6.0 Optical Propagation and Communication

Academic and Research Staff

Prof. J.H. Shapiro, Dr. P. Kumar, Dr. R.H. Rediker, Dr. N.C. Wong

Graduate Students

K.K. Anderson, B.T. Binder, D.E. Bossi, J.K. Bounds, C.J. Corcoran, R.H. Enders, S.M. Hannon, S.-T. Ho, R.K. John, D.R. Lane, K.-W Leong, S.K. Liew, M.W. Maeda, M.B. Mark, D. Park, G. Saplakoglu, R.K. Shu, N.E. Silman, P.T. Yu

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

National Science Foundation (Grant ECS 85-09143)

Jeffrey H. Shapiro, Bradley T. Binder, Jeffrey K. Bounds, Daniel R. Lane, Peter T. Yu

A local area network is prototypically a high-bandwidth (1-10 Mb/s) geographically compact (0.1 - 5 km diameter) packet-switched network that employes twisted pair, coaxial cable, or fiber optics as its transmission medium. These networks interconnect computers within a single company, often within a single building. They are distinguished from wide-area packet networks in that the high-bandwidth, short delay, low-cost transmission media employed in local area networks permit the use of simplified protocols and control strategies.

Atmospheric optical communication links are a natural choice for certain high-bandwidth short-haul terrestrial transmission applications in which cable rights-of-way are unobtainable, or in which frequent link and network reconfiguration is necessary. The utility of these links will be limited primarily by the occasional outages they experience due to local adverse weather conditions.

The natural advantages of atmospheric optical links make them attractive candidates for such local area network (LAN) applications as bridges between buildings containing cable subnetworks, and temporary quick-connects for new outlying hosts for which cable runs are initially unavailable. In this program, we have undertaken a combined analytical and experimental study of the use of atmospheric optical communications in local area networks. A brief summary of recent accomplishments follows.

Experiment

The purpose of the experimental research has been to establish an atmospheric optical communication/LAN test bed for probing the utility of such hybrid networks in actual user environments. Under earlier NSF funding, two through-the-air optical transceivers were constructed, using continuous-wave GaAlAs laser diodes and Silicon APD/preamplifier modules.[1] The initial links were employed for packet transmission over a 150 m outdoor path between buildings on the M.I.T., Cambridge, Mass. campus. They were later modified for direct substitution into the PROTEON proNET cable ring network,[2] which is a 10 Mb/s token passing ring structure in use at M.I.T., Cambridge, Mass. that admits to extensive interconnection through what are called wire centers. During the past year, link hardware has been improved through the addition of automatic gain control to the receivers and feedback temperature compensation to the transmitters.[3] In addition, the hardware[4] and software[3] needed to accumulate internal transceiver status information while network operation is proceeding has been developed and installed. With these advances, remote computation experiments are now proceeding with two IBM-PC computers connected as a 2-node through-the-air laser communication ring network.[3]

Theory

Because future developments in LANs will likely occur in the area of very high speed (100 Mb/s - 1 Gb/s) systems based on single-mode optical fiber, our theoretical work has been aimed primarily at the use of atmospheric optical communications in such networks. Here the impact of atmospheric propagation on network performance is expected to be more severe than in our earlier analysis of 1-10 Mb/s systems.[5] We have explored[6] the viability of placing an atmospheric optical link into some of the proposed very high speed fiber-optic LANs, such as FASNET.[7] In bad weather, the network must cope with optical link outages that will force it to divide into subnetworks. Moreover, in clear weather, the fading due to atmospheric turbulence, which was not a severe problem for Mb/s systems owing to their greater power margin, will affect atmospheric link performance in a way that requires protocol modification. In another problem area, we have made a systematic study[8] of various fiber-optic alternatives for providing very high speed bus communications within a computer. This study has established the trade-offs between serial (bit by bit) and parallel (byte by byte) implementations.

References

[1] K. Wong, "A Variable-Rate Atmospheric Optical Link for Local Area Networks," S.M. Thesis, Dept. of Electr. Eng. and Comp. Sci., M.I.T., Cambridge, Mass., 1984.

