

Chapter 2. Optical Propagation and Communication

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2.1 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.

2.2 Squeezed States of Light

Sponsors

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Project Staff

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2.2.1 Experiments

We have employed optical parametric downconversion in a type-I phase-matched $\text{LiNbO}_3:\text{MgO}$ crystal in our efforts to generate nonclassical light. Our focus has been on the demonstration of squeezed amplification of a below-threshold optical parametric amplifier (OPA) in the gain-saturated regime.² Under gain saturation, the amplified output intensity of an injected coherent-state signal becomes amplitude squeezed, and the large-signal signal-to-noise ratio improves. Using a single-frequency diode-pumped YAG laser as the injection source, we have made extensive mean-field measurements: gain saturation and output lineshape have been studied as functions of the pump and signal powers, as well as the signal frequency, pump frequency and cavity detunings.³ We have found quantitative agreement between theory and experiment for the frequency spacings and widths of the key features in these measurements. We have observed an unsaturated signal-gain of 10^3 for an OPA pumped at 97 percent of threshold with a low level of signal injection. This gain is reduced to 13 at the same pump level when the signal injection is increased by

¹ Laboratory for Physical Sciences, College Park, Maryland.

² N.C. Wong, "Squeezed Amplification in a Nondegenerate Parametric Amplifier," *Opt. Lett.* 16(21): 1698-1700 (1991).

³ K.X. Sun, N.C. Wong, and J.H. Shapiro, "Squeezed Amplification with Cavity Detunings: Mean-Field Behavior," paper presented at the Optical Society of America Annual Meeting, Albuquerque, New Mexico, September 20-25, 1992.

33 dB. Potential applications of an injection-seeded gain-saturated OPA include master-oscillator output amplification and direct-detection digital communication.

2.2.2 Theory

A detailed analysis of the injection-seeded OPA including cavity detunings has been carried out.⁴ Both mean field and noise behavior of the gain-saturated OPA and their dependence on cavity detunings, pump power, and signal injection power have been obtained and used for comparison with our experiments. Direct-detection statistics have been obtained using the quantum analog of the Gaussian moment-factoring theorem, showing that the beat noise will be insignificant in our squeezed-amplification experiments.⁵ We have also developed a two-detector extension of the theory that permits efficient and insightful analysis of recent fourth-order interference experiments⁶ which use entangled photons from a parametric downconverter.

We have continued our study of the fundamental quantum limits on the measurement of phase. Our early work concentrated on the single-mode case,⁷ in which we showed that the Susskind-Glogower probability operator measure (SG-POM) provides the maximum-likelihood (ML) estimate of a c -number phase shift, and we explored a variety of quantum states for use in conjunction with this ML procedure. Recently, we have concentrated on the behavior of two-mode phase measurements which relieve the burden of the single-mode case's Paley-Wiener constraint. Here we have related quantum phase to angular momentum formalism⁸ and elucidated a system for error-free, phase-conjugate communication or finite-precision phase-sensing.⁹ The latter study casts new light on the two-mode

ML estimation problem, viz., it appears that there is no general ML phase-measurement POM for arbitrary input states.

Finally, we have continued and extended our theoretical work on quantum propagation in single-mode fiber.¹⁰ We now have a formalism which includes the Kerr effect, i.e., self-phase modulation (SPM), plus linear loss, and group-velocity dispersion. This construct reduces properly to the standard results of classical theory and linearized quantum theory. Moreover, we have already performed numerical studies which establish the validity limits of the linearized quantum theory for pure SPM, and for SPM plus loss, and we are proceeding with the richer case of SPM plus dispersion.

2.2.3 Publications

Joneckis, L.G., and J.H. Shapiro. "Quantum Propagation in a Kerr Medium: Lossless, Dispersionless Fiber." *J. Opt. Soc. Am. B*. Forthcoming.

Shapiro, J.H. "On the Performance of Optical Phase-Shift-Keying with Preamplify-Feedforward-Homodyne Reception." *IEEE Photon. Technol. Lett.* 4(6): 647-649 (1992).

