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 275 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.

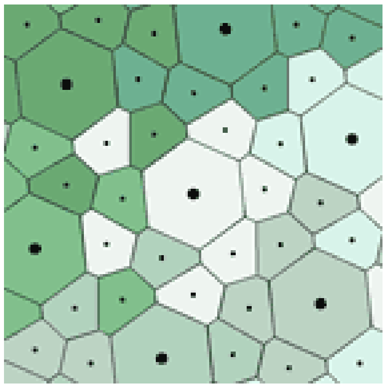
Detailed information about RLE research in AY2008 can be found in RLE Progress Report No. 150. The report is available online at http://www.rle.mit.edu/media/media_pr.html. Following is a summary of research highlights from the past year.

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 numerical techniques associated with problems in bio- and nanotechnology. Applications include microfluidic devices for capturing biological cells, nanophotonic signal processing, biomolecular electrostatic analysis and binding optimization, and Casimir force computation. Their algorithm for three-dimensional simulation of cells in flow is fast enough to simulate cell capture in less than 30 minutes on a workstation, which is orders of magnitude faster than commercial 3-D fluid dynamics software. Professors Karen Willcox (Department of Aeronautics and Astronautics) and Joel Voldman have used this program to optimize cell-trap design. Professor White's 3-D simulation program is tuned to problems of structures mounted on flat substrates, and is thus applicable to a variety of other applications involving beads in flow.

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 developed stochastic high-order basis functions suitable for volumetric discretization of interconnect structures. These basis functions are wideband, and can be easily integrated within a stochastic magnetoquasistatic or full-wave mixed-potential integral equation solver, thus rendering the stochastic formulation computationally efficient. In other work, he has obtained results that characterize the system-level repercussions of vector-field approximation in nonlinear model-order reduction.

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. A particular focus is the development of new transforms for video compression.

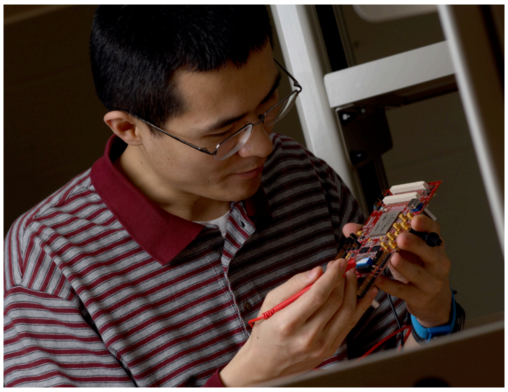


The research of Professor Vivek Goyal and his students has two main foci: acquiring, estimating, and approximating signals, with an emphasis on exploiting transform-domain sparsity, and extending the theory of compression beyond its classical Shannon formulation. During the past year, his group has continued its development of signal compression based on a union-of-subspaces concept, and successfully mapped this abstract formulation to radio-frequency excitation in magnetic resonance imaging (MRI) and to permeability estimation in oil-field exploration. They have also obtained necessary and sufficient conditions for recovery of the K-dimensional subspace containing an N-dimensional signal x from M-dimensional noisy observations of the form $y = Ax + n$, where the matrix A has known random entries. The resulting scaling law, whose sufficient condition derives from a very simple algorithm, obviates many recent results on more complicated algorithms for this problem.

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 quasi-orthogonal high-bandwidth radar waveforms from a deterministic chaotic system.

The research of Professor Vincent Chan and his students addresses a broad range of topics in the general area of networks and communications, with an emphasis on satellite, wireless, and optical systems. Their overarching objective is to develop the scientific base needed to design data communication networks that are efficient, cost optimized, robust, and architecturally clean. Recent research includes the conception of a new fiber-network transport mechanism, called flow switching, for unscheduled large data transactions. The cost-performance tradeoff of flow switching is superior to currently used network transport, which has led to its being adopted by the US government as its architecture for large transactions in C4ISR (command, control, communication, computing, intelligence, surveillance, and reconnaissance).

Professor Gregory Wornell is interested in algorithmic and architectural aspects of design of multimedia networks, wireless communication and sensor networks, and reliable circuits and microsystems. During the past year, he characterized the fundamental limits and associated code structure for physical layer security in wireless communication systems that use multiple-element antennas. In other work, he addressed the fundamental limits of asynchronous communication, an appropriate model for sensor networks in which communication is intermittent, and showed that these limits are achieved by an architecture rather different from what is used in existing systems.



