

## 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 Nonlinear and Quantum Optics

### Sponsor

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### 2.2.1 Quantum Optical Tap

It has been predicted that a gain-saturated optical parametric amplifier (OPA) can offer an improvement in the large-signal signal-to-noise ratio over a conventional phase-insensitive optical amplifier.<sup>1</sup> This unique characteristic can lead to a better

photodetection system and is potentially useful in coherent optical communication networks.

As a prelude to demonstrating the preceding quantum optical tap concept, we have set up an ultralow loss optical parametric oscillator (OPO) for the study of quantum noise correlation. High quality mirrors and a potassium titanyl phosphate (KTP) crystal have permitted stable cw operation of the OPO with a threshold of 30 mW. With a longer crystal, a two-piece lower-loss design, and a 2.7 percent output coupler, the OPO threshold was 150 mW. It is expected that this higher-threshold OPO should yield an intensity correlation between the signal and idler outputs of 80-90 percent and allow us to study the mean-field characteristics, gain saturation, and quantum-noise spectra of an injection-seeded OPA.<sup>2</sup>

Instead of using a large-frame krypton ion laser as a green pump source, we have recently generated over 300 mW of 532 nm light using resonant second harmonic generation of a 500-mW 1.06  $\mu\text{m}$  diode-pumped YAG laser. This cw green source has been utilized to pump a KTP OPO for increased mechanical stability. The system is used for investigating the possibility of self-phase locking in a type-II phase matched OPO using an intracavity quarter-wave plate. The wave plate mixes the two orthogonally polarized subharmonic outputs and provides a means for signal injection for both subharmonics. When the OPO is operated near frequency degeneracy, it is expected that this mutual signal injection should induce self-phase locking, similar to that observed in type-I phase

<sup>1</sup> N.C. Wong, "Squeezed Amplification in a Nondegenerate Parametric Amplifier," *Opt. Lett.* 16(21): 1698-1700 (1991).

<sup>2</sup> K.X. Sun, *Classical and Quantized Fields in Optical Parametric Interactions*, Ph.D. diss., Dept. of Physics, MIT, 1993.

matched OPO.<sup>3</sup> Self-phase locking is of interest in the study of squeezed states and in precision measurements.

### 2.2.2 Quasi-Phase Matched Nonlinear Optics

We have initiated a study of quasi-phase matching (QPM)<sup>4</sup> in lithium niobate with the goal of fabricating QPM nonlinear optical devices that can be operated at any user specified wavelength within the transparency window of lithium niobate, such as in the 1.5  $\mu\text{m}$  optical communication window. Nonlinear optical devices that are fabricated using QPM are potentially useful in many applications such as optical frequency conversion and amplification for optical communication networks. By employing the electric field poling technique,<sup>5</sup> we have successfully obtained domain reversal in a bulk 6-mm-long 240- $\mu\text{m}$ -thick lithium niobate sample with a periodicity of 21.5  $\mu\text{m}$ . We are in the process of testing the QPM material in a three-wave mixing experiment with inputs of 782 nm from a Ti:sapphire laser and 1064 nm from a diode-pumped YAG laser. Improvements in the QPM fabrication process are also in progress in order to obtain more uniform and longer gratings.

### 2.2.3 Squeezed-State Generation in Optical Fiber

In theoretical work, we have been establishing the limits on squeezed-state generation in optical fiber. We have shown that the Raman noise which accompanies the noninstantaneous Kerr effect sets a new limit on the degree of quadrature-noise squeezing that can be obtained from continuous-

