Chapter 2. Optical Propagation and Communication

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2.1 Introduction

The central theme of our research 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

Sponsor

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Project Staff

Professor Jeffrey H. Shapiro, Dr. Ngai C. Wong, Dr. Lance G. Joneckis, Scott R. Shepard, Ke-Xun Sun

The central focus of our research has been gain-saturated operation of an optical parametric amplifier (OPA). 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, an operating regime known as squeezed amplification.[2] We have performed a detailed study of the mean-field characteristics, gain saturation, and quantum-noise spectra of an injection-seeded OPA including arbitrary cavity detunings of the three interacting waves.[3] Comparison with our mean-field experimental results using a type-I phase-matched $LiNbO_3$ OPA has shown excellent qualitative agreement. We have also successfully analyzed a thermal-hysteresis effect encountered in our experiment that can severely impact the tuning capability of the OPA.[4]

As part of our squeezed-amplifier theory, we have established the quantum form of the Gaussian moment-factoring theorem and used this theorem to deduce the direct-detection photocurrent noise spectrum from a squeezed amplifier in the Gaussian-state approximation. We have also used this Gaussian-state formalism to explicitly unify the analyses of the three principal nonclassical manifestations of signal-idler state entanglement, i.e., nonclassical signal/idler photon correlation, nonclassical quadrature-noise squeezing, and nonclassical

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[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, *Classical and Quantized Fields in Optical Parametric Interactions,* Ph.D. diss., Dept. of Physics, MIT, 1993.

[4] K.X. Sun, *Classical and Quantized Fields in Optical Parametric Interactions,* Ph.D. diss., Dept. of Physics, MIT, 1993; K.X. Sun, N.C. Wong, and J.H. Shapiro, "Thermal Hysteretic Effects in a Triply-Resonant Optical Parametric Oscillator," paper presented at the Conference on Lasers and Electro-Optics, Baltimore, Maryland, May 2-7, 1993.

signal/idler fourth-order interference.[5] This work clarifies previously ill-understood limits on the semiclassical theory of fourth-order interference. In particular, we show that a quantum signature is demonstrable, in the low-photon-flux regime, at fringe visibilities substantially below 50 percent.

In another theoretical study, we have continued our development of quantum propagation theory for single-mode fiber. Using a coarse-grained time approach based on a phenomenological Kerr-effect time constant, we have been working to evaluate the homodyne-measurement noise spectra for a variety of input and fiber conditions.[6] We have obtained results for continuous-wave (cw) inputs applied to disperionless fiber in the absence and presence of loss. The latter case was handled using the terminated-cumulant expansion (TCE); we are now using this same approach to find the noise spectrum for dispersive propagation with a cw input. We have also begun exploring the value of local-oscillator optimization in pulsed-input homodyne measurements.

2.2.1 Publications

Joneckis, L.G., and J.H. Shapiro. "Quantum Propagation in a Kerr Medium: Lossless, Dispersionless Fiber." *J. Opt. Soc. Am. B* 10(6): 1102-1120 (1993).

Joneckis, L.G., and J.H. Shapiro. "Quantum Propagation in Single-Mode Fiber." Paper presented at the Quantum Electronics and Laser Science Conference, Baltimore, Maryland, May 2-7, 1993.

Joneckis, L.G., and J.H. Shapiro. "Quantum Propagation in Single-Mode Fiber." *Proceedings of the Third Workshop on Squeezed States and Uncertainty Relations,* Baltimore, Maryland, August 10-13, 1993. Forthcoming.

Shapiro, J.H., "Phase Conjugate Quantum Communication with Zero Error Probability at Finite Average Photon Number," *Phys. Script.* T48: 105-112 (1993).

Shapiro, J.H., and K.X. Sun. "Semiclassical vs. Quantum Behavior in Fourth-Order Interference." *J. Opt. Soc. Am. B.* Forthcoming.

Sun, K.X. *Classical and Quantized Fields in Optical Parametric Interactions.* Ph.D. diss., Dept. of Physics, MIT, 1993.

