductor lasers (both quantum cascade and traditional semiconductor lasers), and terawatt laser sources.

## Nonlinear and Solid-State Optics

In recent years, there has been an increase in the development and practical use of solid-state laser and nonlinear optical techniques. Nonlinear optics encompasses the study of fundamental optical physics and its applications. If it were not for the development of intense laser light sources, nonlinear optics would not exist, since the term "nonlinear" refers to the interaction of intense radiation with matter. One example is the generation of radiation at new wavelengths different from the wavelength of the incident light.

Novel nonlinear optical techniques have allowed the generation of record-setting short duration pulses in the near infrared. These techniques have also been used to increase the brightness of pulsed deep-ultraviolet sources by several orders of magnitude. Studies in nonlinear optics focus on quantum coherence effects, such as lasers without inversion and electromagnetically induced transparency, as well as spatial effects, such as the rapidly growing family of spatial solitons. Solitons are novel, ultrashort pulses of laser light that can propagate in a dispersive medium, a medium in which light of different frequencies would ordinarily travel with different velocities. Other fast-growing areas of research in nonlinear optics focus on microstructured and nanostructured materials, such as those used for photonic bandgaps and quasi-phase matching. Similar to the electronic bandgap in a semiconductor crystal, a photonic bandgap is the range of frequencies in a photonic crystal within which photons cannot propagate. Phase matching is a technique used to enhance the distance of coherent energy transfer between waves.

In solid-state optics, much of the current research is focused on an industry-standard material called Nd:YAG, which is an acronym for neodymium: yttrium-aluminum-garnet. Nd:YAG lasers employ a cylindrical rod of yttrium-aluminum-garnet doped with neodymium as its active medium. Studies also focus on tunable solid-state materials such as titanium-doped sapphire ($Ti:Al_2O_3$). The $Ti:Al_2O_3$ laser, a solid-state device that is continuously tunable in the wavelength region from 700 to 1100 nanometers, is suitable for both pulsed and continuous-wave operation.

## Ultrafast Pulses and Optical Phenomena

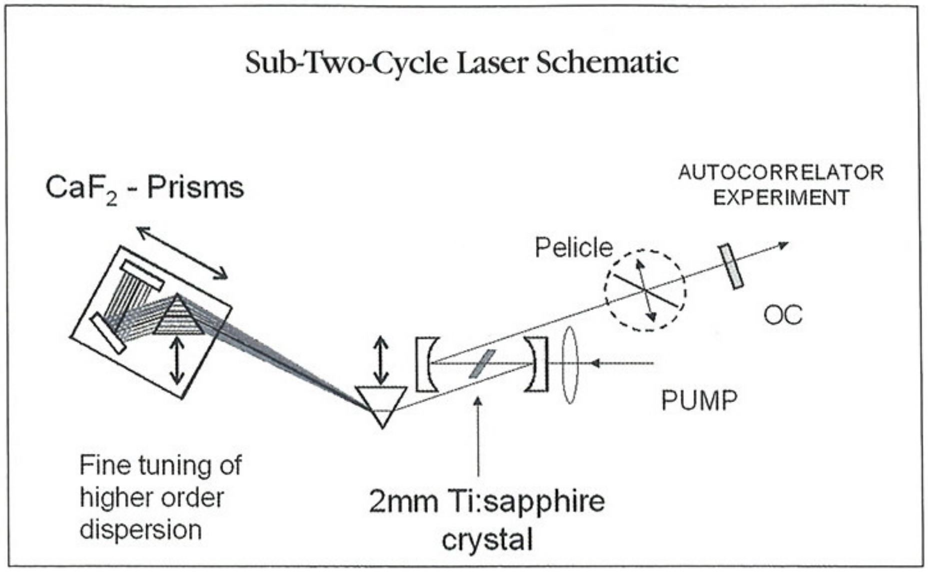
Scientists use several techniques to generate short pulses. One common method, known as modelocking, is divided into three general categories: active, passive, and hybrid (a combination of active and passive). Passive *modelocking* generates the shortest optical pulses. It is achieved simply by introducing a saturable absorber into a laser's cavity. The saturable absorber can be any substance whose absorption coefficient decreases at high levels of incident radiation. This encourages the laser light inside the resonator to bunch into short pulses. In active modelocking, the same result is achieved by inserting an electronically driven modulator into the laser. Instead of a steady stream of light emerging from the laser, by modelocking, one can produce energy bursts of high peak power and short duration in the picosecond ($10^{-12}$ second) or femtosecond ($10^{-15}$ second) domain.

In the past decade, great progress has been made to advance the methods used for generating and measuring ultrafast pulses. Today, commercially available titanium-sapphire lasers and fiber lasers enable widespread use of femtosecond lasers. Investigators no longer have to build these lasers, which are completely solid-state systems. For example, titanium-sapphire lasers can be pumped with frequency-doubled Nd:YAG lasers instead of argon-ion gas lasers, which require high-power input and a very high discharge current.

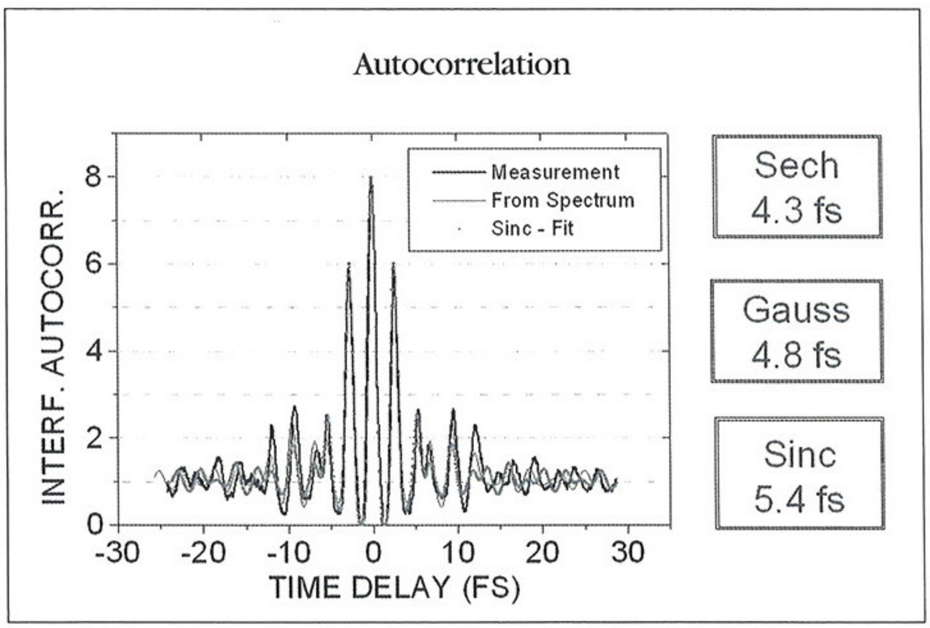
The wide range of applications for ultrashort pulses has also benefited from advances in critical supporting technologies such as pulse diagnostics and characterization. Ultrashort optical signals are often more convenient to manipulate in the spectral or frequency domain rather than directly in the time domain.

The power of using frequency domain techniques can be seen in studies involving pulse compression and shaping as well as other related adaptive pulse manipulation techniques such as *chirping*. Typically observed in the pulsed operation of an optical light source, chirping is a rapid change of the emission wavelength, thus enabling different wavelengths to be transmitted at different times.

Using nonlinear optical techniques, both dye lasers and titanium-sapphire lasers have generated pulses shorter than ten femtoseconds. These pulses are used for time-resolved studies of nonlinear optical processes in a broad range of materials. Short pulses also enable investigators to use nonlinear processes that can generate a spectral continuum of subpicosecond duration for time-resolved spectral diagnostics. Pulses can be made even shorter by employing spectral broadening in an optical fiber, followed by compression with a dispersive grating or prism pair. The development of high-power, high-repetition-rate femtosecond pulse sources promises to introduce new areas of study in time-resolved nonlinear optical processes for materials.




*A diagram of the laser used by RLE's Optics and Devices group to generate 5-femtosecond pulses. A titanium-doped sapphire crystal, excited by light from an argon laser, provides gain for stimulated emission over a wide spectrum. Specially designed mirrors and prisms are used to adjust the round-trip time delays of all the wavelengths in the spectrum so that they stay together as an ultrashort pulse.*



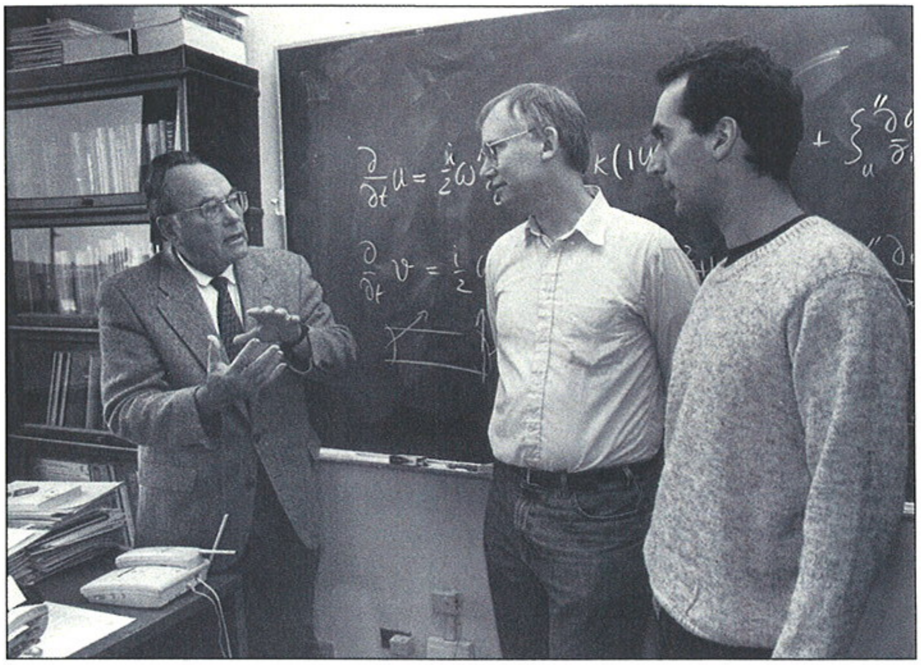

*The measurement of a 5-femtosecond pulse obtained by second-harmonic intensity autocorrelation. The fringe pattern captures the less-than-2-cycle duration.*

## ULTRAFAST OPTICS GROUP AT RLE

In RLE's early days, the study of physical electronics inspired much interest in the ability to characterize electromagnetic noise. Basic research in this area, carried out by Professor Hermann A. Haus (ScD'54), ultimately revealed that optical communication systems operate at the limit set by Heisenberg's Uncertainty Principle. This finding promoted a natural transition from studies of electronic amplifiers to investigations of optical systems, where the limit of quantum-mechanical noise could be detected.