wave (cw) four-wave mixing (fwm) in optical fiber with a spectrum-analysis homodyne measurement.<sup>6</sup> For pulsed squeezed-state generation in fiber, we have shown that local-oscillator (LO) selection is the key to observing the full squeezing generated when the nonlinear interaction is pumped by a transform-limited Gaussian pulse.<sup>7</sup> We have developed a general theory for optimal LO selection for quadrature-noise measurements of arbitrary spatio-temporal quantum states.<sup>8</sup> Using this theory, in conjunction with a single-resonance model for the non-instantaneous Kerr response of single-mode fiber, we have shown that previously suggested LO selections—the bright-fringe LO from a Sagnac interferometer squeezer, a weak-signal fwm LO from a Sagnac interferometer, and a pulse-compressed LO—are all sub-optimum.<sup>9</sup> Furthermore, our general theory has revealed a new squeezing mode for cw-source fiber experiments, namely Raman squeezing.<sup>9</sup> Here, the output from a cw-pumped fiber is homodyned with a LO comprised of two unequal-amplitude, optimally-phased optical frequencies separated by a frequency difference comparable to that of the peak Raman gain.

### 2.2.4 Publications

Patterson, S.G. *Quantum Intensity Noise Correlation in a Type-II Phase Matched Optical Parametric Oscillator*. S.M. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1995.

Shakeel, A. *Enhanced Squeezing in Homodyne Detection via Local-Oscillator Optimization*. S.M. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1995.

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- <sup>3</sup> C.D. Nabors, S.T. Yang, T. Day, and R.L. Byer, "Coherence Properties of a Doubly Resonant Monolithic Optical Parametric Oscillator," *J. Opt. Soc. Am. B* 7(5): 815-820 (1990).
- <sup>4</sup> M.M. Fejer, G.A. Magel, D.H. Jundt, and R.L. Byer, "Quasi-Phase-Matched Second Harmonic Generation: Tuning and Tolerances," *IEEE J. Quantum Electron.* 28(11): 2631-2654 (1992).
- <sup>5</sup> M. Yamada, N. Nada, M. Saitoh, and K. Watanabe, "First-Order Quasi-Phase Matched LiNbO<sub>3</sub> Waveguide Periodically Poled by Applying an External Field for Efficient Blue Second-Harmonic Generation," *Appl. Phys. Lett.* 62(5): 435-436 (1993).
- <sup>6</sup> J.H. Shapiro and L. Boivin, "Raman-Noise Limit on Squeezing in Continuous-Wave Four-Wave Mixing," *Opt. Lett.* 20(8): 925-927 (1995).
- <sup>7</sup> L.G. Joneckis and J.H. Shapiro, "Enhanced Fiber Squeezing via Local-Oscillator Pulse Compression," *Proceedings of Nonlinear Optics: Materials, Fundamentals and Applications*, Waikaloa, Hawaii, July 24-29, 1994.
- <sup>8</sup> A. Shakeel, *Enhanced Squeezing in Homodyne Detection via Local-Oscillator Optimization*, S.M. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1995.
- <sup>9</sup> J.H. Shapiro and A. Shakeel, "Optimizing Homodyne Detection of Quadrature-Noise Squeezing via Local Oscillator Selection," submitted to *J. Opt. Soc. Am. B*.

Shapiro, J.H. "Phase Conjugate Quantum Communication with Optical Heterodyne Detection." *Opt. Lett.* 20(9): 1059-1061 (1995).

Shapiro, J.H., and L. Boivin. "Raman-Noise Limit on Squeezing continuous Wave Four-Wave Mixing." *Opt. Lett.* 20(8): 925-927 (1995).

Shapiro, J.H. "On the Holographic Generation of Squeezed States." *Opt. Lett.* Forthcoming.

Shapiro, J.H., and A. Shakeel. "Optimizing Homodyne Detection of Quadrature-Noise Squeezing via Local Oscillator Selection." Submitted to *J. Opt. Soc. Am. B*.