[2] D.R. Lane, "A Modified Atmospheric Optical Link for Local Area Networks," S.B. Thesis, Dept. of Electr. Eng. and Comp. Sci., M.I.T., Cambridge, Mass., 1985.

[3] B.T. Binder, "Remote Computation with an Atmospheric Optical Ring Network," S.M. Thesis, Dept. of Electr. Eng. and Comp. Sci., M.I.T., Cambridge, Mass., 1986.

[4] A. De Rozairo, "A Data Acquisition System for Atmospheric Optical Links," S.B. Thesis, Dept. of Electr. Eng. and Comp. Sci., M.I.T., Cambridge, Mass., 1986.

[5] T.T. Nguyen, "Atmospheric Optical Communications in Local Area Networks," Ph.D. Diss., Dept. of Electr. Eng. and Comp. Sci., M.I.T., Cambridge, Mass., 1985.

[6] J.K. Bounds, "Atmospheric Optical Communications in Very Fast Local Area Networks," S.M. Thesis, Dept. of Electr. Eng. and Comp. Sci., M.I.T., Cambridge, Mass., 1986.

[7] J.O. Limb and C. Flores, "Description of Fasnet - A Unidirectional Local-Area Communications Network," Bell Syst. Tech. J. *61*, 1413 (1982).

[8] D.R. Lane, "Fiber Optic Alternatives for Fast Bus Communications," S.M. Thesis, Dept. of Electr. Eng. and Comp. Sci., M.I.T., Cambridge, Mass., 1986.

6.2 Squeezed States of Light

Maryland Procurement Office (Contract MDA 904-84-C-6037)
National Science Foundation (Grant ECS 84-15580)

Jeffrey H. Shapiro, Prem Kumar, Ngai C. Wong, Mari W. Maeda, Seng-Tiong Ho, Kin-Wai Leong, Roy K. John, Gurhan Saplakoglu, Roberto K. Shu

Recent work has highlighted the potential applications of squeezed states, also known as two-photon coherent states (TCS), in optical communications and precision measurements. These states have an asymmetric noise division between their quadrature components, with the low-noise quadrature exhibiting lower fluctuation strength than that of a coherent state. We are engaged in a program to generate and verify the quantum noise behavior of squeezed state light and analyze the physics and applications of such light. Our recent progress is summarized below.

Experiments

Our first successful squeezed-state generation experiment produced 0.2 dB of noise reduction below the vacuum-state level in homodyne detection of light that had undergone nearly-degenerate forward four wave mixing in sodium vapor.[1] Following this success, we had to shut down experimental work while our laboratory underwent an extensive renovation. This renovation, completed in September 1986, gave us additional high quality laboratory space for use in future experiments. Since then we have begun work on an improved atomic-vapor squeezed-state experiment using ytterbium. We have also pursued preliminary experiments in the areas of self-phase modulation squeezed-state generation, and squeezed-state generation via feedback photodetection around an optical nonlinearity. These areas represent a radical departure form atomic vapor work, but appear to hold great potential for future applications.

Theory

As a foundation for the preceding experiments, we have continued to work on the theoretical underpinnings of squeezed-state generation. In support of the atomic vapor experiments, we have developed a vector-wave quantum theory for squeezed-state generation via degenerate four-wave mixing,[2] and a scalar-wave quantum theory for squeezed-state generation via non-degenerate four wave mixing.[3] The latter work includes important advances in treating quantum field propagation in material media. In the area of self-phase modulation, we have developed a multimode treatment for the classical and quantum noise transformations produced by this interaction.[4] This analysis transcends the simple coupled-mode theory regime. Finally, we have developed the semiclassical and quantum theories for closed-loop photodetection,[5,6] with the latter including a potential scheme for quasi-state synthesis.

References

[1] M.W. Maeda, P. Kumar, and J.H. Shapiro, "Observation of Squeezed Noise Produced by Forward Four-Wave Mixing in Sodium Vapor," Opt. Lett. *12*, 161 (1987).