Over the years, fundamental optics research in RLE has not only produced advances in the basic understanding of laser noise, but it also has provided the tools that give the spatial and temporal resolution needed to investigate a broad range of phenomena. With the arrival of Professor Erich P. Ippen (SB'62) from Bell Laboratories in 1980, the experimental activities in ultrafast optics expanded considerably. Demonstrations of ultrashort-pulse generation pushed the technology into the femtosecond time domain. Novel measurement techniques were developed and applied to studies of electronic materials as well as molecules. Professor James G. Fujimoto (SB'79, SM'81, PhD'84), who as a graduate student had been responsible for several of these advances, joined the faculty in 1985.

Today, the staff and students who investigate ultrafast optics in RLE's Optics and Devices group work with Professors Haus, Ippen, and Fujimoto. They explore methods to generate ultrashort pulses of light and develop applications to various scientific and engineering studies. Current activities include the basic study of ultrafast phenomena in materials, applications of



*Institute Professor Hermann A. Haus (left) discusses the issues of loss and gain in optical fibers that affect compact soliton states with Professor Peter L. Hagelstein (center) and Research Assistant John M. Fini. Working together, the three investigators have extended a configuration-space theory initially proposed by Professor Hagelstein. Using the Gordon-Haus calculation of momentum noise, they have validated that the configuration-space approach provides a new understanding of this well-known effect. The group also seeks to develop quantum models that predict interference of a soliton as a single quantum particle, which may suggest the possibility of a fundamentally new kind of light interference.* *(Photo by John F. Cook)*

ultrashort pulses to medicine, investigations of optoelectronic device structures, and demonstrations of ultrafast switching and signal processing in optical fibers. Using femtosecond pump-probe techniques, the group studies fundamental carrier dynamics in semiconductor thin films, heterostructure interfaces, metals, and superconductors.

Recently, Professors Ippen, Haus, and Fujimoto collaborated with Visiting Professor Franz X. Kärtner from the University of Karlsruhe to achieve a world record: demonstrating an ultrashort pulse solid-state laser that generates 5-femtosecond pulses. Using novel laser design and modelocking techniques, this solid-state femtosecond laser produces pulse durations that correspond to only two cycles of the electric field. These pulses are the shortest ever generated directly from a laser; so short that their spectral bandwidth spans 650 to 1000 nanometers. The application of this new laser technology promises to yield insights into the fundamental physics of ultrafast processes in a variety of fields including physics, chemistry, and biology.

In exploring the development of all-optical switches and logic gates that can process picosecond pulses for high-rate optical communication systems, the group employs ultrafast photoconductivity in semiconductors, ultrafast photoresistivity in high-temperature superconductors, and the electrooptical effect in semiconductors and dielectrics. The first two methods allow ultrafast optical signals to be converted into electrical signals, and the third enables the optical probing of materials. In this way, the group uses femtosecond optics to generate, control, manipulate, and characterize high-speed and high-frequency electronic signals, devices, circuits, and systems.

The group's work in all-optical nonlinear systems emphasizes the design, construction, and operation of ultra-short-pulse lasers, thus enabling them to explore underlying fast optical and electrical processes. One focus in this area has been the development of fiber interferometer switches that permit large nonlinear interaction. All-optical nonlinear systems play an important role in the quantum theory of measurement. For example, to understand the phenomenon of *squeezing* (the generation of quantum states with reduced noise) in optical fibers, a good understanding of nonlinear quantum processes is necessary. Every measurement involves nonlinear interactions with the system being measured. Thus, understanding such nonlinear processes leads to a better formulation of the theory of quantum measurement.

## High-Speed Properties of Optical Systems

In 1978, Professor Haus' group achieved the first demonstration and explanation of modelocking in a semiconductor diode laser and, in 1983, they introduced the first all-optical waveguide modulator. Today, he and his colleagues pursue studies of pulse propagation in fibers, with particular attention to nonlinear effects such as the *optical Kerr effect,* which is a change of refractive index caused by changes in the intensity of light. The Kerr effect can be balanced by fiber dispersion, thus leading to the propagation of solitons. The soliton method of transmission has been studied by Professor Haus and his colleagues. It enables rapid voice and data communication via long-distance fiberoptic undersea cables without the need for repeating, the process in which signals are detected and regenerated approximately every 100 kilometers to prevent signal deterioration. Solitons can be used in both all-optical switches and in long-distance fiber communication. Studies in this area include the modelocking of fiber lasers and long-distance nonlinear pulse propagation. The group also investigates squeezing in optical fibers, femtosecond studies of novel materials and structures, and ultrafast dynamics in (active and passive) semiconductor devices.

Short-pulse generation, pursued jointly with Professor Ippen's group, is a practical application addressed by this research. Optical fiber lasers constructed in these investigations have generated pulses as short as 65 femtoseconds with nanojoule energies, thus making fiber lasers well suited for ultrahigh-speed instrumentation and fiber-optic communication.

Professor Haus' research also investigates photonic bandgap structures for use as "optical circuit elements," which is similar to his earlier microwave circuit research during the 1940s and 1950s. At that time, lumped electrical circuit elements (such as inductors, capacitors, and resistors) were replaced by wavelength-sized structures. Today, microwave technology has been replaced by miniaturized lumped circuits, and similar ideas can be exploited in the optical domain, where physical properties ensure that replacements with lumped circuits will not occur. In contrast to microwave structures, optical circuits are not shielded by metal. They can be of the photonic bandgap type or, more simply, may use optical waveguides and resonators of high index contrast. These radiate energy, which may cause problems. However, computer studies have shown that proper design can minimize radiation, thus making high-density optical integration possible.

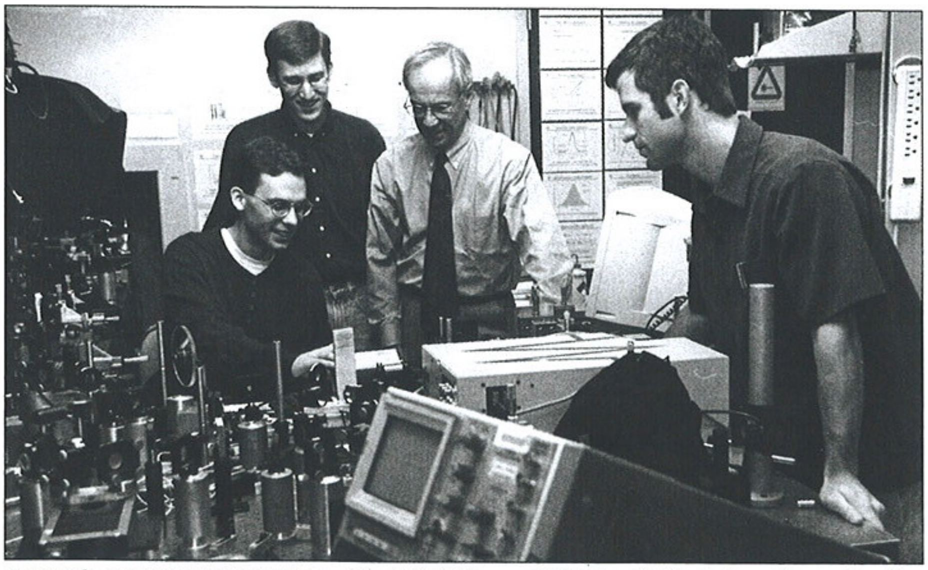
Dispersion-managed soliton propagation is another focus of Professor Haus' research. In optical communications, the use of distinct pulses to represent the bit known as "one" (return to zero or RZ) is used increasingly. Thus, there is a departure from the format that merges two adjacent pulses (non-return to zero or NRZ). However, higher bit rates lead to higher intensities and ultimately to nonlinear effects. Dispersion management is accomplished by using fiber segment sequences with opposite signs of dispersion. Professor Haus' group has recently shown the connection between dispersion-managed solitons and nonlinear Bloch waves. This idea explains the fact that pulses of this type do not lose energy by radiation, which generally happens in periodically perturbed pulse propagation. Consequently, amplifier spacings can be greatly increased, which results in reduced cost. In addition, the group's research has shown that communication using dispersion-managed solitons can achieve higher bit rates than conventional linear propagation in the presence of unavoidable polarization mode dispersion, which leads to pulse spreading. It was found that dispersion-managed solitons are less sensitive to polarization mode dispersion than linear propagation.

In collaboration with Professor Peter L. Hagelstein (SB/SM'76, PhD'81), Professor Haus has used a new configuration space quantum method to address problems involving quantum-optical soliton propagation in fibers. They recently demonstrated a configuration space description of quantum effects in lossy fibers, which yielded a new interpretation of the Gordon-Haus effect in long-distance fiber communication. The Gordon-Haus effect produces timing jitter and bit errors due to the combined action of amplifier noise and fiber nonlinearity. A new interpretation of the effect, developed by Professors Haus and Hagelstein, now describes it as a center of mass jitter due to the loss or gain of a single discrete photon. Their results demonstrate that configuration space models can solve nonlinear quantum optics problems with a simpler formulation than that which is currently used.

