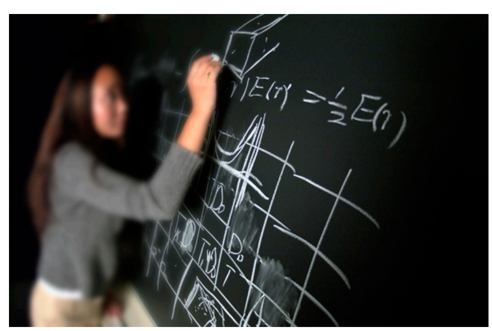
Research Laboratory of Electronics

The Research Laboratory of Electronics (RLE), founded in 1946, is the Institute's first interdisciplinary research laboratory. RLE grew out of the wartime MIT Radiation Laboratory and was formed to bring together physicists and electrical engineers to work on problems in electromagnetic radiation, circuits, and specialized vacuum tubes. Over the years, RLE's research interests have branched in many directions so that today it is the most intellectually diverse of MIT's interdisciplinary research laboratories. Research within RLE today is conducted by approximately 50 faculty members affiliated with the departments of Biological Engineering, Electrical Engineering and Computer Science, Physics, Mechanical Engineering, Materials Science and Engineering, and Mathematics, the Engineering Systems Division, and the Harvard-MIT Division of Health Sciences and Technology. During the past year, approximately 240 graduate students and 50 undergraduates from 10 MIT departments and divisions pursued research within RLE. The research is supported primarily by Department of Defense agencies, the National Institutes of Health, the National Science Foundation, the National Aeronautics and Space Administration, and the Department of Energy. In addition, numerous projects are funded through industry and private foundations. RLE research is widely varied and consists of six major interrelated groupings: circuits, systems, signals, and communications; multiscale bioengineering and biophysics; nanoscale science and engineering; photonic materials, devices, and systems; physical sciences; and quantum computation and communication.

Detailed information about RLE research in AY2007 can be found in RLE Progress Report No. 149. The report is available online at http://www.rle.mit.edu/media/media_pr.html. What follows is a summary of research highlights from the past year.

Circuits, Systems, Signals, and Communications



Professor Jacob White uses a range of engineering design applications to drive research in simulation and optimization algorithms and software. His group's recent efforts have focused on the fundamentals of nonlinear and parameterized model-order reduction, matrix-implicit methods, coupling simulation and optimization, and fast techniques for solving integral equations. Their work on fast algorithms for bio-microelectromechanical (bioMEMS) applications has led to a new fast fluid analysis program for 3-D simulation of biological cells in flow about complicated geometries. This simulation program is being used, in collaboration with Professor Joel Voldman, to investigate design alternatives for micromachined cell-trapping structures.

Professor Luca Daniel leads research ranging from the development of full-wave integral equation electromagnetic field solvers for on-chip interconnects and power distribution grids to the development of techniques for generating parameterized reduced-order models of linear and nonlinear dynamical systems. During the past year he has released source code in the public domain for FastMaxwell, a mixed potential integral equation full-wave electromagnetic field solver. This solver employs a specialized precorrected fast Fourier transform matrix-vector product that allows it to handle very large structures—for example, 10^6 coupled discretized interconnect elements—in less than one hour using only two GB of memory.

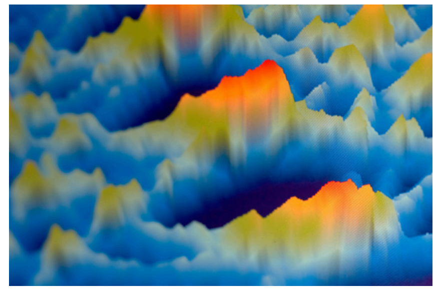
Professor Jae Lim's Advanced Telecommunications and Signal Processing group is developing new video compression methods for use in reducing the bandwidth required for video communications and the storage required for video recording. They have recently completed development of a new approach for reducing blocking artifacts in image and video compression systems.

The research of Professor Vivek Goyal and his students focuses on novel representations of information, algorithms to enable economical data acquisition, and design of excitation sequences for magnetic resonance imaging. Their work in these areas exploits the compressibility of a signal in the acquisition stage, a topic often known as compressed sensing, and it relies on parametric representations that are not bound to traditional linear time-invariant (Fourier domain) approaches. In work on sampling based on finite rate of innovation (FRI), they have used Markov chain Monte Carlo computations to develop algorithms that dramatically reduce noise sensitivity, making FRI-based sampling much more attractive for analog-to-digital conversion. They have also obtained promising results for representing data without regard to order, something that may enable substantial reductions in storage and communication requirements for database and statistical applications.

Professor Alan Oppenheim's Digital Signal Processing group continues to work on a broad array of problems in the area of signal processing and its applications. A primary focus is on algorithm development in general, with applications serving as motivating contexts. Approaches to new algorithms have come from unconventional directions, such as fractal signals, chaotic behavior in nonlinear systems, quantum mechanics, and biology. A recent example is the development of an algorithm for surface mapping using a Markov-modulated Markov chain model of bacterial chemotaxis.

Professor Arthur Baggeroer leads research in a wide variety of topics in ocean acoustics and sonar systems. In one such study, his group has used data from the North Pacific Acoustic Laboratory 2004 BASSEX experiment to study sound propagation in long range-dependent ocean waveguides. Of specific interest in this work is how acoustic models based on ray tracing, coupled-mode theory, or the parabolic approximation predict the scatter field of underwater mountains (seamounts).

