Chapter 5. Optical Propagation and Communication

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5.1 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.

5.2 Squeezed States of Light

Sponsors

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Project Staff

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The squeezed states of light (also called the two-photon coherent states) 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.

5.2.1 Experiments

We have two principal experiments for the generation of nonclassical light: a forward four-wave mixer, and an optical parametric oscillator (OPO). The forward four-wave mixer is a simple, single-beam configuration using atomic sodium vapor. This experiment has its roots in our original suggestions for generating squeezed light via four-wave mixing.[1] However, owing to the complications associated with the Doppler-broadened resonant atomic medium, correct selection of operating conditions for this system have required vastly more sophisticated theoretical considerations.[2] Our best results show approximately 60 percent inferred quadrature-noise squeezing, at our overall measurement efficiency of approximately 40 percent.[3] The results of an extensive set of single-beam measurements are in reasonable agreement with our theory over a large range of experimental parameters. However, we have identified a hitherto unexpected effect — differential pump/probe self-focusing (DPS) — which limits the amount of squeezing obtainable with a Gaussian-beam pump source. Follow-on experiments will address circumvention of the DPS limit by use of high Fresnel number beams, and work with ytterbium vapor will begin, to reap the benefits of a simpler atomic level system than sodium.

In our OPO experiment, we are trying a different approach to nonclassical light. The parametric downconversion process which is involved automatically creates pairs of perfectly correlated photons, one at the signal wavelength and one at the idler wavelength, as a result of absorption of one pump photon. This correlation provides a directly detectable nonclassical signature — perfect intensity correlation between the photocurrents produced by detectors viewing the signal and idler beams separately — and can be adapted, through feedback or feedforward schemes, to produce squeezed light. We have the first Type I phase-matched OPO to show this nonclassical correlation.[4] Our MgO doped $LiNbO_3$ system has yielded approximately 50 percent observed noise reduction in the differenced photocurrent from the signal and idler detectors (see figure 1).

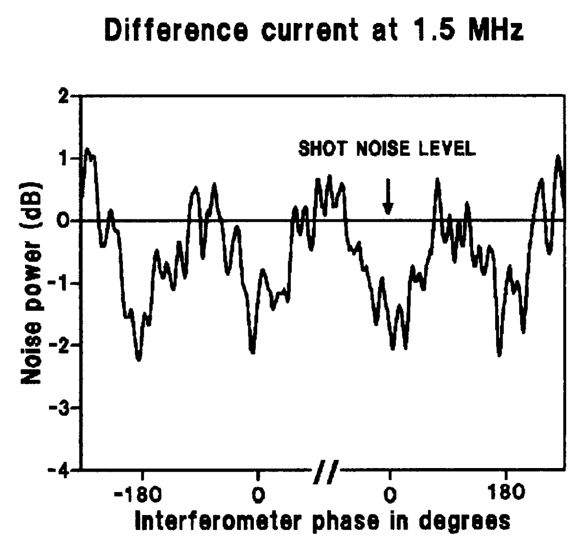

Figure 1. OPO differenced-photocurrent noise power at 1.5 MHz as a function of the relative phase between the arms of an interferometer used to separate the signal and idler beams. The shot noise level is normalized to 0 dB. Nonclassical correlation between the signal and idler is demonstrated by noise powers below 0 dB.

Work is continuing to improve this correlation and to perform feedback and feedforward squeezed-state generation with this setup.

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1 H.P. Yuen and J.H. Shapiro, "Generation and Detection of Two-Photon Coherent States in Degenerate Four-Wave Mixing," *Opt. Lett.* 4 (10): 334-336 (1979); P. Kumar and J.H. Shapiro, "Squeezed State Generation via Forward Degenerate Four-Wave Mixing," *Phys. Rev. A* 30 (3): 1568-1571 (1984).

2 S.-T. Ho, P. Kumar, and J.H. Shapiro, "Quantum Theory of Nondegenerate Multiwave Mixing," *Phys. Rev. A* 35 (9): 3982-3985 (1987); S.-T. Ho, P. Kumar, and J.H. Shapiro, "Quantum Theory of Nondegenerate Multiwave Mixing: General Formulation," *Phys. Rev. A* 37 (6): 2017-2032 (1988); S.-T. Ho, *Theoretical and Experimental Aspects of Squeezed State Generation in Two-Level Media,* Ph.D. diss., Dept. of Electr. Eng. and Comput. Sci., MIT, 1989.