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 copper interconnects and emerging devices like carbon nanotubes and silicon photonics. Professor Stojanovic leads a multidisciplinary silicon photonics team composed of Professors Rajeev Ram, Franz Kärtner, Judy Hoyt, Erich Ippen, and Henry Smith. They have designed the first-ever test chip integrating silicon photonic devices into 65-nm bulk CMOS technology, and the first experimental tests of the resulting chip indicate that its polysilicon platform and standard sub-100-nm lithography provided good optical performance. This work constitutes a true breakthrough in successfully placing the photonics into the same fabrication process in which large digital chips, like microprocessors, are made.

Professor Muriel Médard leads a highly collaborative research group, with research links to the Computer and Artificial Intelligence Laboratory and the Laboratory for Information and Decision Systems at MIT, as well as the California Institute of Technology, the University of California at Los Angeles, the University of Illinois Urbana-Champaign, and the Technical University of Munich—whose central theme is network coding. A key result from this year's research is the development of distributed polynomial-time rate-optimal network codes that work in the presence of Byzantine nodes, e.g., adversaries that may eavesdrop on all nodes and jam a fixed-size subset of the links. These codes are information theoretically secure. They operate in a distributed manner, with no assumed knowledge of the network's topology. Furthermore, only the source and destination nodes need to be modified, and the algorithms may be used over both wired and wireless networks

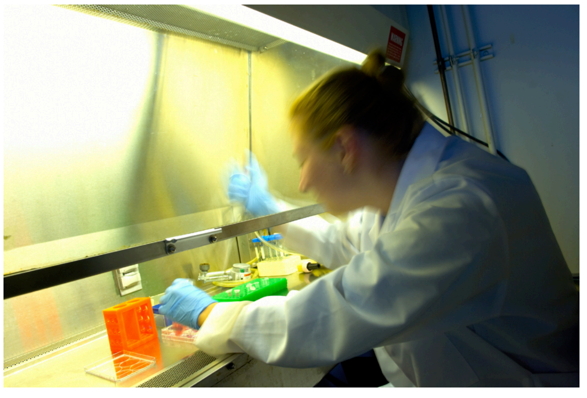
Professor David Staelin is interested in improved methods for remote sensing of global precipitation from current operational meteorological satellites, the analysis of ad hoc

wireless communication networks, and studies of spike-timing models for neural computation. Research accomplishments from the past year include an improved method for estimating global surface precipitation from near real-time satellite data, thus providing an exceptional new tool for monitoring global climate change; new models for predicting urban spectral fading and multipath characteristics as a function of time, frequency, and location using web-based aerial photographs, which suggest strategies for efficient placement of urban wireless communication nodes; and an extended spike-timing model for neural computation that shows how a single neuron might learn to recognize multiple complex spike-timing patterns.

Multiscale Bioengineering and Biophysics

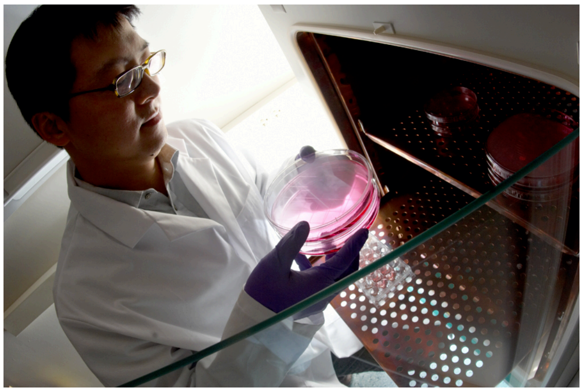
Professor Elfar Adalsteinsson's MRI group is addressing methods for *in vivo* acquisition, reconstruction, and processing of medical imagery via magnetic resonance. An ongoing effort in the group has been the development of parallel excitation methods to overcome the very serious signal inhomogeneity problems in very-high-field human MRI scanners, such as the 7T platform at the Health Sciences and Technology Martinos Center at Massachusetts General Hospital. During the past year, Professor Adalsteinsson and his collaborators from Siemens installed an eight-channel parallel excitation system and validated, in first-ever human studies of this technology, that his algorithms successfully mitigate the excitation inhomogeneity in the human brain. Siemens has already shipped parallel excitation systems, based on Professor Adalsteinsson's prototype, to several other research sites. It seems clear that this mode of signal excitation will be an integral component of 7T human imaging.

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 insights into disease processes. During the past year, Professor Stultz's group has discovered that collagen is locally unfolded—and hence relatively unstable—at room temperature. This counterintuitive result sheds considerable light on how collagen normally functions in the body. They have also explored the structure of the tau protein, which is believed to play an important role in the pathogenesis of Alzheimer's disease (AD), and found novel structural features that explain why a particular tau mutant is predisposed to form disease-promoting aggregating states in the brains of patients with AD.