Sun, K.X., N.C. Wong, and J.H. Shapiro. "Thermal Hysteretic Effects in a Triply-Resonant Optical Parametric Oscillator." Paper presented at the Conference on Lasers and Electro-Optics, Baltimore, Maryland, May 2-7, 1993.

2.3 Multiresolution Laser Radar Range Profiling

Sponsor

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This effort is part of a collaboration on automatic target detection and recognition, with Professors Alan S. Willsky (MIT Laboratory for Information and Decision Systems) and W. Eric L. Grimson (MIT Artificial Intelligence Laboratory) and their students. The unifying theme of the collaboration is the use of multiresolution (wavelet) methods at every stage—from sensor front-end processing, through feature extraction, to the object recognition module—in an overall system.

Our group's activity centers on the application of multiresolution techniques to laser radars. Previously, we have studied maximum-likelihood (ML) estimation for planar range-profiling with a laser radar.[7] The importance of the ML approach lies in its ability to suppress the range anomalies caused by laser speckle. The practicality of the ML approach derives from the utility of the expectation-maximization (EM) algorithm for this problem. In initial work on the multiresolution range-profiling problem, we have shown that the same EM approach can be applied, at any desired wavelet

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[5] J.H. Shapiro and K.X. Sun, "Semiclassical vs. Quantum Behavior in Fourth-Order Interference," *J. Opt. Soc. Am. B,* forthcoming.

[6] L.G. Joneckis and J.H. Shapiro, "Quantum Propagation in a Kerr Medium: Lossless, Dispersionless Fiber," *J. Opt. Soc. Am. B* 10(6): 1102-1120 (1993); L.G. Joneckis and J.H. Shapiro, "Quantum Propagation in Single-Mode Fiber," paper presented at the Quantum Electronics and Laser Science Conference, Baltimore, Maryland, May 2-7, 1993.

[7] T.J. Green, Jr. and J.H. Shapiro, "Maximum-Likelihood Laser Radar Range Profiling with the Expectation-Maximization Algorithm," *Opt. Eng.* 31(11): 2343-2354 (1992).

scale, to perform ML profiling. We are now beginning performance studies on this scheme using Haar wavelets to fit simulated laser radar range data.

2.4 Optical Frequency Division and Synthesis

Sponsors

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  Grant DAAH04-93-G-0399
  Grant DAAH04-93-G-0187

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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 coherent optical communication. We have demonstrated tunable optical frequency division using an optical parametric oscillator (OPO) approach based on an efficient, one-step parametric downconversion process.[8] 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.

2.4.1 Terahertz Optical Frequency Comb Generation

In order to facilitate difference frequency measurements in the THz range, we have developed an optical frequency comb generator based on an efficient electro-optic phase modulator design. By incorporating a microwave waveguide resonator structure in a $LiNbO_3$ electro-optic modulator, the phase velocities of the microwave and optical fields can be matched to maximize the electro-optic modulation at a user-specified microwave frequency. The modulation is further enhanced by placing the modulator inside an optical cavity that is resonant for the input optical beam and generated sidebands. For 1 W of microwave power at 17 GHz, we have obtained an optical frequency comb with a 3-THz span, as shown in figure 1.[9] We have employed the terahertz comb to measure a difference frequency of 1.45 THz between a YAG laser and the signal beam of an OPO with a measurement uncertainty of 1 MHz, limited only by the stability of the two optical sources. In addition to optical frequency metrology, terahertz optical frequency comb generation is potentially useful for frequency identification in a wideband optical communication network.

2.4.2 Tunable Optical Parametric Oscillator

In our first demonstration of a tunable optical frequency divider, the signal-idler difference frequency of a type-II phase-matched KTP OPO was phase locked to a microwave source at 12.3 GHz with excellent signal-to-noise ratio.[10] The tuning range was limited by the 25-GHz bandwidth of the high-speed photodetector. For many applications, a tuning range that is much larger than the detector bandwidth is desirable. We have made use of the terahertz optical frequency comb generator to phase lock the KTP OPO at a difference frequency of 665 GHz. The idler beam was used to drive the terahertz optical frequency comb generator; the resultant beat frequency between the signal and the 39th upper sideband of the comb was detected by a 1-GHz photodetector. We have measured a residual phase noise spectral density of the phase-

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[8] 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).