Professor Gregory Wornell is interested in the algorithmic and architectural aspects of the design of multimedia networks, wireless communication and sensor networks, and reliable circuits and microsystems. During the past year he has developed new physical layer codes that provide both error immunity and privacy in wireless networks by exploiting the variability in the wireless medium. In other work, he has obtained new information-theoretic models and results for synchronization in communication systems. Whereas prior analyses typically assume synchronization, this new work shows how synchronization effects can be explicitly incorporated into system models and has permitted the impact of such model refinements to be assessed.



Professor Vladimir Stojanovic's Integrated Systems group focuses on designing methodology, circuits, and system techniques for on-chip and off-chip interconnects. The group has created a framework for design and performance evaluation of on-chip networks based on equalized interconnects, and also has begun creating test and measurement circuits and putting together the modeling and system framework for similar evaluations of emerging interconnect technologies like carbon nanotubes and silicon photonics. Professor Stojanovic leads a multidisciplinary silicon photonics team comprised of professors Rajeev Ram, Franz Kärtner, Judy Hoyt, Krste Asanovic, Erich Ippen, Henry Smith, Karl Berggren, and Martin Schmidt. Their collective expertise, spanning nanofabrication and photonic device design to circuits and computer architecture, has enabled them to produce the first-ever test chip integrating silicon photonic devices into a mainstream sub-100-nm bulk CMOS flow. Their chip's fabrication did not require process changes, and it demonstrated integration of photonics with electronic circuits.

Professor David Staelin has developed a preliminary space-time adaptive model for neurons—replacing the standard perceptron family of models—that is consistent with a wide range of observed neurological phenomena. He has also been studying the spectral efficiency of interference-limited ad hoc wireless nodes based on optimum multiple-input, multiple-output receiver strategies and 802.11, 2.4 GHz propagation experiments around MIT and Cambridge. Together with Dr. Philip Rosenkranz, Professor Staelin also works on the development of instruments and algorithms for retrieving atmospheric and surface parameters from data collected by airborne or satellite sensors. Recent achievements include a new algorithm for estimating global precipitation using the Advanced Microwave Spectrometer Units on operational weather satellites, and a demonstration that temperature measurements over Antarctica are best accounted for by surface scattering characteristics that are intermediate between specular and Lambertian.

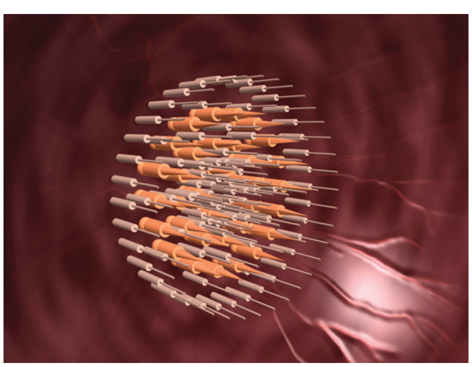
Professors Anantha Chandrakasan and Donald Troxel have developed a computer-aided design (CAD) tool for tile-based 3-D field-programmable gate arrays (FPGAs). It was created from the widely used Versatile Place and Route (VPR) CAD tool for 2-D FPGAs, and allows the efficient Pathfinder-based VPR router to be used, without any modification, for 3-D architectures.

Multiscale Bioengineering and Biophysics

Professor Joel Voldman's research interest is the development of microsystems for manipulating and measuring information from cells. For this work, he draws upon the technologies of microfluidics and electrical trapping. During the past year he has concentrated on two areas: image-based sorting of cells, and cell manipulation to control and study cell-to-cell signaling of embryonic stem cells. He has recently developed an optical approach for cell sorting, using a laser "firehouse" to eject desired cells from a large array of microcells. Another achievement is a new device for cell pairing using microfluidics that efficiently pairs hundreds to thousands of cells in parallel, thus enabling cell fusion studies of somatic cell reprogramming.

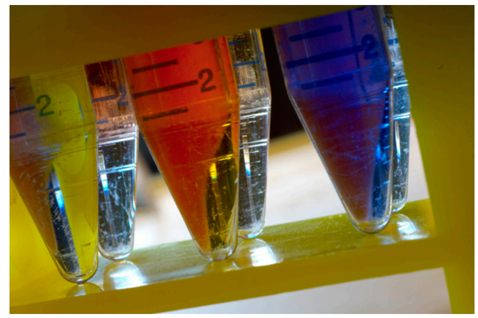
The work in Professor Jongyoon Han's Micro/Nanofluidic BioMEMS group is focused on the development of novel microfluidic and nanofluidic devices and systems for proteomic sample preparation. In collaboration with Professor Steven Tannenbaum of Biological Engineering, he has introduced a novel concept for biomolecule separation that relies on an anisotropic sieving structure, which enables high-throughput size separation of proteins and other smaller biomolecules. This work is part of Professor Han's overall effort to build truly integrated, automatic sample preparation microdevices that will remove a key bottleneck in biological research and have significant impact on early diagnosis of common diseases.