Professor Joel Voldman's research interest is the development of microsystems for manipulating cells for fundamental and applied biology. His group's four themes are (1) technologies for image-based cell sorting, (2) novel dielectrophoretic cell separators for cell screening, (3) microtechnology for studying fundamental stem-cell biology, and (4) microsystems for controlled flight of insects. This year they demonstrated an optical method for sorting cells that uses a laser to push target cells out of microwells, performing image-based sorting of individual mammalian cells in 10,000-site arrays, thus laying the groundwork for a low-cost widely transferable cell-sorting platform. In other work from the past year, the group demonstrated a new electrical method for sorting cells based on electrical properties that is the first electrical cell-separation method to be continuous flow, analog, and independent of cell size.

The work in Professor Jongyoon Han's Micro/Nanofluidic BioMEMS group is focused on developing sample-preparation microdevices for various biosensing problems, including immunoassays and enzyme assays, as well as novel methods for fabricating preconcentrator systems. In collaboration with Professor Steven Tannenbaum of Biological Engineering, he has introduced a novel concept for increasing reaction rate by using his protein preconcentrator devices to concentrate both reactants. Given the widespread use of enzyme assays as diagnostic tools, this scheme can be used in many disease diagnosis applications in which current methods cannot reliably detect low-abundance enzyme activity. In collaboration with Professor Douglas Lauffenburger of Biological Engineering, Professor Han is using the concentration-enhanced enzyme assay to detect and monitor cell kinase activities, with the hope that this technique might reach the single-cell sensitivity level and thus fundamentally improve understanding of cell regulatory pathways.



Professor Mehmet Fatih Yanik works on the development of high-throughput *in vitro* and *in vivo* screening technologies. An exciting development from last year's research is the demonstration of the first high-throughput on-chip small-animal (*Caenorhabditis elegans*) screening technologies using microfluidics and femtosecond laser techniques. These technologies enable high-speed, subcellular resolution studies on awake animals for *in vivo* discovery of genetic/drug factors affecting neural regeneration and degeneration. They have also developed a technique for high-throughput patterning of surfaces with arbitrary protein substrates at submicron resolution, and are now using that technology in a high-throughput study of neurogenesis using primary as well as human embryonic stem-cell-derived neurons.

Professor Rahul Sarpeshkar and his students are working on circuits for low-power neural prosthetics, both for the deaf and for brain-machine interfaces. These circuits have applications for curing deafness with cochlear implants, for recording neural prosthetics (paralysis and dumbness), and for stimulatory neural prosthetics (blindness and deepbrain disorders like Parkinson's disease). During the past year his group has created a circuit for precise charge-balanced neural stimulation without DC blocking capacitors, which should greatly reduce the size of neural implants. They have also demonstrated a novel power-efficient, impedance-modulation telemetry system that allows recording neural prosthetics to dissipate most of their power outside, rather than inside, the brain, thus enabling Mb/s transcutaneous information transmission with mW power.

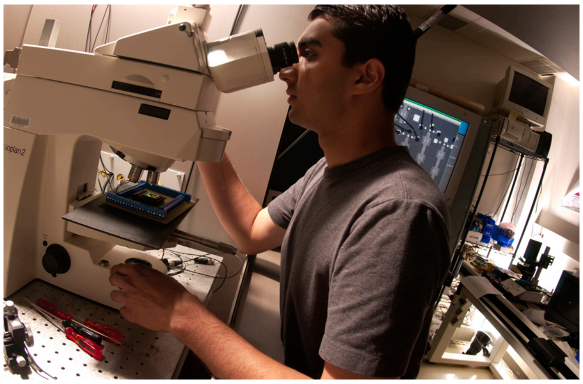
Professor John Wyatt's long-term goal is the development of a chronically implantable wireless retinal implant to restore some level of useful vision to patients with outer retinal diseases, such as retinitis pigmentosa or macular degeneration. During the past year, his group has succeeded in chronically implanting wireless prototype prostheses in three Yucatan minipigs and wirelessly communicating with these devices after implantation. This achievement represents a major integration of circuit design and testing, microfabrication, and assembly and encapsulation, together with continuous redesign to meet surgical requirements and the development of a new surgical technique.

