Chapter 2. Optical Propagation and Communication

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2.1 Introduction

The central theme of our programs has been to advance the understanding of optical and quasi-optical communication, radar, and sensing systems. Broadly speaking, this has entailed: (1) developing system-analytic models for important optical propagation, detection, and communication scenarios; (2) using these models to derive the fundamental limits on system performance; and (3) identifying, and establishing through experimentation the feasibility of techniques and devices which can be used to approach these performance limits.

2.2 Squeezed States of Light

Sponsors

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The squeezed states of light are minimum uncertainty states for the quadrature components of the electromagnetic field which possess an asymmetric noise distribution between the two quadratures. The standard minimum uncertainty state that appears in quantum optics is the Glauber coherent state; it has an equal noise division between the two quadratures and is the quantum analog of the classical electromagnetic wave. Squeezed states are nonclassical and are of interest because their asymmetric noise division can lead to lower noise in photodetection measurements than that achievable with coherent states of the same energy. These noise reductions have been shown, theoretically, to afford significant benefits in interferometric precision measurements and novel guided-wave optical communication devices. We have pursued a vigorous program of experimental and theoretical research on squeezed-state and related nonclassical light.

2.2.1 Experiments

We have employed optical parametric downconversion in a type-I phase-matched $LiNbO_3$:MgO crystal in our efforts to generate nonclassical light. Above threshold, the optical parametric oscillator (OPO) has generated sub-shot-noise intensity correlation—over 50 percent observed noise reduction in the differenced photocurrents from the signal and idler detectors. Our focus has been on the demonstration of squeezed amplification by use of a below-threshold optical parametric amplifier (OPA) in the gain-saturated regime.[2] Under

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2 N.C. Wong, "Squeezed Amplification in a Nondegenerate Parametric Amplifier," *Opt. Lett.* 16(21): 1698-1700 (1991).

gain saturation, the amplified output intensity of an injected coherent-state signal becomes amplitude squeezed, and the signal-to-noise ratio improves. Using a single-frequency diode-pumped YAG laser as the injection source, we have observed classical noise reduction in the signal output as a result of gain saturation. In particular, we have obtained a small-signal noise gain at 4 MHz that is $\sim$ 1 dB lower than the large-signal gain at zero frequency.[3] Due to $\sim$ 8 dB of excess noise of the YAG laser near 4 MHz, quantum noise saturation, and therefore signal-to-noise improvement has not been observed. To observe noise saturation in the quantum regime, we are presently working to reduce the excess intensity noise bandwidth of the YAG laser and to increase the photodetection bandwidth. Potential applications of an injection-seeded gain-saturated OPA include master oscillator output amplification and direct detection digital communication.

2.2.2 Theory

In a detailed study of the OPA or OPO with a strong mean field, we have identified the saturated gain regime in which an injection-seeded OPA generates amplitude squeezing in the signal output and the signal-to-noise ratio improves.[2] Above threshold, an injection-seeded OPO is found to generate more single-beam squeezing at a lower pump level than an unseeded one.

As an application of squeezing and OPOs in the area of precision measurements, a two-arm OPO has been analyzed and proposed as an active gravity-wave detector.[4] The signal and idler waves are internally separated such that the signal beam propagates along one arm of the OPO and the idler beam along the orthogonal arm. By monitoring the phase shift of the signal-idler beat frequency, a sensitive measure of the gravity-wave-induced differential path displacement in the OPO's two interferometer arms is obtained. Furthermore, we have shown that the external phase noise exhibits time-dependent squeezing.

In addition to the OPO/OPA theory, we have been continuing our fundamental attack on the ultimate limits of quantum phase measurement and have renewed our effort to elucidate time constant effects in quantized self-phase modulation. Recent work on quantum phase measurement has focused on two-mode, phase-conjugate detection. Here we have theoretically demonstrated a quantum communication system which affords zero error probability digital communication at finite root-mean-square photon number. This concept also has applications to precision measurements, i.e., it affords the possibility of analog phase-sensing with absolute precision to a prescribed number of decimal places. We have established the optimal state, in a root-mean-square photon number sense, for use with phase-conjugate measurement, and we have obtained the performance of this system in the presence of loss.[5] We found that in the low-loss regime phase-conjugate communication is less sensitive to loss than is number-state communication.