Professor Rahul Sarpeshkar is pursuing a collection of projects in biologically inspired, ultralow-power electronics that will have both medical and general-purpose applications. Motivated by pioneering work on monkeys and humans showing that brain-machine interfaces might offer a cure for patients with paralysis, he has been developing ultralow-power and miniature circuitry for such interfaces that could enable them to work on an implanted 100-mAh battery for 10 years or more with minimal heat dissipation in the brain. As part of this ongoing effort, he has already built the world's most energy-efficient and low-power neural amplifier, a very efficient wireless recharging link, and successfully stimulated the brain of a zebra finch bird. Professor Sarpeshkar's brain-interface research includes collaborations with neurobiologists and engineers from the groups of professors Richard Anderson (California Institute of Technology), Michale Fee (BCS), and John Wyatt.



Professor John Wyatt's long-term goal is the development of a chronically implantable wireless retinal implant to restore some level of useful vision to patients with outer retinal diseases, such as retinitis pigmentosa or macular degeneration. During the past year, his group has developed a tiny hermetically sealed case in an effort to meet the 10-year lifetime requirement of the FDA, and performed dozens of surgical implantation experiments in Yucatan minipigs to test the geometry for surgical compatibility with the eye. Ultimately, these experiments were successful, hence Professor Wyatt expects to chronically implant a working, hermetically sealed, wireless-driven device in a Yucatan minipig in the near future.

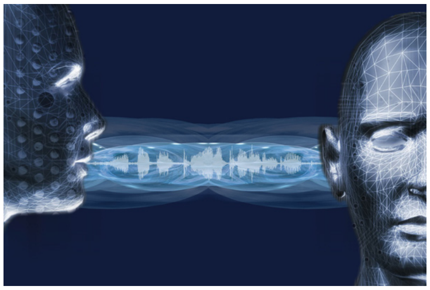
Professor Elfar Adalsteinsson's Magnetic Resonance Imaging (MRI) group is addressing methods for *in vivo* acquisition, reconstruction, and processing of medical imagery via magnetic resonance. Their principal project for the past year has been the development of new methods for mitigating the severe signal inhomogeneity in ultrahigh-field MRI—namely, the emerging 7 Tesla platform for human studies. Their eight-channel parallel radio frequency prototype excitation system has been successfully tested by Professor Adalsteinsson's collaborators at Siemens Medical Solutions in Erlangen, Germany. Other work in which his group has been engaged includes techniques for fast and efficient spectroscopic imaging at 7 Tesla, and the study of magnetic nanoparticles as possible interactive contrast agents for MRI.



The goal of Professor Collin Stultz is to bring physical and theoretical approaches to the forefront of biomedical investigation. By bridging experiment and computation, he develops detailed models that can provide new insights into disease processes. During the past year Professor Stultz's group has elucidated the folding pathway of collagen-like peptides, found novel collagen-like peptides that can be used an immune modulators, performed simulations that help decipher the role that distinct peptides play in the pathogenesis of Alzheimer's disease, and, in collaboration with Professor John Guttag (Department of Electrical Engineering and Computer Science), helped develop novel automated techniques for analyzing large amounts of cardiovascular data.

Professor James Fujimoto divides his research efforts between two areas: biomedical optical imaging and diagnostics, and ultrashort-pulse laser technology. He continues to pioneer optical coherence tomography (OCT), a field created by his group in 1990. OCT is an emerging medical imaging technology analogous to ultrasound. In his medical imaging research, Professor Fujimoto and his collaborators have shown that ultrahigh-resolution OCT detects the subtle intraretinal changes that occur in macular hole formation, and is a superior method for monitoring the effect of surgical intervention. In his ultrashort-pulse laser research, Professor Fujimoto has developed Fourier-domain mode locking, which has enabled OCT axial scans to be performed at a record rate of 370,000 per second.

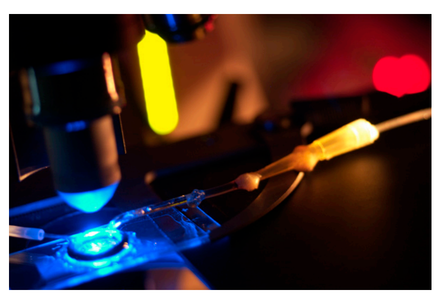
Professor Kenneth Stevens and Dr. Joseph Perkell lead a research group that is developing models to explain how listeners extract discrete sounds and words from continuous speech and how speakers control the speech production system, despite the large variability in the acoustic representation of these units for different speech sounds, talkers, dialects, and manners of speaking. During the past year, the basic physical processes leading to quantal specifications of a number of features of speech sounds have been developed, and they have quantified the basic acoustic and perceptual processes that give rise to these features. The model can form the basis for an approach to automatic recognition of running speech and to text-to-speech synthesis by specifying lexical items in terms of the universal set of quantal-based features, together with rules for articulatory overlap of sounds in running speech.



Professor Louis Braida's research has as its long-term goal the development of improved hearing aids and cochlear implants. Specific goals for his work include evaluating the effects of the style of speech articulation on speech reception by the hearing impaired, developing accurate analytic models to predict the effects of speech-signal alterations on intelligibility, and developing signal processing techniques that will increase the effectiveness of hearing aids. A major focus of his recent work has been developing speech-transmission index (STI) metrics for predicting speech recognition performance by cochlear implant users. In particular, STI and a novel normalized correlation metric were compared with speech reception scores measured for implant users and for subjects with normal hearing listening to a simulation of sound processing for cochlear implants. Under a wide variety of acoustic degradations, both metrics performed fairly well, accurately predicting speech reception trends due to noise level and reverberation.

