

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 60 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 300 graduate students and 50 undergraduates from nine MIT departments and divisions pursued research within RLE. The research is supported primarily by Department of Defense (DOD) agencies, the National Institutes of Health (NIH), the National Science Foundation (NSF), the Department of Energy (DOE), and the National Aeronautics and Space Administration. In addition, numerous projects are funded through industry and private foundations. RLE research is widely varied and now consists of seven major interrelated groupings: circuits, systems, signals, and communications; energy, power, and electromagnetics; multiscale bioengineering and biophysics; nanoscale science and engineering; photonic materials, devices, and systems; physical sciences; and quantum computation and communication. Work in energy, power, and electromagnetics represents a new emphasis within RLE that has been spurred by incorporation of the Laboratory of Electromagnetic and Electronic Systems (LEES) into RLE and creation of the DOE-sponsored Center for Excitonics. The latter is the fourth virtual center hosted by RLE, the others being the NSF-sponsored MIT-Harvard Center for Ultracold Atoms, the W. M. Keck Foundation Center for Extreme Quantum Information Theory (xQIT), and the Interdisciplinary Quantum Information Science and Engineering (iQuISE) program, which is supported by an NSF Integrative Graduate Education and Research Traineeship grant.

Detailed information about RLE research in AY2010 can be found in RLE Progress Report No. 152. The report is available online at http://www.rle.mit.edu/media/media_pr.html. The 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 biotechnology and

nanotechnology. Applications include nanophotonic signal processing (in collaboration with professor Steven Johnson), mass-action kinetics modeling of transduction networks in biological cells (in collaboration with professor Bruce Tidor), fast methods for Casimir force computation (in collaboration with professor Steven Johnson), and cardiovascular system simulation (in collaboration with professor Luca Daniel). A highlight from the past year's research is the demonstration that the widely used immersive boundary (IB) method for computing arterial blood flow has a heretofore unknown instability that can nonetheless be eliminated with judicious low-pass filtering, which does not affect asymptotic convergence. The improved IB method could have widespread use in a variety of fluid-moving-structure problems, such as aero-elastics, biological cells in flow, and biomicroelectromechanical systems.

Professor Luca Daniel has turned his attention to developing variation-aware cosimulation and modeling tools for devices, interconnect, and circuit blocks in new and existing technologies. His goal is to bridge the gap between the individual component-level design and system-level design by providing simulation and modeling tools for all levels of the design hierarchy. Accomplishments during the past year include a Verilog-A implementation of a physical semiempirical short-channel metal-oxide-semiconductor field-effect transistor compact model (in collaboration with professor Dimitri Antoniadis), intrusive and sampling-based approaches for the solution of stochastic partial differential equation problems arising in variation-aware parasitic extraction, work on algorithms for automatic generation of compact dynamical models for interconnect and passives such as radio-frequency inductors or power combiners, and techniques for compact dynamical modeling of nonlinear analog circuits (in collaboration with professor Alexandre Megretski). The approach taken to modeling nonlinear analog circuits has already been applied, in collaboration with professor White and researchers at Merck Pharmaceutical, to generate models for the cardiovascular system.

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, which have the potential for efficient transmission of 3D television signals.

Professor Gregory Wornell is interested in algorithms, architectures, and circuits for communication and storage in wireless, multimedia, and sensor networks; architectures, abstractions, and technology for coherent imaging; and algorithms for the analysis and decoding of neural signals in brain-machine interfaces. During the past year, he has developed a family of highly effective real-time algorithms for decoding intended movements from measured multisensor neural activity. This decoder is based on a feedback control model of the sensorimotor system and exploits an efficient Bayesian inference framework. Other recent accomplishments include the following:



a powerful new dense antenna array architecture for imaging, communication, and related applications; efficient sparse-graph data structures that permit very large amounts of data to be stored in a compressed manner while allowing very fast, online updating of entries using computationally efficient message-passing algorithms; and prototype code families for approaching the capacity of intermittent communications, such as those found in modern sensor networks, by combining synchronization and information transmission.

The research of professor Vivek Goyal and his students spans several areas of signal processing and information theory. Their recent focus has been on problems in information acquisition and representation that exploit sparsity and respect resource constraints such as power limitations. During the past year, his group has demonstrated the importance of a particular type of prior knowledge to compressed sensing, that is, highly efficient information acquisition from signals that are sparse with respect to some fixed basis set. They have shown that conditional rank information, namely knowledge of the relative sizes of nonzero signal components, fundamentally changes the signal-to-noise ratio scaling needed for reliable detection. Using this result, they have designed a random access communication protocol that, for the first time, allows a computationally tractable decoder to avoid limitations from multiple-access interference. In other work, Professor Goyal and his students have been exploring the use of high-speed laser illumination and time-resolved photodetection to see around corners by employing matte surfaces as mirrors. Initial experiments have already demonstrated the validity of the underlying concept.

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 of algorithm development is the use of time warping nonharmonic Fourier analysis of nonuniformly sampled signals, which leads to a range of approximate reconstruction techniques.

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. The current focus of their effort is the technology and architecture encountered in modern heterogeneous networks. At present, such networks suffer from low throughput, long delays, and an inability to guarantee critical message delivery, among other problems. Addressing these shortcomings requires architectural constructs that range from physical media to upper-layer network protocols. Professor Chan's work provided the primary technical input to the networking section of a national-level report, *Creating an Assured Joint DOD and Interagency Interoperable Net-Centric Enterprise*, that was presented by the Defense Science Board to the DOD. This report specifies the core challenges along with the research and development agenda for military internetworking in the coming decade. Moreover, the same tough heterogeneous channel and network conditions are expected to appear in commercial networks of the future as they move increasingly in the

direction of mobile, ultrabroadband services through interconnected wireless, fiber, and satellite networks.

Professor Vladimir Stojanovic's Integrated Systems group focuses on development of methodology, circuits, and system techniques for both traditional and emerging technologies. In collaboration with professors Tsu-Jae King Liu and Elad Alon (University of California, Berkeley) and professor Dejan Markovic (University of California, Los Angeles), his group completed the first successful demonstration of both nanoelectromechanical switch-based circuits and silicon-photonic interconnects integrated within a larger electronic integrated-circuit test platform. Professor Stojanovic, together with professors Rajeev Ram and Henry Smith from RLE and professor Milos Popovic from the University of Colorado, designed the world's first electrophotonic chip in 45-nm silicon-on-insulator complementary metal-oxide-semiconductor technology that features a combination of polysilicon and silicon platforms for photonic components. The experimental results from the fabricated chip indicate that this technology node is capable of producing high-quality photonic devices in the same process as high-performance transistors.