[2] S.-T. Ho, P. Kumar, and J.H. Shapiro, "Vector-Field Quantum Model of Degenerate Four-Wave Mixing," Phys. Rev. A *34*, 293 (1986)

[3] S.-T. Ho, P. Kumar, and J.H. Shapiro, "Quantum Theory of Nondegenerate Multiwave Mixing," Phys. Rev. A *35*, 3982 (1987).

[4] R.K. John, J.H. Shapiro, and P. Kumar, "Classical and Quatum Noise Transformations Produced by Self-Phase Modulation," presented at *IQEC '87* Baltimore, Maryland, April 1987.

[5] J.H. Shapiro, M.C. Teich, B.E.A. Saleh, P. Kumar, and G. Saplakoglu, "Semiclassical Theory of Light Detection in the Presence of Feedback," Phys. Rev. Lett *56*, 1136 (1986).

[6] J.H. Shapiro, G. Sapakoglu, S.-T. Ho, P. Kumar, B.E.A. Saleh, and M.C. Teich, "Theory of Light Detection in the Presence of Feedback," J. Opt. Soc. Am. B in press.

6.3 Laser Radar System Theory

U.S. Army Research Office - Durham (Contract DAAG29-84-K-0095)

Jeffrey H. Shapiro, Martin B. Mark, Dongwook Park, Robert H. Enders, Stephen M. Hannon, Naomi E. Silman, Donald E. Bossi

Coherent laser radars represent a true translation to the optical frequency band of conventional microwave radar concepts. This program is aimed at developing a system theory for the emerging technology of multifunction coherent CO_2 laser radars. It includes a collaboration arrangement with the Opto-Radar Systems Group of M.I.T., Cambridge, Mass. Lincoln Laboratory whereby the experimental portions of the research are carried out with measurements from their CO_2 laser radar test beds. Our recent work is summarized below.

Multipixel Detection Theory

We have derived quasi-optimum range-only and intensity-only processors for the detection of an extended speckle target located at unknown range, azimuth, and elevation, within a speckle (ground) background of known terrain profile.[1] The receiver operating characteristics for these processors have also been obtained, and used to quantify a variety of resolution/performance trade-offs for these systems. Two of the key assumptions in the preceding analysis are being relaxed in a follow-up study,[2] experimental confirmation of the processor performance theory will be sought in future measurements using the M.I.T., Cambridge, Mass. Lincoln Laboratory 2-D pulsed imager laser radar test bed.

Unconventional Laser Radars

We have begun a theoretical study of the combined effects of target speckle, local-oscillator shot noise, and laser frequency instability on a variety of unconventional laser radars, i.e., radars which use range and/or Doppler measurements to perform imaging with spatial resolution beyond the diffraction-limit of the radar optics.[3] Thus far we have completed spatial resolution, carrier-to-noise ratio (CNR), and signal-to-noise ratio (SNR) assessments for 2-D and 3-D synthetic aperture systems. Additional work is underway on range-Doppler imaging and inverse Fourier transform imaging.

References

[1] M.B. Mark, "Multipixel Multidimensional Laser Radar System Performance," Ph.D. Diss., Dept. of Electr. Eng. and Comp. Sci., M.I.T., Cambridge, Mass., 1986.

[3] S.M. Hannon, "Analysis of Quasi-Optimal Multipixel Laser Radar System Processors," S.M. Thesis proposal, Dept. of Electr. Eng. and Comp. Sci., M.I.T., Cambridge, Mass., 1986.

[3] D. Park, "Unconventional Laser Radars," Ph.D. Diss. proposal, Dept. of Electr. Eng. and Comp. Sci., M.I.T., Cambridge, Mass., 1986.

6.4 Fiber-Coupled External-Cavity Semiconductor High Power Laser

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

Robert H. Rediker, Kristin K. Anderson, So Kuen Liew, Christopher J. Corcoran

Last year's annual report described the high spectral purity of the output from an ensemble of five discrete diode lasers when operated cw. The linewidth of the cw output of this external-cavity-controlled ensemble of diode lasers was shown to be less than 7.5 MHz ($\sim 2 \times 10^{-8}$ of the center frequency). Also reported last year was high-spectral-purity pulsed output from this external cavity controlled laser. In 1986 the pulsed operation of this laser was investigated in detail both experimentally and theoretically.