Dr. Bertrand Delgutte is a member of the Eaton-Peabody Laboratory of Auditory Physiology and Dr. Donald Eddington heads the Cochlear Implant Research Laboratory at the Massachusetts Eye and Ear Infirmary. Their collaborative research has a major focus on physiological studies aimed at improving bilateral cochlear implants. In recent bilateral cochlear implant studies, they have found close parallels between the results of neurophysiological, psychophysical, and computational studies in that the responses of both real and model brainstem binaural neurons depend similarly on the parameters of stimulation as the performance of bilaterally implanted human subjects. This result is encouraging for the prospect of restoring the benefits of binaural hearing to the profoundly deaf because it shows that the binaural system operates normally with cochlear implants, despite the significant neuronal loss and the periods of sound deprivation in most implanted patients.

Dr. Mandayam Srinivasan directs the Laboratory for Human and Machine Haptics, known less formally as the Touch Lab. Its work is guided by a broad vision of haptics, including all aspects of information acquisition and object manipulation through touch by humans, machines, or a combination of the two. Recent research highlights from the Touch Lab include *in vivo* studies of the mechanical behavior of intra-abdominal organs whose data can be used to develop tissue models for laparoscopic surgery simulators, and a computationally efficient approach for doing haptics on 3-D deformable models.



Professor Dennis Freeman has made further advances in his investigations of the way the inner ear functions. This year's work has concentrated on otoacoustic emissions—namely, inner-ear-generated sounds that hold promise for providing noninvasive means of studying cochlear physiology. His systematic measurements in humans, chickens, geckos, and frogs all exhibited strong otoacoustic emissions, despite large differences in the inner ear anatomies of these species. Thus, anatomical specializations—like motile outer hair cells in mammals, tall and short hair cells in chickens, and basilar membrane traveling waves in mammals—are not required for these cochlear sound emissions. Ultimately, this work could have application to the clinical diagnosis of hearing disorders.

Nanoscale Science and Engineering

Professor Henry Smith codirects the NanoStructures Laboratory with Professor Karl Berggren. Its dual mission is the development of advanced nanofabrication technology and the application of that technology to research in optical, electronic, and magnetic devices. A highlight from this year's effort in Professor Smith's group is their fabrication of the most advanced ring resonator filters, polarization splitters, and rotators. These silicon photonics components have been used to make hitless and tunable switches and filter banks for high-speed analog-to-digital converters.

Research in Professor Karl Berggren's Quantum Nanostructures and Nanofabrication group has continued on nanometer-length-scale single-photon detectors and new techniques for nanolithography. In particular they have improved their already world-record-holding superconducting nanowire single-photon detectors, and devoted significant effort to understanding the device operation as a foundation for obtaining further performance improvements. This single-photon detector is likely to find applications in interplanetary high-data-rate optical communication systems, high-data-rate quantum key distribution systems, circuit analysis and diagnostic systems, and imaging of biological processes in living tissue. Their nanofabrication work has led to invention of a new electron-beam lithography process that is capable of sub-10-nm resolution. Surprisingly, the discovery came through the addition of a remarkably simple substance to the resist-development solution: salt.

Professor Jing Kong is interested in the fabrication and applications of carbon nanotubes. A key objective of her program is to understand how the synthesis conditions in growing a nanotube affect its chirality and conduction behavior (metallic versus semiconductor). Toward that end, she has used Raman spectroscopy of single-walled nanotubes (SWNTs) to provide convincing evidence of the Kohn anomaly in metallic SWNTs, which is very important to understanding electron-phonon coupling in these nanotubes. She has also developed a technique that can reversibly transform a superhydrophilic MnO_2 nanowire paper into a superhydrophobic paper. The latter form can selectively adsorb oil from water at high speed, and can also be used to separate similar chemicals, such as benzene and toluene, based on their different surface tensions.

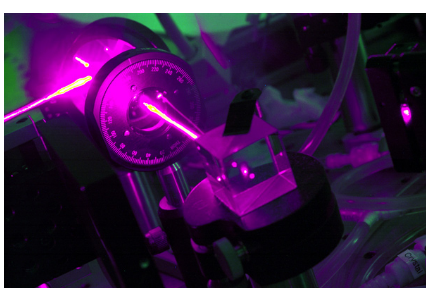
Photonic Materials, Devices, and Systems

Professor Leslie Kolodziejski and Dr. Gale Petrich lead the Integrated Photonic Materials and Devices group, whose focus is the design, fabrication, and characterization of photonic and optoelectronic integrated circuits. As part of the Integrated Photonic

Initiative—which links photonics researchers from RLE with colleagues at MIT Lincoln Laboratory—they have been fabricating an InP-based photonic integrated circuit that is designed to demonstrate an optical logic function. The circuit is now 90 percent complete, and will soon be ready for optical and electronic testing. In other work, they have continued to fabricate and optimize saturable Bragg reflectors for use in the ultrafast fiber lasers being developed by professors Erich Ippen and Franz Kärtner.

