6.0 Optical Propagation and Communication

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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.

6.1 Atmospheric Optical Communications in Local Area Networks

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The distribution of computing resources to a community of users often calls for the use of a local area network (LAN). LANs are characterized by limited geographic scopes and data rates in excess of 1 Mbps. Atmospheric optical communication links can support data rates in the Mbps to Gbps range over kilometer path lengths in clear weather, but are subject to outages caused by fog, snow, etc. These characteristics suggest that atmospheric optical communication links may find LAN applications as bridges between buildings containing cable subnetworks, or as temporary quick-connects for new outlying hosts for which cable runs are initailly unavailable. The viability of such applications will depend on the degree to which network users can be insulated from the vagaries of atmospheric optical communication through a judicious combination of link and network design. In this program, we have have established an experimental 10 Mbps token-ring local area computer network that uses atmospheric optical communications over a 170 m outdoor path on the MIT campus. Objective and subjective performance results have been obtained with this system.

In its initial incarnation, our LAN links two IBM-PC microcomputers that are located along a line-of-sight path in Buildings 36 and NE43 (see figure 6.1). Each of these computers is equipped with a PROTEON proNET interface card. The proNET is a commerical 10 Mbps wire-based token-passing ring network that, along with a variety of other commerical and experimental networks, is presently in use on the MIT campus. We have constructed a pair of atmospheric optical communication transceivers that complete the proNET connections between the IBM-PCs in an electrically transparent fashion.

Each transceiver consists of a 10 Mbps Manchester-coded GaAlAs semiconductor laser diode transmitter and a Si avalanche photodiode direct-detection receiver.[1-3] The transmitters employ feedback power-stabilization circuitry, and the receivers are equipped with automatic gain control circuitry.[3] Status information concerning the transmitted and receiver power levels is accumulated at regular intervals by data-acquisition systems attached to each transceiver.[3,4] These data are time-logged and stored by the computers that comprise the network.

The experimental network has been studied in several ways. Objective measurements of packet-level performance have been obtained by having one microcomputer continuously recirculate a packet around the ring, accumulating error statistics.[3] Clear-weather measurements of this type have been made with optical attentuation inserted into the links and used to corroborate a theoretical model for the noise-induced degradation of link performance. Bad-weather measurements of this type have shown significantly different behavior, which we attribute to the burst-error nature of bad weather operation. This hypothesis, which is still under investigation, is supported by data collected with burst-error sensing software.[5]

In addition to the fundamental packet-level performance measurements, we have used the standard Trivial File Transfer Protocol (TFTP) of the Transmission Control Protocol/Internet Protocol (TCP/IP) to probe the utility of our network by employing the IBM-PC in Building NE43 as a remote disk for the IBM-PC in Building 36; this remote disk is accessed through the atmospheric-optical network.[3] Here, we found that the burst-error behavior encountered in bad weather made network file-transfer operations far more fragile, at the same average received-power level, than in random-error (optically-attenuated) clear weather. This observation was supported by subjective comments culled from log files produced by network users via our network-interface software.[6]