Professor James Fujimoto divides his research efforts between two areas: biomedical optical imaging and diagnostics and ultrashort-pulse laser technology. In his biomedical imaging work, he continues to pioneer optical coherence tomography (OCT), a field his group created in 1990. OCT is a medical imaging technology analogous to ultrasound. During the past year, Professor Fujimoto demonstrated a new technology for ultra-high-speed OCT imaging of the retina using a frequency-swept laser. This approach enables OCT imaging at speeds 10 times faster than previously possible, allowing the acquisition of three-dimensional data sets that have comprehensive structural information. In other work, he has demonstrated record OCT speed and performance in endoscopic imaging studies, and published a demonstration in animals that serves as a step toward clinical development of this new technology. He is beginning clinical endoscopic studies in collaboration with Dr. Hiroshi Mashimo of the Veterans Administration Medical Center.

Professor Kenneth Stevens leads a research group whose principal aims are to develop a model of human production and perception of speech, to explain the bases for the units underlying this model in terms of the biomechanical and bioacoustical structure of the system, and to account for individual differences in the functioning of the model for normal and disordered speech. Work during the past year has concentrated on quantifying the role of acoustic landmarks or abruptness in the acoustic signal for speech, particularly for consonants, with emphasis on the use of this approach in automatic speech recognition.

Dr. Joseph Perkell has two research projects under way: Constraints and Strategies in Speech Production and Effects of Hearing Status on Adult Speech Production. During the past year, he has worked on improving methods for the use of functional magnetic resonance imaging (fMRI), a technique that provides insight into brain function. In collaborative work with the McGovern Institute for Brain Research and Siemens Medical Systems, he has investigated the reliability of detecting speech production-related activity in individuals. Using a recently introduced 32-channel brain-imaging coil coupled with a 3T MRI scanner, he was able to show consistency of detecting speaking-related activity with high spatial accuracy in individuals. This work constitutes an essential precursor to the development of fMRI clinical applications for speech disorders.

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 continuing focus of his work has been developing speech-transmission index and normalized correlation metric models for predicting speech recognition performance by cochlear implant users.



Professor Dennis Freeman has made further advances in his investigations of the way the inner ear functions. This year's work led to the discovery that the tectorial membrane, a gelatinous structure in the inner ear, supports longitudinally propagating traveling waves. This discovery fundamentally changes the way we think about cochlear function. In particular, it reveals a significant shortcoming of conventional models for cochlear tuning and sensitivity. The new understanding that may develop from this work could have application to the clinical diagnosis and treatment of hearing disorders.

Dr. Bertrand Delgutte is a member of the Eaton-Peabody Laboratory of Auditory Physiology. His research addresses the neural basis for speech reception and sound localization in reverberant environments, and the neural sensitivity to interaural time differences (ITDs) in animal models of deaf humans wearing cochlear implants in both ears. Results from the bilateral implant experiments—which were performed with animals that were deafened just prior to the neurophysiology experiments and with those that were congenitally deaf—suggest that deprivation of auditory experience comprising the neonatal period degrades ITD sensitivity. This finding is significant because ITDs are the most important auditory localization cue, and human subjects wearing bilateral implants are known to have much poorer ITD discrimination than normal-hearing subjects.

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. Highlights from this year's effort in Professor Smith's group are fabricating high-quality ring-resonator filters in silicon (in collaboration with Professor Franz Kärtner), demonstrating photonic circuits integrated with a CMOS process line at Texas Instruments (in collaboration with Professors Vladimir Stojanovic and Franz Kärtner), developing a new chemical sensor based on membrane technology (in collaboration with Professor George Barbastathis of Mechanical Engineering), and demonstrating the basic principle of absorptance modulation for compressing the point-spread function in optical imaging.

Research in Professor Karl Berggren's Quantum Nanostructures and Nanofabrication group has continued on nanometer-length-scale single-photon detectors and new techniques for nanoimprint and electron-beam lithography. Working with collaborators from the MIT Lincoln Laboratory, they have demonstrated, for the first time, the ability to detect and count single photons at timescales on the order of 50 ps. These nanowire detectors are thus able to establish the underlying quantum statistics of the optical signals, giving information about the type of source that was used and how that source's behavior varies on very short timescales. Working with Professors Caroline Ross and Edwin Thomas (both from the Department of Materials Science and Engineering), his group has formed lithographic surrogates for block copolymer microdomains. The result is a two-dimensional lattice of self-assembled polymer sphere structures that can be controlled explicitly through the positioning of nearby lithographic silicon pillars. This work is likely to find application in single-magnetic-domain storage or in lithography for beyond-CMOS electronics manufacturing.