Professor Erich Ippen has continued his work on the generation and application of ultrashort optical pulses, while expanding his efforts in the areas of micro- and nanophotonics. Key research accomplishments from the past year include achieving the octave-spanning continuum generation from a high repetition-rate fiber laser/amplifier system that is needed for an optical clockwork, demonstrating supercollimation in a pillar-based 2-D photonic crystal (done in collaboration with professors Leslie Kolodziejski and Marin Soljacic), and demonstration of wavelength tuning, hitless switching, and novel four-ring filters (done in collaboration with professors Henry Smith and Franz Kärtner). Professor Ippen is also the principal investigator for a major multiuniversity program on optical arbitrary waveform generation, whose goal is to provide dramatically new capabilities for optical signal processing, communications, lidar, and sensing.

Professor Yoel Fink is pursuing the theory, design, process development, and characterization of novel structured composite fibers with engineered electronic, photonic, and phononic properties that follow from their mesoscale features. His group has shown that fibers—composed of conductors, semiconductors, and insulators—can share the basic device attributes of traditional wafer-based electronic and optoelectronic devices while being compatible with conventional preform-based fiber-processing methods. As such, these fibers can yield kilometers of functional devices that can be employed to realize sophisticated functions either by integrating a multiplicity of functional components into one fiber, or by employing multiple fibers comprising different functional components, into large-scale 2-D or 3-D geometric constructs. Ultimately, these two approaches could pave the way to multifunctional fabric systems.

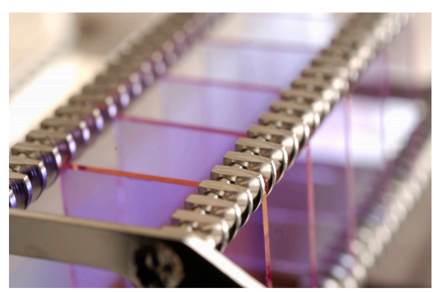


Professor Franz Kärtner is working on ultrashort-pulse generation in the few-cycle regime with applications in frequency metrology, as well as high-density integrated optics made of high-index contrast silicon waveguides and the large-scale timing distribution and synchronization of multiple laser sources and radio-frequency signals. During the past year he has demonstrated the first large-scale (100 m–10 km) sub-10-fs optical timing distribution system and its implementation in the German VUV-free electron laser flash. Together with professors Henry Smith and Erich Ippen, he has designed and demonstrated the first polarization-independent, integrated, high-index contrast optical add-drop multiplexer with telecommunication-grade specifications. Different versions of this device technology are providing the basis for new optical telecommunication products from Pirelli.

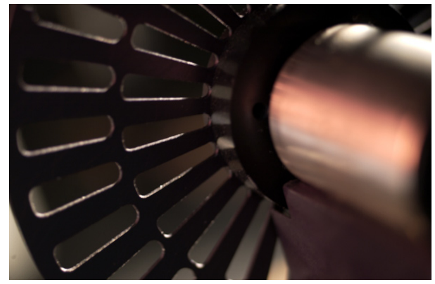
Professor Steven Johnson's research is two-pronged: he works on problems of wave propagation in nanostructured materials, primarily photonic crystals, and he has developed and continues to improve one of the most widely used software libraries for fast Fourier transforms ("the fastest Fourier transform in the West"). Two exciting accomplishments from the past year are his full quantum-mechanical analysis—done in collaboration with Professor Marin Soljacic—of a nonlinear photonic-crystal optical cavity containing a four-level atom that exhibits electromagnetically induced transparency (EIT), and his new fast Fourier transform (FFT) algorithm that uses the fewest algebraic operations and has the lowest coefficient to its $N \log N$ asymptotic complexity. The EIT/photonic crystal work indicates that it is possible, in principle, to form an optical switch in which a single photon can control the transmission of another photon. The FFT work disproves a long-held conjecture as to the minimal number of required algebraic operations.

Professor Marin Soljacic is interested in the theory of electromagnetic phenomena, especially in regards to nanophotonics, nonlinear optics, and wireless power transfer. His recent investigation of using electromagnetic resonance for nonradiative wireless power transfer, done in collaboration with Professor John Joannopoulos, may lead to a technology for charging autonomous electronic devices, such as cell phones and laptop computers. His recent work on the use of surface states that are unique to photonic crystals for optical on-chip trapping of Bose-Einstein condensates may lead to new experimental techniques for atomic physics.

Professor Marc Baldo is interested in electronic and optical processes in molecules, especially as applied to organic solar cells and light-emitting devices. He has recently demonstrated a way to triple the efficiency of fluorescent molecules in organic light-emitting diodes by controlling the spin of the excited atoms. He has also doubled the previous best performance of luminescent solar concentrators, making him optimistic that he can rejuvenate this inexpensive solar collector technology—essentially dead since the 1970s—which promises to be at least 10 times cheaper than conventional solar cells.



Professor Vladimir Bulovic's laboratory is addressing a wide variety of topics related to hybrid organic/inorganic optical and electronic devices. A particularly exciting recent accomplishment, done in collaboration with Professor Martin Schmidt of the Microsystem Technology Laboratories, is his design, fabrication, and testing of electrostatically actuated microshutters used as active shadow masks to pattern evaporated materials. This printing technique, which yielded a maximum resolution of 800 dpi, was employed to print active organic light-emitting device arrays of 400 dpi resolution. Ultimately, this printing technique could enable the patterning of large-area organic optoelectronic devices on diverse substrates.