## 2.3 Multiresolution Laser Radar Range Imaging

### Sponsor

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### Project Staff

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This effort is part of a collaboration on automatic target detection and recognition, with Professors Alan S. Willsky (from MIT's Laboratory for Information and Decision Systems) and W. Eric L. Grimson (from MIT's 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. We have been developing the use of wavelet-based maximum-likelihood (ML) estimation for laser radar range imaging.<sup>10</sup> The importance of the ML approach lies in its ability to suppress the range anomalies caused by laser speckle, while simultaneously providing a physically-motivated, data-dependent route to optimally terminating a coarse-to-fine resolution progression. The practicality of the ML approach derives from the utility of the expectation-maximization (EM) algorithm for this problem together with the special properties of the Haar wavelet basis.<sup>11</sup> ML/EM range processing of typical

128 × 128 raw imagery with an arbitrary multiresolution basis is prone to both an untenable computational burden and numerical sensitivity. With the Haar basis, however, we have developed a fast ML/EM processor that is orders of magnitude faster than the general-wavelet formulation, numerically robust, and fully parallelizable. We have demonstrated the key properties of the fast ML/EM algorithm on real laser radar data, and we are now proceeding to apply this algorithm as a front-end processor to a model-based object recognition module.

### 2.3.1 Publications

Greer, D.R. *Multiresolution Laser Radar Range Profiling of Real Imagery*. M.Eng. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1996.

Greer, D.R., I. Fung, and J.H. Shapiro. "Maximum-Likelihood Multiresolution Laser Radar Range Imaging." Submitted to *IEEE Trans. Image Process.*

## 2.4 Optical Frequency Division and Synthesis

### Sponsors

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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. The focus of this program is to build an optical frequency counter based on a parallel network of phase locked optical parametric oscillators (OPOs) and to apply it to precision measurements. An OPO-based optical frequency counter can be used

<sup>10</sup> I. Fung and J.H. Shapiro, "Multiresolution Laser Radar Range Profiling with the Expectation-Maximization Algorithm," *Proceedings of the Joint ATR Systems and Technology Conference IV*, Monterey, California, November 14-18, 1994.

<sup>11</sup> D.R. Greer, *Multiresolution Laser Radar Range Profiling of Real Imagery*, M.Eng. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1996; D.R. Greer, I. Fung, and J.H. Shapiro, "Maximum-Likelihood Multiresolution Laser Radar Range Imaging," submitted to *IEEE Trans. Image Process.*

to measure, compare, and synthesize frequencies from optical to microwave, with high precision and accuracy. Our research includes the development of a number of enabling technologies such as wideband optical frequency comb generation,<sup>12</sup> tunable cw OPOs,<sup>13</sup> and techniques for operating a parallel network of OPOs.

#### 2.4.1 Terahertz Optical Frequency Comb Generation

In order to facilitate difference frequency measurements in the terahertz 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<sub>3</sub> 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 the generated sidebands. For 1 W of microwave power at 17 GHz, we have obtained an optical frequency comb with a 3-THz span.<sup>12</sup> We have found that the span is limited by the group velocity dispersion of the lithium niobate electro-optic material.

In order to overcome the dispersion limitations, we employed dispersion compensating prism pair, similar to its usage in ultrafast mode-locked lasers. Preliminary results show that indeed the span of the comb can be extended beyond the dispersion limit. However, because of increased intracavity losses of the prism pair, the span is only 3.5 THz. We are now working on replacing the current 1-W microwave amplifier with a 20-W amplifier that should clearly show a greatly enhanced modulation and a larger span. We expect that a 5-10 THz span should be feasible.

#### 2.4.2 Quantum Phase Diffusion Noise of an Optical Parametric Oscillator

It is well known theoretically that the phase between the subharmonic outputs of an optical parametric oscillator undergoes phase diffusion similar to that of a laser.<sup>14</sup> In order to observe this phase diffusion noise, it is necessary to have a stable and constant frequency difference between the two outputs, as in our phase locked KTP OPO. We have made measurements of such a phase locked system with the OPO beat frequency set at 30 MHz. The beat signal was demodulated to yield both the in-phase and quadrature-phase noise spectra. Preliminary results show that the observed noise spectra have the same qualitative behavior as our theoretical model. Quantitatively, the noise powers were higher than expected, due probably to the excess noise from the pump laser. We plan to improve the OPO system to eliminate most of the excess noise in order to obtain the first measurement of the phase diffusion noise of an OPO. This noise measurement is important to optical frequency counting because phase coherence between the optical frequency and the microwave frequency standard is crucial.