## Ultrafast Phenomena and Pulse Generation

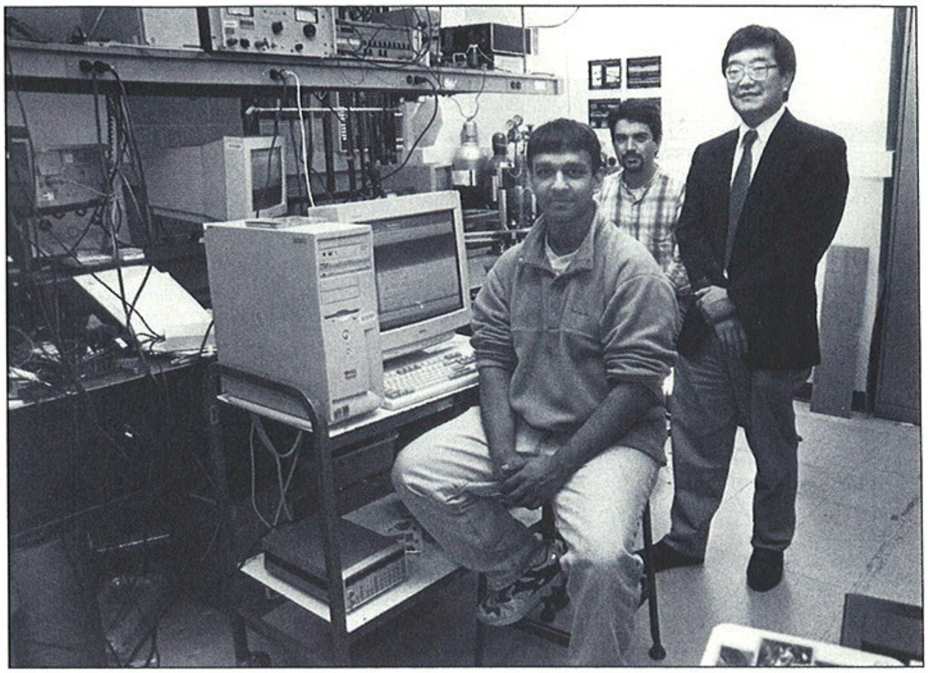
Before joining MIT's faculty in 1980, Professor Ippen was a member of the research staff at AT&T Bell Laboratories, where he and colleague Dr. Charles V. Shank generated the first sub-picosecond optical pulses and pioneered the study of femtosecond-time-scale properties of materials. Today, Professor Ippen's research group in RLE continues to develop innovative methods for generating and measuring ultrashort pulses. They are credited with a series of milestones in the pursuit of shorter pulses and the understanding of ultrafast phenomena. In 1998, a joint effort with Professors Fujimoto and Haus and Visiting Professor Kärtner resulted in the current world record for the shortest pulses obtained directly from a laser. These pulses, with a duration of five femtoseconds, are shorter than two optical cycles. They have already been used in a collaboration between Professors Fujimoto and Ippen to achieve record resolution in optical coherence tomography, making it possible to observe three-dimensional changes in individual living cells. Other potential applications of these pulses include innovative scientific measurement and the establishment of an optical frequency standard.

Using different lasers and wavelength conversion techniques, Professor Ippen's group can generate femtosecond pulses over a broad range of wavelengths. Increased versatility is provided by techniques based on the titanium-sapphire laser, which can be frequency-doubled to cover most of the visible light range, and down-converted by parametric and difference-frequency



*Research Assistants Erik R. Thoen, Daniel J. Ripin, and Matthew E. Grein investigate ultrafast phenomena in materials and devices with Professor Erich P. Ippen (second from right) in RLE's Optics and Devices group. Here, they discuss the use of femtosecond pulses from an optical parametric oscillator to study nonlinearities in semiconductor quantum well structures. (Photo by John F. Cook)* earities in high-speed semiconductor lasers and amplifiers as well as fundamental femtosecond carrier dynamics in semiconductors and metals. Their tunable laser capabilities are also used to demonstrate the characteristics of novel photonic bandgap structures being fabricated by Professor Leslie A. Kolodziejski and her students in RLE's Materials and Fabrication group.

Short-pulse fiber lasers developed by Professor Ippen's group in collaboration with Professor Haus provide the basis for several new projects related to optical signal processing and optical fiber networks. Fiber lasers that produce either broadband femtosecond pulses (to create many wavelength channels simultaneously) or picosecond soliton pulses (for ultrahigh-bit-rate communications) have been demonstrated. The quantum-limited timing jitter exhibited by these lasers makes them interesting as well for high-precision sampling and analog-to-digital conversion. Other applications being investigated include all-optical switching and optical data buffering. These increasingly important efforts are creating stronger ties between the research groups of Professors Ippen and Haus and those of Professors Kolodziejski, Jeffrey H. Shapiro (RLE's Optical Communications group), Henry I. Smith (RLE's Quantum-Effect Devices group), Rajeev J. Ram (RLE's Optics and Devices group), and the Advanced Networks Group and the Electro-Optic Materials and Devices Group at Lincoln Laboratory.



*Medical student Ravi K. Ghanta (left) and Research Assistant Constantinos Pitris, both from the Harvard-MIT Health Sciences and Technology Program, work with Professor James G. Fujimoto in RLE's Optics and Devices group. Mr. Ghanta's research explores optical coherence tomography (OCT) imaging in ophthalmology and cardiology. Mr. Pitris's research employs OCT technology to detect and screen cancerous tumors. In addition to biomedical optics, the femtosecond ultrashort-pulse solid-state laser system shown in the photograph is used for fundamental studies of ultrafast phenomena in materials and devices.*
*(Photo by John F. Cook)*

## Femtosecond Laser Generation and Measurement Techniques

One focus of Professor Fujimoto's group is on the development and application of ultrashort-pulse laser technology, which is capable of operating over a broad spectral range—from the visible to the near infrared. Ultrashort-pulse laser technology is essential for fundamental studies of ultrafast phenomena as well as for applications of high-speed optical and optoelectronic technology in optical communication, optical networks, signal processing, optical memory, instrumentation, and imaging. Professor Fujimoto's group explores ultrashort pulse solid-state lasers that operate over a broad spectral range from the visible to the near infrared, new ultrashort pulse laser generation techniques for compact lasers, and other high-performance lasers based on novel laser designs. The group also investigates nonlinear optics and nonlinear optical materials, including new saturable absorber devices. In addition, they explore the application of femtosecond laser technology for the study of ultrafast phenomena in materials and devices. These studies include pump-probe measurements of ultrahigh-speed femtosecond dynamics, nonlinear interaction of light and matter, nonlinear materials processing, optical data storage techniques, and imaging.

## Laser Medicine and Biomedical Imaging

Another major focus in Professor Fujimoto's laboratory is laser medicine, biomedical optics, and biomedical imaging. His group has performed some of the first studies of femtosecond laser-tissue interaction, and has participated in the development of safety standards for ultrashort-pulse lasers used in retinal applications. In collaboration with investigators at the Massachusetts General Hospital and the Massachusetts Eye & Ear Infirmary, they have invented and developed a new biomedical imaging modality, optical coherence tomography (OCT), to perform high-resolution, cross-sectional imaging in biological tissues. Since its invention in 1990, OCT has been extensively applied in clinical studies to diagnose and monitor diseases of the eye including glaucoma, diabetic retinopathy, and macular degeneration. In an ongoing study of ophthalmic applications for OCT, thousands of patients have been examined in collaboration with Drs. Joel Schuman and Carmen Puliafito of the New England Eye Center. This new technique can image the retina with a 10-micron resolution. It is now being investigated as a clinical diagnostic tool for other human organ systems such as the cardiovascular, pulmonary, and gastrointestinal systems.

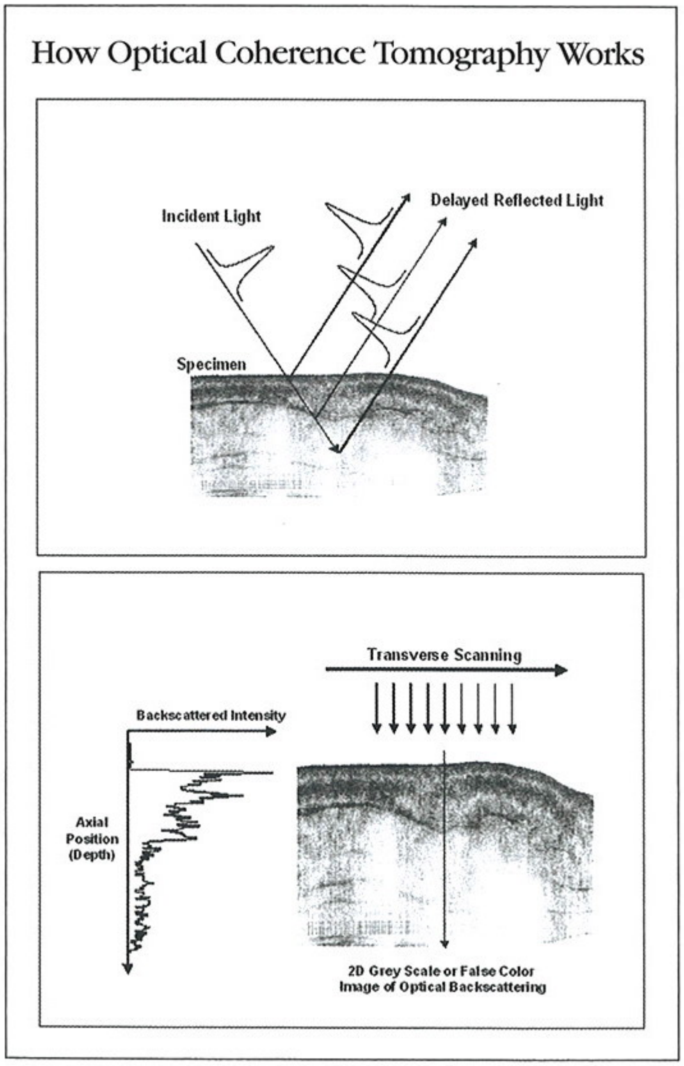
Optical coherence tomography (OCT) is a fundamentally new type of imaging modality that can generate cross-sectional images of the internal structure of biological tissues or materials on a micron scale. OCT is somewhat analogous to ultrasound imaging, but uses light instead of sound. Imaging is performed by measuring the echo time delay and magnitude of backscattered light. Since the velocity of light is extremely high, the echo delays are in the femtosecond regime and cannot be measured using direct electronic detection. High-resolution measurements are performed using correlation techniques, and low-coherence interferometry and image information is generated in cross-sectional planes.