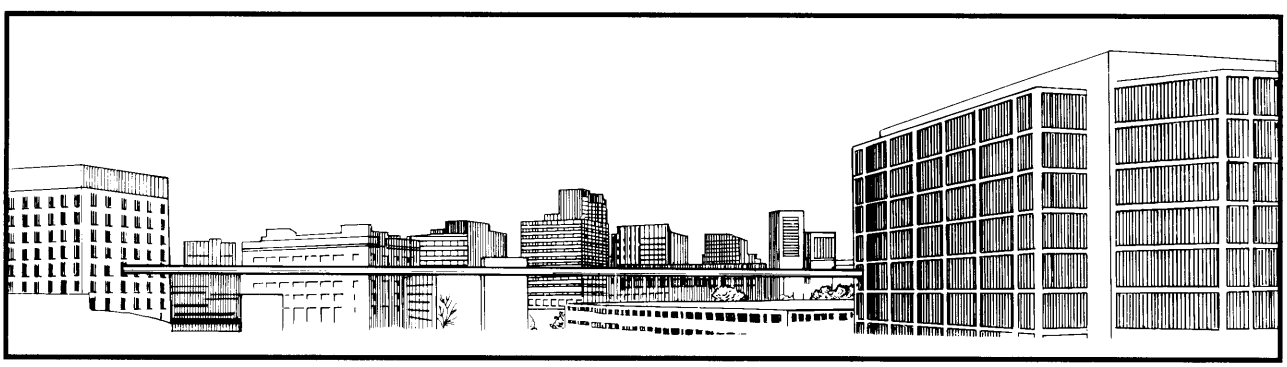

Figure 6.1 In conjunction with two microcomputers and the appropriate software, two laser transmitters and companion receivers form an experimental token-ring local area network (LAN).

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6.2 Squeezed States of Light

Maryland Procurement Office (Contracts MDA 904-84-C-6037, MDA 904-87-C-4044)
National Science Foundation (Grant ECS 84-15580)

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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.

Experiments

We were one of the first groups to report experimental observation of quadrature-noise squeezing.[1] Our measurement, which was a forward four-wave mixing experiment in atomic sodium vapor, exhibited 0.2 dB of squeezing. This was the first squeezing measurement in a Doppler-broadened atomic medium, and was limited by a variety of technical difficulties.[2] Since then we have continued our atomic sodium vapor work with a greatly improved optical configuration. Moreover, the new sodium experiment is preliminary to an experiment in ytterbium vapor. The ytterbium experiment will benefit from a simpler atomic level system than sodium, and will use a pump-recirculation cavity to enhance the squeezing.

The greatest observed quadrature-noise squeezing to date has come from a $LiNbO_3$ optical parametric amplifier,[3], i.e., a below-threshold optical parametric oscillator (OPO). We have begun work on a somewhat similar arrangement in which we intend to concentrate on the above-threshold OPO regime. As compared to the atomic vapor work, the OPO experiment benefits, because it uses a transparent medium, from lower loss and absence of spontaneous emission.

Theory

Our theoretical work on nonclassical light has addressed issues relevant to our experimental work as well as topics concerned with the application of such light beams. In support of the atomic vapor experiments, we have developed a quantum theory for nondegenerate multiwave mixing,[4,5] which includes important advances in the quantum treatment of light-beam propagation in material media in addition to providing operating-point calculations for our experiments. In conjunction with possible experiments in self-phase modulation (SPM) media, such as optical fibers, we have developed a multi-temporal mode single-spatial mode treatment of the classical and quantum noise tranformations of lossless dispersionless SPM.[6] Here we were the first to indicate the necessity of including a medium-dependent time constant in assessing the limit of validity of coupled-mode theory, and in evaluating the quantum-mechanical periodicity of the full nonlinear regime.

We have also made major advances in our understanding of the quantum nature of feedback photodetection. Our initial interest in this area stemmed from its possible use, in conjunction with a quantum nondemolition measurement, for generating nonclassical light.[7] We were able to fully elaborate the relationships between the semiclassical and quantum treatments of these closed-loop systems and to emphasize the importance of explicitly treating the optical delay within the apparatus in order to properly understand the in-loop field commutators.[8] Lately, we have been examining the dual relationships between the state-generation and state-measurement descriptions of closed-loop photodetection.[9]

Finally, we have begun a new fundamental investigation of the sensitivity of quantum phase measurements. This work, which is still in very preliminary form, predicts that substantially lower phase-measurement errors can be obtained, at the same average photon number, than those predicted for optimized squeezed-state interferometers.