Professor Jing Kong is interested in the fabrication and applications of single-walled carbon nanotubes in graphene synthesis and transfer technology and in nanowire assembly and its applications. During the past year, she has developed a method for obtaining large-area, continuous few-layer graphene films that can be transferred onto almost any type of substrate. In collaboration with Professor Francesco Stellacci from Materials Science and Engineering, she has created a nanowire mat—with the touch and feel of paper—that can absorb up to 20 times its weight in oil and can be recycled many times for future use. This nanowire paper, in addition to its environmental applications, could affect filtering and purification of water.

Photonic Materials, Devices, and Systems

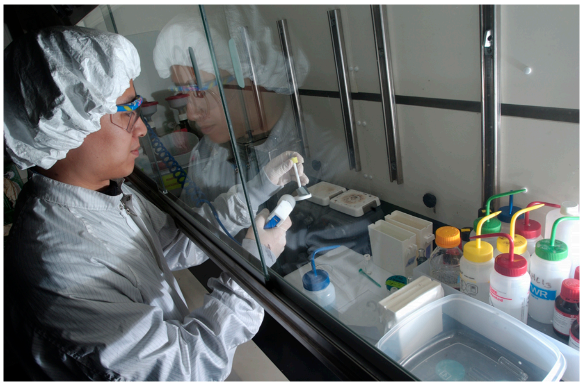
Professor Leslie Kolodziejski and Dr. Gale Petrich lead the Integrated Photonic Materials and Devices group, whose research centers on fabricating optoelectronic devices in III-V compound semiconductors and in silicon. Their active research areas include development of optical logic gates composed of semiconductor optical amplifiers that are monolithically integrated within a Mach-Zehnder interferometer; development of antimonide-based optical sources with emission wavelengths in the 2- to 3-micron region; development of an electrically activated, nanocavity photonic crystal laser; development of high-index-contrast devices using photonic crystals; and development of an ultrabroadband optical modulator centered at 810-nm wavelength for use in plastic optical fiber communication systems. A major accomplishment during the past year was their observation of super-collimation within a photonic crystal composed of a two-dimensional array of silicon rods. Another important advance during this period was the installation of a dedicated III-V, chlorine-based, inductively coupled plasma reactive ion etch tool at MIT, which will positively impact all of the group's research efforts.

Professor Erich Ippen has continued his work on the advancement of femtosecond optical techniques and their application to studies of ultrafast phenomena. He leads an Office of Naval Research Multidisciplinary University Research Initiative program on optical clocks (with six other RLE investigators) and a Defense Advanced Research Projects Agency program on optical arbitrary waveform generation using stabilized femtosecond optical combs. During the past year, his group has achieved further success toward its goal of a fully referenced optical clockwork at 1.5-micron wavelength. With an octave-spanning (1–2 micron) spectrum, generated with a 200-MHz all-fiber laser/amplifier system, they have demonstrated locking of the repetition rate to the optical frequency—a clockwork—via second-harmonic generation and then further referencing the optical frequency to a HeNe standard at 3.39 microns by difference-frequency generation. In other work within his group, Dr. Peter Rakich and Dr. Milos Popovic have invented and analyzed a novel approach to smart photonic devices in which micromechanical potentials can be created and micromechanical motion can be precisely controlled with optical inputs alone.

Professor Franz Kärtner is working on high-repetition-rate femtosecond lasers and optical frequency combs for applications in photonic analog-to-digital conversion, optical clocks, calibration of astrophysical spectrographs (in collaboration with the Harvard-Smithsonian Center for Astrophysics), and optical arbitrary waveform generation. He is also interested in nanophotonics with high-index-contrast silicon waveguides, large-scale timing distribution of multiple laser sources and radio-frequency signals, and attosecond science. During the past year, he has started implementing the first large-scale (100 m to 10 km) sub-10-fs optical-timing distribution system under sponsorship of the European EUROFEL free-electron laser project. Together with Dr. Ronald Walsworth of Harvard, he demonstrated a high-repetition-rate octave-spanning Ti:sapphire laser frequency comb that enables cm/s Doppler spectroscopy to find exoplanets. He has also demonstrated measurement techniques for attosecond timing jitter measurements of low-noise femtosecond lasers.

Professor Steven Johnson's research agenda is to find fresh theoretical approaches to previously intractable problems in nanophotonics, from quantum optics to quasicrystals. In recent work, he developed one of the first computational tools to accurately predict a quantum-mechanical interaction called the Casimir force in complex geometries. Using that tool, his group was able to show, for the first time, that the Casimir force exhibits some surprising nonmonotonic effects when forces from multiple objects are combined. Casimir forces are becoming more and more important in nanomechanical and nanofluidic systems, where such forces play significant roles in problems such as stiction and wetting. Casimir forces are also important in problems of cold-atom trapping and optical tweezers.