For medical diagnostics, OCT can be used as a type of "optical biopsy" to image tissue pathology. It is an especially powerful tool because it has a resolution approaching that of conventional excisional biopsy, and it can perform imaging *in situ* and in real time without the need to excise tissue specimens.

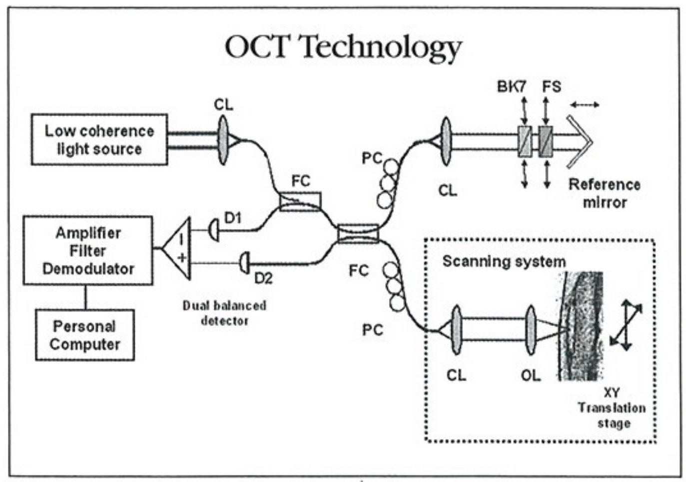
Current collaborations with Dr. Mark Brezinski of Harvard Medical School and the Massachusetts General Hospital are exploring applications of OCT for arterial imaging, early cancer detection, and surgical guidance.

Research on fundamental technology continues and, in the last year, Professor Fujimoto's group has demonstrated cellular-level OCT imaging (*Nature Medicine*, July 1998). High resolution on the cellular level is important for basic research applications of OCT and its use in the detection of early neoplastic (cancerous) changes. Clinical trials have shown that OCT is promising for diagnosing and monitoring diseases. Professor Fujimoto discusses his group's work and the future of OCT in detail in this issue's "Faculty Profile" on page 15.

*by Dorothy Fleischer*

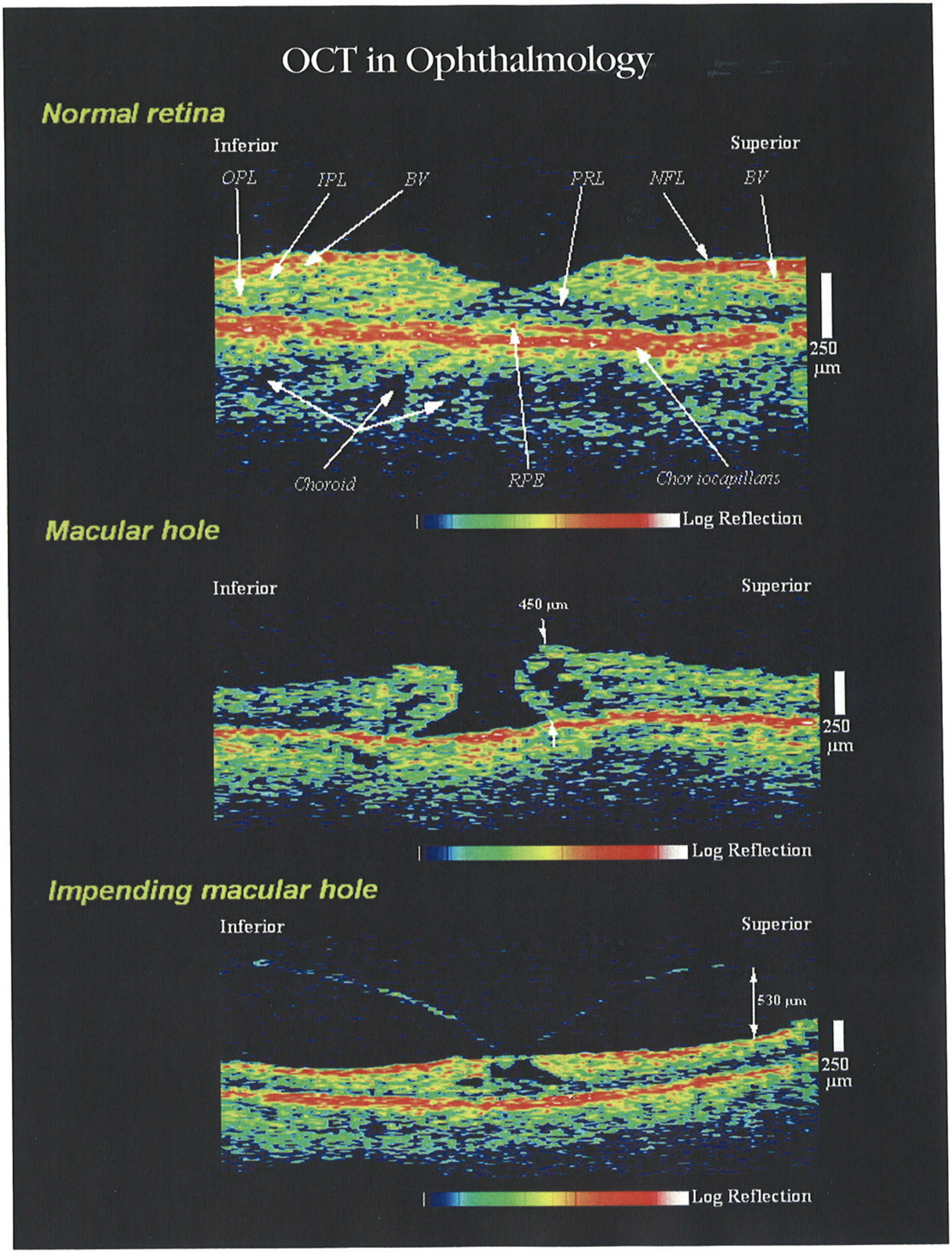



*Top:* *Optical coherence tomography (OCT) is based on optical ranging. Precision measurements of structures are performed by shining a beam of light onto the object and measuring the echo time delay of light that is reflected or backscattered from different internal structures.*
***Bottom:*** *Cross-sectional images of internal structures are generated by scanning the transverse position of the incident optical beam. This results in a two-dimensional array that represents the backscattering of the tissue in a cross-sectional plane.*




***Measuring echoes of light using fiber-optic interferometry.*** *Because the velocity of light is extremely high, it is not possible to measure directly the echo time delay of reflections electronically. A method known as low-coherence interferometry is used to compare back-reflected light from the sample (or specimen) to the light that has traveled a reference path of known length. This provides a precise measurement of the echo time delay of the back-reflected light. The operation of the interferometer is analogous to heterodyne optical detection. Optical coherence tomography can be implemented fiber optically, and draws upon a well-developed technology base.*

***Right: Ophthalmic diagnostics.*** *Optical coherence tomography (OCT) is a powerful diagnostic tool in ophthalmology and provides high-resolution images of retinal structure that cannot be obtained by other means.*
***Top:*** *An OCT image of the normal foveal region of the retina (the front of the retina is at the top). A layer of small capillaries is visible at the back of the retina as a highly scattering structure in red.*
***Center:*** *An OCT image from a patient with deteriorating vision in her left eye. Her visual acuity was 20/80, and an ophthalmoscopic examination showed a full-thickness macular hole. The image clearly shows the hole penetrating the full retina with adjacent swelling or edema.*
***Bottom:*** *An OCT image from the patient's other eye. The ophthalmoscopic examination was almost normal and visual acuity was 20/25. However, the OCT image revealed early stages of a macular hole. If detected early, often these patients can be treated surgically to arrest the development of macular holes and reduce the possibility of vision loss.*

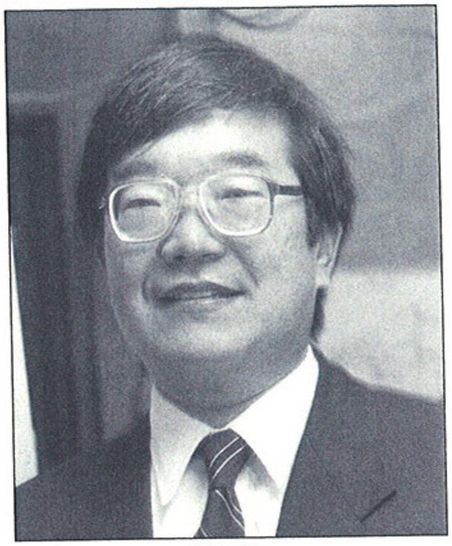

OCT in Ophthalmology
Normal retina
Inferior
Superior
OPL
IPL
BV
PRL
NFL
BV
250 µm
Choroid
RPE
Chor iocapillaris
Log Reflection
Macular hole
Inferior
Superior
450 µm
250 µm
Log Reflection
Impending macular hole
Inferior
Superior
530 µm
250 µm
Log Reflection

# FACULTY PROFILE:

## James G. Fujimoto

*Chicago native Dr. James G. Fujimoto (SB '79, SM '81, PhD '84) joined RLE in 1979 as a graduate student in the Picosecond Laser Optics group working with Professor Michael Salour. Shortly after Bell Laboratories scientist Erich P. Ippen (SB '62) joined the MIT faculty in 1980 to continue his groundbreaking investigations into femtosecond optics, Dr. Fujimoto became affiliated with his research efforts in RLE. Today, their collaborations continue jointly with Institute Professor Hermann A. Haus in the areas of lasers and ultrafast phenomena.*

*In 1985, Dr. Fujimoto was appointed to the faculty in MIT's Department of Electrical Engineering and Computer Science. As his research continued to focus on the development and application of femtosecond laser technology and basic studies in ultrafast phenomena, his activities in this field broadened into the areas of laser medicine and surgery. He and his colleagues are credited with the invention of optical coherence tomography (OCT), a new biomedical diagnostic technique that performs cross-sectional tomographic imaging of microstructures in biological systems. Earlier this year, Dr. Fujimoto received a 1999* Discover *Magazine Award for Technological Innovation (see page 20), which cited his pioneering work on OCT. In the following interview, Dr. Fujimoto describes the impact of OCT technology on healthcare and its possibilities for other medical applications in the future.*



*Professor James G. Fujimoto*
*(Photo by John F. Cook)*

• ***What brought you to MIT?***
I came from a lower middle-class family, and we lived in a working-class neighborhood in Chicago. My parents were Japanese and, because of World War II, neither of them could go to college, although they grew up in California and wanted to go. That had a big impact on our lives. My father was an electrician and had an electrical contracting business. From the time I was five, he'd take me all around Chicago to work with him. Because I was so small, he had me help in tight spaces like ceilings and crawlspaces, where electrical work had to be done. Consequently, I was always interested in electronics and electrical engineering. At twelve or thirteen, I built a television from a kit and thought about a career in television repair.