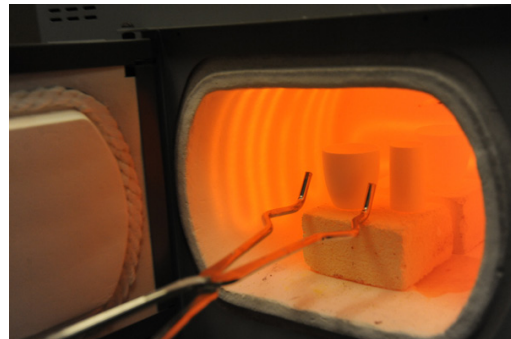
Professor Muriel Médard leads a highly collaborative research group with research links that include the Computer Science and Artificial Intelligence Laboratory and the Laboratory for Information and Decision Systems at MIT, as well as the California Institute of Technology, the University of California at Los Angeles, Harvard University, and Northeastern University. Its central theme is communications, with a special emphasis on the intersection between information theory and networking. A notable recent theoretical development has come through Professor Médard's joint work with professor Michelle Effros (California Institute of Technology), which addressed the separability between channel coding and network coding through the notion of network equivalence. Her practical applications efforts during the past year include work on network coding for body-area networks, underwater communications, peer-to-peer downloads, distributed storage, video security, optical networks, and cooperative wireless telephony. The wireless telephony results, obtained in collaboration with professor Frank Fitzek (University of Aalborg), have led to implementations on cell phones.

Professor Lizhong Zheng is interested in dynamic communication problems. He has recently completed a new formulation of communication that does not require the notion of perfect reliability and hence does not require long block lengths. Instead, his formulation views a communication problem as driving the receiver's knowledge to a desired value or range of values. He has shown that a traditional communication scheme need not be optimal according to his new dynamic metrics, and, conversely, one that is optimized for the new metrics need not be optimal for traditional performance measures. Thus, traditional channel coding, under the assumption of long block lengths,

is in fact not optimal on a symbol-by-symbol basis, offering the possibility of coming up with performance improvements for dynamic communication problems, which he believes will be a key step toward understanding dynamic networked communications. Professor David Staelin is interested in improved methods for remote sensing of global precipitation from current operational meteorological satellites and studies of spike-timing models for neural computation. In his neural signal processing effort, Professor Staelin has developed a theory of how the cortex might learn new information on subsecond time scales using spike processing. Furthermore, he has shown—by theory and time-domain simulations with simple neural threshold-firing models—that perhaps as much as one bit of Shannon information might be stored per synapse using this learning method. The mechanism appears capable of training multiple neural layers efficiently, including both feedforward and feedback neural paths. The feedback paths appear likely to improve cortical sensitivity to sensory signals in noise and to offer advantages of predictive coding when storing information compactly.

Energy, Power, and Electromagnetics

Professor Marc Baldo is the director of the DOE-sponsored Center for Excitonics, an Energy Frontier Research Center whose overarching theme is to supersede traditional electronics with devices that use excitons to mediate the flow of energy. Whereas the former rely on expensive and energy-intensive fabrication processes, the latter are far more suitable for the large-scale production that would be needed to generate sufficient solar cells to have a significant impact on the world energy supply. His own research currently centers on solar cells, light-emitting devices, and spintronic switches. During the past year his group has developed a new optically pumped laser, based on a very-high-quality resonator, whose ultimate promise is to achieve lasing under regular (nonconcentrated) solar illumination. Together with his Center for Excitonics colleagues (professors Mounqi Bawendi, Harry Tuller, and Vladimir Bulovic), Professor Baldo is striving toward new optical devices and materials to preprocess sunlight for solar cells in order to lower the cost and increase the efficiency of solar-generated electricity.



Professor John Kassakian cochairs, with professor Richard Schmalensee, MIT's Future of the Electric Grid study. Together they are guiding a team of eight faculty and 10 students in assessing the current state of the grid and the impact of future technology and policy on the grid's ability to achieve the physical composition and performance parameters being proposed by existing or pending federal and/or state legislation, as well as the promise and practicality of "smart grid" technologies. In his own research, Professor Kassakian (in collaboration with professor Joel Schindall) is exploring the ability of a hybrid battery/double-layer capacitor storage system to provide advantages of longer life, higher available energy, and higher power than a battery-only system in high peak-power applications. He is also developing a shear-force actuated electromechanical engine valve drive whose initial tests have shown improved engine performance at low engine speeds, which is the most significant area of operation.

Induction motor efficiency, ship propulsion, and electrical power systems constitute professor James Kirtley's current research agenda. Accomplishments during the past year include analytical models for induction-motor stray load loss as it is affected by conductor-to-lamination electrical contact and rotor skew, the design of a contra-rotating propeller system for ship propulsion that uses a contra-rotating electric motor, and the use of short-term energy storage to reduce the control effort from conventional power plants needed to maintain power system frequency and to reduce the adverse effects of renewable generation sources such as solar and wind power. Professor Kirtley's power system work is performed in conjunction with the MIT Portugal Program and the Technology Development Program. He is also a member of MIT's Future of the Electric Grid study team, wherein his role is understanding how the transmission and distribution system is likely to evolve and how that evolution will be affected by public policy.

Professor Joel Schindall was acting director of the Laboratory for Electromagnetic and Electronic Systems when LEES became part of RLE on July 1, 2009, whereupon he became an associate director of RLE. As a result, he has played a key role in assuring the smooth transition of the LEES faculty, staff, and students into RLE while maintaining his own research activity aimed at developing a practical energy storage device that combines the long life and rapid charge-discharge capability of a capacitor with the much higher energy storage capacity of a rechargeable battery. The approach is to increase the energy storage capacity of a double-layer capacitor by replacing the usual activated-carbon electrode coating with an array of vertically aligned carbon nanotubes. Professor Schindall's group has successfully fabricated electrode materials using a reactor designed and assembled in LEES, assembled working test cells that confirm the performance of the new ultracapacitor, and demonstrated energy storage densities several times greater than those of today's commercial ultracapacitors.

