Chapter 3. Optical Propagation and Communication

Academic and Research Staff

Professor Jeffrey H. Shapiro, Dr. Robert H. Rediker, Dr. Ngai C. Wong

Graduate Students

Bradley T. Binder, Donald E. Bossi, Christopher V. Corcoran, Robert H. Enders, Stephen M. Hannon, Seng-Tiong Ho, Roy K. John, Kin-Wai Leong, Robert E. Mentle, Lily Y. Pang, Dongwook Park, Gurhan Saplakoglu, Scott R. Shepard, Suzanne D. Lau Shiple, Peter T. Yu, Naomi E. Zirkind

Undergraduate Student

Asli Ural

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.

3.1 Squeezed States of Light

Sponsors

Maryland Procurement Office
(Contract MDA 904-87-C-4044)
National Science Foundation
(Grant ECS 87-18970)

Project Staff

Professor Jeffrey H. Shapiro, Dr. Ngai C. Wong, Seng-Tiong Ho, Kin-Wai Leong, Gurhan Saplakoglu, Scott R. Shepard, Roy K. John

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.

3.1.1 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

---

[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).

technical difficulties.[2] Since then we have continued our atomic sodium vapor work with a greatly simplified, single-beam configuration. This experiment, for which operating conditions were chosen in accordance with the theoretical predictions described below, has yielded 20 percent observed quadrature noise squeezing, corresponding to an inferred squeezing of 50 percent at our overall measurement efficiency.[3] Moreover, the results of this single-beam experiment are in reasonable agreement with our theory over a large range of experimental parameters. A follow-up experiment in ytterbium vapor has been planned. It will benefit from ytterbium's having a simpler atomic level structure than sodium, and it will use pump-recirculation to enhance the squeezing.

The greatest observed quadrature-noise squeezing to date has come from a $LiNbO_3$ optical parametric amplifier,[4] i.e., a below-threshold optical parametric oscillator (OPO). We have begun working on a somewhat similar arrangement, concentrating on the above-threshold OPO regime. Unlike the atomic vapor system, the OPO experiments use a transparent medium, which results in lower losses and an absence of spontaneous emission. Thus far, we have demonstrated stable above-threshold OPO operation near frequency degeneracy, and have performed preliminary transmitted-pump noise measurements.[5] These measurements have confirmed the expected classical-noise clamping of a doubly-resonant oscillator, which is the starting point for our theory for a potential quantum-noise eater, described below.

3.1.2 Theory

Our theoretical work on nonclassical light has addressed issues relevant to our experimental work as well as topics concerned with the application of these light beams. In support of the atomic vapor experiments, we have developed a quantum theory for nondegenerate multiwave mixing,[6] 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 our OPO experiment, we have developed a linearized quantum analysis for the transmitted-pump noise of a doubly-resonant oscillator.[7] This theory shows that the classical-noise clamping does not extend directly to the quantum domain. In fact, the vacuum noise from the unexcited, backward-propagating pump is transferred, fairly efficiently, to the transmitted forward-propagating pump through two-way interaction with the doubly-resonant signal and idler modes. Thus, we are investigating the use of this

---

[2] M.W. Maeda, P. Kumar, and J.H. Shapiro, "Squeezing Experiments in Sodium Vapor," *J. Opt. Soc. Am. B* 4:1501 (1987).

[3] S.-T. Ho, N.C. Wong, P. Kumar, and J.H. Shapiro, "Single-Beam Squeezing in a Doppler Broadened Medium," Annual Meeting of the Optical Society of America, Santa Clara, California, 1988; S.-T. Ho, *Theoretical and Experimental Aspects of Squeezed State Generation in Two-Level Media,* Ph.D. diss., Dept. of Electr. Eng. and Comp. Sci., MIT, 1989.

[4] L.-A. Wu, M. Xiao, and H.J. Kimble, "Squeezed States of Light from an Optical Parametric Oscillator," *J. Opt. Soc. Am. B* 4:1465 (1987).