My father wanted me to attend a local college in Chicago. Initially, I planned to go to the Illinois Institute of Technology (IIT). A family friend, whom I called Uncle Tom, played bridge with my father. He always came over early just to talk to me about interesting things, like how the Egyptians built the pyramids without the use of modern surveying equipment. He was the only person I knew from my parents' generation who had gone to college and who understood the implications of attending a good university. So, Uncle Tom told my father that MIT was the only engineering school that everyone recognized. He said to my father, "But, of course you can't afford to send him to MIT!" My father was so upset by this challenge that he vowed to send me to MIT if I was accepted. He couldn't stand the embarrassment of not sending me here.

At that time, I was also studying classical organ at the American Conservatory of Music in Chicago and was considering a music career. My music teacher knew that I had mixed feelings about choosing a career in music versus science. She told me that music was very competitive and the possibility of succeeding to concert level was very small. In the performing arts, she told me, there's no middle ground. In science, there's more room for different levels of skill. She said that although I was quite good, she didn't feel I would attain concert level, and she felt that my artistic ability could be realized in science as well as in music. It was hard for me to leave music behind, knowing that I'd never again reach the level that I had achieved then.

So, the factors that brought me to MIT were my Uncle Tom, who challenged my father into sending me here, and my music teacher, who advised me to leave music. Both of them were exceptionally talented people with great insight into art and science. I believe the most instrumental decision in my life was to come to MIT. If I had gone to a local college in Chicago, I wouldn't have had the level of training and the exceptional opportunities that I've had here.

• ***How did you become involved with laser optics research at RLE?***
After receiving my bachelor's degree in 1979, I was applying to graduate schools when Professor Michael Salour joined the MIT faculty. I didn't have a specific research interest and everything seemed intriguing. Mike recruited me for his research group in RLE, which was working on solid-state physics and picosecond laser optics. Mike was an interesting and controversial faculty member with an unusual background. He had been a pilot for United Airlines, and he was licensed to fly commercial aircraft. His family also had a company that bought and sold Lear jets. He'd borrow his family's jet, announce he was going to London, and ask students in the lab to join him. Unfortunately, I never flew with him. He ultimately left MIT to go into business and has since founded several highly successful high-tech companies. Although he didn't fit the academic mold, he was brilliant and

charismatic. Mike attracted good people to his group, and I was exposed to high-quality science and state-of-the-art work. However, difficulties in the group prompted me to leave after receiving my master's degree in 1981. I then began to work with Erich Ippen, who had recently come to RLE from Bell Labs.

• ***Did you have a mentor?***

In my professional career, Professor Erich Ippen has been the most influential figure. He is internationally renowned as one of the fathers of femtosecond optics along with Dr. Chuck Shank, who is now the director of the Lawrence Berkeley Lab. Working with Erich was a unique opportunity, and his research style influenced my own approach to science. He is good at identifying the most significant component of a problem, and then advancing scientific knowledge by targeting that component. Over the years, my own group has followed this approach, which is reminiscent of the Bell Lab's style.

• ***What are the implications of generating the shortest and fastest optical pulses?***

Short pulses establish the resolution at which we can do a measurement. The shorter the pulse, the higher the resolution that is possible. When we have increased measurement capabilities, then we can look at different phenomena or processes that could not have been investigated before. This can provide a powerful insight into whatever area we're applying it in—whether it's solid-state physics, high-speed optical devices for communication, or fiber optics. The ability to generate the shortest pulses is also like any other precision measurement or world-record endeavor. There's the challenge of trying to set a world record and the knowledge that we're competing internationally with top groups. My group participated in the record-breaking pulse duration project jointly with Professors Ippen and Hermann Haus. Right now, I'd say we're closely tied with the Swiss Federal Technical Institute in Zurich for the world's shortest pulses. Some people say our group has the shortest pulse, but others say it's the group in Zurich.

When you develop a new technology, in the beginning, things are simple because not much has been done before, but there's a productivity-versus-time curve. At first, the curve rises slowly because, when a field is new, not much is known. Then, it rapidly accelerates upward as the technology advances, which enables problems to be solved. Finally, it plateaus, because only the most challenging problems remain. Quantum advances or paradigm changes follow this kind of development. For example, the Internet is now in a rapid growth phase. Ultimately, it will plateau. When developing a new technology or doing research, one tries to ride this curve and to push advances ahead of the curve as much as possible. As you progress, the levels of control and expertise also increase.

Short pulses establish the resolution at which we can do a measurement. The shorter the pulse, the higher the resolution that is possible.

• ***How would you describe your group's approach to its different areas of research?***

The overall theme of our work is to develop new optical tools that allow us to measure and understand phenomena that we couldn't investigate before. We're active in two different areas: ultrafast phenomena and biomedical optics. Both are related by the common theme of optics, but each approach is different. The study of ultrafast phenomena is more closely related to classical quantum electronics and the application of optics to spectroscopy and communication. In our case, we study ultrafast processes. Our emphasis in studying ultrafast optics is on developing short-pulse lasers and ultrafast measurement technology. Once we have this technology, we can apply it to different areas and use it to understand processes that we couldn't measure before. This is similar to Harold Edgerton's approach to strobe photography, which permitted the understanding of high-speed mechanical processes that could not be investigated before.

In biomedical optics, we focus on technologies that have an impact on healthcare. Our group is credited with the invention and development of optical coherence tomography (OCT), which is a new modality for biomedical imaging. Here, our approach is to develop a technology with broad-based applications and apply them in both research and clinical medicine. This is different from our ultrafast phenomena research because we must work in close collaboration with the clinical community. Basic science and clinical medicine use different methodologies and address different issues, so we need to develop a multidisciplinary approach to integrate the various approaches. The standards for clinical research are very high and a new technology must meet stringent criteria for safety, clinical efficacy, and cost effectiveness.

Our research in biomedical optics is driven by a different motivation than our more basic research in ultrafast optics. In medicine, if one successfully develops a technology that impacts on healthcare, its effect on society is cumulative over time. If that technology can reduce morbidity and mortality by even small percentages, then, over time, that translates to hundreds of thousands of lives saved or the possibility for significant reductions in human suffering from a particular illness. In this case, if we look at what we perceive as relatively small percentages, the impact on humankind can be significant. That's one reward of this research, but it's difficult to achieve.

Another major difference between ultrafast and biomedical optics research is the time it takes to make an impact. If one develops a new ultrafast optics device that's important to the Internet, it can be brought to the marketplace quickly and have a rapid impact. In contrast, the time scale in medicine can be much longer because developing technology is only the first step. In healthcare, to show that a new technology is useful and will have a clinical impact, we must first identify a specific clinical application. Next, we must look at existing treatments and determine whether a new approach is necessary. Does it benefit patient care? Does it reduce cost? Is it truly effective? To show statistical significance, we must perform clinical studies on a patient population large enough to account for gender, age, race, and other variables. We must ask if a new diagnostic or treatment will be effective for all patients in a statistically reasonable way. It also takes a long time to move technology from the research laboratory into the clinic, and then to gather this data from clinical studies. Time is also needed for the clinical community to adopt something new. Even if something's been demonstrated to be effective, it may not be automatically adopted. So, the time scale for realizing new technologies in medicine is quite different from optics.

Our research in femtosecond optics and biomedical optics has been interesting because we can often borrow approaches and methodologies used in one area and apply them to other areas. In addition, there is always an interplay between basic science, technology, and applications. Developing and applying state-of-the-art technologies allows us to explore fundamental problems and advance scientific knowledge. Conversely, the problems and practical needs in science and medicine determine which technologies will be useful and will have an impact.

> Our emphasis in studying ultrafast optics is on developing short-pulse lasers and ultrafast measurement technology. Once we have this technology, we can apply it to different areas and use it to understand processes that we couldn't measure before.

• ***What is the significance of OCT technology?***

OCT is a fundamentally new mode of imaging. It allows us to look at internal cross-sectional microstructure in real time—not only in biological systems, but also in materials, devices, or anything we can measure optically. It's analogous to ultrasound in the sense that we measure light and high-speed echoes reflected from tissues. One advantage of OCT is that it enables us to look at structures without the need to perform a biopsy. Excisional biopsy and histopathology [the science concerned with microscopic changes in diseased tissues] are gold standards for diagnosis, especially for cancer. The clinician removes a specimen of tissue, which is then processed, sectioned into thin slices, and examined under a microscope. Excisional biopsy allows the clinician to see the glandular organization as well as the cellular structure of tissue; however, it requires that tissue be removed and processed. With OCT, not only can we image tissue with a resolution approaching that of histopathology, but the imaging also can be performed in real time without the need to excise tissue specimens.