Our work on quantum self-phase modulation is a renewal of earlier research on the Kerr-effect nonlinearity.[6] Previously, we had identified the need to include a material time constant in the quantum theory of such interactions. Whereas the earlier work assumed a phase-insensitive (coherent state) input, our new results allow for an arbitrary phase-sensitive (squeezed state) input.[7] We are concentrating our attention on identifying experimentally accessible quantum artifacts of this time constant. It appears that the inclusion of a small amount of broadband classical input noise may well provide the key—it leads to homodyne noise spectra which diverge from the coupled-mode limit in a manner that depends on the value of the quantum time constant.

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[3] N.C. Wong, K.X. Sun, and J.H. Shapiro, "Squeezed Amplification in a Gain-Saturated Parametric Amplifier," Paper presented at the Optical Society of America Annual Meeting, San Jose, California, November 3-8, 1991.

[4] N.C. Wong, "Gravity-Wave Detection via an Optical Parametric Oscillator," *Phys. Rev. A,* forthcoming.

[5] J.H. Shapiro, "Phase-Conjugate Quantum Communication at Zero Error Probability with Finite Average Photon Number," paper presented at the Optical Society of America Annual Meeting, San Jose, California, November 3-8, 1991.

[6] R.K. John, J.H. Shapiro, and P. Kumar, "Classical and Quantum Noise Transformations Generated by a Kerr Nonlinearity," *Digest of the International Quantum Electronics Conference,* Baltimore, Maryland, April 26-May 1, 1987.

[7] L.G. Joneckis and J.H. Shapiro. "Classical and Quantum Noise Transformations Generated by a Kerr Nonlinearity," paper presented at the Optical Society of America Annual Meeting, San Jose, California, November 3-8, 1991.

2.2.3 Publications

Ho, S.T., P. Kumar, and J.H. Shapiro. "Quantum Theory of Nondegenerate Multiwave Mixing. II. Adiabatic Elimination via Slowly Varying Amplitude Approximation." *Phys. Rev. A* 43(7): 3939-3948 (1991).

Ho, S.T., P. Kumar, and J.H. Shapiro. "Quantum Theory of Nondegenerate Multiwave Mixing. III. Application to Single-Beam Squeezed State Generation." *J. Opt. Soc. Am. B* 8(1): 37-57 (1991).

Ho, S.T., N.C. Wong, and J.H. Shapiro. "Single-Beam Squeezed-State Generation in Sodium Vapor and its Self-Focusing Limitations." *Opt. Lett.* 16(11): 840-842 (1991).

Joneckis, L.G., and J.H. Shapiro. "Classical and Quantum Noise Transformations generated by a Kerr Nonlinearity." Paper presented at the Optical Society of America Annual Meeting, San Jose, California, November 3-8, 1991.

Shapiro, J.H. "Going Through a Quantum Phase." Paper presented at the Workshop on Squeezed States and Uncertainty Relations, College Park, Maryland, March 28-30, 1991.

Shapiro, J.H. "Phase-Conjugate Quantum Communication at Zero Error Probability with Finite Average Photon Number." Paper presented at the Optical Society of America Annual Meeting, San Jose, California, November 3-8, 1991.

Shapiro, J.H., and S.R. Shepard. "Quantum Phase Measurements: A System-Theory Perspective." *Phys. Rev. A* 43(7): 3795-3818 (1991).

Shepard, S.R. "On the Measurement of Time for the Quantum Harmonic Oscillator." Paper presented at the Workshop on Squeezed States and Uncertainty Relations, College Park, Maryland, March 28-30, 1991.

Wong, N.C. "Squeezed Amplification in a Nondegenerate Parametric Amplifier." *Opt. Lett.* 16(21): 1698-1700 (1991).