3 S.-T. Ho, *Theoretical and Experimental Aspects of Squeezed State Generation in Two-Level Media,* Ph.D. diss., Dept. of Electr. Eng. and Comput. Sci., MIT, 1989; S.-T. Ho, N.C. Wong, and J.H. Shapiro, "Self-Focusing Limitations on Squeezed State Generation in Two-Level Media," to appear in *Coherence and Quantum Optics VI*, eds. L. Mandel, E. Wolf, and J.H. Eberly (Plenum: New York, 1989).

4 K.-W. Leong, *Intensity Quantum Noise Reduction with an Above-Threshold Optical Parametric Oscillator,* Ph.D diss. prop., Dept. of Electr. Eng. and Comput. Sci., MIT, 1990.

5.2.2 Theory

Our recent theoretical work on nonclassical light has addressed issues relevant to our experimental work with both the four-wave mixer[5] and the optical parametric oscillator.[6] In addition, we have begun a new fundamental investigation of the sensitivity of quantum phase measurements. This work, which is based on quantum estimation theory, has provided some fundamental justification for identifying the probability operator measure (POM) associated with the Susskind-Glogower phase measurement as the correct description of quantum phase. Using this measurement with an optimal choice of state, we have found that substantially lower phase-measurement errors can be obtained, at the same average photon number, than those predicted for optimized squeezed-state interferometers.[7]

This result has motivated our work to determine an explicit realization of the Susskind-Glogower POM. Toward that end we have established an analogy with the familiar optical heterodyne realization of the annihilation operator POM. This has led to a commuting observables picture of the Susskind-Glogower POM on a larger, signal cum apparatus, state space,[8] as well as the definition and principal properties of two new classes of quantum states, the coherent phase states and the squeezed phase states.[9] Work on quantum phase is continuing through connections between digital signal processing theory that arise because of the Fourier transform relations that exist between the number and phase representations of an arbitrary ket.

5.3 Laser Radar System Theory

Sponsor

U.S. Army Research Office - Durham
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Project Staff

Professor Jeffrey H. Shapiro, Stephen M. Hannon, Thomas J. Green, Jr., Naomi E. Zirkind, Robert E. Mentle

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

5 S.-T. Ho, P. Kumar, and J.H. Shapiro, "Quantum Theory of Nondegenerate Multiwave Mixing," *Phys. Rev. A* 35 (9): 3982-3985 (1987); S.-T. Ho, P. Kumar, and J.H. Shapiro, "Quantum Theory of Nondegenerate Multiwave Mixing: General Formulation," *Phys. Rev. A* 37 (6): 2017-2032 (1988); S.-T. Ho, *Theoretical and Experimental Aspects of Squeezed State Generation in Two-Level Media,* Ph.D. diss., Dept. of Electr. Eng. and Comput. Sci., MIT, 1989; S.-T. Ho, N.C. Wong, and J.H. Shapiro, "Self-Focusing Limitations on Squeezed State Generation in Two-Level Media," to appear in *Coherence and Quantum Optics VI*, eds. L. Mandel, E. Wolf, and J.H. Eberly (Plenum: New York, 1989).

6 K.-W. Leong, *Intensity Quantum Noise Reduction with an Above-Threshold Optical Parametric Oscillator,* Ph.D. diss. prop., Dept. of Electr. Eng. and Comput. Sci., MIT, 1990; K.-W. Leong, N.C. Wong, and J.H. Shapiro, "Pump Noise in an Optical Parametric Oscillator Operated Above Threshold," paper presented at the Annual Meeting of the Optical Society of America, Santa Clara, California, Oct. 30 - Nov. 4, 1988.

7 J.H. Shapiro, S.R. Shepard, and N.C. Wong, "Ultimate Quantum Limits on Phase Measurement," *Phys. Rev. Lett.* 62 (20): 2377-2380 (1989).

8 J.H. Shapiro, S.R. Shepard, and N.C. Wong, "A New Number-Phase Uncertainty Principle," to appear in *Coherence and Quantum Optics VI*, eds. L. Mandel, E. Wolf, and J.H. Eberly (Plenum: New York, 1989).

9 J.H. Shapiro, S.R. Shepard, and N.C. Wong, "Coherent Phase States and Squeezed Phase States," to appear in *Coherence and Quantum Optics VI*, eds. L. Mandel, E. Wolf, and J.H. Eberly (Plenum: New York, 1989); T.A. Brennan, *The Statistical Behavior of Coherent and Squeezed Phase States,* S.B. thesis, Dept. of Physics, MIT, 1989.