Professor Qing Hu's research is focused on the development of terahertz (THz) lasers and real-time THz (T-ray) imaging. His THz quantum cascade lasers have achieved world-record performance in many respects: the highest operating temperature in the pulsed mode (170 K), the highest operating temperature in continuous-wave mode (117 K), the highest power levels (250 mW), and the longest wavelength (190 μm). He has also performed T-ray imaging at a video rate of approximately 20 frames/second using one of his sources. More generally, these THz sources will be of great importance in opening up this spectral region for sensing, imaging, and high-bandwidth communications.

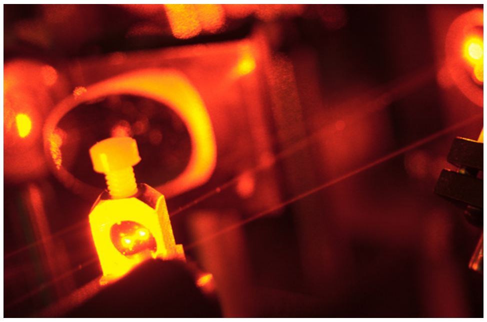
Professor Rajeev Ram's Physical Optics and Electronics group has three primary themes: integrated photonics, biophotonics and bioprocesses, and thermodynamics of semiconductor devices. Highlights from the past year include demonstrating a heterojunction thermophotovoltaic device whose open-circuit voltage exceeds that of any previous device having a comparable band gap, and demonstrating a charge-coupled device thermoreflectance lock-in technique that achieved a record 18 mK temperature resolution. Professor Ram is also the director of the Center for Integrated Photonic Systems and in charge of the Integrated Photonics Initiative.

Professor Peter Hagelstein works on a variety of applied problems relating to an unconventional approach to energy generation, as well as the general problem of thermal-to-electrical energy conversion. During the past year he has worked with a Canadian company to test their prototype cold fusion reactor, which is based on the Yang–Koldomasov effect. Measurements made at MIT failed to exhibit the excess heat observed in earlier experiments in Canada. His theoretical efforts have focused on excess-heat models for Fleischmann-Pons type experiments, including development of models that demonstrate excitation of a large quantum from one set of two-level systems to another with coupling to a low-energy oscillator, and direct coherent energy exchange between the oscillator and two-level system when the energies are incommensurate.

Physical Sciences

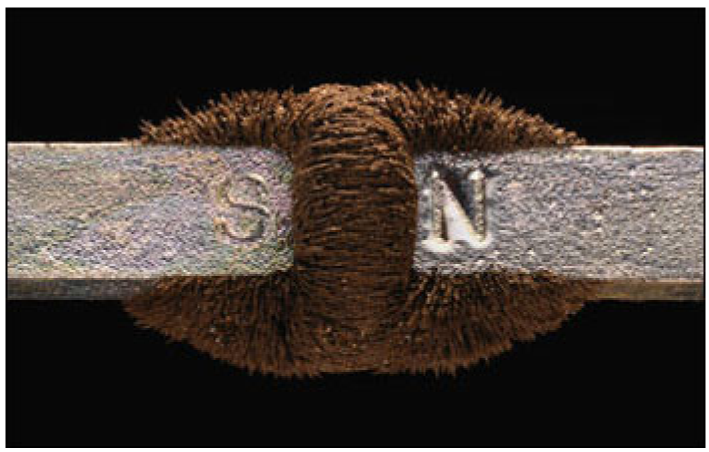
Professor Vladan Vuletic is interested in new methods for manipulating atoms and light in a regime wherein quantum mechanical aspects dominate their behavior and properties. His group has realized a quantum memory for single photons, in which a single quantum spin wave is stored in a laser-cooled atomic ensemble and later converted with very high efficiency (90 percent) into a photon. This system can also be used as a nonclassical, high-brightness source of indistinguishable photon pairs. A quantum memory is an essential element for building a quantum repeater that, in turn, would enable long-distance communications with its security ensured by the fundamental laws of quantum physics.

Professor Wolfgang Ketterle's research concentrates on the properties of Bose-Einstein condensates and degenerate Fermi gases, the use of ultracold atoms for precision measurements, and the study of many-body physics through experiments with quantum degenerate gases. Highlights from the past year's work include the first stability study of superfluid currents in a moving optical lattice near the Mott insulator transition, radio-frequency spectroscopy of pairing in the normal and superfluid phases of a strongly interacting Fermi gas with imbalanced spin populations, and a new phase-sensitive recombination-rate technique for atom interferometer readout. Professor Ketterle directs the MIT-Harvard Center for Ultracold Atoms.



Professors Daniel Kleppner and Thomas Greytak are engaged in research on ultracold hydrogen, using an entirely new approach to cooling and trapping hydrogen that is based on buffer-gas loading. This approach represents a radical departure from all previous cold-hydrogen experiments, and thus has required the design and creation of major new apparatus. In addition to their work on a new valved cell for trapping and evaporative cooling, they have been doing supporting studies of atomic collisions at very low temperatures, including both the elastic collisions that facilitate the cooling process and the inelastic collisions that are detrimental to that process.