Wong, N.C. "Gravity-Wave Detection via an Optical Parametric Oscillator." *Phys. Rev. A*, forthcoming.

Wong, N.C. "Squeezed Amplification in a Gain-Saturated Parametric Amplifier." Paper presented at the Conference on Quantum Electronics and Laser Science, Baltimore, Maryland, May 12-17, 1991.

Wong, N.C., K.X. Sun, and J.H. Shapiro. "Squeezed Amplification in a Gain-Saturated Parametric Amplifier." Paper presented at the Optical Society of America Annual Meeting, San Jose, California, November 3-8, 1991.

Wong, N.C. "Gravitational Wave Detection via an Optical Parametric Oscillator." Paper presented at the Optical Society of America Annual Meeting, San Jose, California, November 3-8, 1991.

2.3 Optical Frequency Division

Sponsors

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An optical parametric oscillator (OPO) efficiently converts an input pump into two intense, coherent subharmonic outputs whose frequencies are tunable and whose sum frequency equals the pump frequency. By measuring the output frequency difference relative to a microwave source, the output frequencies are precisely determined, and the OPO functions as an optical frequency divider.[8] Optical parametric dividers (OPDs) can be operated in series or in parallel to measure, compare, and synthesize frequencies from optical to microwave, with high precision and resolution. This new technique of optical frequency division will be important in precision measurements, optical frequency standards, and coherent optical communications.

We have successfully phase locked the signal-idler output beat frequency of our two-element KTP OPO to a microwave synthesized signal at 9.36 GHz, thus demonstrating the OPO approach to

[8] N.C. Wong, "Optical Frequency Division Using an Optical Parametric Oscillator," *Opt. Lett.* 15(20): 1129-1131 (1990).

tunable optical frequency division.[9] The demodulated signal-idler beat spectrum of the phase-locked OPO shows a beatnote linewidth of no more than a few Hz, indicating that the output frequency linewidths are limited mostly by the pump laser frequency noise rather than the inherent OPO phase diffusion noise. The design of our two-element KTP OPD permits systematic and continuous frequency tuning. Together with its low threshold (40 mW) and high conversion efficiency (30%), the KTP OPD can be useful in potential applications such as optical communications.

We have proposed the use of OPDs to generate a 10 THz, precision optical frequency comb.[10] By pumping a set of 10 OPDs at 750 nm wavelength, the outputs at 1.5 μm wavelength serve as major frequency markers at 0.5 THz frequency intervals. Strong external phase modulation of the OPD outputs is used to maintain the phase-locked loops and to provide minor frequency markers at $\sim$ 20 GHz intervals. In a dense fiber-based optical communication network, this scheme greatly simplifies the identification of channel frequencies over the entire bandwidth with kHz precision and accuracy, thus increasing its channel capacity.

As an application in the field of precision measurements, we have analyzed theoretically the use of a two-arm OPO as an active gravity-wave detector.[11] The signal and idler waves are internally separated such that the signal beam propagates along one arm of the OPO and the idler beam along the orthogonal arm. By monitoring the phase shift of the signal-idler beat frequency, a sensitive measure of the gravity-wave-induced differential path displacement in the OPO's two interferometer arms is obtained. The advantages of a low-loss all-solid-state OPO detector include its insensitivity to pump frequency noise and signal detection in a quiet radio frequency region.

2.3.1 Publications

Lee, D., and N.C. Wong. "Tunable Optical Frequency Division Using a Phase-Locked Optical Parametric Oscillator." *Opt. Lett.* 17(1): 13-15 (1992).

Wong, N.C. "Gravitational Wave Detection via an Optical Parametric Oscillator." Paper presented at the Optical Society of America Annual Meeting, San Jose, California, November 3-8, 1991.

Wong, N.C. "Gravity-Wave Detection via an Optical Parametric Oscillator." *Phys. Rev. A,* forthcoming.

Wong, N.C. "Precise Optical Frequency Comb Generation based on Optical Parametric Oscillators." Paper presented at the Optical Society of America Annual Meeting, San Jose, California, November 3-8, 1991.

