Chapter 2. Optical Propagation and Communication

Academic and Research Staff

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

Visiting Scientists and Research Affiliates

Dr. Lance G. Joneckis[1]

Graduate Students

Jeffrey K. Bounds, L. Reginald Brothers, Irene Fung, Donald R. Greer, Bobby Y. Lai, Dicky Lee, Elliott J. Mason, Phillip T. Nee, Steven G. Patterson, Asif Shakeel

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

Maryland Procurement Office
Contract MDA 904-93-C4169
Contract MDA 903-94-C6071

Project Staff

Professor Jeffrey H. Shapiro, Dr. Ngai C. Wong, Dr. Lance G. Joneckis, Jeffrey K. Bounds, Elliott J. Mason, Phillip T. Nee, Steven G. Patterson, Asif Shakeel

2.2.1 Quantum Optical Tap

An optical parametric amplifier (OPA) is a nearly ideal nonresonant generator of nonclassical light: its signal and idler beams exhibit quantum entanglement which can be sensed as sub-shot-noise photon correlation or as a sub-shot-noise quadrature squeezing. It has been suggested that a gain-saturated OPA can provide a new route to nonclassical light-beam generation,[2] without recourse to joint signal/idler measurements. In particular, it may be possible to preserve the input large-signal signal-to-noise ratio (SNR) of the amplified channel in such an arrangement. Thus, a quantum optical tap for binary-phase-shift-keying (BPSK) could then be developed: such a tap would incur neither signal strength nor SNR degradation in either of its output channels, i.e., its signal and tap output ports.

As a prelude to demonstrating the preceding quantum optical tap concept, we have set up an ultralow loss optical parametric oscillator (OPO) for 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. Another KTP OPO with a longer crystal and a two-piece lower-loss design has been found to have a threshold of 20 mW. It is expected that the KTP OPOs should yield an intensity correlation between the signal and idler outputs of 90 percent and allow us to study the mean-field characteristics, gain saturation, and quantum-noise spectra of an injection-seeded OPA.[3]

---

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.

We have begun an experiment to resonantly generate the second harmonic of a 500-mW 1.06 μm YAG laser. The goal is to obtain stable cw operation and a high conversion efficiency of 60-80 percent in the second-harmonic generation. If successful, this arrangement will serve as a compact, low-noise pump source for KTP OPOs. Moreover, for degenerate OPO operation, the YAG laser can be used as the local oscillator for homodyne detection of quadrature-noise squeezing.

2.2.2 Quasi-Phase Matched Nonlinear Optics

We have initiated a study of quasi-phase matching (QPM)[4] in lithium niobate with the goal of fabricating QPM nonlinear optical devices that can be operated at any user specified wavelength, such as in the 1.5 μm 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,[5] we have successfully obtained domain reversal in a bulk 250-μm-thick lithium niobate sample. To achieve QPM it is necessary to obtain a periodic grating pattern of regular and domain reversed material in lithium niobate with a grating period of 5-15 μm maintained over a length of 1 cm. We are in the process of fabricating domain-reversed material in a periodic grating pattern.

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. Recently, 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 four-wave mixing in optical fiber.[6]

For pulsed squeezed-state generation in fiber, we have shown that local-oscillator (LO) pulse compression is the key to observing the full squeezing generated when the nonlinear interaction is pumped by a transform-limited Gaussian pulse.[7] We are now working on the theory of optimal LO selection for quadrature-noise measurements of arbitrary spatio-temporal quantum states.

2.2.4 Quantum Phase Measurements

Recently, a great deal of attention has been given to the phase problem for a single-mode quantum field. Previously, we showed that there are significant physical differences—with potentially important practical consequences—that emerge if the focus in phase-based quantum communication and precision measurement is shifted from single-mode fields to two-mode fields.[8] In particular, with a two-mode field it is possible to achieve perfect (i.e., zero error probability) K-ary phase-based digital communication at a root-mean-square (rms) photon number of K/2. This same rms photon number is also sufficient for a phase-based precision measurement of a c-number phase shift whose observation error is guaranteed to be no more than $\pm \pi/K$. The capabilities of these schemes for phase-based digital communication and precision measurement are radically different from those of their single-mode counterparts. Indeed, in single-mode phase-based communication it is impossible to achieve zero error probability at finite average photon number. Likewise, a single-mode phase measurement at finite average photon number cannot realize probability-one confinement of the measurement error to any proper subinterval of $(-\pi, \pi]$.