Shapiro, J.H., and K.X. Sun. "Direct Detection of Gaussian-State Light." Paper presented at the Optical Society of America Annual Meeting, Albuquerque, New Mexico, September 20-25, 1992.

Shapiro, J.H., and N.C. Wong. "Optical Amplifiers, Phase-Shift Keying, and Signal-to-Noise Ratio." Paper presented at the Optical Society of

⁴ K.X. Sun, N.C. Wong, and J.H. Shapiro, "Squeezed Amplification with Cavity Detunings: Mean-Field Behavior," paper presented at the Optical Society of America Annual Meeting, Albuquerque, New Mexico, September 20-25, 1992; K.X. Sun and J.H. Shapiro, "Squeezed Amplification with Cavity Detunings: Noise Behavior," paper presented at the Optical Society of America Annual Meeting, Albuquerque, New Mexico, September 20-25, 1992.

⁵ J.H. Shapiro and K.X. Sun, "Direct Detection of Gaussian-State Light," paper presented at the Optical Society of America Annual Meeting, Albuquerque, New Mexico, September 20-25, 1992.

⁶ A.M. Steinberg, P.G. Kwiat, and R.Y. Chiao, *Phys. Rev. Lett.* 68(16): 2421-2424 (1992).

⁷ J.H. Shapiro and S.R. Shepard, "Quantum Phase Measurement: A System Theory Perspective," *Phys. Rev. A* 43(7): 3795-3817 (1991).

⁸ S.R. Shepard, *Phase of the Quantum Harmonic Oscillator*, Ph.D. diss., Dept. of Electr. Eng. and Comput. Sci., MIT, 1992.

⁹ J.H. Shapiro, "Phase Conjugate Quantum Communication with Zero Error Probability at Finite Average Photon Number," submitted to *Phys. Scripta*.

¹⁰ L.G. Joneckis and J.H. Shapiro. "Quantum Propagation in a Kerr Medium: Lossless, Dispersionless Fiber," *J. Opt. Soc. Am. B*, forthcoming.

America Annual Meeting, Albuquerque, New Mexico, September 20-25, 1992.

Shapiro, J.H. "Phase Conjugate Quantum Communication with Zero Error Probability at Finite Average Photon Number." Submitted to *Phys. Script*.

Shepard, S.R. *Phase of the Quantum Harmonic Oscillator*. Ph.D. diss., Dept. of Electr. Eng. and Comput. Sci., MIT, 1992.

Sun, K.X., N.C. Wong, and J.H. Shapiro. "Squeezed Amplification with Cavity Detunings: Mean-Field Behavior." Paper presented at the Optical Society of America Annual Meeting, Albuquerque, New Mexico, September 20-25, 1992.

Sun, K.X., and J.H. Shapiro. "Squeezed Amplification with Cavity Detunings: Noise Behavior." Paper presented at the Optical Society of America Annual Meeting, Albuquerque, New Mexico, September 20-25, 1992.

Wong, N.C. "Gravity-Wave Detection via an Optical Parametric Oscillator." *Phys. Rev. A* 45(5): 3176-3183 (1992).

2.3 Optical Frequency Division and Synthesis

Sponsors

Charles S. Draper Laboratories
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Project Staff

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Frequency division and synthesis in the optical domain play an important role in modern optical precision measurements, optical frequency standards, and optical communication. We have demonstrated optical frequency division using an optical parametric oscillator (OPO) approach based on an

efficient, one-step parametric downconversion process.¹¹ An OPO converts an input pump into two intense, coherent subharmonic outputs whose frequencies are tunable and whose sum frequency equals the pump frequency. By phase locking the output frequency difference to a microwave source, the output frequencies are precisely determined, and the OPO functions as an optical frequency divider. OPO frequency dividers can be operated in series or in parallel to measure, compare, and synthesize frequencies from optical to microwave with high precision and resolution.