Wong, N.C. "Proposal for a 10 THz, Precision Optical Frequency Comb Generator." Submitted to *IEEE Photonics Tech. Lett.*

Wong, N.C., and D. Lee. "Experimental Demonstration of a Tunable Optical Frequency Divider." Paper presented at the American Physical Society, Spring Meeting, Washington, D.C., April 22-25, 1991.

Wong, N.C., and D. Lee. "Optical Parametric Division." Invited paper. Accepted for presentation at the 46th Symposium on Frequency Control, Hershey, Pennsylvania, May 27-29, 1992.

Wong, N.C., and D. Lee. "A Tunable Optical Parametric Oscillator for Precision Measurements." Paper presented at the Optical Society of America Annual Meeting, San Jose, California, November 3-8, 1991.

2.4 Laser Radar System Theory

Sponsor

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Project Staff

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Coherent laser radars represent a true translation to the optical frequency band of conventional microwave radar concepts. Owing to the enormous

[9] D. Lee and N.C. Wong, "Tunable Optical Frequency Division Using a Phase-Locked Optical Parametric Oscillator," *Opt. Lett.* 17(1): 13-15 (1992).

[10] N.C. Wong. "Proposal for a 10 THz, Precision Optical Frequency Comb Generator," submitted to *IEEE Photonics Tech. Lett.*

[11] N.C. Wong, "Gravity-Wave Detection via an Optical Parametric Oscillator," *Phys. Rev. A*, forthcoming.

wavelength disparity between microwaves and light, laser systems offer vastly superior space, angle, range, and velocity resolution as compared to their microwave counterparts. However, the resolution benefits associated with the shortness of laser wavelengths are accompanied by the penalties of this wavelength region: the ill-effects of atmospheric optical wave propagation in turbulent or turbid conditions, and the speckle patterns resulting from target roughness on wavelength scales. The ensuing trade-off between resolution advantages and propagation/speckle disadvantages makes it likely that laser radars will fill new application niches, rather than supplant existing microwave systems.

We have been working to quantify the preceding issues through development and experimental validation of a laser radar system theory. Our work includes a collaboration arrangement with the Opto-Radar Systems Group of the MIT Lincoln Laboratory, whereby the experimental portions of the research are carried out with measurements from their CO_2 laser radar test beds.

2.4.1 Target Detection and Recognition Theory

We have been developing the appropriate target-detection theory for multipixel multidimensional laser radar imagers, including those systems which augment their active-sensor channels with a forward-looking infrared (FLIR) passive channel. Our development of generalized likelihood-ratio tests (GLRTs) and associated receiver operating characteristics (ROCs) for this problem has addressed the realistic case of detecting a spatially-resolved, speckle target embedded in a spatially-resolved, speckle background. The target, if it is present, has unknown azimuth, elevation, range, and reflectivity. The background reflectivity is also unknown. Results of theory, computer simulation, and experiments have supported and quantified the intuitive notion that additional sensor dimensionality significantly improves detection performance. In recent work, we have removed the previous restriction of coarse-range (2-D) pulsed imager operation, by introducing the correct statistical model for fine-range (3-D) pulsed-imager operation.[12] We have also eliminated the assumption that the background's planar range profile is known, by using the expectation-maximization algorithm to obtain maximum-likelihood background range estimates.[13] This approach is both calculationally convenient and amenable to generalization to higher-order range fits. Finally, we have extended our framework to include the problem of maximum-likelihood target recognition, providing, for the first time, near-optimal processor structure and performance results for this M-ary decision task.[14]

2.4.2 Laser Radar Tomography

Through collaboration with the Laser Radar Measurements Group of the MIT Lincoln Laboratory, we have completed an investigation of the effects of target speckle on tomographic laser radar imaging.[15] Impulse-response descriptions for the mean image behavior of Doppler-time-intensity (DTI) and range-time-intensity (RTI) operation have been obtained. These impulse responses show space-variant effects commensurate with results obtained from experiment and simulation. Carrier-to-noise ratio and signal-to-noise ratio formulas were also derived for both DTI and RTI imagers. We found that speckle noise can be suppressed, without resolution loss, by increasing the number of projections employed.