The dual foci of professor David Perreault's research group are advancing power electronics technology and applying power electronics to improve the performance of systems such as those used for solar energy generation, for microprocessor power delivery, and for radio-frequency (RF) power amplifiers. Research highlights from the past year include new circuit topologies and controls for realizing very-high-efficiency power converters to interface between low-voltage DC sources such as photovoltaic modules and the AC grid and a new RF power amplifier technology that provides both high efficiency and wideband linear operation. Patents have been filed on both of these technologies. Enphase Energy, which sponsors the power converter research, is in the process of negotiating an exclusive license for that technology. The RF power amplifier, which is being developed in collaboration with professor Joel Dawson, has applications in medical imaging and resonant DC-to-DC conversion in addition to its obvious relevance to communications. These new application areas will be subjects of future work in Professor Perreault's group.

Professor Jeffrey Lang's research addresses the analysis, design, and control of electromechanical systems, with an emphasis on high-performance electrical machine systems, microscale electromechanical actuators and sensors (MEMS), and distributed electromechanical structures. A key research accomplishment from the past year is the

successful demonstration of two different vibration-to-electrical energy harvesters. The first, which has a weight of less than 1 g, can produce 1 mW of electrical power. It is intended to harvest energy from the wing beat of a moth during flight. The second can produce between 100 mW and 1 W of power from the vibrations present during down-hole oil-well drilling operations. This past year also saw the publication of the book *Multi-Wafer Rotating MEMS Machines*, edited by Professor Lang, which documents the work performed during the 13-year-long MIT Micro Engine Project to develop a microscale gas-turbine-powered electrical generator.

Professor David Trumper's research efforts are centered on the design of novel precision electromechanical systems. He is currently collaborating with professors Jeffrey Lang and Markus Zahn on the creation of an electromagnetic nanoimager. So far, theory and preliminary experiments have been developed for a novel electromagnetically driven imager that can image the surface and near-surface volume of samples of interest, including integrated circuit structures. This technology can be applied to any nanoimaging problem. Professor Trumper has also formulated theory on the magnetic dual of this imaging system.

Professor Markus Zahn and his students are engaged in research on electromagnetic fields and media. Application areas of interest are dielectric physics and high-voltage breakdown in gases, liquids, and solids; electrohydrodynamics and ferrohydrodynamics; and the development of dielectrometry and magnetometry sensors for nondestructive testing. Key achievements from the past year include models for positive streamer initiation and propagation and electrical breakdown in dielectric liquids such as transformer oil, Kerr electro-optic field mapping experiments to determine means for increasing the electrical strength of dielectrics used in advanced electrical power systems, and ultrasound velocimetry measurements of ferrofluid spin-up flows in uniform and nonuniform rotating magnetic fields.

"No Watt Left Behind" is the mantra of professor Steven Leeb's research group, whose central focus is energy efficiency. Their work comprises a broad-ranging look at the way electro-thermal-mechanical systems use energy in buildings, with an eye toward advanced technology demonstrations in fault detection and diagnostics, intelligent lighting, power electronics, waste heat recovery, metering, and control. Whereas much current thinking about energy efficiency in "smart" buildings involves a decentralized network of sensors serving as a centralized control for a largely decentralized collection of loads producing waste heat, Professor Leeb is pursuing a new, economically attractive approach to waste heat recovery and operating schedule optimization. This approach uses an easily installed centralized monitor that serves loads with decentralized control configured to permit centralized collection of waste heat. During the past year his group designed, constructed, and tested demonstrations for solving key problems associated with this new approach, including new signal processor hardware for metering that supports wired, wireless, and stored data access and a retrofit electrical sensor that measures the current in the utility feed while requiring no skilled installation.

Professor Peter Hagelstein has devoted most of his research effort to developing models for excess heat in the Fleischmann-Pons experiment. In addition, he has published his

results on a novel thermal-to-electric energy converter that takes advantage of Coulomb coupling arising from near-surface electric fields, and he has continued his work on modeling thermal diodes. A significant accomplishment from the past year's research is his development of new models for computing energy exchange and excitation transfer rates from lossy spin-boson models in the limit in which the number of oscillator quanta exchanged is very large. This new model permits accurate calculations to be performed when as many as 10^8 quanta are exchanged.

Dr. Chathan Cooke is studying metal-insulator interfaces and energetic electron-photon beam interactions. His metal insulator research uses a combination of high-resolution ultrasonics to measure space charges near these interfaces and high-sensitivity conduction measurements at high voltages to quantify the terminal currents associated with interface charge accumulations. The goal of this work is to improve the insulation systems used in enclosed electrical power apparatuses. Dr. Cooke's energetic radiation work uses electron and photon beams produced by the Van de Graff accelerator facility in the High-Voltage Research Laboratory. In a collaboration with the Orthopedics Biomechanics and Biomaterials Group from the Massachusetts General Hospital, these beams have been used to develop improved lifetime materials for hip and knee implants.

Multiscale Bioengineering and Biophysics



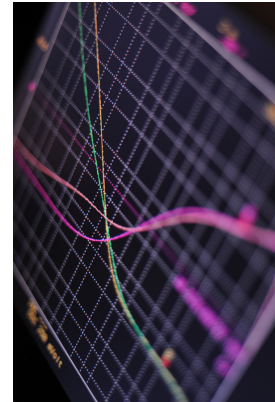
The research of professor Collin Stultz is focused on understanding conformational changes in biomolecules that play important roles in common human diseases. His group uses an interdisciplinary approach that combines computational modeling with biochemical experiments to make connections between conformational changes in macromolecules and disease progression. In recent work, his group has developed new methods for modeling

the unfolded state of tau protein, which is believed to play an important role in the formation of neurotoxic aggregates in the brains of patients with Alzheimer's dementia. Using a combination of experimental data and molecular modeling, the group has uncovered new insights into the complex array of structures that tau can adopt under physiologic conditions. The long-term goal of this work is to understand the conformations of tau protein that are prone to self-associate. Once these conformations have been identified, inhibitors to prevent their formation can be designed in a rational manner. Such molecules could then provide viable therapies for Alzheimer's dementia.

Professor Elfar Adalsteinsson's group is developing methods for magnetic resonance imaging (MRI) in human health and disease. An ongoing trend in MRI is the push to high-field-strength imaging because of the improved signal-to-noise ratio and thus better spatial resolution and shorter imaging times it provides. Professor Adalsteinsson works on overcoming the severe signal inhomogeneity problem that plagues such high-field-strength systems. In the past few years, he has validated the parallel transmit RF system for overcoming this problem. The present phase of that research is the

management of specific absorption rate (SAR), which is a regulated safety parameter that measures the deposition of heat in tissue. During the past year his group has designed and implemented a workflow pipeline to estimate local SAR via numerical methods and monitor multichannel RF waveforms in real time to detect any deviation from the allowed waveforms. In other work, he has been drawing upon the theory of compressed sensing to achieve MRI speed-up through the use of sparse sampling and related reconstruction algorithms.