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6.3 U.S.-Japan Seminar on Quantum Mechanical Aspects of Quantum Electronics

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U.S. Navy - Office of Naval Research (Contract N00014-87-G-0198)

Jeffrey H. Shapiro

The continuing rapid developments taking place in quantum electronics cut across a wide swath of research activities including atomic and solid-state physics, nonlinear optics and spectroscopy, and quantum light beams and quantum measurement. Strong research programs in these areas presently exist in the United States and Japan. The fourth in a series of U.S.-Japan Seminars on Quantum Electronics was held from July 21 to July 24, 1987 in Monterey, California. Professor J.H. Shapiro, of MIT, served as the U.S. Coordinator for this event, and Professor H. Takuma, of the University of Electro-Communications, Tokyo, served as the Japanese Coordinator. Major funding for this Seminar was obtained from the U.S. National Science Foundation, and the Japan Society for the Promotion of Science. The Seminar program focused on topics of very current interest including: neutral atom trapping; ultrahigh stability sources and ultrahigh resolution spectroscopy; squeezed states of light; and nonlinear optics of semiconductors. A Proceedings was produced under funding from the U.S. Office of Naval Research.[1]

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6.4 Laser Radar System Theory

U.S. Army Research Office - Durham (Contracts DAAG29-84-K-0095, DAAL03-87-K-0117)

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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 wavelength disparity between microwaves and light, laser systems offer vastly superior space, angle, range, and velocity resolutions 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.

Multipixel Detection Theory

We have been developing the appropriate target-detection theory for multipixel multidimensional laser radar imagers. We have 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.[1] This problem has been 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. The structure of these processors coincides with those employed in ad hoc designs, i.e., the intensity-only system searches for intensity contrast, and the range-only processor seeks out vertical objects. The great advance in our work over ad hoc treatments is its associated performance results,[1] which allow analytical trade-off assessments to be made between radar-system parameters and target-detection performance. Our initial performance results, which were limited to intensity-only and range-only processors, have since been generalized to relax certain structural assumptions.[2] They have also been verified through computer simulation of the fundamental pixel-statistics developed and experimentally confirmed in earlier work.[3] This simulation program is now being used to obtain performance results for the joint range-intensity processor; a laser radar experiment is being planned to test the performance predictions obtained from the simulation.

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,[4] 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. For a variety of observation structures, e.g., intensity-only, range-only, joint range-intensity, etc., it turns out the the Kalman filter problem that results is non-standard in that the nth-frame observation statistics involve a signal-dependent noise term. Nevertheless, we have been able to develop a filtering procedure and performance equations for the resulting observation equations.

High-Resolution Optical Imagers

A microwave synthetic aperture radar (SAR) exploits coherent target-return processing to achieve an along-track spatial resolution better than its antenna's diffraction limit. It also uses its range resolution capability to enhance its cross-track spatial resolution. In a similar vein, a microwave range-Doppler (RD) radar uses its range and Doppler resolutions to obtain high spatial-resolution imagery of rotating objects. We have been studying the translation of SAR and RD techniques into the optical-wavelength region.[5] Like our previous studies of angle-angle imagers, this work on high-resolution imagers has focused on the following key performance measures: spatial resolution, carrier-to-noise ratio (CNR), and signal-to-noise ratio (SNR). We have developed results for performance under ideal operating conditions, and then examined the effects of laser frequency instability, turbulence, and target/radar motion errors on system performance.

Adaptive Optics for Laser Radars

The speckle-target performance of coherent laser radars improves with increasing aperture size in free space. In the presence of atmospheric turbulence, however, the performance of a conventional coherent laser radar does not improve above turbulence-limited values as aperture size is increased beyond an atmospheric coherence length. We have been studying the use of adaptive optics to compensate for the turbulence-induced degradations of spatial resolution and CNR in an angle-angle imager.[6] The goal of this work is to understand the improvement in performance that can be obtained, in principle, with adaptive optics, and to specify the structure of the systems needed to approach this improved performance. To date, the performance gains that accrue when turbulence can be perfectly measured and corrected have been established. A scheme for measuring the turbulence parameters from target returns has been postulated, and shown to suffer from an unfortunate coupling between fluctuations that are due to turbulence and those that are due to target speckle. Work is continuing on both the separation of the turbulence and speckle contributions, and on what can be done with combined turbulence/speckle information if the preceding separation cannot be effected.