#### 2.4.3 Optical Frequency Division

A key element of the optical frequency counter is a 3:1 optical frequency divider in which the input to output frequency ratio is 3:1. The first step is to generate an approximate ratio of 3:1 by three-wave mixing of the inputs  $3f$  and  $2f + \delta$  to yield a difference frequency of  $f - \delta$ . A second step involves a second-stage three-wave mixing of the input  $2f + \delta$  and the output  $f - \delta$  to yield a second output at  $f + 2\delta$ . By measuring the beat frequency between the two outputs at  $3\delta$  and setting  $\delta$  to zero, an exact 3:1 frequency ratio is obtained.

We have previously used the nonlinear optical crystal cesium titanyl arsenate (CTA) for generating  $\sim 3:1$  frequency ratio by three-wave difference frequency mixing.<sup>15</sup> More recently, we have tested the crystal lithium borate (LBO) and obtained similar results. The LBO crystal has been well character-

<sup>12</sup> 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.* 19(4): 245-247 (1994).

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

<sup>14</sup> R. Graham and H. Haken, "The Quantum Fluctuations of the Optical Parametric Oscillator," *Z. Physik* 210: 276-302 (1968).

<sup>15</sup> B. Lai, N.C. Wong, and L.K. Cheng, "Continuous-Wave Tunable Light Source at 1.6  $\mu\text{m}$  by Difference-Frequency Mixing in CsTiOAsO<sub>4</sub>," *Opt. Lett.* 20(17): 1779-1781 (1995).

ized and has very good optical properties compared with the CTA crystal. However, its nonlinear coefficient is a few times smaller than that of CTA. We are currently preparing the second three-wave mixing step using another CTA crystal with a different crystal cut.

#### 2.4.4 Publications

Brothers, L.R., and N.C. Wong. "Optical Frequency Comb Generation for Terahertz Difference-Frequency Measurements." *Proceedings of the SPIE Laser Frequency Stabilization and Noise Reduction Conference*, San Jose, California, February 9-10, 1995.

Lai, B., N.C. Wong, and L.K. Cheng. "Continuous-Wave Tunable Light Source at 1.6  $\mu\text{m}$  by Difference-Frequency Mixing in  $\text{CsTiOAsO}_4$ ." *Opt. Lett.* 20(17): 1779-1781 (1995).

Lee, D., and N.C. Wong, "Quantum Phase Diffusion Noise Measurements in a cw Optical Parametric Oscillator." *Proceedings of the 7th Rochester*