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 he demonstrated the ability to remotely control the flight of the moth *Manduca sexta*, the culmination of a Defense Advanced Research Projects Agency (DARPA) program focused on creating cyborg insects. Through the combined efforts of a team of investigators from MIT, the University of Washington, and the University of Arizona, a lightweight wireless system incorporating microfabricated electrodes was interfaced with the animals' central nerve cords to alter their flight. These results were reported in an oral presentation at the MEMS 2010 conference. Professor Voldman is now trying to apply his electrical-neural interface technology to humans, for whom it may have therapeutic benefit.

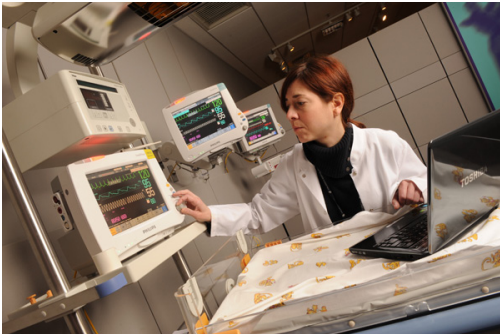


During the past year, the work in professor Jongyoon Han's Micro/Nanofluidic BioMEMS group has focused mainly on exploring novel application areas of micro/nanofluidic systems that go beyond the biomolecule separation and protein sample preparation applications that they have already pioneered. The new seed projects he is incubating span diverse application areas such as neural prosthetic devices and seawater desalination. His group of two postdoctoral associates and five graduate students in the Singapore-MIT Alliance for Research and Technology Center are working on microfluidic systems for diagnostics in rural, resource-limited settings. A breakthrough result from his recent research is a novel process for converting seawater to fresh water by means of an electrokinetic phenomenon known as concentration polarization. With this approach he has demonstrated approximately 99 percent salt rejection at recovery rates of 50 percent or above and an energy consumption of less than 3.5 Wh/L, which is comparable to the performance of state-of-the-art reverse osmosis desalination systems while significantly reducing the possibility of membrane fouling and salt accumulation that plagues those conventional systems.

Professor Mehmet Fatih Yanik works on the development of high-throughput screening technologies, large-scale neuronal regeneration screens and analysis of results, protein micropatterning technologies for high-content neuronal assays, and nuclear reprogramming using mRNA. During the past year his group had many high-profile achievements, including the first high-throughput zebrafish imaging and screening platform, the first repeatable mRNA transfection technique for nuclear reprogramming,

the first large-scale in vivo laser microsurgery screen to study neuronal regeneration, and the first large-scale neuronal assays using protein-micropatterned substrates. Although these technologies are being developed to investigate neuronal development and regeneration, they are likely to find applications in other areas of biology.

Professor Martha Gray is developing a framework for imaging biomarkers in osteoarthritis. While there are several emerging methods for measuring features that may provide important clinical or biological information in this regard, there is not yet a clear road map for validating and qualifying these metrics. NIH and various professional organizations have recognized this challenge and are working with their members to address it. Professor Gray has been part of several working groups on this issue that have been organized by the Foundation for the National Institutes of Health Biomarkers Consortium, Radiological Sciences of North America, and the Arthritis Foundation. In addition, she has been developing programs that will build capacity and become an innovation engine in health-related areas. These recently or soon to be launched programs are the Translational Health Sciences and Technology Institute and m+Vision. The former is an academic institution in India that is modeled on the Harvard-MIT Division of Health Sciences and Technology. The latter is a program aimed at building biomedical imaging, broadly construed, in Madrid and advancing imaging globally.

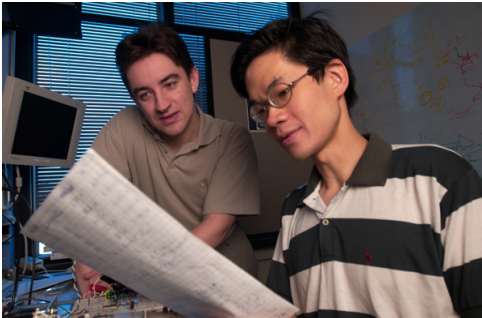


Professor George Vergheze leads the Computational Physiology and Clinical Inference group, which brings together concepts from signal processing, systems and control theory, modeling, and estimation to address questions in clinical medicine and physiology. The group's current focus is enhanced monitoring of adult and neonatal patients in critical care. A major research highlight from the past year was the demonstration and validation of noninvasive, patient-specific, calibration-

free, beat-by-beat estimation of intracranial pressure (ICP). ICP monitoring is critical in the management of traumatic brain injury. The standard methods for clinical treatment require drilling a hole in the skull to place a subdural solid-state sensor or to advance a catheter through the brain tissue. In either case, the attendant risks of morbidity and infection limit such measurement to the sickest of patients. Professor Vergheze's group uses minimally invasive or noninvasive measurement of the arterial blood pressure waveform—obtained radially via catheter or from a finger via a pressure-sensing cuff—combined with simultaneous transcranial Doppler measurement of the cerebral blood flow's velocity waveform in the middle cerebral artery. Processing these time-locked data using a physiologically based model then yields ICP estimates. The methodology has been successfully applied using data from comatose patients that were provided by a collaborator at Addenbrooke's Hospital in Cambridge, England, and a patent application has been filed.

Professor John Wyatt leads the Boston Retinal Implant Project, whose 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. Engineering development is currently under way to create an implant that can be presented to the Food and Drug Administration (FDA) in 24 months to request permission to perform chronic implantation on a small number of human volunteers. During the past year, Professor Wyatt's team built and bench tested its first retinal implant with the reverse telemetry for verifying implant functionality in an animal and measuring electrode impedance. Reverse-telemetry devices were then implanted in the eyes of two Yucatan minipigs and successfully stimulated and monitored over the period of a few months.