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.

5.3.1 Multipixel Detection 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. Previously, we established the structure of quasi-optimum intensity-only, range-only, and joint range-intensity processors for deciding whether or not a speckle target is present within an image frame.[10] This problem was solved for the realistic case in which the target, if it is present, has unknown azimuth, elevation, range, and reflectivity, and in which there is a spatially-extended speckle background of unknown reflectivity.

Recently, we have reported on the quasi-optimum processors that include the passive channel as well.[11] The great advance in all of our work — over alternative ad hoc treatments — is its associated performance theory, which allows trade-off assessments to be made between radar-system parameters and target-detection performance. Our initial analytic performance results were limited to intensity-only and range-only processors.[12] They were later verified by a computer simulation, which also provided the first quantitative measure of the performance improvement afforded by joint range-intensity processing.[13] The simulation has since been extended to include the full panoply of detection processors.[11] The simulations show that, in general, adding a sensor dimensionality significantly improves detection performance. These results have been confirmed, experimentally, using the MIT

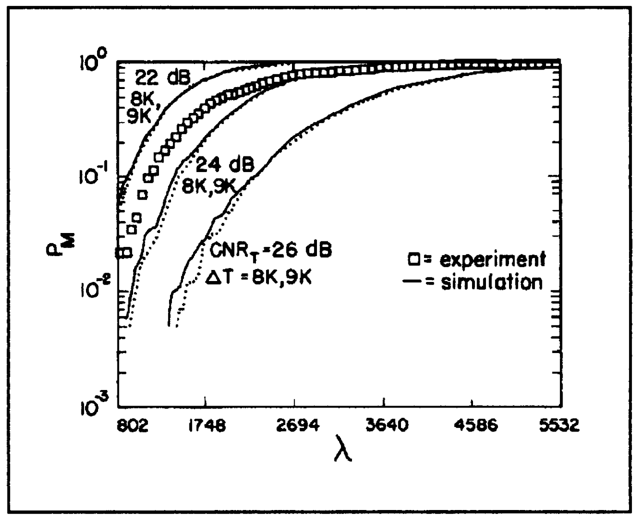

Figure 2. Experimental and computer-simulated miss probabilites (P_M) for a joint range-intensity-passive processor plotted vs. detection threshold λ. The experimental performance is well fit by simulation using a 23 dB target carrier-to-noise ratio (CNR_T) and at thermal contrast (ΔT) between 8 and 9 K. These parameter values are consistent with those inferred directly from the experimental data.

10 M.B. Mark and J.H. Shapiro, "Multipixel, Multidimensional Laser Radar System Performance," *Proc. SPIE* 783, 109-122 (1987); S.M. Hannon and J.H. Shapiro, "Laser Radar Target Detection with a Multipixel Joint Range-Intensity Processor," *Proc. SPIE 999*, 162-175 (1988).

11 S.M. Hannon, *Detection Processing for Multidimensional Laser Radars,* Ph.D. diss., Dept. of Electr. Eng. and Comput. Sci., MIT, 1990; S.M. Hannon and J.H. Shapiro, "Active-Passive Detection of Multipixel Targets," *Proc. SPIE* 1222 (1990).

12 M.B. Mark and J.H. Shapiro, "Multipixel, Multidimensional Laser Radar System Performance," *Proc. SPIE* 783, 109-122 (1987).

13 S.M. Hannon and J.H. Shapiro, "Laser Radar Target Detection with a Multipixel Joint Range-Intensity Processor," *Proc. SPIE* 999, 162-175 (1988).

Lincoln Laboratory multidimensional laser radar test bed (see figure 2).[11]

5.3.2 Multipixel Laser Radar Target Tracking

The preceding target detection work is a multipixel multidimensional single-frame theory. Once a laser radar has detected a target, it will usually need to track that target. Here we have a multipixel multidimensional multiframe task. In recent work,[14] we have established a basic theory for such tracking problems. The correct pixel-level statistics are used to develop the first and second moments of an observation equation for use in a Kalman-filter track-while-image linear least-squares algorithm. The preceding development assumed there were no background reflectors, i.e., an uplooking geometry was presumed. We have now recast the analysis[15] to handle the downlooking geometry that is employed in our detection work.