[5] K.-W., Leong, N.C. Wong, and J.H. Shapiro, "Pump Noise in an Optical Parametric Oscillator Operated Above Threshold," Annual Meeting of the Optical Society of America, Santa Clara, California, 1988.

[6] S.-T. Ho, N.C. Wong, P. Kumar, and J.H. Shapiro, "Single-Beam Squeezing in a Doppler Broadened Medium," Annual Meeting of the Optical Society of America, Santa Clara, California, 1988; S.-T. Ho, *Theoretical and Experimental Aspects of Squeezed State Generation in Two-Level Media,* Ph.D. diss., Dept. of Electr. Eng. and Comp. Sci., MIT, 1989; S.-T. Ho, P. Kumar, and J.H. Shapiro, "Quantum Theory of Nondegenerate Multiwave Mixing," *Phys. Rev. A* 35:3982 (1987); S.-T. Ho, P. Kumar, and J.H. Shapiro, "Quantum Theory of Nondegenerate Multiwave Mixing: General Formulation," *Phys. Rev. A* 37:2017 (1988).

[7] K.-W., Leong, N.C. Wong, and J.H. Shapiro, "Pump Noise in an Optical Parametric Oscillator Operated Above Threshold," Annual Meeting of the Optical Society of America, Santa Clara, California, 1988.

arrangement to transfer the reduced quantum noise from a squeezed-vacuum backward pump to the intense forward pump to create a quantum noise eater — a device driven by an intense, coherent-state beam whose output is an intense squeezed-state beam.

We have also continued to advance 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.[9] 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 to properly understand the in-loop field commutators.[10] Lately, we have developed the duality between the state-generation and state-measurement descriptions of closed-loop photodetection, and have studied the statistics of closed-loop heterodyne detection.[11] In the latter case, we showed that a coherent-state driven heterodyne-feedback system can mimic the open-loop heterodyne statistics of an arbitrary density operator.

Finally, we have begun a new fundamental investigation of the sensitivity of quantum phase measurements. This work, which is based on quantum estimation theory, predicts that substantially lower phase-measurement errors can be obtained, at the same average photon number, than those predicted for optimized squeezed-state interferometers.[12] Basically, as shown in the figure, this is because an interferometer — even a squeezed-state interferometer — is a constrained approach to measuring the phase shift imposed on an optical beam. Our analysis shows that the best performance results from making the Susskind-Glogower phase operator measurement on a phase-shifted quantum mode whose input state has number-ket expansion coefficients that are inversely proportional to the photon number, up to a truncation point.

3.2 Laser Radar System Theory

Sponsor

U.S. Army Research Office
(Contract DAAL03-87-K-0117)

Project Staff

Professor Jeffrey H. Shapiro, Dongwook Park, Robert H. Enders, Stephen M. Hannon, Naomi E. Zirkind, Robert E. Mentle

Coherent laser radars represent a true translation to the optical frequency band of conventional microwave radar concepts. Because of the enormous wavelength disparity between microwaves and light, laser systems offer vastly superior space, angle, range, and velocity resolution in comparison with 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 turbulent or turbid conditions on atmospheric optical wave propagation 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 micro-

---

[8] S.R. Shepard and J.H. Shapiro, "Ultimate Quantum Limits on Phase Measurement," Annual Meeting of the Optical Society of America, Santa Clara, California, 1988.

[9] H.A. Haus and Y. Yamamoto, "Theory of Feedback-Generated Squeezed States," *Phys. Rev. A* 34:270 (1986).

[10] J.H. Shapiro, G. Saplakoglu, 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* 4:1604 (1987).

[11] G. Saplakoglu, *Photodetection Feedback Systems,* Ph.D. diss., Dept. of Electr. Eng. and Comp. Sci., MIT, 1988.

[12] S.R. Shepard and J.H. Shapiro, "Ultimate Quantum Limits on Phase Measurement," Annual Meeting of the Optical Society of America, Santa Clara, California, 1988.

