

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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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.

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. Our best results in an initial series of measurements show approximately 60 percent inferred quadrature-noise squeezing, at our overall measurement efficiency of approximately 40 percent. More importantly, these experiments have identified differential pump-probe self-focusing as the major limiting factor in achieving optimal squeezing in atomic vapor four-wave mixing

pumped by a Gaussian beam.¹ We have been improving both the vacuum setup and the detection electronics of our four-wave mixer, preparatory to a new series of measurements aimed at circumventing the self-focusing regime via use of higher Fresnel-number pump profiles.

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. Our MgO doped LiNbO₃ system has yielded approximately 50 percent observed noise reduction in the differenced photocurrents from the signal and idler detectors.² This initial setup—a three-element cavity—has since been replaced by a simpler, two-element arrangement with vastly superior mechanical stability. We are presently working on a more compact, more stable version of the Mach-Zehnder interferometer used to separate the signal and idler beams produced by the OPO.

5.2.2 Theory

Our theoretical work on nonclassical light has addressed issues relevant to our squeezed-state generation experiments involving four-wave mixing³ and optical parametric oscillation.⁴ The former has examined the broad range of effects affecting choice of an optimal operating point for four-wave mixing squeezed state generation, e.g., spontaneous emission, Doppler broadening, Gaussian-beam profile, etc. The latter has pro-

vided a linearized quantum theory for OPO signal-idler correlation, demonstrating the extreme sensitivity of the low-frequency differenced photocurrent spectrum to pump excess noise when there is an intracavity loss mismatch between the signal and idler beams. This sensitivity has led us to propose that a sub-shot-noise intracavity absorption spectrometer could be built by modulating the OPO pump beam.

In addition to these squeezed-state generation theories, we have been continuing our fundamental attack on the ultimate limits of quantum phase measurement. Here we have made substantial inroads in understanding the properties of the Susskind-Glogower (SG) phase measurement—the maximum-likelihood measurement of a single-mode field's quantum phase. Several new classes of nonclassical states related to this measurement have been identified and analyzed, and a deep analogy between number-phase wavefunction representations and causal discrete-time waveforms has been explored.⁵ Work is continuing on ways to realize the SG measurement, and on the multimode phase measurement problem.

5.2.3 Publications

Ho, S.T., P. Kumar, and J.H. Shapiro. "Quantum Theory of Nondegenerate Multiwave Mixing III. Application to Single-Beam Squeezing." *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." Submitted to *Opt. Lett.*

Ho, S.T., N.C. Wong, and J.H. Shapiro. "Self-Focusing Limitations on Squeezed State Generation in Two-level Media." In *Coherence and Quantum Optics VI*. Eds. L. Mandel, E. Wolf, and J.H. Eberly. New York: Plenum, 1990.

¹ S.T. Ho, N.C. Wong, and J.H. Shapiro, "Single-Beam Squeezed State Generation in Sodium Vapor and its Self-Focusing Limitations," submitted to *Opt. Lett.*

² K.W. Leong, N.C. Wong, and J.H. Shapiro, "Nonclassical Intensity Correlation from a Type-I Phase-Matched Optical Parametric Oscillator," *Opt. Lett.* 15(19): 1058-1060 (1990).

³ S.T. Ho, P. Kumar, and J.H. Shapiro, "Quantum Theory of Nondegenerate Multiwave Mixing III. Application to Single-Beam Squeezing," *J. Opt. Soc. Am. B* 8(1): 37-57 (1991).

⁴ N.C. Wong, K.W. Leong, and J.H. Shapiro, "Quantum Correlation and Absorption Spectroscopy in an Optical Parametric Oscillator in the Presence of Pump Noise," *Opt. Lett.* 15(6): 891-893 (1990).

⁵ J.H. Shapiro and S.R. Shepard, "Quantum Phase Measurement: A System Theory Perspective," *Phys. Rev. A*, forthcoming.

Leong, K.W., N.C. Wong, and J.H. Shapiro. "Non-classical Intensity Correlation from a Type-I Phase-Matched Optical Parametric Oscillator." *Opt. Lett.* 15(19): 1058-1060 (1990).

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

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Shapiro, J.H., S.R. Shepard, and N.C. Wong. "Coherent Phase States and Squeezed Phase States." In *Coherence and Quantum Optics VI*. Eds. L. Mandel, E. Wolf, and J.H. Eberly. New York: Plenum, 1990.

Shapiro, J.H., S.R. Shepard, and N.C. Wong. "Fourier Theory, Uncertainty Relations, and Quantum Phase." Paper presented at 17th International Conference on Quantum Electronics, Anaheim, California, May 21-25, 1990.