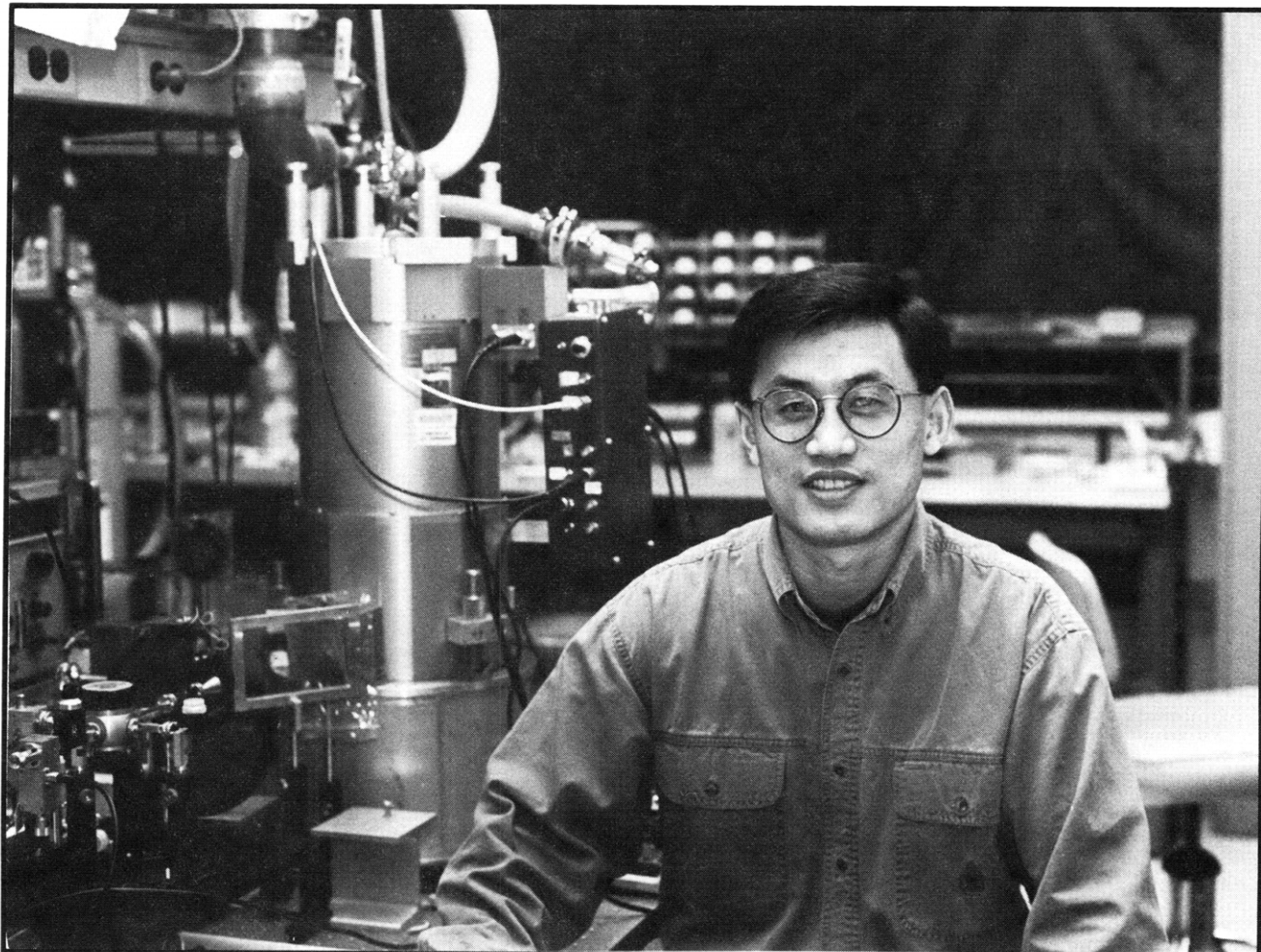
*Conference on Coherence and Quantum Optics*, Rochester, New York, June 7-10, 1995.

Lee, D., and N.C. Wong, "Tuning Characteristics of a cw Dual-Cavity KTP Optical Parametric Oscillator." Paper presented at SPIE Solid State Lasers and Nonlinear Crystals, San Jose, California, February 5-7, 1995.

Wong, N.C. "Optical-to-Microwave Frequency Chain Utilizing a Two-Laser-Based Optical Parametric Oscillator Network." *Appl. Phys. B* 61: 143-149 (1995).

Wong, N.C., B. Lai, P. Nee, and E. Mason. "Experimental Progress toward Realizing a 3:1 Optical Frequency Divider." *Proceedings of the Fifth Symposium on Frequency Standards and Metrology*, Woods Hole, Massachusetts, October, 15-19, 1995.

Wong, N.C. "New Applications of Optical Parametric Devices." Invited paper presented at SPIE Solid State Lasers and Nonlinear Crystals, San Jose, California, February 5-7, 1995.



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