Photonic Systems and Technology, 1999-2000

Externally Funded Research Projects

Lightwave Propagation, Cavity Self-Formation, and Lasing in Strongly Scattering Media
H. Cao, S.-T. Ho*, and R. P. H. Chang
Sponsor: National Science Foundation

This project investigates lasing processes that our group discovered recently in polycrystalline or nanocrystalline ZnO and GaN particle semiconductors. We postulate that formation of closed loops and photon localization are possible mechanisms for lasing. Our research activities include: (1) near-field microscopic measurement of the intensity distribution; (2) numerical simulation of lightwave propagation and cavity formation in random media; and (3) fabrication of optoelectronic devices such as waveguides and lasers with semiconductor polycrystalline and nanoparticle films on various substrates. If successful, our work could improve the understanding of nanoparticle films and the physics of nanostructures, potentially leading to novel device applications.

Science of New Materials
S.-T. Ho*
Sponsor: National Science Foundation

This is a collaborative effort with research groups in the Materials Science, Chemistry, and Physics Departments to study new materials for device applications. Current research projects include: (1) novel optical phase and amplitude modulators based on erbium-doped ferroelectric thin films; (2) potentially low-voltage, high-speed optical phase and amplitude modulators based on self-assembled organic polymers having very high electro-optic coefficients; (3) large-bandgap semiconductors; and (4) materials having strain-induced quantum dots / wires.

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*Denotes Photonic Systems and Technology Group faculty member(s), listed in alphabetical order.

Self-Assembled Materials Systems and Devices for RF / Lightwave Integrated Circuits

S.-T. Ho*

Sponsor: Defense Advanced Research Projects Agency

Present-generation radio frequency (RF) systems are severely challenged by the lack of compact, lightweight, inexpensive components capable of efficient broadband analog signal distribution and processing. This research is a focused collaborative program to develop and implement a unique multilayer materials system for very low-voltage, ultrahigh-frequency electro-optic modulators for RF / lightwave integrated circuits.

High Detection Efficiency Photon Counters at 1064nm and Their Use in a Novel Quantum Imaging Scheme

P. Kumar*

Sponsor: National Aeronautics and Space Administration

This is a training grant for Paul Voss. Indium gallium arsenide and germanium avalanche photodiodes (APD's) are being studied when used as photon counters. Methods of optimizing the low-light-level performance of APD's in the near infrared are being investigated. A related objective is to adapt the statistical technique of optical homodyne tomography (OHT) for use in LIDAR applications. OHT has the advantage that relatively inexpensive high-quantum-efficiency PiN photodiodes can be used in low-light applications where photon counting is usually required. The idea behind OHT is similar to medical tomography where a 2-D or 3-D mass distribution is reconstructed from measurements of absorption at many particular angles, but in OHT it is the quantum state of radiation that is reconstructed from statistics of interference between a local oscillator and a very weak signal.

Instrumentation to Characterize Cache Memory Buffers and Regenerators for Optically Digital Communication and Processing at the Quantum Limit

P. Kumar*

Sponsor: Air Force Office of Scientific Research

This grant is to purchase an ultrafast synchronously pumped optical parametric oscillator. The instrument, which is a tunable source of sub-picosecond pulses in the 1.3 – 1.5 μm communication band, will be used to characterize novel all-optical devices such as fiber-optic cache-memory buffers and optical regenerators that are being developed to demonstrate optically digital communication and processing at the quantum limit. Such devices will also be essential for deploying packet-switched, ultrahigh-speed, time-division multiplexed, all-optical networks capable of operating at speeds in excess of 100 Gb/s.

Instrumentation to Measure the Error Performance of Quantum-Limited Optical Bit-Processing Devices that Utilize Short-Pulse Parametric Interactions

P. Kumar*

Sponsor: Air Force Office of Scientific Research

This grant is to purchase a digital data analyzer (DDA) which combines the functions of pulse-pattern generation and error detection into one instrument. The DDA measures the error performance of optical bit processing devices that include fiber-optic cache-memory buffers, tunable clock recovery modules, and picosecond-pulse all-optical regenerators. All of these take advantage of the ultrafast parametric nonlinearity of glass fiber. We are developing these devices to demonstrate optical digital communication and processing at the quantum limit. Such devices will be capable of operating at speeds in excess of 100 Gb/s, and will be essential for deploying packet-switched ultrahigh-speed time-division multiplexed all-optical networks.