Shapiro, J.H., S.R. Shepard, and N.C. Wong. "Fourier Theory, Number-Ket Causality, and Rational Phase States." Paper presented at Nonlinear Optics '90, Kauai, Hawaii, July 16-19, 1990.

Shapiro, J.H. "Going Through a Quantum Phase." Paper presented at the 1990 United States - Japan Seminar on Quantum Electronic Manipulation of Atoms and Fields, Kyoto, Japan, September 3-7, 1990.

Wong, N.C., K.W. Leong, and J.H. Shapiro. "Quantum Correlation and Absorption Spectroscopy in an Optical Parametric Oscillator in the Presence of Pump Noise." *Opt. Lett.* 15(6): 891-893 (1990).

Wong, N.C., K.W. Leong, and J.H. Shapiro. "Non-classical Intensity Correlation from a Type I Phase Matched Optical Parametric Oscillator." Paper presented at 17th International Confer-

ence on Quantum Electronics, Anaheim, California, May 21-25, 1990.

Wong, N.C., K.W. Leong, and J.H. Shapiro. "Quantum Correlation and Absorption Spectroscopy in an Optical Parametric Oscillator." Paper presented at the Annual Meeting of the Optical Society of America, Boston, Massachusetts, November 4-9, 1990.

5.3 Optical Frequency Division

Sponsors

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Project Staff

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An optical parametric oscillator (OPO) converts with high efficiency an input pump, of frequency ν_p , into two intense, coherent subharmonic outputs, a signal (ν_1) and an idler (ν_2), whose frequencies are tunable and whose linewidths are essentially limited by the input pump linewidth. Energy conservation requires that

$$\nu_p = \nu_1 + \nu_2. \quad (1)$$

By phase-locking the output difference frequency

$$\delta = \nu_1 - \nu_2 \quad (2)$$

relative to a microwave, millimeter wave or even infrared reference source, the output frequencies are precisely determined:

$$\nu_{1,2} = \nu_p \pm \delta, \quad (3)$$

and the OPO functions as an optical frequency divider.⁶ OPO-dividers 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 areas of precision measurements, optical frequency standards, and coherent optical communications.

To demonstrate the feasibility of optical frequency division, we use a 2-element OPO using a type-II

⁶ N.C. Wong, "Optical Frequency Division using an Optical Parametric Oscillator," *Opt. Lett.* 15(20): 1129-1131 (1990).

KTP crystal. We have obtained stable cw single-mode operation of our KTP-OPO near its frequency degeneracy, $\nu_1 \approx \nu_2$. Angle tuning of the crystal permits the output frequency separation δ to be set anywhere within 1 THz of degeneracy. We have made direct frequency measurement of the subharmonic output difference frequency δ up to 26 GHz, limited only by the photodetector frequency response and available microwave electronics. Continuous tuning of about 0.5 GHz around the set point is obtained through temperature tuning of the crystal and a piezoelectrically controlled cavity length servo.

We have therefore successfully demonstrated the first tunable optical frequency divider using a KTP-OPO with excellent tuning characteristics—any frequency separation within 1 THz of frequency degeneracy can be obtained by angle and temperature tuning of the crystal. We are in the process of: (1) stabilizing the pump laser frequency to reduce the beatnote jitter; and (2) extending the beat frequency measurement beyond 26 GHz.

5.3.1 Publications

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

Wong, N.C. "Optical Frequency Measurement and Synthesis Using Optical Parametric Oscillators." Paper presented at the Annual Meeting of the Optical Society of America, Boston, Massachusetts, November 4-9, 1990.

5.4 Laser Radar System Theory

Sponsor

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Contract DAAL03-87-K-0117

Project Staff

Professor Jeffrey H. Shapiro, Bradley T. Binder, Thomas J. Green, Jr., Robert E. Mentle

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

length disparity between microwaves and light, laser systems offer vastly superior space, angle, range, and velocity resolution when 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 collaborative arrangement with the Opto-Radar Systems Group of MIT Lincoln Laboratory, under which the experimental portions of the research are carried out with measurements from their CO₂ laser radar test beds.

5.4.1 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. 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 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.⁷ This work applied to 2-D pulsed imagers, i.e., the range information was limited to resolution cells broader than target depth, and assumed that a background range-profile was known. We are now deriving the corresponding 3-D pulsed imager results—here fine-range information is used to resolve targets in depth—and using the estimation-maximization algorithm to obtain maximum-likelihood background range estimates.

⁷ S.M. Hannon and J.H. Shapiro, "Active-Passive Detection of Multipixel Targets," *Proc. SPIE* 1222: 2-23 (1990).

5.4.2 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. We had previously established the basic theory for such tracking problems in an upward-looking, i.e., a background-free, scenario. During the past year, this generalized Kalman-filter approach has been converted to the downward-looking case, viz. background is now included.⁸ Furthermore, this new work has used analysis plus computer simulation to understand the loss-of-lock that can occur in track-while-image operation.