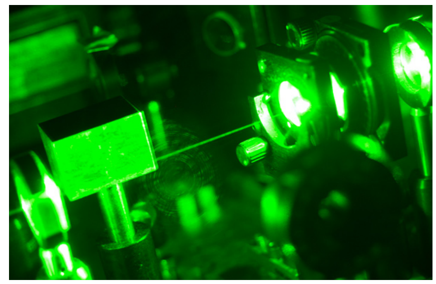
Professor Jin Kong's research on electromagnetics addresses a variety of problem areas, including left-handed metamaterials, unexploded ordnance detection, and modeling the trapping and binding forces between particles. A key research highlight from the past year is his experimental demonstration that a 1-D metamaterial structure can be realized by printing subwavelength paired S-shaped metallic strips on one side of a dielectric substrate. This arrangement is much easier to fabricate than conventional double-sided structures. As a result, it should be possible to make controllable metamaterials by incorporating lumped active elements into the structure. Left-handed metamaterials are of great importance because they have direct applications to antenna design, cloaking, and radome design for communications, air defense, and surveillance.



Professor Abraham Bers is engaged in theoretical research on plasma electrodynamics and its applications. During the past year, he has completed his research on stimulated electroacoustic scattering in intense laser-plasma interactions that is of interest for inertial confinement fusion. He is in the process of finishing a first-year graduate text, *Plasma Physics and Plasma Electrodynamics*, to be published by Oxford University Press.

Quantum Computation and Communication

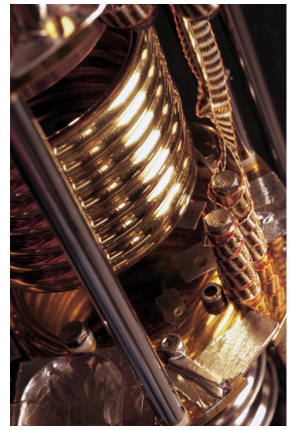
Professor Seth Lloyd investigates methods for constructing quantum computers and quantum communication systems using atomic physics, quantum optics, and superconducting electronics, and he collaborates with experimental groups at MIT and elsewhere in these areas. During the past year he has begun work on quantum illumination—the use of entanglement to improve target detection performance in a lossy, noisy environment. He has also been investigating the ultimate physical limits to the accuracy of sensing and measurement that are set by the laws of quantum physics.



Professor Jeffrey Shapiro and Dr. Franco Wong lead the Optical and Quantum Communications group, which has been working on the generation of entangled photons and their applications in quantum communications and quantum cryptography. During the past year they have used their bidirectionally pumped, continuous-wave, polarization-Sagnac parametric down-conversion source of hyperentangled photon pairs to implement the Fuchs-Peres-Brandt (FPB) probe. The FPB probe is the most powerful individual attack on the Bennett-Brassard 1984 quantum key distribution protocol, and is of interest to put the security of privacy-amplified key distillation to a rigorous experimental test. Other experimental work has produced a pulsed ultraviolet pump laser for another polarization-Sagnac downconverter, whose initial performance is approaching the design specifications for free-space quantum key distribution. The group's theoretical efforts have delineated the boundary between classical and quantum imaging in both optical coherence tomography and ghost imaging, and have continued determination of the fundamental limits on classical information transmission over bosonic (optical communication) channels.

The research in Professor Isaac Chuang's group is aimed at harnessing the resources of quantum physics for novel information technology capabilities. Toward that end, they are working on the theory of fault-tolerant quantum computation, and implementations of basic quantum gates based on trapped ion systems. During the past year they have demonstrated loading of $^{88}Sr^{+}$ ions into a 0.5-mm-scale printed circuit board surface-electrode ion trap. By canceling the stray electric fields along two of the trap's principal axes, they were able to achieve trap lifetimes in excess of 10 minutes. This system allows for rapid prototyping and testing of different surface-electrode geometries, and may serve as a convenient tool for the loading of ions into microstructure trap arrays.

Professor Terry Orlando is using superconducting circuits as components for quantum computing and as model systems for nonlinear dynamics. The goal of present research is to use superconducting quantum circuits to realize a fully functional quantum bit (qubit), to perform measurements on qubits, to model sources of qubit decoherence, and to develop scalable quantum algorithms. The particular device being studied is made from a loop of niobium interrupted by three Josephson junctions, storing a persistent-current qubit. His group fabricated deep-submicron Josephson junctions, necessary to realize a large qubit tunnel-coupling, by means of a trilayer optical lithography process.



Mach-Zehnder interferometry of the persistent-current qubit in these Josephson junctions showed remarkable agreement with theory, including recent measurements that were made at frequencies below the linewidth. In other work, the group has demonstrated microwave-induced cooling in a superconducting flux qubit, which is an analog to the optical cooling that is employed with trapped ions and atoms and is generalizable to other solid-state systems.

W. M. Keck Foundation Center for Extreme Quantum Information Theory

The W. M. Keck Foundation Center for Extreme Quantum Information Theory was created in January 2007. The center, known by its acronym xQIT, is led by Professor Seth Lloyd (director) and Professor Jeffrey Shapiro (codirector). Although xQIT relies on RLE for administrative support, its faculty researchers are drawn from throughout the Institute's transdepartmental activity in quantum information science. The xQIT faculty are conducting research into the fundamental physics of information processing. Their work is oriented toward solving three well-known hard theoretical problems in quantum information science:

- What problems can computers solve if they operate using the entire repertory of physical phenomena, including strange quantum-mechanical effects such as entanglement?
- What are the ultimate limits on the capacities of communication channels when their performance is limited by noises of quantum-mechanical origin?
- How accurately can we measure and control the universe around us when confronted with limit set by quantum physics?