2.4.3 Publications

Binder, B.T. *Laser Radar Tomography: The Effects of Speckle.* Ph.D. diss., Dept. of Electr. Eng. and Comput. Sci., MIT, 1991.

Green, T.J., Jr., and J.H. Shapiro. "Maximum-Likelihood Laser Radar Range Profiling with the Expectation-Maximization Algorithm." Submitted to *Opt. Eng.*

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12 T.J. Green, Jr., J.H. Shapiro, and M.M. Menon, "Target Detection Performance Using 3-D Laser Radar Images." *Proc. SPIE* 1471: 328-341 (1991).

13 T.J. Green, Jr., and J.H. Shapiro, "Maximum-Likelihood Laser Radar Range Profiling with the Expectation-Maximization Algorithm," submitted to *Opt. Eng.*

14 T.J. Green, Jr., *Three-Dimensional Object Recognition Using Laser Radar,* Ph.D. diss., Dept. of Electr. Eng. and Comput. Sci., MIT, 1992.

15 B.T. Binder, *Laser Radar Tomography: The Effects of Speckle,* Ph.D. diss., Dept. of Electr. Eng. and Comput. Sci., MIT, 1991.

Green, T.J., Jr. *Three-Dimensional Object Recognition Using Laser Radar.* Ph.D. diss., Dept. of Electr. Eng. and Comput. Sci., MIT, 1992.

Green, T.J., Jr., J.H. Shapiro, and M.M. Menon. "Target Detection Performance Using 3-D Laser Radar Images." *Proc. SPIE* 1471: 328-341 (1991).

Mentle, R.E., and J.H. Shapiro. "Track-While-Image in the Presence of Background." *Proc. SPIE* 1471: 342-353 (1991).

2.5 Fiber-Coupled External-Cavity Semiconductor High Power Laser

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During 1991, quantitative experiments and associated theory were performed towards the understanding of the physics of the fiber-coupled external-cavity semiconductor high-power laser. The understanding that has been gained is also relevant in general to semiconductor laser arrays within external cavities and to monolithic semiconductor diode arrays. The issue of phasing the outputs from the coherent ensemble of elements in the array, which has been addressed in this work, is important for all arrays. Polarization, phasing the inputs to the external cavity, and coherence of the output from the external cavity have been studied.

The threshold current of the ensemble increases as the polarization of the radiation input to the cavity from one of the fibers is changed from the cavity's lowest threshold mode (TE). In addition, the output polarization of the ensemble rotates away from TE by up to 5 degrees. The experimental results are in agreement with theory.

The output spectrum of the ensemble tunes in wavelength and passes through a series of secondary modes of operation as the optical-path-length of one of the fiber inputs is increased. At these new wavelengths, the ensemble operates with lower output power in the dominant mode and greater output power in the side modes. At these new wavelengths the total power output was also reduced. A computer simulation found the intersections of the resonant frequencies of the fiber inputs to the cavity, computed the gain at these wavelengths (including the effects of non-perfect anti-reflection coating on the front facet of each laser diode), and predicted the output power in each of these modes. The program also tracked the maximum-gain wavelength of the ensemble as the optical-path-length of a single fiber is increased and predicted the wavelength tuning of the ensemble. The wavelength tuning results are in agreement with experimental data. At higher wavelength shifts, however, the predicted output power in the predominant operating modes is higher than the experimental results.

The coherence between different pairs of the five gain elements decreases with increasing spatial separation between the fiber inputs to the cavity. The coherence also decreases with larger slit widths in the spatial filter inside the cavity. The results are explained based on spontaneous emission inside the five separate gain elements and the action of the spatial filter. The coherence does not depend on phase changes of the optical inputs into the external cavity.

Publications

Corcoran, C.J., and R.H. Rediker. "Operation of Five Individual Lasers as a Coherent Ensemble by Fiber Coupling into an External Cavity." *Appl. Phys. Lett.* 59(7): 759-761 (1991).