Several years ago, we developed OCT for applications in ophthalmology. Working with Eric Swanson, who was then at MIT Lincoln Laboratory, and Drs. Carmen Puliafito and Joel Schuman at the New England Eye Center, we began clinical studies in ophthalmology. Once we had OCT in the clinical environment, it opened a wide range of possibilities. Since OCT could generate images of the retina that were not previously possible, it allowed us to better investigate and diagnose a wide range of diseases such as glaucoma and macular edema. One of our research assistants, Michael Hee, was an MD/PhD student in the Harvard-MIT Health Sciences and Technology Program who worked on these first clinical studies. It was a very exciting time and things really moved quickly. During his doctoral studies, Michael published over thirty peer reviewed scientific articles. In 1995, Michael and our collaborators published a book on clinical applications of OCT in ophthalmology. The book is essentially an atlas on using OCT for ophthalmology and is intended as a reference for clinicians who want to use the technology for diagnosis. It describes how OCT was used for specific case studies and for imaging retinal diseases such as macular holes, age-related macular degeneration, diabetic retinopathy, and glaucoma.

• ***What do you see as OCT's future applications?***

Working with Dr. Mark Brezinski at the Massachusetts General Hospital and the Harvard Medical School, we've expanded the range of OCT's applicability to image almost any tissue in the human body. This is an important advance, but it also makes future directions complicated because of the many possibilities that it presents. Generally, we've looked at three application scenarios. The first scenario involves imaging pathology in structures where conventional excisional biopsy cannot be used, such as the eye. We're also considering applications to coronary artery disease. OCT has been used in combination with catheter techniques to look at the pathology of arteries and determine whether intervention is needed. A second application scenario is guiding surgery on sensitive structures. By seeing beneath the surface of tissues, we can guide precision surgeries such as microsurgery or neurosurgery. The third and perhaps most interesting application is early cancer detection. Most screening or diagnostic procedures rely on biopsy. However, biopsies take a very small specimen, and a common problem is sampling error. Sometimes, if the biopsy misses the cancer, there can be a false negative result—the biopsy is normal, but the patient has cancer. OCT technology can be used to image inside the tissue and, since we're not excising its structure, we can get much better sampling coverage then excisional biopsy. OCT may be able to reduce the false negative rate that's associated with excisional biopsy. In addition, with biopsy, a specimen must be removed and then time is required to process it. Ultimately, with future clinical studies, it may also be possible to make a diagnosis based on OCT imaging in real time.

OCT is significant because it represents a fundamentally new imaging modality and it has a wide range of applications. We understand its ophthalmic applications best, and it's becoming more widespread in that area. Almost 10,000 patients have been examined with OCT at the New England Eye Center, and there are about 200 OCT systems in use internationally. With the next generation of the technology, we hope it will achieve widespread clinical use, to the point where it is available in every ophthalmologist's office. The other application areas are less mature, and we have much more work to do. Because there are so many different possibilities, it's hard to say which ones will be more significant.

One of the best things about working in the Boston area is that we have good connections with some of the best medical schools in the world, and we have access to top collaborators and clinical infrastructures in medical research. We're now in the process of setting up a variety of multidisciplinary collaborations with area hospitals and investigators. We have about eight clinical protocols that are looking into areas such as ophthalmology, gastroenterology, pulmonology, orthopedic surgery, oral cancer, and female reproductive oncology.

> . . . we've expanded the range of OCT's applicability to image almost any tissue in the human body. This is an important advance, but it also makes future directions complicated because of the many possibilities that it presents.

**• *Do you envision OCT fitting in with other emerging technologies?***
Generally, any technology that is electronic or generates data in electronic form can do processing, extract diagnostic information from images, transmit images over the Internet, and digitally archive them. For more modern clinical studies, a database is very important because a diagnosis or therapy must be effective across a large cross section of the population. Now, computer technologies can more readily integrate different types of modalities and combine information to achieve statistical accuracy. The other issue, for medical diagnosis or intervention, involves minimally invasive treatment. One approach combines classical open-field surgery with surgical guidance and planning methods. Other approaches use minimally invasive techniques, such as laparoscopes, or other kinds of manipulations through very small incisions. In the case of coronary artery disease, catheters are used in combination with radiography to reduce the need for coronary bypass surgery. What we're doing with OCT is still futuristic. It's one thing to look at our images, to see what we can do with them, and then say it's intriguing. However, modern medicine is complex because of cost and management issues. To be successful, we must find specific applications where OCT is truly the best solution, where it will be clinically effective, where it will reduce healthcare costs, and, at the same time, improve patient outcomes. The challenge in medical research is trying to achieve all of these.

**• *I understand you're now applying OCT to nondestructive evaluation for materials in manufacturing.***
We've had collaborations with the National Institute of Standards and Technology in this area. Applications for imaging technology span a broad range of topics, and materials science is one of those. There are situations in process control for manufacturing when a nondestructive evaluation approach is needed to measure cross-sectional structures like those in composite polymers or thin films. However, in process control applications, like semiconductor processing, the economic basis is very different from OCT applications in healthcare. For example, if your semiconductor process line has a large throughput and something will improve your yield, then cost is not a factor. By comparison, the throughput in healthcare is relatively low and everything is expensive because it's so highly personalized.

**• *What is your role in providing technology transfer for OCT?***
A major issue is effecting the transition of OCT from the research laboratory into the clinical industrial world. Ultimately, we want a device that is robust and reliable to be used in the clinic or in commercial applications. This transition is essential if a new technology is to have an impact. In 1992, my collaborators and I founded a company that transferred OCT technology into the ophthalmology field. The company, Advanced Ophthalmic Devices, has since been acquired by Humphrey Instruments. They introduced an OCT device for clinical ophthalmology in 1996, and are currently engineering a second-generation OCT product line. In 1998, we realized that OCT had potential in a wide range of clinical applications in addition to ophthalmology. In order to develop this technology, we started another company called Coherent Diagnostic Technology (CDT). CDT was founded by my collaborators Mark Brezinski, Eric Swanson, and me. It is headed Dr. Paul Magnin, the former head of Hewlett-Packard's Imaging Systems Division. In a joint venture with Carl Zeiss, Inc., CDT works in strategic partnership with large medical organizations to develop OCT applications in internal medicine. Our aim is to maintain CDT's focus on core competence in state-of-the-art OCT technology and to develop partnerships with one or more companies that already have a presence

in the clinical marketplace. This arrangement combines the creative drive of a start-up with the experience and market presence of an established company.

*• What is needed for continued progress in your field?*

What's most important is the talent and motivation of the people involved. A multidisciplinary collaborative team that works well together can accomplish amazing things. I've been especially fortunate to work with talented senior investigators, visiting scientists from several international institutions, doctoral students in our department, and MD/PhD students from the Harvard-MIT Health Sciences and Technology Program.

*• What are your hopes in terms of your research providing a direct benefit to society?*

As I mentioned earlier, our research is divided into two areas. The study of ultrafast phenomena is a form of fundamental research. We're trying to advance the understanding of ultrahigh-speed processes. These are relevant to understanding physical phenomena in solid-state electronic and optoelectronic devices, which will bear on both high-speed communication and computation. This research is closer to traditional physics because we're looking at fundamental issues. In biomedical applications, particularly ophthalmology, we've been fortunate to develop technologies that are in use clinically, but there's still much more work to be done. We're trying to develop OCT technology to the point where there will be widespread clinical benefits for patients. A diagnostic tool like OCT could be especially useful in ophthalmology to identify patients with early-stage retinal disease. In many diseases, such as glaucoma or diabetic retinopathy, symptoms like loss of vision can be irreversible. However early-stage detection and treatment can help to preserve vision before the symptoms appear.

*• What is your most significant achievement?*

From a personal point of view, it has been the opportunity to train advanced personnel in the area of scientific research. When I look back on the graduate students or postdocs whom I've trained and had the opportunity to work with, many of them have become leaders in femtosecond or biomedical optics.

*• What's the most rewarding aspect of your career?*

In a research and teaching organization of this type, there's the opportunity to explore different aspects of teaching at both the graduate and undergraduate levels. There's also research, where you hope that you can come up with creative ideas and advance scientific knowledge. In addition, there's administration of a research group, which can be like operating a small business. The reward is that you can integrate all these things and broaden the scope of your experience and expertise.

> To be successful, we must find specific applications where OCT is truly the best solution, where it will be clinically effective, where it will reduce healthcare costs, and, at the same time, improve patient outcomes. The challenge in medical research is trying to achieve all of these.

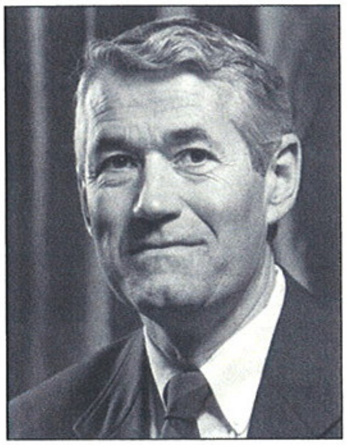
*• How would you characterize your approach to teaching?*

Until recently, I haven't thought of myself as a teacher because I haven't felt that I've had sufficient experience to have something unique to contribute to the students. I've always thought of myself as trying to understand things and to improve my own technical and artistic capabilities. Being at MIT has provided me with the opportunity to continue my own development by working with top people in my field. Certainly, teaching a class requires special skill. You must engage students, present information clearly, and motivate people. It's much like performance art. However, teaching also involves working with students over long periods. For example, when I studied music, I worked with my teacher for six years. To me, that's the core of teaching. It's not only an opportunity to learn from the person you're teaching, but it's also trying to pass on a methodology as opposed to just the knowledge base itself. I believe that methods and techniques are more important than the details of how to do a calculation or an experiment. Of course, you must master those, so I'm not saying that they're not important. However, it's harder to foster new ways of thinking and to improve a student's methodology than to simply pass on information.