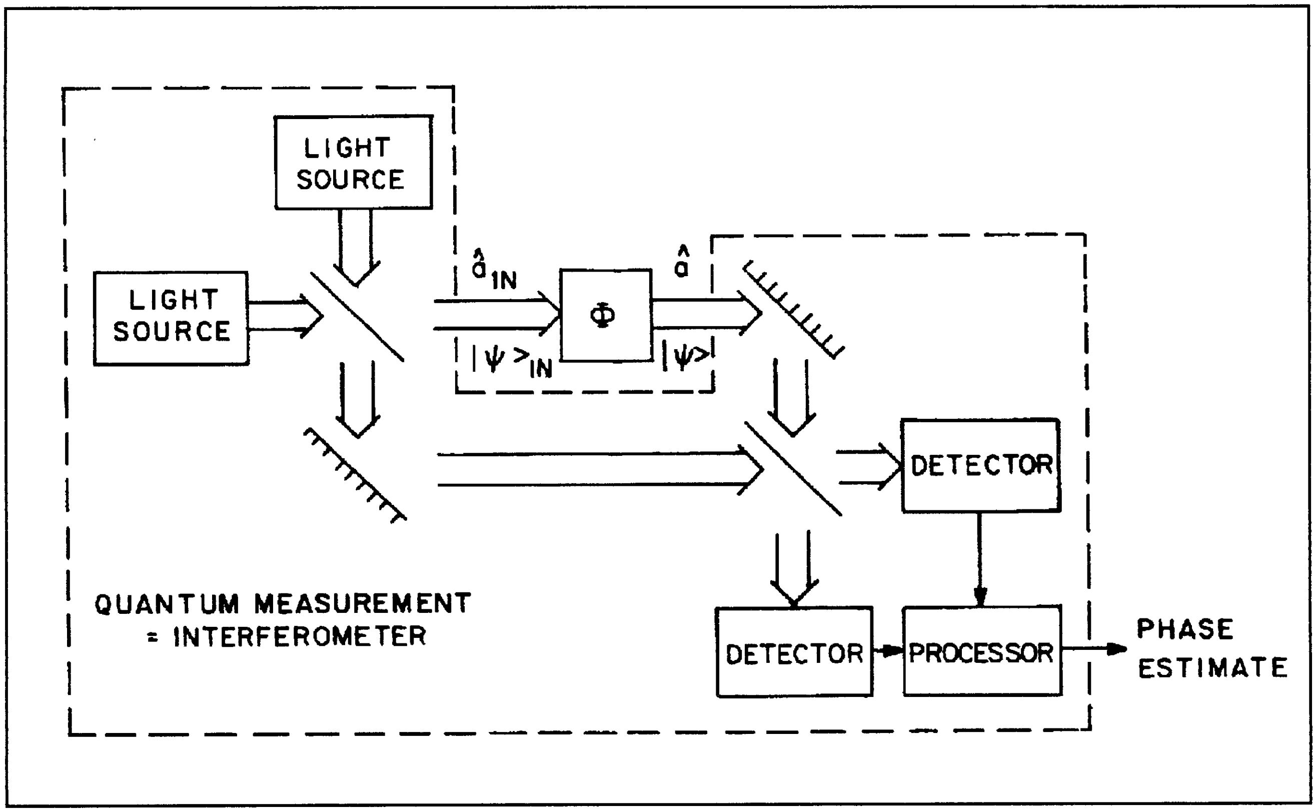

Figure 1. Schematic showing an interferometer as a structured quantum phase measurement. The ultimate limits on measuring the phase shift Φ of a single-mode field of annihilation operator $\hat{a}_{IN}$ in state $|\psi_{IN}>$ are reached by a measurement operator that does *not* satisfy the interferometer's structural constraints.[8]

wave systems. We have been working to quantify the preceding issues through development and experimental validation of a laser radar system theory. We have a collaborative arrangement with the Opto-Radar Systems Group at MIT's Lincoln Laboratory under which the experimental portions of the research project are performed using their CO_2 laser radar test beds.