5.4 Fiber-Coupled External-Cavity Semiconductor High Power Laser

Sponsor

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Grant N00014-89-J-1163

Project Staff

Dr. Robert H. Rediker, Lily Y. Pang, Christopher J. Corcoran, D. Shane Barwick

During this year, we have achieved the milestone of five semiconductor gain elements (lasers with one facet AR coated) fiber-coupled into the external cavity and acting as a coherent ensemble. The combined output from the external cavity is that of a coherent laser. We have *experimentally* verified the concept of this program. In this concept, high average powers were obtained by fiber coupling of physically separated individual lasers and/or monolithic arrays into an external cavity. In this way, the density of power that has to be dissipated can be kept below the value at which it would cause excessive heating and/or would require complicated and space consuming coolers.

Preliminary experiments have been performed on the sensitivity of the ensemble external cavity operation to changes in the optical length of the fiber or to rotation of the output polarization of the fiber. To first order, there is no effect due to a change in the optical length of one of the fibers and thus there must be a compensating self-adjustment to keep the output phase constant. The operation of the ensemble external-cavity laser is more sensitive to rotation of the polarization from one fiber than is the operation of a single external-cavity laser.

Publications

Pang, L.Y. *Polarization Effects on an External Cavity Controlled Ensemble of Fiber-Coupled Semiconductor Diode Lasers.* S.M. thesis. Dept. of Electr. Eng. and Comput. Sci., MIT, 1989.

Rediker, R.H., C. Corcoran, L.Y. Pang and S.K. Liew. "Validation of Model of External-Cavity Semiconductor Laser and Extrapolation from 5-element to Multi-element Fiber-Coupled High-Power Laser." *IEEE J. Quantum Electron.* QE-25(6): 1547-1552 (1989).

Corcoran, C., and R.H. Rediker. "Operation of Five Discrete Diode Lasers as a Coherent Ensemble by Fiber-Coupling into an External Cavity." To be published in the *Technical Digest of Conference on Electoptics and Lasers* CLEO 90, Anaheim, California, May 1990. Washington, DC: Optical Society of America, 1990.

[14] R.H. Enders and J.H. Shapiro, "Laser Radar Tracking Theory," *Proc. SPIE* 999, 192-207 (1988).

[15] R.E. Mentle, *Laser Radar Performance Theory for Track-While-Image Operation,* S.M. thesis prop., Dept. of Electr. Eng. and Comput. Sci., MIT, 1989.

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

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Project Staff

Dr. Robert H. Rediker, Donald E. Bossi, Suzanne D. Lau-Shiple

This program, initiated in March 1987, explores fundamental issues associated with optical wavefront corrections using integrated guided-wave optical devices in GaAlAs. Device fabrication and optimization are being performed at MIT Lincoln Laboratory while results are being evaluated at RLE.

Two tasks were emphasized during 1989. The first has been the development of an adiabatic antenna (an antenna that remains single-mode and loses no energy out of this mode) with an antenna pattern in which almost all of the energy is in a highly-directional central lobe. The second task that is being addressed is the measurement of the wavefront phase. This task includes the development of heterostructure waveguides, bends and Y-junctions, two- and three-guide couplers and phase modulators. These optical components must be consistent with the eventual goal of integration with electronic components on the same chip.

Reduced-confinement GaAlAs slab-waveguide antennas have been fabricated by using an improved MBE growth technique to produce longitudinal variations in the refractive index and thickness of a waveguide film. This technique utilizes the fact that for substrate surface temperatures above 650°C the sticking coefficient of Ga on GaAs decreases with increasing temperature, while below 650°C this sticking coefficient is essentially independent of temperature. By using both growth-temperature regimes and by applying graded heating to the substrate wafer throughout the growth process, the entire reduced-confinement antenna is now produced in a single MBE run without breaking vacuum. The experimentally determined beam divergences for both the guide and the antennas are in excellent agreement with those predicted from the width and Al composition of both these structures. Up to a 37 percent reduction in the beam divergence due to the antenna has been measured.

Numerical simulations demonstrate that requirements on both the amplitude and phase profiles at the antenna output impose a stringent lower limit on the acceptable taper length for optimal device performance. However, by choosing an appropriate taper function, such as a parabolic index profile, the minimum necessary taper length is reduced. For example, a 69 percent reduction in transverse beam divergence, from 16 degrees to 5 degrees FWHM, is attainable from a 1 mm-long taper for which the cladding and film thicknesses total $> 9\ \mu$m.

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. Therefore, two optical wavefront phase tilt measurement configurations have been developed theoretically to measure the wavefront phase tilt, regardless of input power non-uniformity. The first consists of a Y-junction interferometer with a phase dither applied to one of the input arms. The second consists of a three-guide coupler with inputs to the outer arms; a square-wave bias phase function, which switches between zero and $\pi/2$ radians, is applied to one of the input arms. Work is underway to build these two measurement configurations.