The two-mode phase measurement scheme referenced above relies on generating an entangled state, and the use of a quantum measurement which is the two-mode generalization of the Susskind-Glogower probability operator measure. As yet, there are no explicit approaches available for realizing either of these abstractions. In our

4 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).

5 M. Yamada, N. Nada, M. Saitoh, and K. Watanabe, "First-Order Quasi-Phase Matched $LiNbO_3$ Waveguide Periodically Poled by Applying an External Field for Efficient Blue Second-Harmonic Generation," *Appl. Phys. Lett.* 62(5): 435-436 (1993).

6 J.H. Shapiro and L. Boivin, "Raman-Noise Limit on Squeezing Continuous Wave Four-Wave Mixing," *Opt. Lett.*, forthcoming.

7 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.

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

present program, however, we have relieved the measurement part of this realization burden. Specifically, we have shown that zero error probability phase-based digital communication and $\pm\pi/K$ accuracy phase-based precision measurement can be accomplished—at an average photon number of approximately $K\sqrt{3/2}$ —via optical heterodyne detection.[9] Again, an appropriate two-mode entangled state is needed for which a generation technique is currently being sought.

2.2.5 Publications

Joneckis, L.G., 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.

Shapiro, J.H. "An Eclectic Tour of Quantum Optical Communications." Invited paper presented at the 1994 Annual Meeting of the Optical Society of America, Dallas, Texas, October 2-7, 1994.

Shapiro, J.H. "Phase Conjugate Quantum Communication with Optical Heterodyne Detection." *Opt. Lett.* Forthcoming.

Shapiro, J.H., and L. Boivin. "Raman-Noise Limit on Squeezing continuous Wave Four-Wave Mixing." *Opt. Lett.* Forthcoming.

Shapiro, J.H., and K.-X. Sun. "Semiclassical versus Quantum Behavior in Fourth-Order Interference." *Proceedings of Nonlinear Optics: Materials, Fundamentals and Applications,* Waikaloa, Hawaii, July 24-29, 1994.

Shapiro, J.H., and K.-X. Sun. "Semiclassical versus Quantum Behavior in Fourth-Order Interference." *J. Opt. Soc. Am. B* 11(6): 1130-1141 (1994).

2.3 Multiresolution Laser Radar Range Profiling

Sponsor

U.S. Air Force - Office of Scientific Research
Grant F49620-93-1-0604

Project Staff

Professor Jeffrey H. Shapiro, Irene Fung, Donald R. Greer

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. Our own 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.[10] 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 the current program, we have shown that the same EM approach can be applied, at any desired wavelet scale, to perform ML profiling. Using the Haar wavelet basis, we have demonstrated the use of this technique on simulated laser-radar range data.[11] In this study, we have established an efficient, weight-based stopping rule for terminating the coarse-to-fine progression of multiresolution ML estimation. We are presently working on improving the computational efficiency of our ML/EM approach so that this technique can be applied to real laser-radar test bed data from the Opto-Radar Systems Group of MIT Lincoln Laboratory.

---

9 J.H. Shapiro, "Phase Conjugate Quantum Communication with Optical Heterodyne Detection." *Opt. Lett.,* forthcoming.

10 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)

11 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.

2.3.1 Publications

Fung, I. *Multiresolution Laser Radar Range Profiling with the Expectation-Maximization Algorithm.* S.M. thesis. Dept. of Electr. Eng. and Comput. Sci., MIT, 1994.

Fung, I., 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.

2.4 Optical Frequency Division and Synthesis

Sponsors

MIT Lincoln Laboratory
Advanced Concepts Program
Contract CX-16335
U.S. Army Research Office
Grant DAAH04-93-G-0399
Grant DAAH04-93-G-0187

Project Staff

Dr. Ngai C. Wong, L. Reginald Brothers, Bobby Y. Lai, Dicky Lee

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 study the feasibility of establishing an optical frequency counter based on a parallel network of phase-locked optical parametric oscillators (OPOs). It includes the development of a number of enabling technologies, such as wideband optical frequency comb (OFC) generation,[12] tunable cw OPOs,[13] and techniques for operating a parallel network of OPOs. An OPO-based optical frequency counter can be operated to measure, compare, and synthesize frequencies from optical to microwave, with high precision and accuracy.