3.2.1 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 detecting speckle targets within an image frame.[13] This problem has been solved for the realistic case in which the target, if present, has unknown azimuth, elevation, range, and reflectivity, and in which there is a spatially-extended speckle background of unknown reflectivity. The structures of the intensity-only and range-only processors coincide 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 joint range-intensity processor uses the intensity information as a quality measure for the range data; thus, even in the case of zero intensity contrast, the intensity data is still valuable to the joint range-intensity processor. The great advance in our work over ad hoc treatments is the associated performance results, which allow trade-off assessments to be made between radar-system parameters and target-detection

---

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

performance. Our initial analytic performance results were limited to intensity-only and range-only processors.[14] These results have since been verified by computer simulation, which has also provided the first quantitative measure of the performance improvement afforded by joint range-intensity processing.[15] Over an interesting range of radar and scenario parameters, the joint processor is at least 1 dB more efficient in its use of transmitter power than the best of intensity-only and range-only processing used separately. A laser radar experiment is now underway to test the performance predictions obtained from the simulation.

3.2.2 Multipixel Laser Radar Target Tracking

The preceding target detection work is a multipixel multidimensional single-frame theory. Once a laser radar has detected the target, the need to track that target presents a multipixel multidimensional multiframe task. In recent work,[16] 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., 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. Sample calculations have indicated that these trackers should be capable of sub-pixel steady state accuracies. Moreover, although our generalized Kalman filter does not satisfy the standard theorem for Kalman-filter stability, we have been able to prove that our filter will be stable for the laser radar tracking problem.

3.2.3 Optical Synthetic Aperture Radar

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. We have studied the translation of SAR techniques into the optical-wavelength region.[17] Similar to 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. These results clearly show how SAR operation trades off CNR for improved resolution in each dimension. They also suggest that optical SAR operation may be feasible in the near future.

---

[14] M.B. Mark and J.H. Shapiro, "Multipixel, Multidimensional Laser Radar System Performance," *Proc. SPIE* 783:109 (1987).

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

[16] R.H. Enders and J.H. Shapiro, "Laser Radar Tracking Theory," *Proc. SPIE* 999:192 (1988); R.H. Enders, *Laser Radar Tracking Theory: Track-While-Image Operation,* Ph.D. diss., Dept. of Electr. Eng. and Comp. Sci., MIT, 1988.

[17] D. Park, *High-Resolution Laser Radar Performance Analysis,* Ph.D. diss., Dept. of Electr. Eng. and Comp. Sci., MIT, 1988; D. Park and J.H. Shapiro, "Performance Analysis of Optical Synthetic Aperture Radars," *Proc. SPIE* 999:100 (1988).

3.2.4 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 considered the use of adaptive optics to compensate for the turbulence-induced degradations in angle-angle imaging of an extended speckle target.[18] In this study, we showed that virtually all turbulence degradations — on spatial resolution, CNR, range and Doppler measurement accuracy — can be suppressed if perfect turbulence-phase compensation can be applied to both the transmitter and local-oscillator beams. More importantly, we proposed and analyzed a multi-wavelength radar configuration, which is capable of making the necessary turbulence measurements, despite the intertwining of turbulence and speckle phases that plague single-wavelength, speckle-target adaptive optics.

3.3 Fiber-Coupled External-Cavity Semiconductor High Power Laser

Sponsor

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

Project Staff

Dr. Robert H. Rediker, Lily Y. Pang, Christopher V. Corcoran, Asli Ural

In the previous *Progress Report*, we reported on the experimental validation of the model of the operation of the coherent ensemble of five diode gain elements (lasers with one facet AR coated) within the external cavity laser. With this validation, extrapolation to an ensemble with a multiplicity of gain elements is possible. For cw coherent output powers of the order of 10 W or larger, fiber coupling of physically separated individual gain elements and/or monolithic arrays keeps the density of dissipated power below the value at which excessive heating would be caused.