Corcoran, C.J., R.H. Rediker, and K. Rauschenbach. "Effects on the Operation of an External-Cavity Laser of Phase Differences Between Multiple Inputs into the Cavity." Paper presented at the IEEE Lasers and Electro-Optical Society (LEOS) Annual Conference, San Jose, California, November 4-7, 1991.

Rediker, R.H, K.A. Rauschenbach, and R.P. Schloss. "Operation of a Coherent Ensemble of Five Diode Lasers in an External Cavity." *IEEE J. Quantum Electron.* 27(6): 1582-1593 (1991).

2.6 Analog Processing of Optical Wavefronts Using Integrated Guided-Wave Optics

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In wavefront sensing and correction, it is envisioned that 10^3-10^4 basic modules would be used. In integrated optics, as in integrated circuits, it is important to relax the requirements on individual components and require that the operation of the integrated optics (circuits) be independent of significant component variations. The wavefront is sensed by interferometers between the multiplicity of through waveguides with the arms of the interferometers evanescently coupled to adjacent waveguides. The input powers to the interferometer arms will not be equal as a result of (1) the input power to the waveguide array being nonuniform and (2) unequal coupling by the evanescent couplers.

A Y-junction interferometer phase measurement technique has been developed which is independent of the power or power ratio in the input arms. The technique is intended for use in the basic module of the proposed integrated optical system for use at GaAs wavelengths that produces a flat-phase output wavefront. A proof-of-concept AlGaAs guided-wave Mach-Zehnder interferometer was employed to demonstrate measurement and correction of a phase difference between the arms using this technique. Results have been obtained for cases of successive steps in the phase difference between the interferometer arms, of random phase differences, and of intentional power imbalance between the arms. Power ratios greater than 10:1 between the arms have been created by applying a high voltage to a phase modulator in one arm so that power is absorbed via electro-absorption and/or by forward-biasing a modulator in one arm so that power is absorbed by carrier absorption. The experimental results on the phase measurement and phase correction have been independent of power imbalance up to these ratios of greater than 10:1.