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 (OFC) 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 the generated sidebands. For 1 W of microwave power at 17 GHz, we have obtained an optical frequency comb with a 3-THz span.[12]

We have investigated the effects of small microwave frequency detuning on the OFC spectrum. Without detuning a symmetric spectrum is obtained and the span of 3 THz is entirely limited by the dispersion of the lithium niobate crystal. By detuning +2.3 MHz, we have observed an asymmetric spectrum, expanding towards the shorter wavelengths and contracting from the longer wavelengths because the detuning brings the shorter wavelengths into resonance and the longer wavelengths out of resonance. The one-sided span toward the shorter wavelengths is found to be 2.3 THz. Further detuning returns the spectrum to a symmetric shape but with a much smaller span. By using positive and negative detuning it is therefore possible to extend the OFC spectrum to a span of 4.6 THz. We are presently working on compensating the dispersion in order to extend the spectrum span to 10 THz or more.

2.4.2 Tunable Optical Parametric Oscillator

Optical parametric generation has been well known for producing tunable radiation over a broad spectral range. This has been realized in pulsed OPOs but not in cw OPOs. The doubly-resonant condition in cw operation, in which both the signal and idler waves are resonant with the cavity, prevents continuous frequency tuning. A singly resonant cw OPO can be tuned continuously, but at the expense of a much higher threshold power. We have developed a novel dual-cavity configuration that retains the

[12] 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).

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

low-threshold capability of an ordinary doubly-resonant system, and at the same time is capable of continuous tuning. By employing two separate cavities to resonate the signal and idler waves independently, the output frequencies become continuously tunable. Experimentally, we have observed a tuning range of 1 GHz, which is 100 times more than a single-cavity OPO. Theoretically, the tuning range is limited only by the phase-matching bandwidth of the nonlinear crystal, which is about 50-100 GHz for KTP.

We have discovered that the limiting factors for the tuning range are the weak pump resonance and the resonant leakage between the two cavities. As the OPO is tuned, the weak resonance of the pump field reduces the circulating pump intensity to a level below the threshold, thus effectively limiting the tuning range. Leakage of the signal and idler waves is caused by the imperfect coating of the polarizing beam splitter that is used to separate the signal and idler beams. Resonant leakage occurs when the idler cavity is resonant with the leaked signal field, which effectively leads to a lossy signal cavity, and vice versa. Lossy cavities increase the threshold and hence limit the tuning range. We are in the process of minimizing their effects by utilizing the angle walkoff of KTP to separate the two beams, thus eliminating the polarizing beam and improving the tuning range.

2.4.3 Three-Wave Mixing in CTA

It is potentially useful to have a tunable source at 1.5 μm for optical communications. We have used a new nonlinear optical crystal, cesium titanyl arsenate (CTA), to generate tunable radiation by three-wave difference-frequency mixing.[14] By using a krypton ion laser at 531 nm as the pump and a tunable Ti:sapphire laser as the input signal, we have generated 1 μW of tunable radiation from 1567 nm to 1653 nm. The use of a resonant cavity for frequency mixing has yielded an output power of ~100 μW. We have also determined that the CTA phase-matching angle for generating a 3-to-1 OPO frequency divider pumped at 532 nm is $\theta = 90°$, $\phi = 48°$. We have not observed parametric oscillation due to the quality of the crystal. We are presently investigating the use of other nonlinear crystals with better crystal quality such as lithium borate for demonstrating a 3-to-1 OPO.

2.4.4 Publications

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.* 19(4): 245-247 (1994).