Professor Marc Baldo is interested in electronic and optical processes in molecules, especially as applied to organic solar cells and light-emitting devices. The main result of the past year's research is a new type of solar concentrator, which he calls the organic solar concentrator. It is a flat-plate solar collector that achieves concentration factors in excess of 10 without needing to track the sun. This advance should enable lower-cost photovoltaic power, and can also be used indoors to gather diffuse light for powering portable electronic devices.



Professor Vladimir Bulovic's laboratory is addressing a wide variety of topics related to hybrid organic/inorganic optical and electronic devices. Among his group's research achievements from the past year is the demonstration of a second-generation molecular-jet printer for producing organic electroluminescent thin films. This work, done in collaboration with Professor Martin Schmidt of the Microsystems Technology Laboratories, has recently led to the formation of a technology start-up company, named TJet Technologies, that has licensed the technology and intends to develop an industrial-scale printer. Other research from Professor Bulovic's laboratory includes the first white-light-emitting quantum-dot light-emitting device for use as a planar white-light source in full-color active-matrix displays and in future solid-state lighting, and a fundamental finding, relating the energy-level disorder in molecular organic thin films to the electrostatic interactions between polarizable molecular charge distributions, that is broadly applicable to proper understanding of a multitude of physical processes in organic thin-film solids and related devices.

Professor Qing Hu's research is focused on developing terahertz (THz) quantum cascade lasers and electronics; real-time THz (T-ray) imaging using quantum-cascade lasers and focal-plane cameras; and high-power, mid-infrared quantum cascade lasers with high wall-plug efficiency. 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. A highlight from the past year is his group's work aimed at developing an integrated optical isolator, which has remained an unsolved problem in photonics. They have successfully demonstrated Faraday rotation in a semiconductor waveguide that is compatible with conventional processing techniques, and proposed a design for a fully integrated polarization-independent isolator. Professor Ram is also the director of the Center for Integrated Photonic Systems and in charge of the Integrated Photonics Initiative.

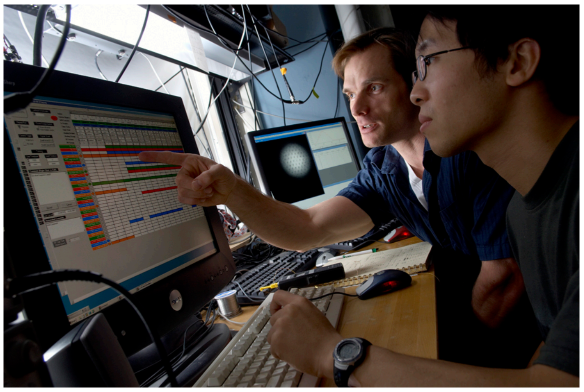
Professor Peter Hagelstein works on a variety of applied problems relating to an unconventional approach to energy generation. During the past year, he has concentrated on documenting the key theoretical advances he has made in this area. These advances include exploitation of a rotation for the spin-boson and Dicke problems that allows for the treatment of multiphoton transitions in first-order perturbation theory, new dynamical models for coherent direct energy exchange between a two-level system with a large transition energy and an oscillator with a small characteristic energy, observation that excitation transfer can be enhanced by many orders of magnitude with the introduction of loss to spoil the destructive interference within the model, a proposal for a new kind of model with conjugate coupling to strongly enhance excitation transfer rates, and a proposal for a new experiment in which the electron mass is shifted as a consequence of quantum noise in the drive current of an inductor.

Professor John Joannopoulos has been working on the theory of strong interactions between light and matter, as facilitated by novel combinations of geometric design and material choices. These interactions include enhanced nonlinear optics, magneto-optical effects, shock waves, acousto-optical interactions, and photocurrent production in solar cells. A highlight from recent research in his group is the theoretical demonstration that photonic-crystal structures can dramatically increase the efficiency of solar energy collection in thin silicon films, thus reducing the cost compared with the conventional thick-layer devices currently in use. In other photonic-crystal research, Professor Joannopoulos has shown that the self-focusing of light in a nonlinear medium can be controlled, eliminated, or converted to self-collimation by using an appropriately designed photonic crystal.