Publications

Bossi, D.E., W.D. Goodhue, and R.H. Rediker. *Integrated and Guided-Wave Optics.* 1989 Technical Digest Series Vol. 4. Washington, DC: Optical Society of America, 1989, pp. 80-83.

Bossi, D.E., W.D. Goodhue, M.C. Finn, K. Rauschenbach, J.W. Bales and R.H. Rediker. "Reduced-Confinement Antennas for GaAlAs Integrated Optical Waveguides." *Appl. Phys. Lett.* 56 (5): 420-422 (1990).

Bossi, D.E., W.D. Goodhue, M.C. Finn, K. Rauschenbach and R.H. Rediker. "Fabrication and Enhanced Performance of Reduced-Confinement GaAlAs Tapered-Waveguide Antennas." To be published in the *Technical Digest of the Topical Meeting on Integrated Photonics Research,* Hilton Head, South Carolina, March 1990. Washington, DC: Optical Society of America.

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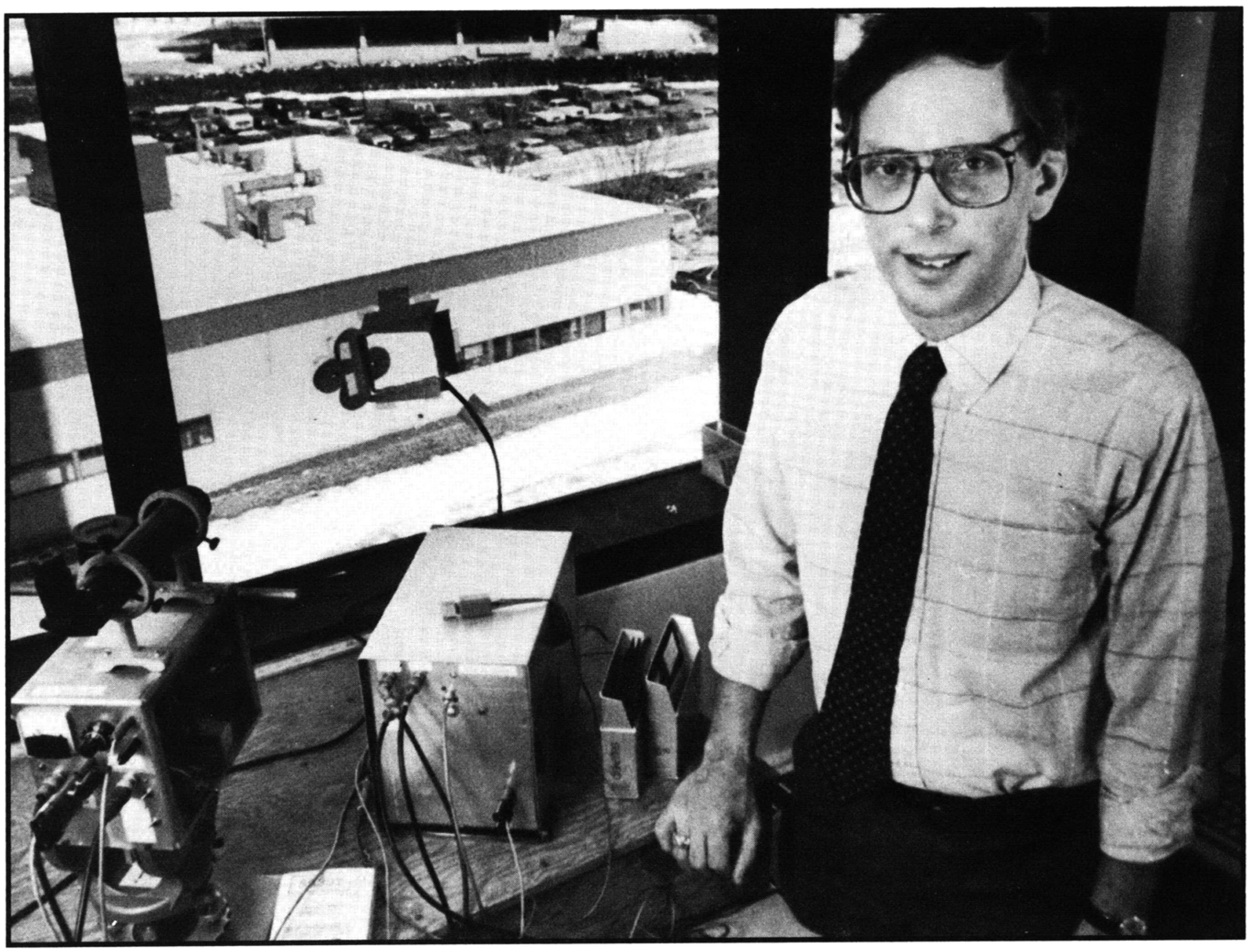