[9] L.R. Brothers, D. Lee, and N.C. Wong, "Terahertz Optical Frequency Comb Generation and Phase Locking of Optical Parametric Oscillator at 665 GHz," *Opt. Lett.*, forthcoming.

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

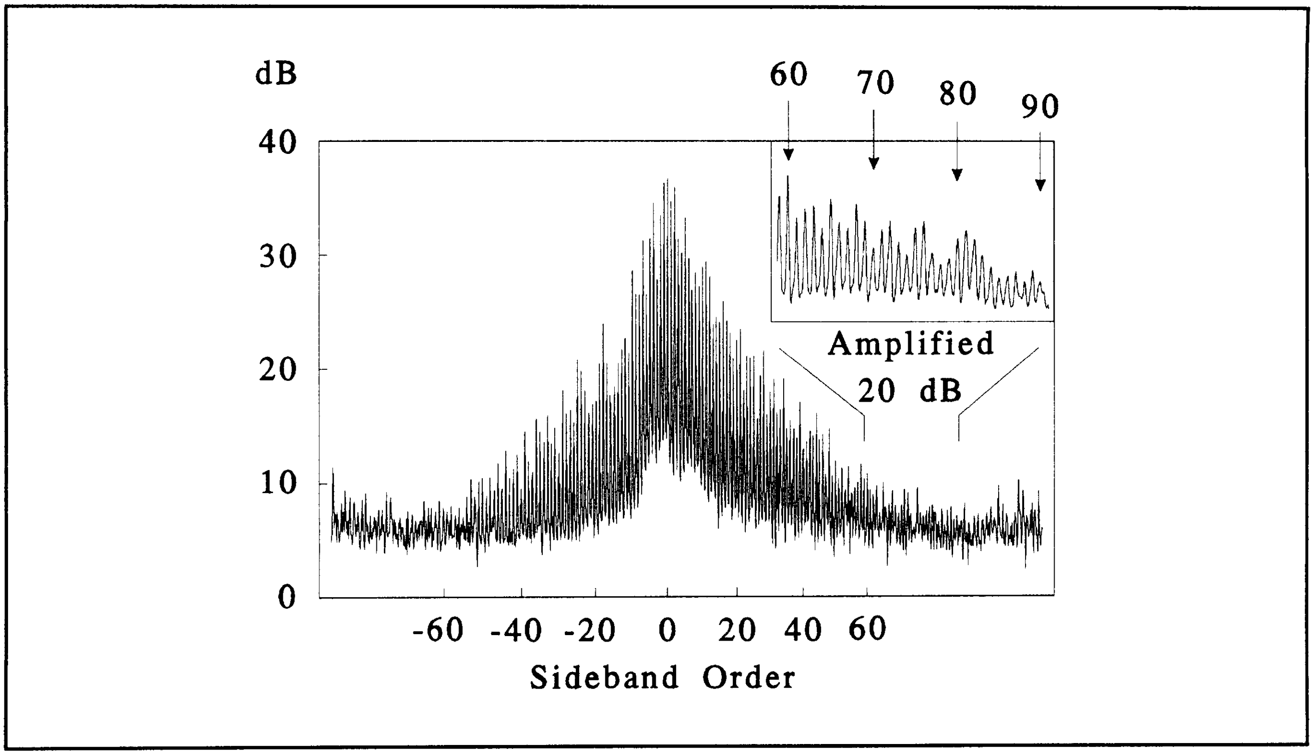

Figure 1. Optical spectrum analyzer trace of the optical frequency comb, with a mode spacing of 17.05 Ghz. The inset shows an amplified portion of the spectrum.

locked OPO of 0.2 mrad/$\sqrt{Hz}$.[11] The high spectral purity obtained in the experiment shows that phase locking at an even higher difference frequency is possible.