Professor Rahul Sarpeshkar and his students are working in three principal areas: cytomorphic circuits inspired by gene-protein and protein-protein circuits in cells; brain-machine interfaces for the treatment of blindness, paralysis, and Parkinson's disease and for large-scale wireless experimental neuroscience; and noninvasive cardiac monitoring. A major achievement from the past year is the publication of Sarpeshkar's book *Ultra Low Power Bioelectronics: Fundamentals, Biomedical Applications, and Bio-Inspired Systems*. This book outlines how large-scale gene-protein and protein-protein networks in biology can be mapped to integrated circuits in electronics that mimic their computationally intensive stochastic dynamics exactly and efficiently. This mapping has given birth to what may potentially be a promising new field of electronic design that he terms "cytomorphic electronics." Such electronics can be useful both for rapid simulations of complex biological networks and for mapping principles of robust analog feedback circuit design to synthetic cellular circuits.

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 that his group created in 1990. OCT is a medical imaging technology analogous to ultrasound, measuring the echo time delay and magnitude of backscattered or backreflected light to generate cross-sectional images of the internal structure of biological tissues or materials with micron scale resolution. In medical diagnostics, OCT can function as a type of "optical biopsy" to image tissue pathology with a resolution approaching conventional excisional biopsy and histopathology. During the past year, LightLab, a company founded by Eric Swanson (formerly of MIT Lincoln Laboratory), Dr. Mark Brezinski (Massachusetts General Hospital and MIT), and Professor Fujimoto, received FDA approval for the use of intravascular OCT imaging. Intravascular OCT imaging promises to have a significant impact on the diagnosis and treatment of heart disease.

During the past year, Dr. Joseph Perkell has performed a series of experiments that address the perceptually important aspects of speech's spectral structure in time-varying sound sequences. In order to test whether auditory feedback is involved in the

planning of complex articulatory gestures in time-varying phonemes, he studied native Mandarin speakers' responses to a time-varying perturbation of the trajectory of the first formant frequency during their production of the triphthong /iau/. These experiments added evidence that time-varying aspects of speech movements are programmed very precisely and that the feedforward component of this programming may be modified when temporal aspects of the produced sounds do not match preprogrammed auditory expectations. Such results are compatible with a neurocomputational model in which motor goals consist partly of regions in multidimensional auditory-temporal space and speech is produced with a combination of feedforward and feedback control.

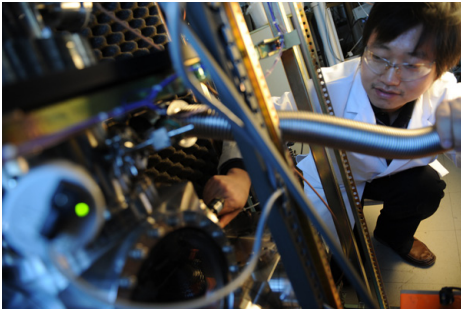
Professor Louis Braidá and Dr. Charlotte Reed have been exploring links between the senses of hearing and touch. At least since the time of Aristotle the senses have been thought to be distinct, but new work in their group indicates that hearing and touch can interact in the formation of auditory-tactile percepts. In particular, they have used rigorous quantitative psychophysical techniques and models of cross-modal integration to demonstrate that certain combinations of auditory and tactile stimuli result in a significant increase in detectability above performance when the stimuli are presented in isolation. This research has significance in the advancement of basic sensory science. Moreover, it will guide the future development of auditory-tactile aids for persons with severe to profound hearing impairment, as well as the treatment of speech-production disorders that may be caused by a disruption of the normal integration of auditory and somatosensory feedback.

Dr. Bertrand Delgutte is a member of the Eaton-Peabody Laboratory of Auditory Physiology. His research addresses the neural mechanisms of listening in everyday environments composed of noise and reverberation. One focus of his work is the neural basis for speech reception and sound localization in reverberant environments. Another focus is neural sensitivity to interaural time differences (ITDs)—the most important sound localization cue—in animal models of bilateral cochlear implants. His recent experiments with bilateral implants were performed on cats that had experienced a relatively long period (six months) of auditory deprivation after being deafened as adults. He found that ITD sensitivity in these animals was better than that of congenitally deaf cats but worse than that of acutely deafened cats that had normal hearing until the neurophysiological experiment. These results are in harmony with studies in human subjects wearing bilateral cochlear implants, which also show that the age of onset and duration of deafness have an impact on perceptual ITD quality.

Professor Dennis Freeman has made further advances in his investigations of the way the inner ear functions. During the past year he has begun to apply Doppler optical coherence microscopy, an OCT-based technique that he has developed, to measure sound-induced motions of inner ear structures in living animals. For example, he has used this method to measure high-frequency motion in the inner ear of a living gerbil by imaging directly through a naturally occurring opening called the round window. His research could have application to the clinical diagnosis and treatment of hearing disorders.

Dr. Mandayam Srinivasan leads the Laboratory for Human and Machine Haptics, whose work is guided by a broad vision of haptics that includes all aspects of information acquisition and object manipulation through touch by humans, machines, or a combination of the two involving environments that can be real or virtual. Over the past few years, his laboratory has developed and tested the BlindAid system, which combines audio and haptic feedback. Users employ a haptic interface that enables them to touch and feel a virtual environment through a hand-held stylus. The goal of the project is to develop a user-friendly system that allows people who are blind to explore and build cognitive maps of unknown virtual spaces through haptic exploration supported by audio feedback.

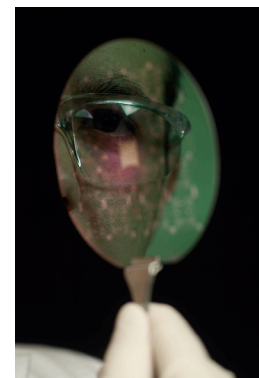
Nanoscale Science and Engineering



Research in professor Karl Berggren's Quantum Nanostructures and Nanofabrication group has continued to focus on sub-10-nm-length-scale fabrication and on superconducting nanowire single-photon detectors. A highlight from the past year's work came in the area of template self-assembly, where he published a major result regarding the templating of nanoscale linear features using sparse cylindrical patterns. This work is currently being patented, and it is expected to find utility in the semiconductor industry, where creation of nanoscale lithographic features is becoming increasingly costly. By reducing the amount of patterning required in comparison with top-down methods such as electron-beam lithography, the template self-assembly method will greatly reduce the costs of nanoscale pattern generation.

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. During the past year Professor Smith's efforts were directed toward the following projects: the development of technology for fabricating 3D photonic crystals by stacking prepatterned membranes, the development of a 1- to 2-keV version of spatial-phase-locked electron-beam lithography, the use of absorbance modulation to enable optical microscopy beyond the classical diffraction limit, the use of optical communication for intrachip connection of microprocessor cores, and the use of absorbance modulation for interference lithography.