Professor Marin Soljacic is interested in the theory of electromagnetic phenomena, especially with regard to nanophotonics, nonlinear optics, and wireless power transfer. His 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. Other recent work from Professor Soljacic's group has shown how the Purcell effect can be used to tailor optical nonlinearities and how magneto-optic effects can be used to create one-way waveguides in photonic crystals.

Physical Sciences

Professor Wolfgang Ketterle's research concentrates on the properties of Bose-Einstein condensates and degenerate Fermi gases, the use of ultracold atoms to realize new forms of matter with strong interactions and strong correlations, and the behavior of quantum degenerate gases as novel systems for the study of many-body physics including phase transitions, superfluidity, and vortices. Highlights from the past year include major new results for ultracold fermions that determined the phase diagram of the superfluid Fermi gas and settled a two-year controversy. This work determined the size of superfluid fermion pairs, providing microscopic information about the new high-temperature superfluids. The pair size for fermions with resonant interactions was found to be 80% of the interparticle spacing, the smallest pairs found so far for fermionic superfluids. Professor Ketterle directs the MIT-Harvard Center for Ultracold Atoms.



Professor Martin Zwierlein joined the Physics Department faculty and RLE at the start of AY2008. He is interested in the properties of ultracold gases of atoms and molecules, with emphasis on strongly interacting mixtures of fermionic atoms that can realize several paradigms of many-body physics. In his newly established laboratory, he is building an apparatus that can simultaneously produce degenerate gases of lithium-6 and potassium-40 atoms. Toward that end, he has already succeeded in laser cooling and trapping about 50 million of the potassium-40 atoms, despite this isotope's having a very low natural abundance of 0.01%. In accompanying theoretical research, Professor Zwierlein has derived a general theory for the hitherto unexplained reduction in the density-dependent clock shifts that occur in ultracold Fermi gases when interactions are resonantly enhanced.

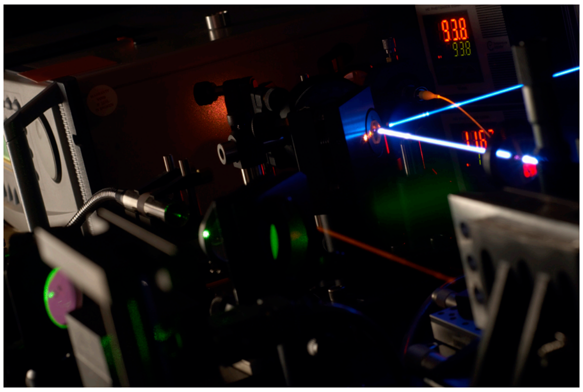
Professor Vladan Vuletic is interested in quantum optics and quantum information processing using laser-cooled atomic ensembles. His group uses the controlled atom-light interaction in combination with measurements at the quantum level to prepare novel quantum-mechanical states of many-body systems that may have important applications in precision measurement devices and quantum information processing. During the past year, they have demonstrated an atomic clock operating below the standard quantum limit (SQL)—i.e., the fundamental limit on the precision of an atomic clock when measurements are performed on a collection of independent particles. Their clock makes use of quantum-mechanical correlations (entanglement) between the particles to reduce the measurement noise to 7 dB below the SQL. In other work, they have demonstrated a quantum memory for the polarization state of a single photon, which constitutes an important building block for quantum information-processing systems in which quantum bits are stored locally and transported over long distances as single photons.

The late Professor Jin Kong led the Center for Electromagnetic Theory and Applications. Together with Dr. Bae-Ian Wu, he addressed a variety of problem areas, including, and especially, left-handed metamaterials and their applications. Left-handed metamaterials exhibit negative refractive-index behavior, which makes them of great importance owing to their direct applications to antenna design, cloaking, and radome design for communications, air defense, and surveillance.

Quantum Computation and Communication

Professor Seth Lloyd's work focuses on problems of information processing in both the quantum-mechanical and classic regimes. He is the director of the W. M. Keck Foundation Center for Extreme Quantum Information Theory (xQIT), and leads a group that has investigated the fundamental limits on the capacity of communication channels, derived bounds on the sensitivity of measurement devices, and constructed novel designs for quantum computers and quantum memories. During the past year, Professor Lloyd devised a novel quantum protocol for make private queries to a database.

This work, done in collaboration with RLE visitors Dr. Vittorio Giovannetti and Dr. Lorenzo Maccone, led to a design for a quantum random access memory that enables such private queries. Together with Professor Jeffrey Shapiro and the xQIT quantum communication team he originated a method for significantly improving the sensitivity of target detection and imaging systems through use of quantum resources. The method, called quantum illumination, uses entanglement to, in effect, tag signal photons to make them more distinguishable from noise photons.