5.4.3 Laser Radar Tomographic Imaging

Through collaboration with the Laser Radar Measurements Group of MIT Lincoln Laboratory, we have begun an investigation of the effects of target speckle on tomographic laser radar imaging. Initial work has focused on determining the impulse-response description for Doppler-time-intensity operation. Our results suggest that use of additional target projections suppress speckle in back-projection and filtered-backprojection imaging, without drastically affecting image resolution.⁹

5.4.4 Publications

Green, T.J., Jr., J.H. Shapiro, and M.M. Menon. "Target Detection Performance Using 3-D Laser Radar Images." Accepted for presentation at Society of Photo-Optical Instrumentation Engineers OE '91, Orlando, Florida, April 1-5, 1991.

Hannon, S.M., and J.H. Shapiro. "Active-Passive Detection of Multipixel Targets." *Proc. SPIE* 1222: 2-23 (1990).

Mentle, R.E. *Laser Radar Performance Theory for Track-While-Image Operation*. S.M. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1990.

Mentle, R.E., and J.H. Shapiro. "Track-While-Image in the Presence of Background." Accepted for presentation at Society of Photo-Optical Instrumentation Engineers OE '91, Orlando, Florida, April 1-5, 1991.

5.5 Fiber-Coupled External-Cavity Semiconductor High Power Laser

Sponsor

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Project Staff

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During 1989, we achieved the milestone of five semiconductor gain elements (lasers with one facet AR coated) fiber-coupled into the external cavity and operating as a coherent ensemble. This year we have quantified the properties of the ensemble external-cavity operation. The cavity output has been shown to be in a single spectral line with a linewidth less than the instrumental resolution (7.5 MHz) of the Fabry-Perot spectrum analyzer used. The phase at the fiber input to the cavity has been changed by stretching each fiber as required using piezoelectric transducers. When the optical path lengths of all of the fibers were initially adjusted to give maximum output power and then the length of one of the fibers changed, the output power decreased and then increased in sequence as the output wavelength changed. This is in theoretical agreement with the inputs from all the fibers being initially in phase and then as the length of one fiber is changed seeking new wavelengths for in-phase operation. With the input phases to the cavity randomized by suitable adjustments of fiber lengths, the output is generally multimode, and the power is about two-thirds of the maximum above and relatively insensitive to change in the length of one of the fibers. Further quantitative experiments and associated theory will be performed in 1991 towards understanding the physics of ensemble external-cavity operation.

⁸ R.E. Mentle, *Laser Radar Performance Theory for Track-While-Image Operation*, S.M. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1990.

⁹ B.T. Binder, *Laser Radar Tomography: The Effects of Speckle*, Ph.D. diss. proposal, Dept. of Electr. Eng. and Comput. Sci., MIT, 1990.

Publications

Corcoran, C., and R.H. Rediker. "Operation of Five Discrete Diode Lasers as a Coherent Ensemble by Fiber-Coupling into an External Cavity." *Technical Digest Series 7*: 552-554 (1990). Washington, D.C.: Optical Society of America, 1990.

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Schloss, R.P., K.A. Rauschenbach, and R.H. Rediker. "Operation of a Coherent Ensemble of Five Diode Lasers in an External Cavity." *IEEE J. Quantum Electron.* Forthcoming.

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

Sponsor

U.S. Air Force - Office of Scientific Research
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F49620-90-C-0036

Project Staff

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This program, initiated in March 1987 and renewed in June 1990, explores fundamental issues associated with optical wavefront corrections using integrated guided-wave optical devices in GaAlAs. Device fabrication and optimization are being performed at Lincoln Laboratory while results are being evaluated at RLE.

Two tasks have continued to be emphasized during 1990. 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 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