Professor Jing Kong is interested in the fabrication and applications of single-walled carbon nanotubes, graphene synthesis and transfer technology, and nanowire assembly and its applications. Her recent work includes the use of transparent graphene electrodes in organic solar cells instead of the usual indium-tin-oxide electrodes. By tuning the work function of these graphene electrodes, she was able to improve the organic solar cells' power conversion efficiency to as high as 86 percent. In other research, she has successfully synthesized large-area hexagonal thin films of boron nitride—down to a few atomic layers—that can be transferred to various



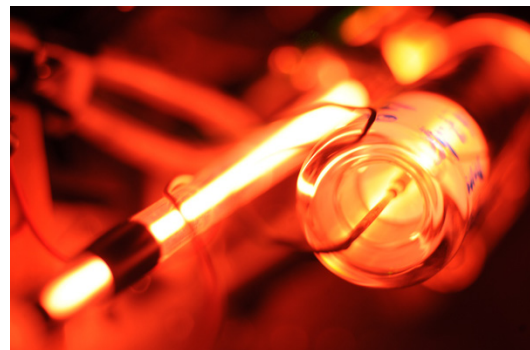
substrates. This material has been predicted to be very useful as a gate material for graphene transistors or deep-ultraviolet light emitters. A patent application has been filed for the synthesis technique.

Photonic Materials, Devices, and Systems

Professor Leslie Kolodziejski and Dr. Gale Petrich lead the Integrated Photonic Materials and Devices group, whose research centers on fabrication of optoelectronic devices in III-V semiconductors. Active areas of research include the development of an optical logic gate composed of semiconductor optical amplifiers integrated within a Mach-Zehnder interferometer, the development of optical sources with emission wavelengths longer than 1.55 microns, the development of saturable Bragg reflectors for ultrashort pulse lasers, and the development of an ultrabroadband optical modulator centered at 810-nm wavelength. A highlight from the past year's research is the observation of lasing in both the test structures within the optical logic-gate die and InP-based structures that were designed to emit at wavelengths of 1.75, 1.85, and 1.95 microns. The observation of lasing from the test structures within the optical logic die indicates that the semiconductor optical amplifiers (SOAs) have sufficient gain to overcome the losses inherent to the integration of optical devices within the photonic integrated circuit. Using these SOAs within a Mach-Zehnder interferometer permitted the intensity of the resulting optical signal to be modulated by controlling the biases on the SOAs.

Professor Erich Ippen has continued his work on the advancement of femtosecond optical techniques and their application to studies of ultrafast phenomena. He leads a DARPA program on optical arbitrary waveform generation using stabilized femtosecond optical combs. During the past year, he has used a new saturable Bragg reflector—developed by Professor Kolodziejski—to obtain shorter pulses and higher repetition rates from femtosecond fiber lasers, thereby improving the output characteristics and robustness of his 1 GHz soliton lasers. He has also succeeded in amplifying femtosecond pulses at 1.5 microns to continuum-generating energies (2 nJ) at a repetition rate of 1 GHz, which is four times the repetition rate previously achieved. The ability to generate truly precise and arbitrary optical waveforms should provide dramatically new capabilities for optical signal processing, communications, lidar, and sensing. A near-term application, being pursued at Lincoln Laboratory, is face recognition at multikilometer distances.

Professor Franz Kärtner is working on low-noise femtosecond lasers and frequency combs, photonic analog-to-digital converters, femtosecond timing distribution in x-ray free electron lasers, optical parametric chirped-pulse amplification to generate high-energy carrier-envelope phase-controlled pulses, and attosecond science. Key research accomplishments during the past year are the demonstration of ultralow-jitter pulse trains from solid-state lasers that approach sub-100 attoseconds in the 1 kHz to 10 MHz



frequency range, the first implementation of his sub-10-fs timing distribution system at the vacuum-ultraviolet free electron laser Fermi in Trieste, the demonstration of an integrated coherent interleaver that enables coherent interleaving of pulses from 625 MHz to 10 GHz, and the demonstration of an integrated 11-channel silicon ring filter bank for a photonic analog-to-digital converter (done in collaboration with professors Henry Smith and Erich Ippen). The possibility of 100-attosecond jitter from femtosecond lasers is especially exciting in that it enables overcoming the sampling bottleneck in today's electronic analog-to-digital converters by three orders of magnitude.

Professor Steven Johnson's research agenda concentrates on the design and modeling of photonic devices, especially those in which electromagnetic effects occur on the scale of the wavelength of light. Among his many research achievements from the past year is his demonstration that multiple resonances can be used with new classes of efficient optical frequency converters that, for example, can be employed to perform quantum-limited conversion from infrared to terahertz frequencies. Other work of note is his demonstration, on fundamental theoretical grounds, that electromagnetic invisibility cloaks become increasingly difficult to realize as the size of the object to be cloaked increases and are probably unachievable in practice except for objects not much bigger than the wavelength of light. In addition, his study of Casimir forces, specifically his new techniques that allow the quantum Casimir force to be calculated for a wide variety of important geometries, has direct relevance for micromechanical and microfluidic systems.

Professor Vladimir Bulovic's laboratory is addressing a wide variety of research topics, including the physical properties of organic thin films, structures, and devices; the physical properties of devices incorporating nanocrystal quantum dots; optoelectronics and electronics with nanostructured material systems; large-area electronics using organic and metal-oxide field effect transistors; hybrid organic/inorganic materials and structures; printed MEMS structures; and strong quantum electrodynamic coupling in organic thin-film structures. Notable accomplishments from the past year include substantial improvements in the efficiency of hybrid organic/quantum-dot light-emitting diodes (LEDs) through printing of close-packed monolayers of different quantum-dot (QD) types inside an identical QD-LED structure and the development of a new process that enables the first rapid fabrication of metallic MEMS without lithographic processing. The MEMS fabrication relies on dimensionally stable contact printing, and the flexible, paper-thin device arrays produced by this method may enable such applications as pressure-sensing skins for people and vehicles, phased-array detectors for acoustic imaging, and novel adaptive-texture displays.