Professor Jeffrey Shapiro and Dr. Ngai Chuen (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. Experimental work during the past year has led to the first measurement of the joint temporal distribution for signal/idler photon pairs emitted from a pulsed parametric downconverter. Another experimental effort used the group's single-photon two-qubit quantum logic to demonstrate entanglement distillation. The group's theoretical work has delineated the boundary between classic and quantum imaging in ghost imaging, two-photon diffraction-pattern imaging, and broadband two-photon imaging, and has continued determination of the fundamental limits on classic information transmission over bosonic (optical communication) channels in both single-user and multiuser scenarios. Of interest with regard to the bosonic channel research is the recent conjecture, by Professor Shapiro and his students, known as the entropy photon-number inequality (EPnI). The EPnI is the quantum analog of the well-known entropy power inequality (EPI) of classic information theory. Only partial evidence in support of the EPnI has been obtained so far, but its proof—which is being sought by analogy with proof techniques used to establish the EPI—would close a variety of outstanding questions in bosonic-channel information theory.

The research in Professor Isaac Chuang's group is directed toward developing experimental devices and the associated fundamental theory needed to realize large-scale, reliable quantum information processing systems. Of particular interest has been realizing a new interface between single-atom ions and semiconductor chips with long quantum coherence time, and developing a theory for quantum error-correction codes for fault-tolerant quantum computation. The most exciting result from his laboratory this year has been its successful fabrication of three new generations of trapped-ion chips for confining and manipulating a single trapped strontium ion. The atom sits about 75 microns above the chip surface, and it remains in its quantum-mechanical state for about one second. This is a record for motional coherence time in such small traps, representing an improvement of more than two orders of magnitude compared with the best previous art.

Appointments, Awards, and Events

The following appointments and awards were made in AY2008.

Professor Muriel Médard was promoted to professor of electrical engineering.

Professors Elfar Adalsteinsson and Collin M. Stultz were promoted to associate professor of electrical engineering and computer science and health sciences and technology.

Professor Vivek K. Goyal was promoted to associate professor of electrical engineering.

Professor Mehmet Fatih Yanik was appointed Robert J. Shillman assistant professor of electrical engineering.

Professor Martin Zwierlein received the Klung-Wilhelmy-Weberbank Prize for physics.

Professor Mehmet Fatih Yanik was appointed a David and Lucille Packard Foundation fellow.

Professor Mehmet Fatih Yanik received an NIH Director's New Innovator Award.

Professor Mehmet Fatih Yanik was named a TR35 Young Innovator by *Technology Review.*

Professor Henry I. Smith was elected to the American Academy of Arts and Sciences.

Professor Franz X. Kärtner was elected a fellow of the Optical Society of America.

Professor Jacob K. White was elected a fellow of the Institute of Electrical and Electronics Engineers (IEEE).

Professor Jeffrey H. Shapiro was co-recipient of the 2008 Quantum Electronics Award from the IEEE Lasers and Electro-Optics Society.

Professor Stephen E. Harris presented the Hermann Anton Haus Lecture.

Professor Leslie A. Kolodziejski received a Department Head Special Recognition Award from the Department of Electrical Engineering and Computer Science.

Professor Terry P. Orlando received a Graduate Student Association Graduate Counselor Award.

Professor Elfar Adalsteinsson received the Thomas A. McMahon Mentoring Award from the Division of Health Sciences and Technology.

Professor Marc A. Baldo received the 2008 Albert van Rennes Teaching Award.

Professor Vladimir Bulovic received the 2008 HKN Best Instructor Award.

Roozbeh Ghaffari and Michael Vahey received 2008 Helen Carr Peake Research Prizes.

Roozbeh Ghaffari was a co-recipient of the 2008 MIT 100K Entrepreneurship Competition prize.

Krista Van Guilder was promoted to manager of media and design.

Cheryl Charles was promoted to fiscal officer for post-award administration.

Nan Lin was appointed fiscal officer for pre-award administration.

Susan A. Parker was appointed fiscal officer for post-award administration.

Rita Tavilla was appointed major programs coordinator.

Maxine P. Samuels was promoted to financial coordinator.

Lorraine J. Simmons was promoted to financial Coordinator.

James M. Daley received a 2008 MIT Excellence Award.

David W. Foss received the 2007 Steven Wade Neiterman Award.

Catherine Bourgeois received a 2008 MIT Infinite Mile Award.

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 promoted four women (including two minorities) on its headquarters staff and appointed three other women to its headquarters staff.

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/.