2.3.1 Demonstration of Optical Frequency Division

We have employed a type-II phase-matched KTP OPO for demonstrating the concept of optical parametric division. A three-element cavity design consisting of the KTP crystal and two cavity mirrors has been constructed. The mirrors are rigidly attached to a spacer block to provide excellent mechanical stability. This cavity design permits systematic and continuous frequency tuning of the outputs and stable operation of the OPO. We have successfully demonstrated frequency division in the optical regime by phase locking the two OPO subharmonic outputs at 1.06 μm to a microwave synthesized signal (2-25 GHz) with a residual beat-note linewidth of 25 mHz, limited by the resolution of the spectrum analyzer.¹² This indicates that the OPO has very low phase noise, which can be further suppressed by phase locking it to a microwave source. This exceptionally high spectral purity should also allow us to study the quantum phase diffusion noise of an OPO.

2.3.2 High-Frequency Phase-Velocity-Matched Electro-Optic Modulator

In order to facilitate phase locking of the OPO outputs with a difference frequency of ~ 1 THz or more, an optical frequency comb with a large frequency span is required. We have developed a new electro-optic modulator that is capable of generating hundreds of sidebands at a spacing of 20-40 GHz. By incorporating a microwave waveguide structure in a LiNbO_3 electro-optic modulator,

¹¹ N.C. Wong, "Optical Frequency Division using an Optical Parametric Oscillator," *Opt. Lett.* 15(20): 1129-1131 (1990); D. Lee and N.C. Wong, "Tunable Optical Frequency Division using a Phase-Locked Optical Parametric Oscillator," *Opt. Lett.* 17(1): 13-15 (1992).

¹² D. Lee and N.C. Wong, "Stabilization and Tuning of a Doubly Resonant Optical Parametric Oscillator," submitted to *J. Opt. Soc. Am. B*.

the phase velocities of the microwave and optical fields can be matched to maximize the interaction length.¹³ We have been able to obtain a single-pass modulation index of 0.4 with 1 W of rf power at a driving frequency of 17.2 GHz. Our next step is to place the modulator inside an optical resonator to increase the effective interaction length, thus making it possible to generate sidebands with a span of over 1 THz. Preliminary results in a 12.4 GHz modulator shows a one percent output power at the fifth order sideband at 62 GHz.¹⁴ In addition to optical frequency division, THz optical sideband generation is potentially useful for frequency identification in a wideband optical communication network.

2.3.3 Optical Frequency Counter

We have proposed an optical frequency counter that is capable of measuring any optical frequency from the UV to the near IR relative to a microwave frequency standard.¹⁵ The concept is to measure the frequency difference of two known ratios (1/2 and 2/3) of an optical frequency f relative to the cesium clock. By employing a parallel network of phase-locked OPOs and wideband modulators to link the $(1/2)f$ and $(2/3)f$ frequencies, a precise and accurate optical frequency comb can be provided in the $\sim 1\text{-}2\text{-}\mu\text{m}$ wavelength region. By using this comb, most optical frequencies from the UV to the near IR can be measured or synthesized. We have begun an experimental program to implement this frequency counter. Using a Ti:sapphire laser at $\sim 775\text{ nm}$ ($f=387\text{ THz}$) as the pump source, our initial efforts will be to demonstrate a 2:1 OPO frequency divider with subharmonic outputs at $1.5\ \mu\text{m}$, which is also useful as an alternative source for fiber-optic communication.

2.3.4 Publications

Lee, D., and N.C. Wong. "High-Performance Optical Parametric Oscillator," *Proceedings of the SPIE Frequency Stabilized Lasers and Their Applications*, Boston, Massachusetts, November 1992.

Lee, D., and N.C. Wong. "Tunable Optical Frequency Division using a Phase-Locked Optical Parametric Oscillator." *Opt. Lett.* 17(1): 13-15 (1992).

Lee, D., and N.C. Wong. "Stabilization and Tuning of a Doubly Resonant Optical Parametric Oscillator." Submitted to *J. Opt. Soc. Am. B*.

Wong, N.C. "Gravity-Wave Detection via an Optical Parametric Oscillator." *Phys. Rev. A* 45(5): 3176-3183 (1992).

Wong, N.C. "Optical Frequency Counting from the UV to the Near IR." *Opt. Lett.* 17(16): 1155-1157 (1992).