We have also developed a cw dual-cavity doubly resonant OPO (DRO) that provides a wider tuning range than the usual single-cavity OPO. Because of the stringent requirement of simultaneous cavity resonance of the signal and idler waves in a single-cavity DRO, mode hops usually occur if the cavity length is tuned by more than 1-2 nm, or ~ 10 MHz in output frequencies in our DRO system. To overcome this lack of tuning capability, signal and idler waves are separated internally by a polarizing beam splitter and resonated in separate cavities. In this way, the threshold remains low while continuous frequency tuning is achieved by varying the two cavities separately. Our preliminary results show that the cavity length could be tuned over 60 nm, or 600 MHz, in the output frequencies. The threshold for the dual-cavity DRO was 55 mW compared with 47 mW for a single-cavity DRO. The tuning range of the dual-cavity DRO is expected to be limited by the angle phase matching bandwidth of the KTP crystal of ~ 50-100 GHz. This development may lead to a wider use of cw OPOs as convenient and tunable radiation sources for many applications.

2.4.3 Publications

Brothers, L.R., and N.C. Wong. "Terahertz Optical-Frequency Comb Generation." Paper presented at the Optical Society of America Annual Meeting, Toronto, Canada, October 3-8, 1993.

Brothers, L.R., D. Lee, and N.C. Wong. "Terahertz Optical Frequency Comb Generation and Phase Locking of Optical Parametric Oscillator at 665 GHz." *Opt. Lett.* Forthcoming.

Lee, D., and N.C. Wong. "Stabilization and Tuning of a Doubly Resonant Optical Parametric Oscillator." *J. Opt. Soc. Am. B* 10(9): 1659-1667 (1993).

Lee, D., N.C. Wong, and L.R. Brothers. "Frequency Tuning and Stabilization of a KTP Optical

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[11] L.R. Brothers, D. Lee, and N.C. Wong, "Terahertz Optical Frequency Comb Generation and Phase Locking of Optical Parametric Oscillator at 665 GHz," *Opt. Lett.*, forthcoming.

Parametric Oscillator." Paper presented at the Optical Society of America Annual Meeting, Toronto, Canada, October 3-8, 1993.

Wong, N.C., and D. Lee. "Frequency Tuning and Phase Locking of an Ultrastable Doubly Resonant Optical Parametric Oscillator." Paper presented at the 1994 Advanced Solid-State Lasers, Salt Lake City, Utah, February 7-10, 1994.

Wong, N.C., D. Lee, and L.R. Brothers. "CW Phase-Locked Optical Parametric Oscillator as a Tunable Source for Terahertz Radiation." *Proceedings of the SPIE Nonlinear Optics for High-Speed Electronics,* Los Angeles, California, January 25, 1994.

Wong, N.C., D. Lee, and L.R. Brothers. "Optical Frequency Counting Based on Parametric Downconversion." Paper presented at the 1993 International Symposium on Atomic Frequency Standards and Coherent Quantum Electronics, Nara, Japan, August 18-20, 1993.

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

Sponsor

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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 the 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.