Research on fiber coupling must be concerned with changes induced by the fiber in the polarization of radiation. In 1988, we investigated the effect of changing this polarization by placing a rotatable half-wave plate in front of one of the elements. The gain elements produced TE polarized radiation. When the half-wave plate rotated the polarization 90 degrees, the radiation from the element behind the polarizer became TM so that at the spatial filter all the radiation remained TE. (TM and TE radiation are orthonormal and do not interfere with each other.) The ensemble operation was also studied while rotating the polarization of the radiation from gain element by various angles between 0 degrees and 90 degrees. Two main conclusions were noted from the experiment: 1) the ensemble continued lasing, although at lower power, for all polarization rotations, and 2) the results are completely consistent with the model of ensemble operation.

The external cavity of the laser is being modified so that the gain elements will be coupled by fibers into the cavity. Also, the external fixtures that couple the radiation efficiently from the gain elements into the fiber have been designed and built. In addition, AR coating, fiber lensing, and other topics are being studied.

---

[18] N.E. Zirkind and J.H. Shapiro, "Adaptive Optics for Large Aperture Coherent Laser Radars," *Proc. SPIE* 999:117 (1988); N.E. Zirkind, *Adaptive Optics for Large Aperture Coherent Laser Radars*. Ph.D. diss., Dept. of Electr. Eng. and Comp. Sci., MIT, 1989.

Publications

Pang, L., C. Corcoran, and R.H. Rediker, "The Effect of Varying the Input Polarization on an External Cavity Controlled Ensemble of Five Diode Lasers," *Technical Digest of the OSA Annual Meeting* (1988), p. 175, and also in *Proc. IEEE LEOS Conference* (1988), p. 480.

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

Liew, S.K.C., *Supermode and Output Spectral Tuning of a Coherent Array of Discrete Diode Lasers.* S.M. thesis, Dept. of Electr. Eng. and Comp. Sci., MIT, 1988.

Ural, A.S., *Effects of Polarization and Heat on a Semiconductor Diode Laser in an External Cavity*. S.B. thesis, Dept. of Electr. Eng. and Comp. Sci., MIT, 1988.

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

Sponsor

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

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 Lincoln Laboratory while results are being evaluated at RLE. The optical laboratory for evaluating the results has been upgraded to a first class, fully-equipped facility. During 1988, two key areas of research were addressed. We have begun to examine the design, fabrication, and optimization of: 1) dielectric waveguides in GaAlAs for single-mode operation at $\lambda = 0.85\ \mu m$, and 2) adiabatic antennas to efficiently couple light between these waveguides and free space.

The waveguides are being fabricated in GaAlAs grown using a metal-organic chemical vapor deposition (MOCVD) technique. The fabrication is being optimized to reduce the optical attenuation of these waveguide structures.

Waveguide antennas efficiently and effectively reduce the far-field optical beam divergence. This is extremely desirable when coupling from the strongly confined modes of integrated optical waveguides to free-space radiation. We have successfully demonstrated the fabrication and operation of a reduced-confinement GaAlAs "tapered" waveguide antenna for use at GaAs laser wavelengths. This antenna is tapered in the sense that the confinement of the guided-mode is reduced near the sample endface both by physically reducing the waveguide dimension and, more importantly, by reducing the refractive index difference between the wavequide film and the cladding along the length of the guide.[19] The optical waveguide antenna is fabricated using a novel MBE growth technique which employs localized substrate heating to produce GaAlAs waveguide films that vary in Al concentration and film thickness across the surface of a wafer. In preliminary measurements, this antenna has been shown to produce a ~40% reduction in the far-field output beam divergence from a single-mode GaAlAs slab waveguide. The tapered antenna geometry which we describe is particularly advantageous because it permits fabrication of *two-dimensional* GaAlAs individual antenna structures.

---

[19] The concept of a tapered dielectric antenna has been used at microwave frequencies since the 1940's in a device known as the polyrod antenna. See, for example, G.E. Mueller and W.A. Tyrell, "Polyrod Antennas," *Bell Syst. Tech. J.* 26:873 (1947).

Publication

Bossi, D.E., W.D. Goodhue, and R.H. Rediker, "Reduced-Confinement GaAlAs Tapered Waveguide Antenna," *Technical Digest of the Integrated and Guide-Wave Optics Meeting*, 1989, p. 80.