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6.5 Fiber-Coupled External-Cavity Semiconductor High Power Laser

U.S. Navy - Office of Naval Research (Contract N00014-80-C-0941

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We have reported in previous progress reports the high-spectral-purity pulse and cw coherent output that has been obtained from a linear array of five discrete external-cavity diode lasers by placing in the cavity a spatial filter at the Fourier plane of the lens system between the AR-coated diodes and the feedback mirror. We now report results on the intensity and phase distribution of the near field of the ensemble. Results were obtained for spatial filters with various ratios of slit opening to the slit center-to-center spacing. For all filters of practical interest, two eigenmodes are shown to exist: in one, the outputs from adjacent diodes are in phase: in the other they are 180° out of phase. These eigenmodes are switched by moving the filters laterally by half the 10.42 μm spacing between the centers of their slits. The theoretical explanation of the experimental results clearly validates the model that has been used to explain the operation of the coherent ensemble. With this validation, extrapolation of the performance obtained with the ensemble of five lasers to that of an ensemble with a large multiplicity of lasers is possible.

Limited tuning of the output wavelength has also been accomplished by effectively varying the center-to-center slit spacing.

Publication

Rediker, R.H., S.K. Liew, and C. Corcoran, "Near Field Distribution and Output Wavelength Tuning of a Coherent Array of Discrete Diode Lasers," *J. Opt. Soc. Am. A* 4 (13):74 (1987).

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

U.S. Air Force - Office of Scientific Research (Contract F49620-87-C-0043)