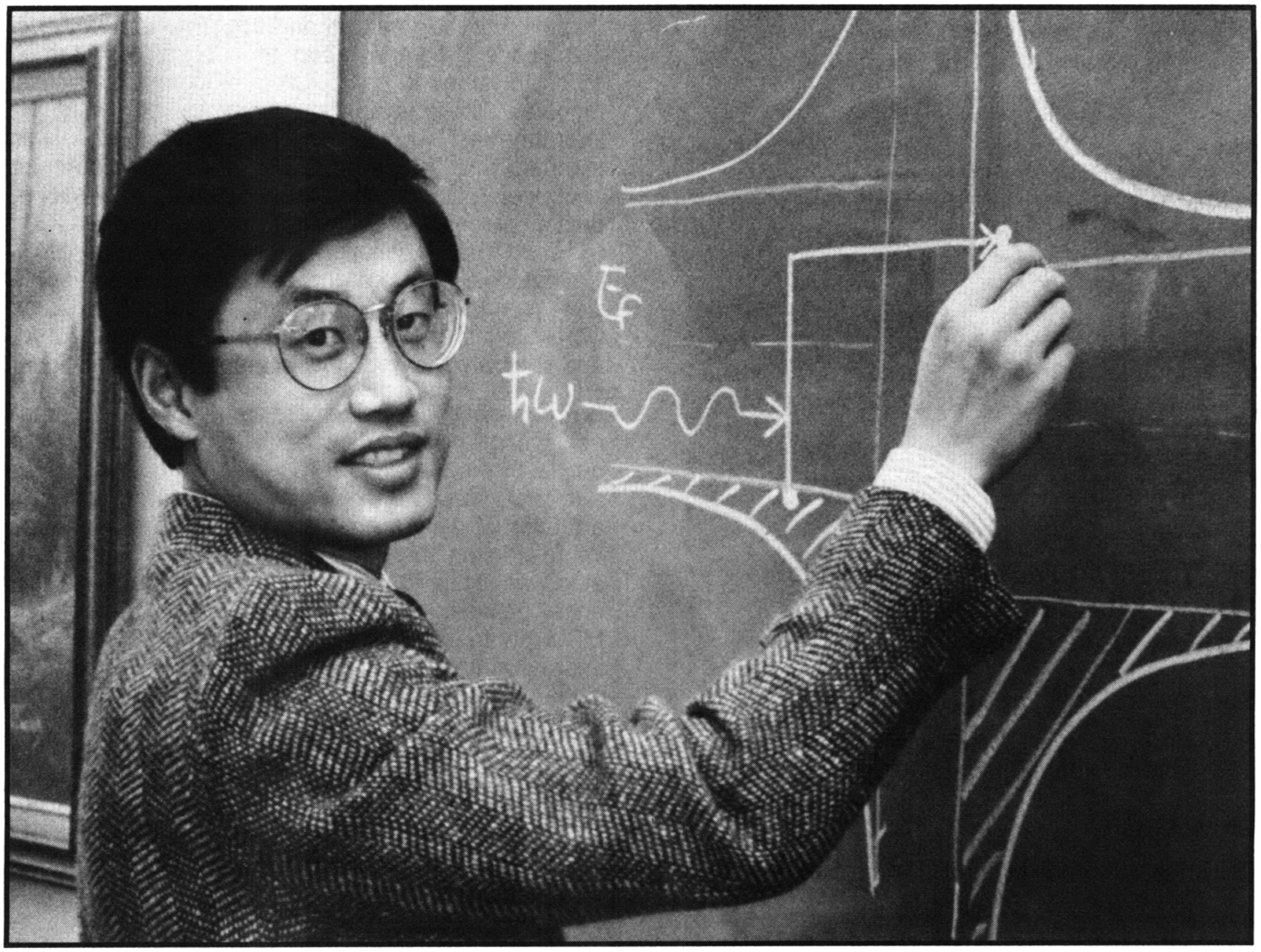
In *RLE Progress Report No. 135*, we stated that the experimental results on the phase measurement and phase correction were independent of the power difference between the interferometer arms up to a ratio of greater than 50:1. We also wrote in last year's progress report that it was decided in 1992 to embark on building a complete optical module. The on-chip detector at the output of the interferometer was to also be incorporated in this planned module. In the previous work, the detector has been off chip. In this past year, a semiconductor processing technique was developed and used so that fabrication of all components (e.g., waveguides, couplers and detectors) of the module was compatible. The *complete* optical modules were fabricated; their performance was measured, and compared favorably with theoretical predictions.

We can now report in more detail on the components of the complete module. The phase on the output of the through waveguides was varied using a reverse biased p^+-n^--n^+ structure incorporated into a portion of the waveguide. A small dither was also impressed on the phase. A Y-junction interferometer was used to obtain the relative phase difference between the two waveguides. Integrated MSM photodetectors, 17x69 mm in size with total internal reflection mirror coupling, were used for signal detection. Both the interferometer and detector were fabricated and operated between the two 30 μm-separated through waveguides. The phase dither detection system made it possible to adjust appropriately the relative phase between the outputs of the two through waveguides, largely independent of the power ration between the individual guides.

2.5.1 Publications

Golubovic, Boris. *Basic Module for an Integrated Optical Phase Difference Measurement and Correction System.* S.M. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1993.

Lau, S.D., J.P. Donnelly, C.A. Wang and R.H. Rediker. "Integrated AlGaAs Waveguides for Optical Phase Difference Measurement and Correction." *IEEE J. Quantum Electron.* Forthcoming.



Professor Qing Hu