Integrated Devices for Terabit / Second 1.3 and 1.5 Micron WDM / TDM Network Applications

P. Kumar,* S.-T. Ho,* and B. W. Wessels*

Sponsor: Defense Advanced Research Projects Agency / Air Force
Multidisciplinary University Research Initiative

We are developing novel, compact, integrated, optoelectronic and optical devices for use in ultrahigh-speed wavelength-division-multiplexed and time-division-multiplexed networks. The devices include: (1) fiber-optic parametric-amplification-based storage buffers, tunable pulsed oscillators, time-domain demultiplexers, clock extractors, and regenerators; (2) microcavity lasers, modulators, and multiplexers / demultiplexers; and (3) thin-film optically active waveguide modulators and amplifiers. These devices will be capable of operating at speeds approaching 1 terabit per second. A number of specific collaborative research projects are being pursued. The collaboration spans three academic disciplines and an industrial partner (a small business subcontractee).

Nonlinear Fiber-Optics with Picosecond Pulses for All-Optical WDM/TDM Systems

P. Kumar* and W. Kath

Sponsor: National Science Foundation

Recent development of the "all-wave" optical fiber opens up the possibility of massive wavelength-division multiplexing across a wavelength range that extends from 1200 to 1600 nm. To take advantage of this ever-widening transmission window, a collaborative experimental / theoretical research program is undertaken to demonstrate control of short pulses (< 1 ps) in fiber-optic communication systems and networks by use of parametric amplification. Our theoretical and experimental work has shown that parametric amplification can process signals optically while suppressing a number of effects that are detrimental to high bit-rate (potentially approaching 100's of Gbit/s per channel) transmission, storage, clock recovery, regeneration, and wavelength conversion.

Quantum Information Technology: Entanglement, Teleportation, and Quantum Memory

P. Kumar* and H. P. Yuen*

Sponsor: Army Research Office
Multidisciplinary University Research Initiative (with MIT)

This multidisciplinary university research initiative (MURI) addresses key issues relevant to the development of quantum information technology. The preeminent obstacles to such development include the difficulty of transmitting quantum information over noisy and lossy quantum communication channels, recovering and refreshing the quantum information that is received, and then storing the information in a reliable quantum memory. To overcome these obstacles, MIT and Northwestern have assembled a multidisciplinary theoretical / experimental team in the areas of quantum communication and measurement, quantum computation, nonclassical light-beam generation and detection, nonlinear optics in bulk crystals and optical fiber, computational complexity and error-correcting codes, and atomic physics. This team is conducting a research program that addresses: (1) entanglement, teleportation, and quantum storage using singlet photon states; (2) entanglement and teleportation using field quadratures; and (3) new paradigms for quantum communication and memory. The Northwestern effort focuses on the generation of entangled-photon pulses in optical fibers and the theory of quantum communication and fiber quantum memory.

Quantum Optics with a Q-Switched Pump Source

P. Kumar*

Sponsor: Office of Naval Research

High pump power, a must for most nonlinear optical effects, is easily obtained with the use of a Q-switched laser. Recently, we have demonstrated that such a laser can be employed in quantum-optics experiments with great success. Unlike the case with optical cavities, quantum effects are

observed in a single-pass traveling-wave type of interaction with a nonlinear medium, resulting in a large temporal bandwidth. Our approach to quantum-light generation has been followed in many laboratories around the world. We have demonstrated the generation of squeezed states of light, twin-beam states of light, and sub-Poissonian states of light. Using a setup that self-generates a matched local oscillator for the detection of squeezing, in 1994 we observed 5.8±0.2 dB of quadrature squeezing, which is still the highest to date for a single-pass traveling-wave experiment. In this program, we are conducting such proof-of-principle experiments that demonstrate the use of a Q-switched pump laser in the generation and application of pulsed twin-beams and squeezed states of light. In the past few years, our major thrust has been to perform pulsed sub-shot noise imaging experiments. In particular, we have demonstrated quantum correlations in images that have been parametrically amplified and performed experiments to show that noiseless image amplification is possible with optical parametric amplifiers.

Squeezed Light Generation by Means of Traveling-Wave $\chi^{(2)}$ Interactions in Lithium Niobate Waveguides

P. Kumar*

Sponsor: National Science Foundation

This is an experimental program to develop an integrated lithium-niobate waveguide device for use as a reliable, compact source of highly-squeezed-light with relatively low-power mode-locked lasers. The experiments rely on traveling-wave degenerate second-harmonic generation and optical parametric amplification exploiting the $\chi^{(2)}$ nonlinearity of lithium niobate. These experiments are based on our analyses of traveling-wave degenerate $\chi^{(2)}$ interactions in which two indistinguishable fundamental-frequency photons and one second-harmonic photon participate. This is a collaborative project with Prof. M. Fejer of Stanford, who is fabricating and developing the required integrated, quasi-phasematched, low-loss, lithium niobate waveguides.