Professor Qing Hu's research is devoted to 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 (186 K without and 225 K with an applied magnetic field), the highest operating temperature in continuous-wave mode (117 K), the highest power levels (250 mW), and the longest wavelength (190 microns). He has also performed T-ray imaging at a video

rate of approximately 20 frames per second using one of his sources and developed a novel tuning mechanism—qualitatively different from what is used in all other tunable lasers—enabling continuous tuning over a 330 GHz frequency range. 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: the demonstration of photonic devices in state-of-the-art complementary metal-oxide-semiconductor integrated circuit processes, the demonstration and analysis of solar thermoelectric power generation as an alternative to photovoltaics, and the development of precommercial prototypes of microscale automated cell culture

systems. Achievements from the past year include exploration of precision fabrication techniques needed for realizing an optical isolator that can easily be incorporated into standard III-V semiconductor photonic circuits; the design, fabrication, and testing of a microchemostat that will permit continuous cell cultures under controlled environmental conditions; and development of a compact and robust photoacoustic spectroscopy system whose tunability will permit detection of a wider variety of trace gases than is possible with conventional systems. Professor Ram is also the director of the Center for Integrated Photonic Systems and in charge of the Integrated Photonics Initiative.

Professors Marin Soljacic and John Joannopoulos work on theory and experiments for electromagnetic phenomena, especially those involving nanophotonics, nonlinear optics, and wireless power transfer. Their major achievement during the past year concerns one-way waveguides. An ordinary waveguide supports propagation both forwards and backwards. A one-way waveguide supports only waves propagating in a single direction. Obstacles and disorder can no longer reflect waves, which exhibit 100 percent transmission in numerical simulations even across seemingly impassable perfectly conducting barriers. This phenomenon, which is analogous to quantum Hall edge states, can arise from gyromagnetic materials. Professors Soljacic and Joannopoulos have performed a successful experimental demonstration of one-way wave guidance. This new waveguide could be of great value for large-scale integrated optics, in which preventing reflected light signals from entering—and destabilizing—active devices is a significant problem.

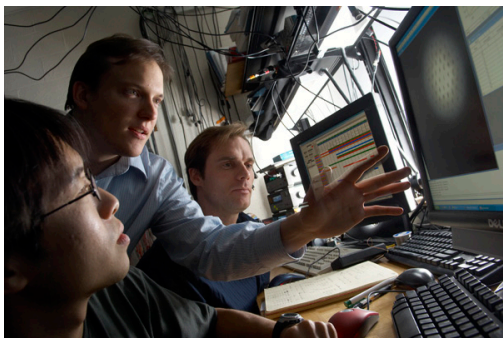
Professor Yoel Fink's research interests are the theory, design, process development, and characterization of fibers with engineered electronic, photonic, and phononic properties that follow from their elaborate structure and multiscale features. A major accomplishment from his past year's research was showing that fibers need not be static devices. This was done by demonstrating, for the first time, piezoelectricity in a thermally drawn fiber. Other achievements include showing that metal-insulator-semiconductor fibers can be used as photodetectors that provide axially resolved

information, demonstrating the ability to write crystalline domains into particular fiber segments that enable simple fiber-memory functions, and incorporating electrically switchable liquid crystal domains into fiber structures, which may lead to development of fiber-based displays.

Physical Sciences

Professors Wolfgang Ketterle and David Pritchard are studying the properties of bosonic and fermionic quantum gases. One purpose of this research is to use ultracold atoms to realize new forms of matter with strong interactions and strong correlations. In this way, they can perform quantum simulations of simple Hamiltonians. Another focus derives from the fact that quantum degenerate gases are novel systems in which to explore many-body physics, including phase transitions, superfluidity, vortices, and quantum magnetism. Their recent work has used a gas of ultracold fermionic lithium in which the strength of the repulsive interactions was increased by tuning an external magnetic field close to a Feshbach resonance. They observed nonmonotonic behavior of lifetime, kinetic energy, and size, providing strong evidence for Stoner instability, that is, a phase transition to a ferromagnetic state. This experiment can be regarded as a quantum simulation of a simple Hamiltonian—the hard-core Fermi gas—for which even the existence of a phase transition has not been proven. Professor Ketterle also directs the MIT-Harvard Center for Ultracold Atoms.

Professors Thomas Greytak and Daniel Kleppner have been completing their studies in the area of ultracold atoms, which were aimed at examining collisions between exotic atoms at temperatures so low that there is a reasonable chance of comparing the results with detailed theoretical predictions. Of particular interest was the role played by filled outer electron shells in shielding magnetic moments carried by unpaired inner electrons. A secondary goal of the research was to determine the suitability of these exotic atoms for evaporative cooling into the micro-Kelvin regime.



Professor Martin Zwierlein is an experimentalist who is interested in the properties of ultracold gases of atoms and molecules as a universal test bed for condensed matter and nuclear theory. The interactions between atoms in his gases can be made as strong as quantum mechanics allows. Last year the focus of his work was to obtain the equation of state of such strongly interacting gases and to perform the first measurement of transport properties in these systems. Because of the universality of the gas under study, these results can be compared with those found for the quark-gluon plasma, a substance found in the early universe and recreated in heavy-ion collision experiments in accelerators. So far he has studied only two fermionic atoms of the same species but in different spin states. Over the past year he realized cooling toward nanokelvin temperatures, opening the possibility for equilibrium and transport studies on Fermi-Fermi mixtures (${}^6\text{Li}$ - ${}^{40}\text{K}$) with imbalanced masses, the formation of Bose-Einstein condensates of heteronuclear molecules, and the creation of dipolar molecules.

Professor Vladan Vuletic is interested in the experimental realization of quantum mechanical many-body states with quantum correlations (entanglement). Such states are central to quantum computation and communication. Moreover, they may result in improved performance of measurement devices such as clocks, interferometers, and gyroscopes. During the past year, his group experimentally generated quantum mechanically correlated states of a large atomic ensemble—known as spin-squeezed states—with the largest amount of spin squeezing seen to date. Using these states the group demonstrated, for the first time, an atomic clock that operates at a precision three times beyond the standard quantum limit (i.e., the fundamental performance limit for any devices that operate by measurement of independent particles). Future time and frequency standards, and perhaps even commercial atomic clocks, may use Professor Vuletic's technique to improve their stability beyond the standard quantum limit.