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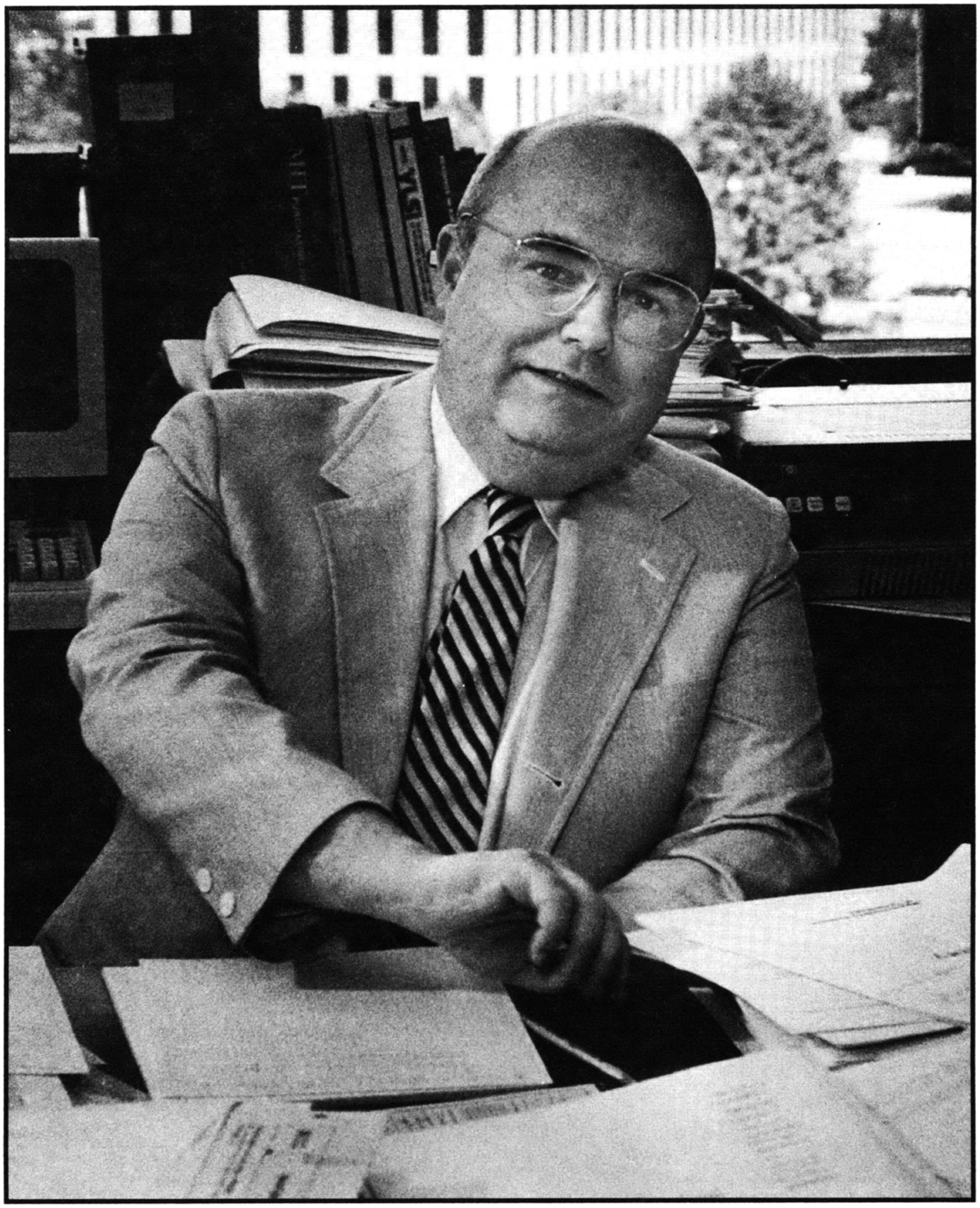

Professor Jonathan Allen, Director, Research Laboratory of Electronics