Imaging of Early-Stage Breast Cancers

A. Taflove*

Sponsor: U.S. Army Breast Cancer Program

This is a predoctoral training grant for Milica Popovic. Novel time-domain inverse scattering techniques involving finite-difference time-domain (FDTD) computational electromagnetics modeling are used to obtain breast tissue parameters needed for subsequent ultrawideband microwave imaging of tumors.

Multiband Antennas for Portable Wireless Communications Devices

A. Taflove*

Sponsor: T&M Antennas, Inc.

Finite-difference time-domain (FDTD) computational electromagnetics modeling is applied to design and evaluate novel multiband antennas for use in handheld wireless cellular and PCS telephones. Of particular interest are antennas that can be integrated into the plastic cases of these devices without any external appearance, provide high radiation efficiency and good bandwidth, and yet generate specific absorption rate (SAR) exposure levels within the head of the user that are significantly below the SAR's generated by widely used external whip and stubby antennas.

Defect Structure of Epitaxial Wide Gap III–N Semiconductors

B. W. Wessels*

Sponsor: National Science Foundation

The defect structure of epitaxial gallium nitride and other wide-bandgap semiconductors is under investigation to optimize their electrical properties. Of special interest are the factors that determine

p-type conductivity. Measurement techniques include photoluminescence spectroscopy, transient photoluminescence, and photocapacitance spectroscopy.

Instrumentation for Integrated Photonic Device Research
B. W. Wessels*
Sponsor: Ballistic Missile Defense Organization
A chemical vapor deposition reactor is being acquired for the metal-organic vapor phase epitaxy of ferroelectrics. This apparatus will be used in research in thin films for integrated optics.

Materials Research Science & Engineering Center
B. W. Wessels*
Sponsor: National Science Foundation
This project involves the synthesis and characterization of ferroelectric thin films for nonlinear optical applications. This is a collaborative project involving faculty from the departments of Electrical and Computer Engineering, Materials Science and Engineering , and Chemistry.

Thermal Spraying of Meso-Electronic Multilayers and Sensors
B. W. Wessels*
Sponsor: Defense Advanced Research Projects Agency / State University of New York Stonybrook
In this collaborative project between the State University of New York (SUNY) at Stony Brook and Northwestern, thermal spraying is being developed to form thick-film dielectric materials directly on substrates at temperatures below 200˚C. Direct writing of lines is being explored. Important potential applications of this technology include sensors and antennas.

Thin Film Modulators for Si-Based Optoelectronics
B. W. Wessels*
Sponsor: Ballistic Missile Defense Organization / SVT Associates
This is an STTR program to develop integrated optics using silicon as a platform. Metal-organic molecular beam epitaxy techniques for this purpose are being developed. The ultimate goal is to develop integrated electro-optic modulators for telecommunications applications.

Amorphous Computing in a High-Speed Secure Quantum Network via Anonymous Quantum Keys
H. P. Yuen* and P. Kumar*
Sponsor: Defense Advanced Research Projects Agency
This project is a proof-of-concept experimental effort to demonstrate the anonymous-key and secret-key quantum cryptographic techniques theoretically introduced by the P.I., H. Yuen. These techniques, which utilize the quantum noise of ordinary laser light, are well suited for deployment over the fiber-optic core networks that carry most of the Worldwide Web traffic.

Lightwave Cryptographic Techniques
H. P. Yuen*, M. Sarrafzadeh, and A. Sahakian
Sponsor: Defense Advanced Research Projects Agency
The objective of this project is to develop new cryptographic techniques, and to modify the important existing ones, for applications to encryption and authentication in energy-constrained sensors with limited memory and computational capability. The goal is to minimize power consumption in order to maximize the lifetime of the sensor operation and the amount of useful processing that can be carried out within the lifetime.