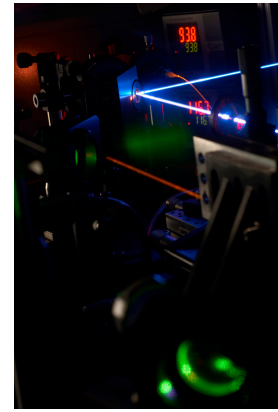
Quantum Computation and Communication

Professor Seth Lloyd's work focuses on problems of information processing in both the quantum mechanical and classic regimes. He is the director of 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. With visiting scientist Dr. Lorenzo Maccone and the group of professor Aephraim Steinberg (University of Toronto), he has developed a novel theory for the quantum mechanics of closed timelike curves. Based on teleportation, this theory shows how a closed timelike curve can be regarded as a quantum channel that sends information from the future to the past. Unlike the prevailing theory of such curves, Professor Lloyd's approach is susceptible to experimental testing. In collaboration with professor Alan Aspuru-Guznik (Harvard University), he has extended his theory of photosynthetic transport in terms of quantum walks. With postdoctoral associate Masoud Mohseni, he has shown how the symmetric structure of photosynthetic molecules gives rise to super transfer (i.e., the quantum transport analog of superradiance).

Professor Paola Cappellaro joined the MIT faculty and RLE in fall 2009, and she has established the Quantum Engineering group. Her goals are to study quantum control and to develop quantum devices, thus connecting quantum theory to engineering applications. During the past year she has been constructing a set-up for the control of nitrogen-vacancy (NV) centers in diamond that includes a custom-built confocal microscope for the initialization and readout of the electronic spin associated with an NV center as well as advanced microwave and RF field control for the manipulation of the electronic and nearby nuclear spins. In theoretical work, she has proposed an approach for improving the sensitivity of nano-diamond magnetometers and investigated a scheme for using the NV-based magnetometer to detect tiny magnetic fields created by the nuclear spins in organic samples. This technique could open the way to performing nuclear magnetic resonance (NMR) measurements at the nanoscale.

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 demonstrated high-quality

distribution of 1.3-micron polarization-entangled photon pairs generated from a fiber-coupled periodically poled potassium titanyl phosphate waveguide over 200 m of fiber-optic cables. This work, done in collaboration with the group of professor Karl Berggren, employed time-multiplexed measurements made with a superconducting nanowire single-photon detector and achieved an average two-photon quantum interference visibility of 97.7 percent without subtraction of accidentals. In theoretical work, done in collaboration with Dr. Zachary Dutton and Dr. Saikat Guha of Raytheon BBN Technologies, it was shown that squeezed-vacuum injection and phase-sensitive amplification can be used to substantially improve the spatial resolution of a soft-aperture laser radar system that employs a conventional laser transmitter in conjunction with homodyne detection. Other theory demonstrated that the quadrature-entangled light from spontaneous parametric downconversion enables a high-data-rate optical communication protocol that is immune to passive eavesdropping. An experimental demonstration of that protocol is now under way, and the theory is being extended to seek ways of thwarting active eavesdropping.



The research in professor Isaac Chuang's group is directed toward understanding and demonstrating the harnessing of resources provided by quantum physics for novel applications in information technology. During the past year, his group's experimental efforts have focused on integrating quantum bits made of single atoms with quantum bits realized with superconducting electronics and quantum bits made of single photons so as to reap the best features of each physical modality. The group's theoretical work concentrated on developing quantum error-correcting codes and methodologies that go beyond the standard additive quantum code framework. A major achievement of the past year was the demonstration of a novel method for laser cooling a single trapped ionized atom using light amplified in an optical cavity. This result opens the door to new approaches to precision spectroscopy of molecular ions and the initialization of quantum bits for quantum computation. Its publication, in *Physical Review Letters*, was selected by the American Physical Society for a highlight in *Physics Synopses*. Professor Chuang is also the director of the iQuISE program.

The research in professor Terry Orlando's Quantum Circuits and Quantum Computation group is aimed at demonstrating quantum control of superconducting qubits. Their work includes the characterization and mitigation of decoherence mechanisms in these solid-state devices. During the past year, they have demonstrated the longest coherence times ($T_1 = 11.7 \mu\text{s}$, $T_2 = 23 \mu\text{s}$) of any modality for superconducting qubits. The error rate in this qubit is below 0.1 percent, approaching the level that will enable the use of quantum error-correction protocols. The device that showed this extraordinary performance was fabricated at NEC Corporation in Japan, and testing was performed at MIT in collaboration with Lincoln Laboratory. The device's long coherence time will permit the use of NMR-inspired pulse sequences and dynamical decoupling techniques, thus bringing superconducting quantum computation closer to fruition.

Appointments, Awards, and Events

The following appointments and awards were made in AY2010.

Professor Vladimir Bulovic was promoted to professor of electrical engineering.

Professor Luca Daniel was granted tenure.

Professor Mehmet Fatih Yanik was promoted to associate professor of electrical engineering.

Professor Vladimir M. Stojanovic was appointed Emanuel E. Landsman associate professor of electrical engineering and computer science.

Dr. Paola Cappellaro was appointed assistant professor of nuclear science and engineering.

Professor Joel E. Schindall was appointed associate director of the Research Laboratory of Electronics.

Professor Martin W. Zwierlein received an Office of Naval Research Young Investigator Award.

Professor Qing Hu was elected a fellow of the Institute of Electrical and Electronics Engineers.

Professor Qing Hu was elected a fellow of the American Association for the Advancement of Science.

Professor Jongyoon Han received the Young Innovator Award from the American Chemical Society journal *Analytical Chemistry*.

Professor Wolfgang Ketterle was appointed founding editor of the *Virtual Journal of Atomic Quantum Fluids*.

Professor Yoshihisa Yamamoto presented the Hermann Anton Haus Lecture.

Professor Rajeev J. Ram was named a Margaret MacVicar Fellow.

Professor Alan V. Oppenheim received the Graduate Student Association Academic Counselor Award.

Professor David E. Pritchard received the Earl M. Murman Award for excellence in undergraduate advising.

Professor George C. Verghese received a Burgess and Libby Jamieson Award honoring great teaching over a long period of time.

Professors Vladimir M. Stojanovic, Mehmet Fatih Yanik, and Martin W. Zwierlein received 2010 Jonathan Allen Junior Faculty Awards.

Natasa Blitvic and Shirley Xiaomeng Shi were awarded Claude E. Shannon Research Assistantships for 2010–2011.

Krista Van Guilder received a 2009 American Graphic Design Award.

William J. Adams was appointed Windows server and systems infrastructure administrator.

Elizabeth A. Goldberg was appointed human resources administrator.

Amanda J. Bailey was appointed fiscal officer for preaward administration.

Cynthia C. Shen was appointed fiscal officer for postaward administration.

Catherine M. Bourgeois was appointed senior financial assistant.

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, among them 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 appointed four women to the 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/>.