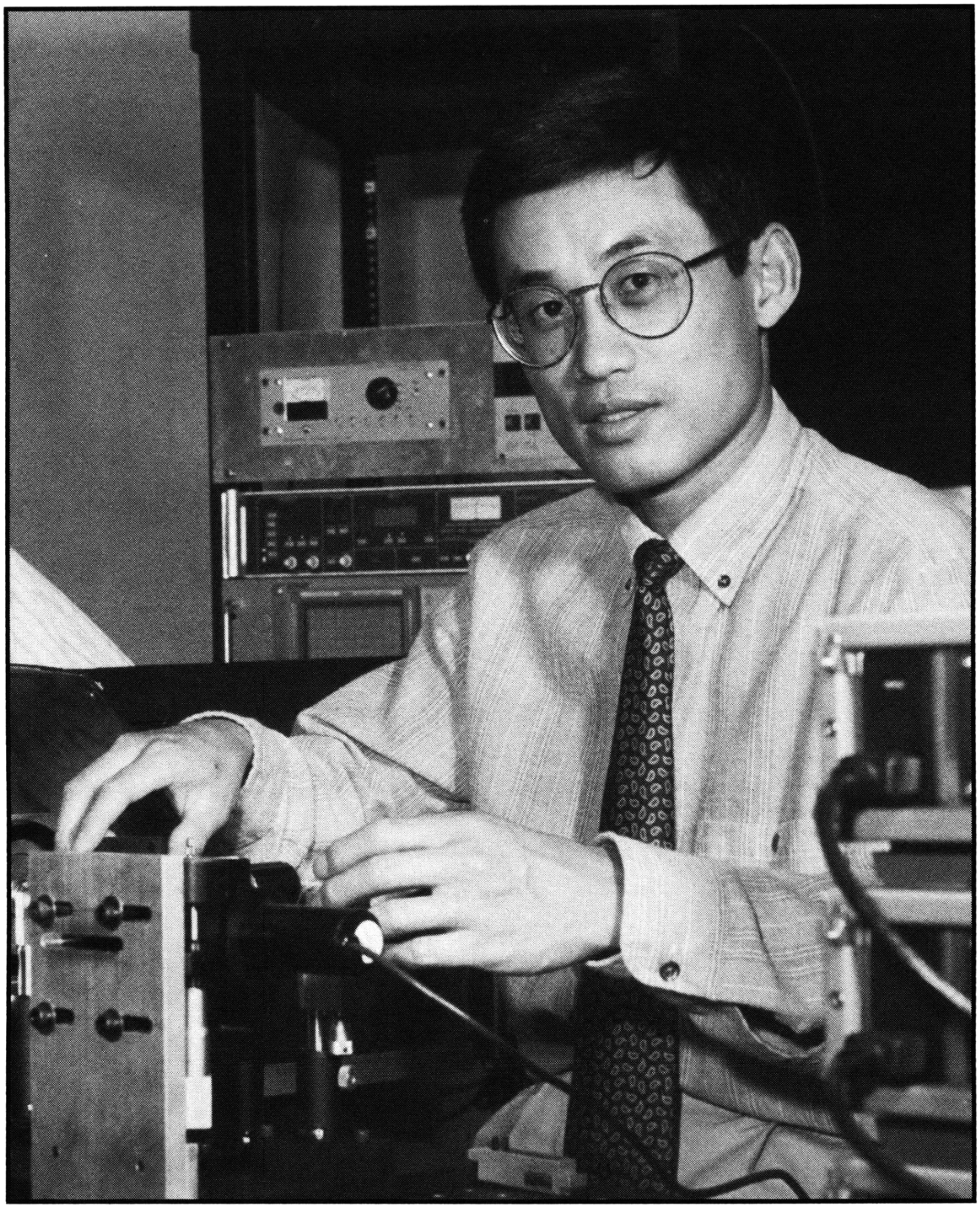
The Mach-Zehnder interferometer was fabricated using a dielectric-loaded strip waveguide structure. The modal characteristics of these waveguides were modelled theoretically and compared to experimental results. The waveguide propagation loss was less than 1 dB/cm measured at 862 nm by a Fabry-Perot technique. The abrupt bend and Y-junction insertion loss was measured as a function of angle. The abrupt bend insertion loss was $\approx$0.20 dB/bend for 0.5 degree angle and the Y-junction insertion loss was $\approx$0.37 dB for a 1.0 degree full angle. Phase modulators were fabricated by a selective Be ion implantation, followed by rapid thermal annealing, to form a p^+-n-n^+ structure. The phase in the waveguides was modulated via the electrooptic effect by reverse biasing the p-n structure. The compositions of the AlGaAs epilayers were chosen to minimize electroabsorption at the desired operating wavelengths and voltages. The phase modulators were modelled by a perturbation analysis and a more exact series solution analysis of the waveguide in the presence of an electric field. The more exact analysis is generally applicable to any arbitrary waveguide structure with index profile $n^2(x)$ that can be expressed as a polynomial function of position x.

Publications

Bossi, D.E., W.D. Goodhue, L.M. Johnson, and R.H. Rediker. "Reduced-Confinement GaAlAs Tapered Waveguide Antennas for Enhanced Far-Field Beam Directionality." *IEEE J. Quantum Electron.* 27(3): 687-695 (1991).

Lau, S.D., J.P. Donnelly, C.A. Wang, R.B. Goodman, and R.H. Rediker. "Optical Wavefront Phase Tilt Measurement and Correction Using AlGaAs Integrated Guided-Wave Components." Paper presented at the Integrated Photonics Research Topical Meeting, Monterey, California, April 9-11, 1991, pp. 124-125.

Lau, S.D., J.P. Donnelly, C.A. Wang, R.B. Goodman, and R.H. Rediker. "Optical Phase Difference Measurement and Correction Using AlGaAs Integrated Guided-Wave Components." *IEEE Photon. Tech. Lett.* 3(10): 902-904 (1991).



Professor Qing Hu