RLE 60th Anniversary Celebration

The Research Laboratory of Electronics marked the 60th anniversary of its founding—and looked ahead to its future—with a series of celebratory events occurring throughout the 2006–2007 academic year. Professor Leslie A. Kolodziejski chaired the RLE 60+ Committee that organized the *Beyond the Limits* Colloquium Series, the RLE 60+ Technical Gala, and the RLE 60+ Family and Friends Carnival. *Beyond the Limits* brought research leaders from RLE's six research themes to share the excitement of their work and to provide glimpses into the future. In September, Dr. Henrique Malvar (Microsoft) spoke on "Recent Advances in Digital Processing of Images and Audio." In October, Dr. David DiVincenzo (IBM) presented "Quantum Computing Origins and Directions." Professor Brian Moore (University of Cambridge) described "Using Psychoacoustics to Explore Cochlear Function: Basic Mechanisms and Applications to Hearing Aids" in November, and in December, Professor William Phillips (National Institute of Standards and Technology and the University of Maryland) spoke on "A Bose Condensate in an Optical Lattice: Cold Atomic Gases Confront Sold-State Physics." In February, Professor Steven Quake (Stanford University) discussed "Biological Large Scale Integration." Professor Sir John Pendry (Imperial College) presented "The Perfect Lens: Resolution Beyond the Limits of Wavelength" in March. April saw Professor Stephen Forrest

(University of Michigan) speak on "Electronics on Plastic: A Solution to the Energy Challenge, or a Pipe Dream?" Videos from the *Beyond the Limits* Colloquia can be viewed on MIT World at http://mitworld.mit.edu/. The RLE 60+ Technical Gala on June 1 showcased ongoing research with an array of more than 100 posters and demonstrations representing the broad spectrum of activities under way within the laboratory. The RLE 60+ Friends and Family Carnival, which was held on June 3 at the Glen Ellen Country Club in Millis, MA, was a fun-filled afternoon of food, games, and good times for all members of RLE—faculty, staff, and students—and their families.

Appointments, Awards, and Events

The following appointments and awards were made in AY2007.

Professor Rajeev J. Ram was promoted to professor of electrical engineering.

Professors Vladimir Bulovic and Vladan Vuletic received tenure.

Professor Karl K. Berggren was promoted to associate professor and appointed Emanuel E. Landsman associate professor of electrical engineering.

Professor Luca Daniel was promoted to associate professor of electrical engineering.

Professor Vivek Goyal was appointed Esther and Harold E. Edgerton assistant professor of electrical engineering.

Professor Collin M. Stultz was appointed W. M. Keck assistant professor of biomedical engineering.

Professor Yoel Fink was named a Margaret MacVicar Faculty Fellow.

Professor Collin M. Stultz received the Jonathan Allen Junior Faculty Award.

Professor Daniel Kleppner received the National Medal of Science and the 2007 Frederic Ives Medal of the Jarus W. Quinn Endowment from the Optical Society of America.

Professor Jin A. Kong received an honorary doctorate from the Université Paris X-Nanterre.

Professor Qing Hu was elected a fellow of the American Physical Society.

Professor Marin Soljacic was named a TR35 Young Innovator by *Technology Review*.

Professor Alan V. Oppenheim received the 2007 Jack S. Kilby Signal Processing Medal from the IEEE.

Professor Eli Yablonovitch presented the Hermann Anton Haus Lecture.

Professor Rajeev J. Ram received the 2006 Global Indus Technovators Award.

Professor Anantha P. Chandrakasan received the 2007 Eta Kappa Nu Award for Excellence in Teaching.

Professor Dennis M. Freeman received the 2007 IEEE/ACM Award for Excellence in Undergraduate Advising.

Professor Leslie A. Kolodziejski received the 2007 EECS Graduate Student Association Award for Best Counseling.

Jianping Fu and Darren Whiten received 2007 Helen Carr Peake Research Prizes.

Sasha Devore won the Helen Carr Peake Research Assistantship for AY2008.

Joseph F. Connolly received a 2007 MIT Excellence Award.

Cheryl Charles and Lorraine J. Simmons received 2007 MIT Infinite Mile Awards.

Affirmative Action

RLE has worked and will continue working to increase the number of women and minorities in career positions in the laboratory, in the context of the limited pool of qualified technical applicants and the unique qualifications of RLE's sponsored research staff. Specific measures will include maintaining our high standards for recruitment procedures, which include sending job postings to minority colleges and organizations, working closely with the RLE faculty/staff supervisor at the beginning of each search to identify ways of recruiting minority and women candidates for the new position, and being committed to finding new techniques to identify women and minority candidates more effectively. During the past year RLE has hired an underrepresented minority woman as assistant fiscal officer.

Jeffrey H. Shapiro
Director
Julius A. Stratton Professor of Electrical Engineering

More information about the Research Laboratory of Electronics can be found at http://www.rle.mit.edu/.