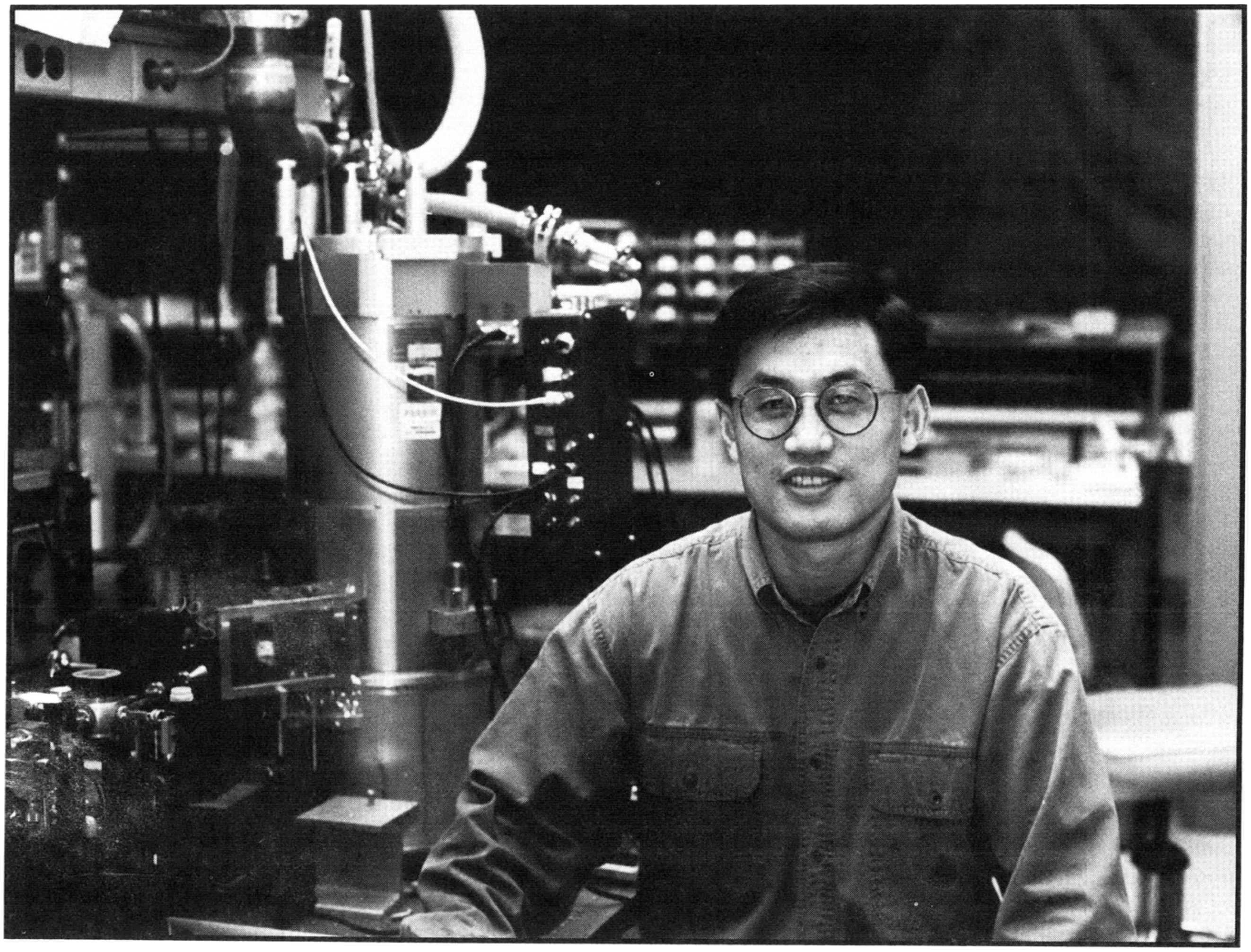
Lee, D., and N.C. Wong. "Tuning Characteristics of a cw Dual-Cavity KTP Optical Parametric Oscillator." Paper presented at the Conference on Lasers and Electro-Optics, Anaheim, California, May 8-13, 1994.

Wong, N.C., and D. Lee. "Frequency Tuning and Phase Locking of an Ultrastable Doubly Resonant Optical Parametric Oscillator." Paper presented at the Advanced Solid-State lasers Topical Meeting, 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, L.R. Brothers, and B. Lai. "Optical Frequency Measurement and Synthesis using Nonlinear Optical Techniques." Invited paper presented at the Conference on Lasers and Electro-Optics, Anaheim, California, May 8-13, 1994.

[14] B.Y.F. Lai, *A Tunable Light Source at 1.6 μm by Difference-Frequency Mixing in Cesium Titanyl Arsenate,* S.M. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1995.



Professor Qing Hu (Photo by John F. Cook)