PACT: Power-Aware Architectural and Compilation Techniques
P. Banerjee, M. Sarrafzadeh, A. N. Choudhary, A. Moshovos, and H. P. Yuen*
Sponsor: Defense Advanced Research Projects Agency

The objective of the PACT Project is to develop power-aware architectural techniques and associated compiler and CAD tool support. The specific goals of the PACT project are:

- Develop novel architectural and compiler concepts at various levels that can reduce the total energy consumption in specific applications by factors of 10-100X over conventional, non-power-aware architectures.
- Develop compiler techniques to automate the process of generating efficient code that is within a factor of two of the best manual approach with respect to optimizing power under performance and resource constraints.
- Demonstrate the usefulness of the compiler and architectural concepts on some real applications.

We will target specific algorithms / applications that are of interest to DOD. Moreover, we will develop a prototype of a general-purpose memory system chipset to be used on a variety of systems and applications.

Reliable Computation with Unreliable Components
H. P. Yuen*
Sponsor: Defense Advanced Research Projects Agency

This study explores the fundamental information-theoretic basis of fault-tolerant computation with imperfect and/or imprecise devices.

Patents Issued

S.-T. Ho* and M. K. Chin, "Oval Resonator Device," WO 00/72065, 2000.

J. E. Bridges, A. Taflove*, S. C. Hagness, and A. V. Sahakian, "Microwave Antenna for Cancer Detection System," U.S. Patent No. 6,061,589, May 9, 2000.

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Books

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Symposium Sessions Organized / Chaired

S.-T. Ho,* Program Chair, “Photonic Technology for the 21st Century,” *SPIE Int. Symp. on Optical Science, Engineering, and Instrumentation*, Singapore, Oct 1999.

P. Kumar*, Member Advisory Committee, *Fifth Int. Conf. on Quantum Communication, Measurement, and Computing*,” Capri, Italy, July 3–8, 2000.

P. Kumar*, Member Organizing Committee, *Seventh Int. Conf. on Squeezed States and Uncertainty Relations*, Boston, MA, June 1–6, 2001.

B. W. Wessels*, Member Organizing Committee, *Materials Research Society Fall 1999 Symposium*

B. W. Wessels*, Organizer, 1999 MRS Symposium: *“Thin Films for Optical Waveguide Devices”*

B. W. Wessels*, Member Organizing Committee, *American Physical Society Conf.,* March 2000.

Invited Talks and Seminars

S.-T. Ho*, “Photonic Technology for the 21st Century,” *SPIE Int. Symp. on Optical Science, Engineering, and Instrumentation*, Singapore, Oct. 1999.

P. Kumar*, “Some Recent Classical and Quantum Applications of Nonlinear Fiber-Optics,” Lucent Technologies, Photonics Networks Department, Holmdel, NJ, Sept. 3, 1999.

P. Kumar*, “Quantum Computing,” *Odyssey*, Chicago Public Radio (WBEZ 91.5 FM), Sept. 7, 1999.

P. Kumar*, “Nonlinear Fiber-Optics with Picosecond Pulses for All-Optical TDM Systems,” *MIT EECS/RLE Seminar Series on Optics and Quantum Electronics*, Cambridge, MA, Dec. 1, 1999.

P. Kumar*, “Quantum Correlations in Parametric Amplification: Their Measurement for Testing the State Reduction Rule of Quantum Mechanics,” *Winter Institute on Foundations of Quantum Theory and Quantum Optics*, S. N. Bose National Center For Basic Sciences, Calcutta, India, Jan. 1–13, 2000.

P. Kumar,* “Integrated Devices for Terabit Per Second 1.3 and 1.5 Micron WDM/TDM Network Applications,” *AFOSR Contractors and Grantees Workshop*, SRI, Menlo Park, CA, May 25–26, 2000.

P. Kumar,* “MIT/NU Collaboration on Quantum Information Technology: Entanglement, Teleportation, and Quantum Memory,” *Quantum Communication and Quantum Memory (QCQM) Initiative Kickoff Meeting*, CECOM, Ft. Monmouth, NJ, June 13–14, 2000.

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A. Taflove*, “FDTD – How Complex a Problem Can We Solve?,” Special Millennium Session, *IEEE Antennas and Propagation Society Int. Symp.,* Salt Lake City, UT, July 2000.

B. W. Wessels*, “Synthesis of Ferroelectric Oxide Epitaxial Thin Films by Metal Organic Vapor Phase Epitaxy for Nonlinear Optical Applications,” *12th Int. Symp. on Integrated Ferroelectrics and 3rd European Meeting on Integrated Ferroelectrics*, Aachen, Germany, March 2000.

H. P. Yuen*, “Anonymous Key Quantum Cryptography,” conference name ???, Capri, Italy, July 2000.

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