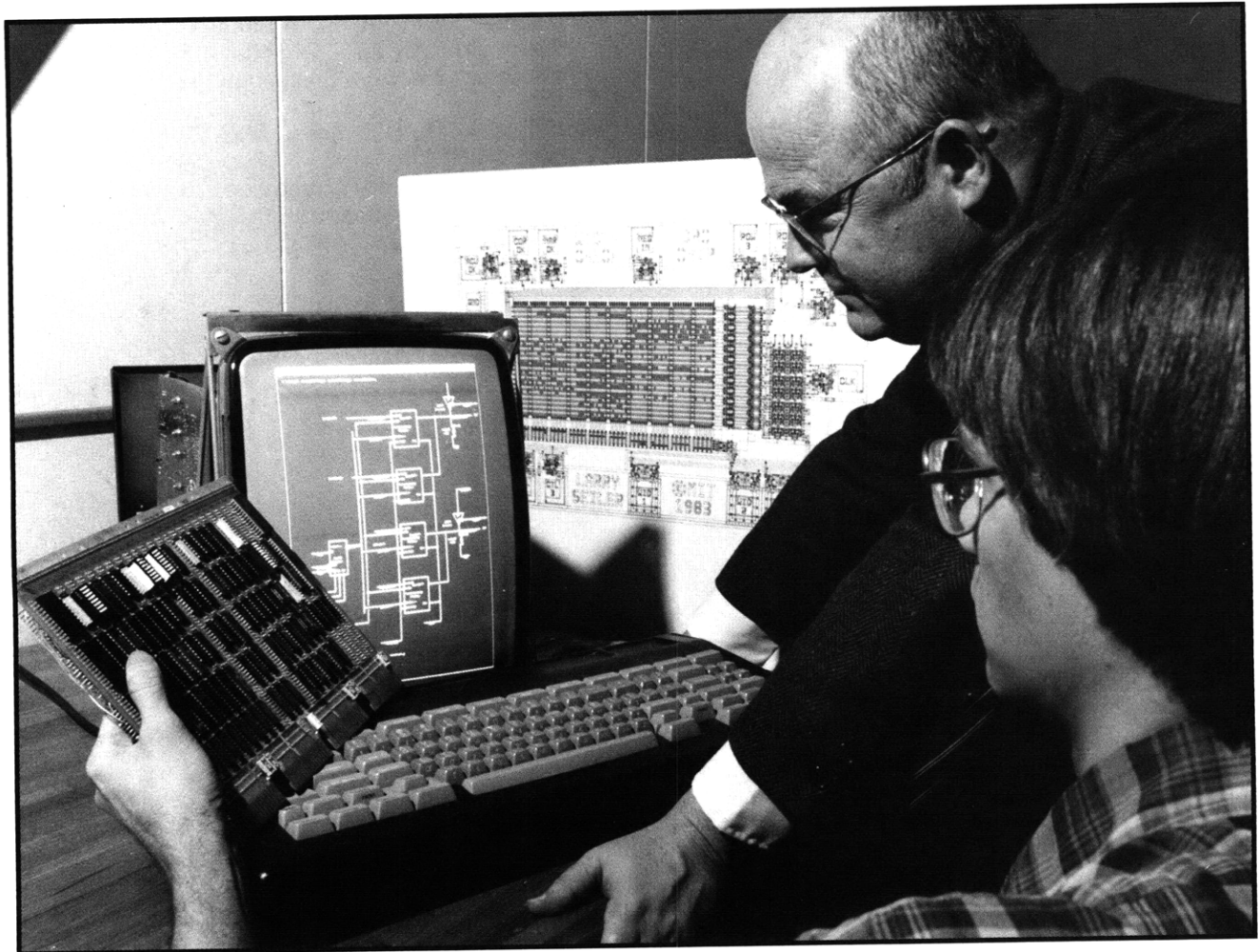
improved MBE growth technique to produce longitudinal variations in the refractive index and thickness of a waveguide film. This technique utilizes the fact that, for substrate surface temperatures above 650°C, the sticking coefficient of Ga on GaAs decreases with increasing temperature, while, below 650°C, this sticking coefficient is essentially independent of temperature. By using both growth-temperature regimes and 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. Forty percent reduction in the beam divergence due to the antenna has been measured.

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 small-amplitude phase dither is applied to the interferometer arms, and the phase tilt between the adjacent through waveguides is determined, independent of power inequality, by the ratio of the amplitudes of the fundamental and second harmonic terms. The voltage from the interferometer output is fed back to an electrode on the through waveguide to set the desired tilt.

A proof-of-concept AlGaAs Mach-Zehnder experimental interferometer system has been designed and built to validate the phase measurement and correction. In this system, there are four p-n junction phase modulators, two on each arm of the interferometer. The sinusoidal dither voltage is applied to one electrode, a voltage V_θ to vary the phase in one arm applied to a second electrode, and the feedback voltage used to maintain a zero phase difference between the output of the two arms applied to a third electrode. The fourth electrode can be forward biased to investigate amplitude as well as phase change.

Publications

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- 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." *Technical Digest Series* 5: 41-42 (1990). Washington, D.C.: Optical Society of America, 1990.
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- Goodhue, W.D., D.E. Bossi, M.C. Finn, J.W. Bales, and R.H. Rediker. "Reduced-Confinement GaAlAs Tapered-Waveguide Antenna Grown by Molecular-Beam Epitaxy." *J. Vac. Sci. Technol.* B8 (2): 349-351 (1990).



From left, Professor Jonathan Allen, Director of the Research Laboratory of Electronics, and graduate student Larry D. Seiler are inspecting the design of a system for high-speed design rule checking which uses four custom integrated circuits in a novel architecture.