*• What would you like to tell students who are contemplating a career in science?*

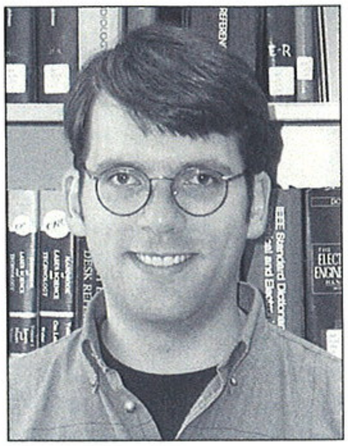
I don't think there's a profound shortcut to success. It's a combination of many things. To be successful, people need to adapt to the situation around them. Sometimes that requires you to become a different person; that is, to continuously grow and try new approaches. In any collaboration, everyone comes with a different perspective. There's always a range of people with different skills and expertise, with strengths and weaknesses in different areas, and with different personalities. We're surrounded by extremely intelligent and talented people; you should emulate the best characteristics and methods of each person around you. The other component to success is hard work. You must be interested enough in what you're doing to take the time to refine your skills and technique. It's like practicing music. You can't do something at a creative level without commitment, either in the arts or in science. A career in science can be tremendously rewarding, and you will have great opportunities, but you must have a strong commitment to strive for excellence.

# circuit breakers

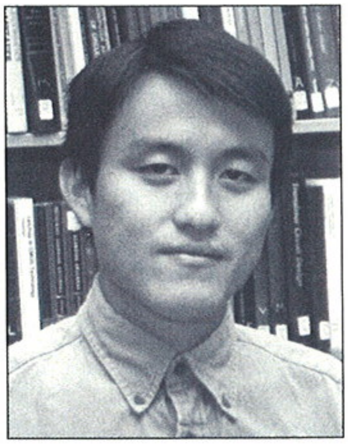


***Dr. Robert J. Birgeneau,*** Dean of Science and the Cecil and Ida Green Professor of Physics, was appointed president of the University of Toronto, effective July 1, 2000. A former RLE associate director and principal investigator in the Surfaces and Interfaces group, Professor Birgeneau has served as dean of science since 1991, and was chair of the Department of Physics from 1988 to 1991. He joined the MIT faculty in 1975. A graduate of the University of Toronto (BSc'63) and Yale University (PhD'66), Professor Birgeneau is internationally recognized for research in solid-state physics. He has made important contributions to the field of condensed-matter physics, including investigations into the phase-transition behavior of novel states of matter and the microscopic physics of high-temperature superconductors. A recipient of numerous awards, he recently received the American Physical Society's Julius Edgar Lilienfeld Prize for 2000. The prize acknowledges outstanding contributions to physics by an individual who also has exceptional skills in lecturing to diverse audiences. Professor Birgeneau was cited for using neutron and x-ray scattering to elucidate the structure, phase transitions, and excitations of materials that are paradigms of important statistical mechanical models, and for his ability to convey the excitement of physics to a broad range of audiences. In addition to his research, Professor Birgeneau recently led a pioneering study that analyzed the status of women faculty in MIT's School of Science. *(Photo by John F. Cook)*

***Dr. David J. Carter*** (PhD'98) was appointed research engineer in RLE's Quantum-Effect Devices group, effective May 15, 1999. Since 1993, Dr. Carter has worked with Professor Henry I. Smith in RLE's NanoStructures Laboratory on the fabrication, characterization, and design of micro- and nanometer-scale structures. His research has included sub-50-nanometer device fabrication using x-ray nanolithography as well as low-temperature transport studies of Coulomb blockade in coupled quantum dots fabricated in gallium arsenide/aluminum-gallium arsenide heterostructures. A graduate of Dartmouth College (AB'88, MS'90), Dr. Carter has served in RLE as a research assistant and postdoctoral associate. His ongoing research will involve the development of a zone-plate-array nanolithography system that operates at the 4.5-nanometer wavelength. *(Photo by John F. Cook)*



***Dr. Joseph G. Desloge*** (SM'94, PhD'98) was appointed research scientist in RLE's Sensory Communication group, effective October 1, 1998. Working with Principal Research Scientist Dr. Patrick Zurek, Dr. Desloge has investigated the design, development, and evaluation of advanced signal processing for hearing aids, as well as the development of array signal-processing algorithms. Previously, he served as a research assistant in RLE and designed a novel processing technique for adaptive array systems that attenuated interference sources while preserving the desired target source. A graduate of Cornell University (BS'92), Dr. Desloge is a member of Tau Beta Pi, Eta Kappa Nu, and Sigma Xi. *(Photo by John F. Cook)*

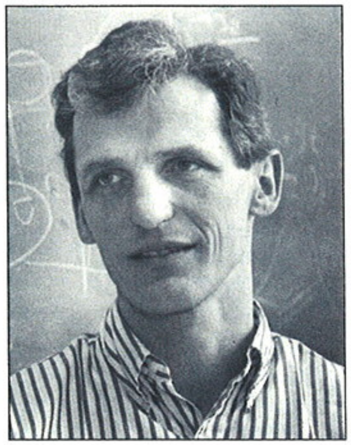


***Dr. Shanhui Fan*** (PhD'97) was appointed research scientist in RLE's Surfaces and Interfaces group, effective July 1, 1999. A graduate of the University of Science and Technology of China ('92), Dr. Fan has worked with Professor John D. Joannopoulos since 1993 as a research assistant and a postdoctoral associate in RLE. The focus of his research has been on the theory of photonic bandgap materials and their application to the design of novel photonic crystal devices. Dr. Fan's work has also involved ongoing collaborations with several experimental groups at MIT to fabricate photonic bandgap devices using state-of-the-art microfabrication techniques. *(Photo by John F. Cook)*

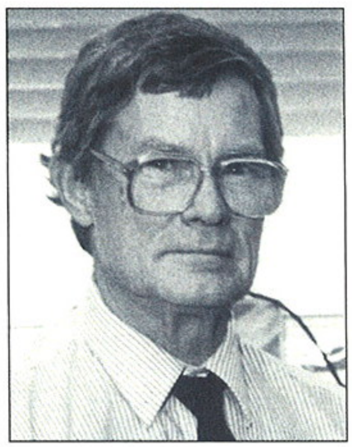
***Dr. James G. Fujimoto*** (SB'79, SM'81, PhD'84) received the 1999 *Discover* Magazine Award for Technological Innovation in Medical Diagnostics sponsored by the Christopher Columbus Foundation. The award recognizes Professor Fujimoto's pioneering work on optical coherence tomography (OCT), which is a new type of imaging technology. OCT generates cross-sectional images of tissue microstructure on a micron scale and functions as a type of optical biopsy (see this issue's cover article and "Faculty Profile"). The award was presented June 5, 1999, at *Discover* magazine's 10th annual awards ceremony at Epcot-Walt Disney World in Florida. A principal investigator in RLE's Optics and Devices group, Professor Fujimoto's research focuses on femtosecond laser generation and measurement techniques, studies of ultrafast phenomena in electronic and optoelectronic materials and devices, and laser applications to medicine. He joined the MIT faculty as an assistant professor in 1985, becoming associate professor in 1988 and full professor in 1994. Since 1994, he has been a visiting professor of ophthalmology at the Tufts University School of Medicine. Professor Fujimoto is a fellow of the Optical Society of America and the Institute of Electrical and Electronic Engineers and is a member of the American Association for the Advancement of Science and the American Physical Society. *(Photo by John F. Cook)*

**Dr. Marc A. Kastner,** head of the Department of Physics and Donner Professor of Science, was named co-recipient of the American Physical Society's Oliver E. Buckley Condensed Matter Physics Prize for 2000. The prize recognizes outstanding theoretical or experimental contributions to condensed-matter physics. Professor Kastner and two co-recipients, Drs. Gerald J. Dolan and Theodore A. Fulton, were cited for pioneering contributions to single-electron effects in mesoscopic systems. In the 1980s, both Drs. Dolan and Fulton had worked on the development of the single-electron transistor (SET) at Bell Laboratories. Professor Kastner, a principal investigator in RLE's Quantum-Effect Devices group, is recognized for pioneering a semiconductor SET that turns off and on once for every electron added to it. These novel devices provide new insight into the behavior of electrons confined to small areas and contribute to knowledge of quantum-mechanical processes in semiconductor devices. Using the SET, Professor Kastner and his group continue to investigate the Kondo effect, a phenomenon theoretically predicted to occur in semiconductor nanostructures. *(Photo by John F. Cook)*

**Dr. Wolfgang Ketterle,** the John D. MacArthur Professor of Physics, was named co-recipient of The Franklin Institute's 2000 Benjamin Franklin Award in Physics. The annual awards program of the institute recognizes leading men and women of science from around the world. Professor Ketterle and two co-recipients, Drs. Carl Wieman (SB'73) and Eric Cornell (PhD'90), were cited for their epoch-making experimental confirmation of the existence of Bose-Einstein condensation in dilute alkali vapors and for their studies of the properties of a gas in the degenerate quantum regime. Drs. Wieman and Cornell, currently on the faculty at the University of Colorado, had previously conducted related research as students in RLE's Atomic, Molecular, and Optical Physics group. Professor Ketterle, now a principal investigator in that group, was one of the first scientists to observe the phenomenon of Bose-Einstein condensation in dilute atomic gases. This important advance in 1995 enabled his research group to realize the first atom laser in 1997. *(Photo by John F. Cook)*



*Dr. Wolfgang Ketterle*



**Dr. John G. King** (SB'50), the Francis Freedman Professor of Physics Emeritus, was awarded the American Association of Physics Teacher's 2000 Oersted Medal. The association's most prestigious award recognizes notable contributions to the teaching of physics. Professor King joined RLE in 1950 as a thesis student and later worked with Professor Jerrold R. Zacharias on studies that led to the development of the first commercial atomic frequency standard. He also served as RLE's associate director from 1973 to 1976. A leading proponent of educational innovation and reform, Professor King has introduced several teaching methods, including the physics project lab and corridor labs, courses with take-home experiments, and concentrated study. In addition, he has worked on the development of scientific playgrounds and educational science resources for students in grades K-12. *(Photo by John F. Cook)*