Wong, N.C. "Proposal for a 10 THz, Precision Optical Frequency Comb Generator." *IEEE Photon. Technol. Lett.* 4(10): 1166-1168 (1992).

Wong, N.C., and D. Lee, "Optical Parametric Division," *Proceedings of the 1992 IEEE Frequency Control Symposium*, pp. 32-38, Hershey, Pennsylvania, May 27-29 1992.

2.4 Fiber-Coupled External-Cavity Semiconductor High Power Laser

Sponsor

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Project Staff

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The experimental portion of this program ended in December 1991, and the program terminated officially when we submitted the final report to the Office of Naval Research in August 1992. During 1992, we expanded the theory of an optical maser first proposed by W.E. Lamb in 1964, using a traveling wave model to describe our experimental polarization results. The experimental results on *spatial* coherence were also more fully explained.

¹³ B.Y. Lee, T. Kobayashi, A. Morimoto, and T. Sueta, "Picosecond Electro-Optic Modulator/Deflector with Velocity Matching," paper presented at the Conference on Lasers and Electro-Optics, Baltimore, Maryland, May 12-17, 1991.

¹⁴ N.C. Wong and D. Lee, "Optical Parametric Division," *Proceedings IEEE Frequency Control Symposium*, Hershey, Pennsylvania, May 1992, p. 32; N.C. Wong, D. Lee, and L.R. Brothers, "Tunable Optical Frequency Division," *Digest of the International Quantum Electronics Conference*, Vienna, Austria, June 1992, p. 110.

¹⁵ N.C. Wong, "Optical Frequency Counting from the UV to the Near IR," *Opt. Lett.* 17(16): 1155-1157 (1992).

Because this program, which was considered a very long shot when started in 1980 under predecessor grant number N00014-80-C-0941, was becoming of commercial interest, in 1991 the principal investigator requested that the Navy project officer not renew the grant. The last sentence of the final report to the Navy reads, "It is hoped that ONR, by sponsoring this high-risk, long shot, has significantly contributed to the industrial competitiveness of our country."

Publications

Corcoran, C.J., and R.H. Rediker. "The Dependence of the Output of an External-Cavity Laser on the Relative Phases of Inputs from Five Gain Elements." *IEEE Photon. Tech. Lett.* 4(11): 1197-1200 (1992).

Corcoran, C.J. *Operation of Five Individual Laser Diodes as a Coherent Ensemble by Fiber Coupling into an External Cavity*. Ph.D. diss., Dept. of Physics, MIT, 1992.

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

Sponsor

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Project Staff

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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 for individual components while requiring that operation of the integrated optics (circuits) is 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 non-uniform

and (2) unequal coupling by the evanescent couplers.

In last year's *RLE Progress Report* (Number 134), we stated that the experimental results on the phase measurement and phase correction have been independent of the power difference between the interferometer arms up to ratios of greater than 10:1. It has since been experimentally determined that the phase measurement and the phase correction are independent of this power imbalance up to ratios of 50:1.

With this successful result and those from prior years, it was decided in 1992 to embark on building a complete basic optical module. The on-chip detector at the output of the interferometer is also incorporated in this planned module. In the previous work, the detector has been located off-chip. The semiconductor processing design we developed ensures that the components (e.g., waveguides, couplers and detectors) of the module are fabricated to be compatible. GaAs/AlGaAs epistructures, which are used for making the module, have been specified and are on hand. Individual processing steps have been specified and optimized. We have received the photolithography masks, which we designed.