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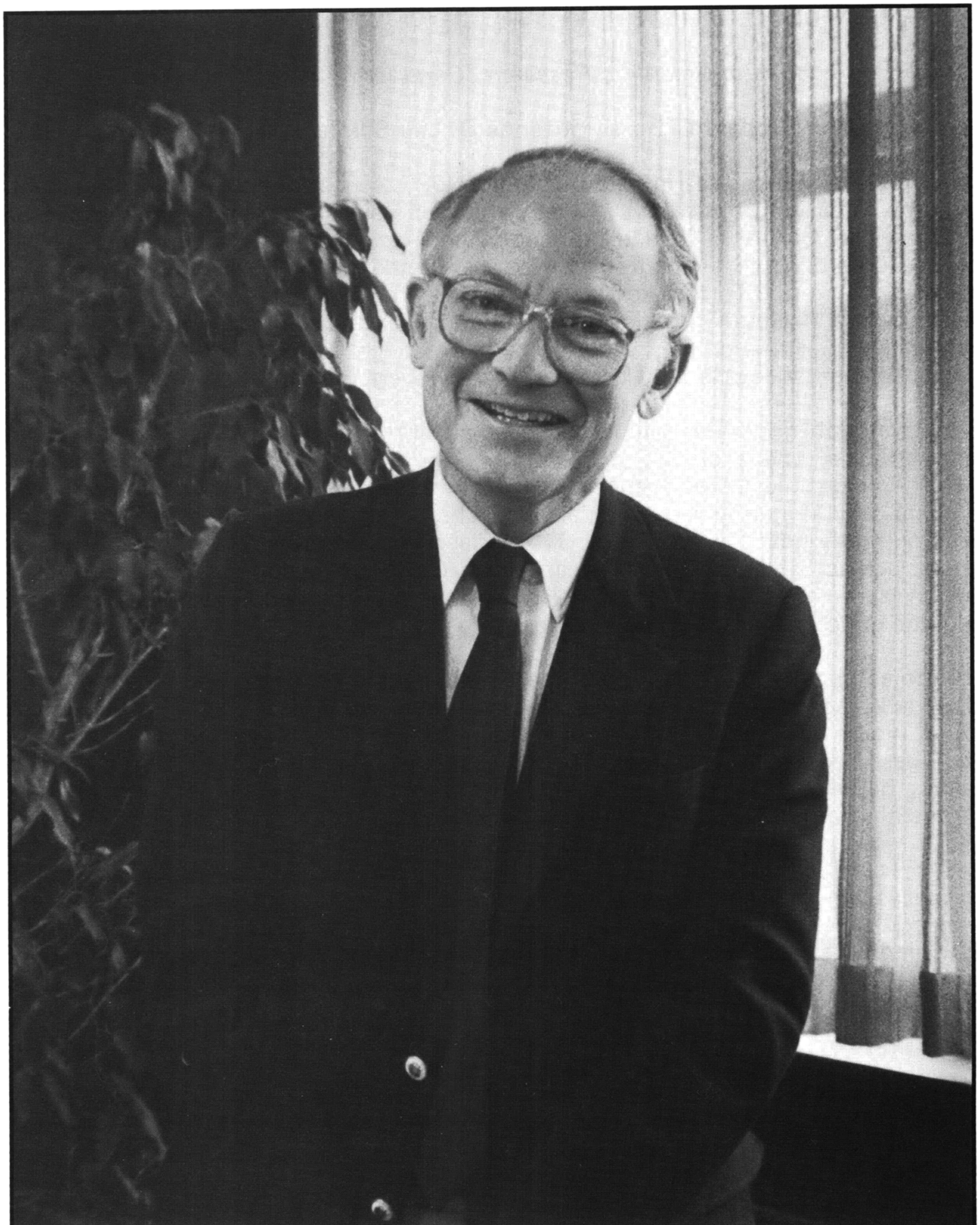
This program, which was initiated in March 1987, seeks to explore the fundamental issues associated with optical wavefront correction using integrated guided-wave optical devices in GaAlAs. Device fabrication and optimization are performed at MIT Lincoln Laboratory and evaluation will be performed at the Research Laboratory of Electronics. During 1987, two key areas of research have been addressed. Namely, we have begun to examine the design, fabrication, and optimization of 1) dielectric waveguides in GaAlAs for single-mode operation at $\lambda = 0.85$ μm, and 2) adiabatic antennas to efficiently couple light between these waveguides and free space.

Heterojunction ridge waveguides have been fabricated in GaAlAs. For these first devices epitaxial layers of $Ga_{1-x}Al_xAs$ were grown upon a GaAs substrate using a metal-organic chemical vapor deposition (MOCVD) technique. A waveguide ridge was then chemically etched in the epitaxial film. The performance of these waveguide devices is currently being evaluated at GaAlAs laser wavelengths. The goals of this experiment are to optimize the fabrication of GaAlAs waveguides for single-mode operation at $\lambda = 0.85$ μm and to examine the optical attenuation (loss) of these waveguide structures at the same wavelength.

For the antennas the concept of a tapered waveguide (a waveguide which tapers to a point) is being pursued. This dielectric antenna is the optical analog to the polyrod antenna which is used at microwave frequencies. The advantages of adiabatic waveguide antennas are as follows: 1) they serve as a means to increase the coupling efficiency between free-space radiation and the guided optical modes; and 2) for an array of single-mode waveguides they will increase the efficiency with which the radiating (or receiving) surface is filled. Our first experimental tapered antennas were fabricated in $Ti:LiNbO_3$ because this is currently a more established waveguide technology. The devices which were incorporated on the first sample include a variety of taper lengths and taper angles. Experimental evaluation of these devices is currently underway. Using a fabrication technique that has been independently developed at Lincoln Laboratory, a program is underway which we believe will produce two-dimensional tapered waveguide antennas in GaAlAs.



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