**Dr. Andrew J. Oxenham** was appointed research scientist in the Sensory Communication group, effective June 1, 1999. Dr. Oxenham's experiments on the psychoacoustics of normal and impaired hearing in RLE seek to develop improved hearing aids and cochlear prostheses. His work in normal and pathological auditory perception focuses on compressive cochlear nonlinearity and how it affects the additivity

of masking and temporal integration. This nonlinearity is greatly affected by sensorineural hearing loss, and understanding its perceptual consequences may be important for improved hearing aids. Dr. Oxenham's quantitative modeling of basic auditory functions has provided a deeper understanding of the performance of hearing-impaired listeners. His development of a behavioral measure for basilar membrane nonlinearity in the cochlea resulted in the first estimate of basilar membrane compression in humans that supported physiological studies. A graduate of the University of Surrey (B.Mus.'92) and the University of Cambridge (PhD'96), Dr. Oxenham was a senior research scientist at Northeastern University's Department of Speech-Language, Pathology, and Audiology from 1998 to 1999. From 1995 to 1997, he was a research fellow at the Institute for Perception Research in Eindhoven. Dr. Oxenham is a member of the Acoustical Society of America.
*(Photo by John F. Cook)*

***Dr. Rajeev J. Ram,*** assistant professor of electrical engineering and computer science, was selected to participate in the Fifth Annual Symposium on Frontiers of Engineering. Seventy-eight of the nation's top young engineers attended the three-day event sponsored by the National Academy of Engineering, which was held October 14-16, 1999, in Irvine, California. The symposium brings together engineers ranging in age from 30 to 45 who perform leading-edge research in industry, academia, and government. Participants are nominated by fellow engineers or by an organization. This year's group was chosen from a field of more than 170 candidates. The Frontiers of Engineering symposiums began in 1995 in response to the increasingly interdisciplinary nature of engineering and allows young engineers to learn about developments in other fields. Since joining the MIT faculty in 1997, Professor Ram has carried out a wide range of theoretical and experimental research on high-speed semiconductor lasers. Earlier this year, he received an Office of Naval Research Young Investigator Award for his work on cascade interband laser receivers.
*(Photo by John F. Cook)*

*Dr. Walter A. Rosenblith*

***Dr. Walter A. Rosenblith,*** Institute Professor Emeritus, received the Okawa Prize from the Okawa Foundation for Information and Telecommunications on November 25, 1999. The annual Okawa Prize is presented to those individuals who have contributed to society in terms of research and development of new technologies in the information and telecommunications arena. Professor Rosenblith was cited for outstanding and pioneering contributions to the progress of biomedical engineering, especially the use of on-line computer analysis of brain activity, and to auditory biophysics, as well as to the promotion of international scientific cooperation. After joining the MIT faculty in 1951, Professor Rosenblith played a crucial role in the development of RLE's Communications Biophysics group in the mid- to late 1950s. Using computers to explore the electrical nature of the central nervous system, he and his colleagues brought innovative computer technology to bear on basic research in biology and medicine.
*(Photo by John F. Cook)*

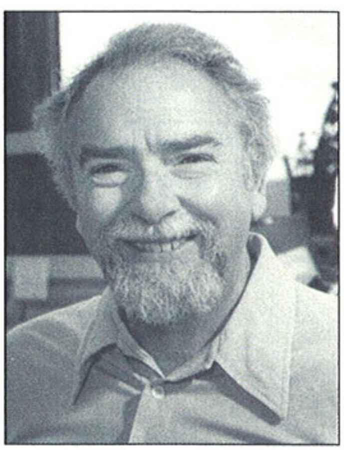
***Dr. Jeffrey H. Shapiro*** (SB'67, SM'68, EE'69, PhD'70) was appointed to the Julius A. Stratton Professorship in the Department of Electrical Engineering and Computer Science (EECS). Professor Shapiro is a principal investigator in RLE's Optical Communications group and served as department associate head of the EECS Department from 1989 to 1999. Under his guidance, his group in RLE was first to generate squeezed-state light in a Doppler-broadened atomic medium. In his more recent research, Professor Shapiro has investigated communication theory for precision measurement, communication, and remote sensing systems that operate in the optical frequency regime. *(Photo by John F. Cook)*

***Dr. Rahul Sarpeshkar*** (SB'90) was appointed assistant professor in the Department of Electrical Engineering and Computer Science, and joined RLE's faculty in the Circuits and Systems group, effective June 3, 1999. Professor Sarpeshkar, who received his doctorate from the California Institute of Technology in 1997, works in the general area of VLSI design for adaptive sensory and neural systems. His efforts combine analog VLSI modeling of neural systems, particularly hearing and vision; device physics, noise, and circuit design; and hybrid approaches to efficient computation. Professor Sarpeshkar's research in modeling noise, nonlinearity, and gain control in the cochlea has enabled him to build an artificial cochlea with an improved dynamic range of those previously built. His work in RLE will involve the use of analog and hybrid VLSI chips to study the fundamental issues of distributed gain control in the cochlea. The insights gained from this research will contribute to improved cochlear implants and robust front ends for speech recognition. *(Photo by John F. Cook)*

## 1999 Taplin Awards

Two RLE investigators received 1999 John F. and Virginia B. Taplin Awards announced by the Harvard-MIT Division of Health Sciences and Technology in June 1999. The purpose of the HST Taplin Awards is to build infrastructure in biomedical engineering, physics, and chemistry. *(Photos by John F. Cook)*

***Dr. Julie E. Greenberg,*** a research scientist in RLE's Sensory Communication group, has developed interactive course notes for distance learning. This project will improve communications by using an interactive Web-based package for biomedical engineering education. The goal of the project is to make biomedical engineering concepts easier to understand for students who have a variety of backgrounds, and to assemble a collection of interactive modules for biomedical signal and image processing that can be used in courses at MIT, Harvard, and elsewhere.



***Dr. Thomas F. Weiss*** (SM'59, PhD'63), the Thomas and Gerd Perkins Professor of Electrical and Bioengineering, has developed a cellular homeostasis software simulator. The software created by Professor Weiss, a principal investigator in RLE's Auditory Physiology group, enables students in bioengineering, biophysics, cell biology, and physiology to perform simulation experiments on a model cell and examine the results with a flexible graphics software package. Each element of the model is selected from a user-selectable, expandable library, which can be edited by the user. Once the cell is designed, users can then perform simulation experiments.

# Publications

## RLE Progress Report

***RLE Progress Report Number 141*** is available from the RLE Communications group at no charge within the United States. ***Progress Report Number 141*** covers the period January through December 1998. It provides detailed information about the research objectives, projects, and publications of RLE's research groups. Faculty, staff, and students who participated in each project are listed, in addition to current RLE personnel, and funding sources are identified. ***The Progress Report*** is also available in the Publications section of RLE's website at http://rleweb.mit.edu.

RLE welcomes inquiries regarding the laboratory's research. To request an ***RLE Progress Report***, please contact:

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Room 36-412
77 Massachusetts Avenue
Cambridge, MA 02139-4307
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## RLE Technical Reports

The following new technical reports are available from MIT Document Services:

***A Framework for Non-Gaussian Signal Modeling and Estimation,*** by Shawn M. Verbout. RLE TR No. 626. 1999. 240 pp.

***TX-0 Computer History,*** by John A. McKenzie. RLE TR No. 627. 1999. 37 pp.

***Coding Approaches to Fault Tolerance in Dynamic Systems,*** by Christoforos Hadjicostis. RLE TR No. 628. 1999. 196 pp.

***Experimental Invetigation of Frictional Properties of the Human Fingerpad,*** by Jung-Chi Liao and Mandayam A. Srinivasan. RLE TR No. 629. 1999. 157 pp. Touch Lab Report No. 11.

***Encoding and Decoding of Shape in Tactile Sensing,*** by Balasundara I. Raju and Mandayam A. Srinivasan. RLE TR No. 630. 1999. 104 pp. Touch Lab Report No. 12.

***Untrasound Backscatter Microscope for*** In Vivo ***Imaging of Human Fingertip,*** by Balasundara I. Raju and Mandayam A. Srinivasan. RLE TR No. 631. 1999. 72 pp. Touch Lab Report No. 13.

***Determination of the Viscoelastic Properties of the Human Fingerpad,*** by Amanda Sue Birch and Mandayam A. Srinivasan. RLE TR No. 632. 1999. 98 pp. Touch Lab Report No. 14.

Please contact MIT Document Services directly for prices and other information about RLE technical reports:
Telephone: 617-253-5668 Fax: 617-253-1690 Email: docs@mit.edu

## RLE on the Web

Internet users are invited to browse RLE's extensive Web pages, which contain this and previous issues of ***RLE currents.*** The laboratory's website is located at http://rleweb.mit.edu/.

# Imaging with Echoes of Light

***This issue of RLE currents features the laboratory's explorations into generating ultrashort pulses of light and developing applications to science and engineering, including optical coherence tomography, a new type of imaging technology.*** ***See article on page 3.***

***Ultrahigh resolution optical coherence tomography.*** *Research in optical coherence tomography (OCT) continues to yield important advances. Clinical OCT images have already achieved resolutions ranging from 10 to 15 microns. While this is sufficient for imaging in many applications, it is still not enough for cellular resolution. Recent advances have improved OCT's resolution to 1 to 2 microns, thus enabling cross-sectional tomographic visualization of cellular structure. This figure is an example of cellular-level imaging in a living African frog (Xenopus laevis) tadpole. Although this level of image resolution is still only possible in a laboratory setting, these results have important implications for biologists and for future clinical applications in cancer diagnosis. The ability to produce images with subcellular resolution in a clinical setting would further enhance OCT's diagnostic capabilities. Thus, these results suggest the potential of this technology and its evolution through ongoing research.*

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