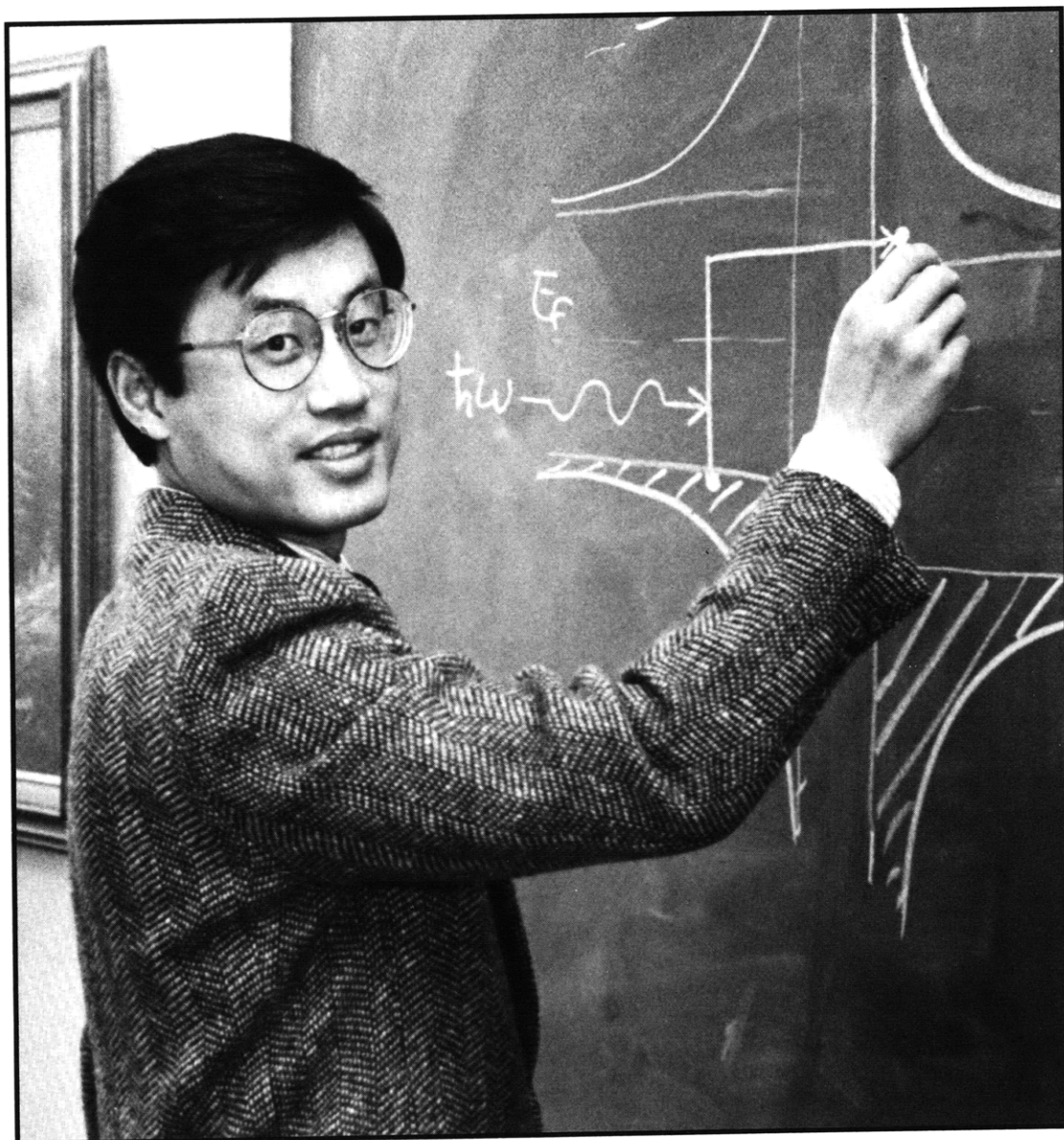
In 1992 the project dealt primarily with process definition and experimentation necessary for ongoing module fabrication. In the early part of 1993, we will complete the first basic modules, measure their performance, and compare their operation with theoretical predictions.

Publications

Lau, S.D., J.P. Donnelly, C.A. Wang, and R.H. Rediker. "Integrated AlGaAs Waveguide Components for Optical Phase Difference Measurements and Correction." Submitted to *IEEE J. Quantum Electron.*

Lau, S.D. *Optical Phase Difference Measurement and Correction Using AlGaAs Guided-Wave Components*. Ph.D. diss., Dept. of Electr. Eng. and Comput. Sci., MIT, 1992.

Pheiffer, Brian K. *Integrated AlGaAs Reduced-Confinement Tapered Waveguide Antennas*. S.M. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1992.



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