Figure 6.1 is a schematic of the external-cavity arrangement. Linewidths of the order of the 7.5-MHz instrument resolution have been obtained. To achieve this high spectral purity in a pulse mode of operation, three alternate gain elements (elements number one, three, and five in Fig. 6.1) are operated cw and the intermediate two elements are pulsed. For a coherent ensemble of only three alternate gain elements, the spacing between the major intensity maxima in the Fourier plane (the filter plane) is decreased by a factor of 2 relative to the spacing with all five elements operating coherently. As a result, the lasing threshold for the three-element ensemble is much higher because significant radiation hits the opaque areas of the filter. A calculation of the single-pass filter transmission for this case yields a value of 0.48 as compared to the transmission of 0.92 when all five elements are running.

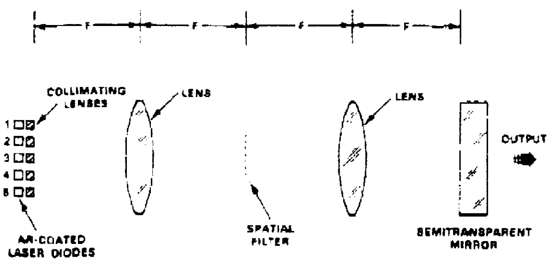

Figure 6.1. : Schematic of multiple-element external-cavity arrangement showing the placement of the five antireflection-coated diode lasers, the associated collimating optics, the two lenses, spatial filter, and end mirror. As indicated on the figure, the elements are seperated by the focal length of the lenses so the light undergoes a Fourier transform four times during one round trip through the cavity.

The spectral output of the ensemble when operated with current pulses applied to elements number two and four and cw excitation to the other three was measured for two different cases. First, the dc biases on the two pulsed elements were set so the laser ensemble was just above threshold when the pulse was off. In this case, the spectrum for the pulse output remains at the value set by the low-level cw output of the external cavity. The linewidth in this case is within the 7.5-MHz instrument resolution. It should be pointed out that if any of the five external-cavity lasers operating independently without the spatial filter are pulsed from below threshold, there is a 1-Å ($\approx$40 GHz) output frequency shift (chirp) during the pulse, and there is still a chirp larger than 1.5 GHz if all five elements of the coherent ensemble with the spatial filter are pulsed simultaneously from above the ensemble threshold. For the second case, the dc biases on the two pulsed elements were reduced to a point where the ensemble was well below threshold with the pulse off. The measured linewidth is 9 MHz.

The narrow linewidth pulses can be explained by a compensation effect. Refractive index and gain in pulsed elements two and four are changing because of increased temperatures and carriers caused by the increased current. In the other three elements, however, changes occur in the opposite direction because of decreased temperatures and carriers and the simultaneous decrease in carrier lifetime.

A third case which has implications for an all-optical repeater is to operate elements one, three and five at a high enough level so this ensemble of alternate elements is just below threshold. A very small pulse output from elements two and four brings the entire ensemble above threshold with an output pulse well over a factor of 100 (20 dB) larger than the input pulse. The practical implementation of this all optical repeater would surely be different from the sketch of Fig. 6.1, but would use the same principle of obtaining gain by changing the spatial configuration of the electromagnetic field in the Fourier plane.

Publications

[1] K.K. Anderson, R.H. Rediker, and L.J. Van Ruyven, "Pulsed Operation of an Array of Diode Lasers with Feedback in the Fourier Plane and a Chirp Less Than 7.5 MHz Measurement Resolution," Technical Digest of 6th Topical Meeting on Intergrated and Guided Wave Optics (IGWO), Atlanta, Georgia, February 1986, p. 30.

[2] K.K. Anderson and R.H. Rediker, "High Spectral Purity cw and Pulsed Output from an Ensemble of Discrete Diode Lasers," Appl. Phys. Lett. *50,* 1 (1987).