Chapter 2. Optical Propagation and Communication

Academic and Research Staff

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

Visiting Scientists and Research Affiliates

Dr. Robert Bonney, Dr. Thomas J. Green, Jr.

Graduate Students

Jeffrey K. Bounds, Asuman E. Koksal, Elliott J. Mason, Phillip T. Nee, Elisa C. Pasquali, Chen-Pang Yeang

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 903-94-C6071

Project Staff

Professor Jeffrey H. Shapiro, Dr. Ngai C. Wong, Dr. Robert Bonney, Jeffrey K. Bounds, Elliott J. Mason, Phillip T. Nee

2.2.1 Self-Phase Locked Optical Parametric Oscillator

In a type-II phase matched optical parametric oscillator (OPO) the signal and idler outputs are orthogonally polarized, hence no polarization interference or phase locking occurs between the two fields. By adding an intracavity quarter-wave plate to the OPO cavity, the signal and idler polarizations are mixed and mutual injection locking becomes feasible when the OPO is operated near frequency degeneracy. We have previously observed self-phase locking in a potassium titanyl phosphate (KTP) OPO by use of an intracavity quarter-wave plate.[1] We made the surprising discovery that there were two distinct self-phase locked states that differed in their thresholds and signal-idler phase differences, and we have confirmed this discovery with theoretical calculations. In our theoretical model we find that the temperature operating range of the self-phase locked OPO is of the order of 100-mK-wide, which is small considering that the temperature bandwidth of a normal KTP OPO is more than 20 degrees C. We are making further studies to resolve some inconsistencies between the existing model and observations of the self-phase locked OPO with respect to the change in cavity length and crystal temperature in the pre-locking and post-locking regimes. This work improves our understanding of OPO operation and is useful for implementing OPO-based optical frequency dividers.[2]

2.2.2 Quasi-Phase Matched Nonlinear Optics

Quasi-phase matching (QPM)[3] in periodically poled lithium niobate (PPLN) is an important technique for nonlinear frequency generation because it allows efficient operation at any user-specified wavelength within the transparency window of lithium niobate.

1 E.J. Mason and N.C. Wong, "Observation of Two Distinct Phase States in a Self-Phase Locked Type-II Phase-Matched Optical Parametric Oscillator," *Opt. Lett.* 23(22): 1733-35 (1998).

2 N.C. Wong, "Optical-to-Microwave Frequency Chain Utilizing a Two-Laser-Based Optical Parametric Oscillator Network," *Appl. Phys. B* 61(2): 143-49 (1995).

3 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): 2631-54 (1992); 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): 435-36 (1993).

Ease of fabrication, large nonlinearity, and room-temperature noncritically phase-matched geometry make PPLN a nonlinear material of choice in many applications. Potential devices applications include channel frequency conversion and signal amplification for dense wavelength-division-multiplexed (DWDM) optical communication networks.

We have recently demonstrated an OPO that utilizes a Brewster-cut PPLN crystal in a four-mirror folded cavity configuration.[4] Since all the interacting wavelengths are co-polarized, Brewster windows on PPLN can be advantageously used to minimize reflection losses at all wavelengths. This approach, which eliminates potentially costly and difficult-to-manufacture multilayer antireflection coatings at multiple wavelengths, is especially attractive for widely-tunable PPLN-based OPOs. We achieved continuous-wave (cw) nearly-degenerate operation in an OPO containing a 1-cm-long PPLN crystal with a grating period of 20.1 μm. The threshold was 100 mW for a pump wavelength of 796 nm. The OPO was operated near 50 degrees C, and we observed degradation of the OPO operation over time due to photorefractive damage that increased the effective cavity loss and hence the threshold. The photorefractive damage was likely caused by the presence of ~532-nm-wavelength sum-frequency generation from the pump and the OPO's subharmonic outputs. In addition, we observed second harmonic generation at 398 nm that had a temperature bandwidth of ~1 degrees C. The grating period of 20.1 μm was exactly 8 times the grating period (2.51 μm) necessary for the ultraviolet (UV) generation. This eighth-order quasi-phase matching should, in principle, yield essentially no UV output. However, due to domain wall spreading which amounted to as much as 1 μm deviation in the poled-to-unpoled domain duty cycle, the grating period was no longer eighth order and UV output could be generated, as confirmed by our numerical simulation. In the experiment, we observed that in the presence of UV generation the output of difference-frequency generation between the pump and a 1.596-μm-wavelength probe slowly degraded to half of its initial value over a period of 20 minutes. By tuning the crystal's temperature away from its UV-generation peak, the degradation was eliminated. This experiment demonstrates the feasibility of low-loss Brewster-cut PPLN OPOs and the importance of sufficiently reducing the effects of photorefractive damage. Our future periodically-poled devices may be fabricated in lithium tantalate, because it is more resistant to photorefractive damage than is lithium niobate, although this advantage comes at the expense of a smaller nonlinear coefficient.

2.2.3 Quantum Noise Propagation in Nonlinear Media

In Jeffrey Bounds' recently completed Ph.D. dissertation,[5] we have taken a new, fundamental look at the propagation of quantum noise in nonlinear optical media, with special attention to squeezed-state generation via the Kerr effect in optical fiber. Good quantum mechanical descriptions of noise evolution with propagating optical waves are critical to understanding the processes which currently limit the generation of squeezed radiation in nonlinear materials.

In Bounds' dissertation, a general quantum optical model is developed, from fundamental principles, to describe optical propagation in a broad variety of nonlinear media. The central distinction of the resulting quantum macroscopic propagation model (QMPM) is that material susceptibilities, representing the field's interaction with matter, are replaced with quantum mechanical operators. These quantum material operators comprise material response functions corresponding to the semiclassical susceptibilities and material noise operators representing the true quantum mechanical nature of the material. The material noise operators play important roles in the noise evolution of propagating fields. A specific model for squeezing in fiber was developed from the general QMPM, incorporating the combined effects of dispersion, linear loss, Raman scattering, forward Brillouin scattering (GAWBS), and two-photon absorption. We have solved the linearized cw-pump version of this model and used it to examine the interplay between nonlinearity, dispersion, and noise in optical-fiber squeezed-state generation. This cw theory draws upon our previous work on optimum local-oscillator selection[6] and represents both a fundamental redevelopment and a substantial extension

4 P.T. Nee, *Optical Frequency Division via Periodically Poled Lithium Niobate-Based Nonlinear Optics,* Ph.D. diss., Department of Electrical Engineering and Computer Science, MIT, 1999.

5 J.K. Bounds, *Quantum Noise Propagation in Nonlinear Media*, Ph.D. diss., Department of Electrical Engineering and Computer Science, MIT, 1999.

6 J.H. Shapiro and A. Shakeel, "Optimizing Homodyne Detection of Quadrature-Noise Squeezing by Local-Oscillator Selection," *J. Opt. Soc. Am.* A 14(2): 232-49 (1997).

of our earlier study of the Raman-noise limit on fiber squeezing.[7] Using the QMPM-based cw model we have found that low levels of two-photon absorption, resulting from germanium-doping of fiber, may impose critical limits on fiber squeezing. Forward Brillouin scattering is shown to behave exactly as low-frequency Raman scattering and to seriously limit fiber squeezing at low frequencies. The cw composite model is applied to the parameters of several fiber squeezing experiments described in the literature, and the model is shown to predict with fair accuracy the squeezing results in most cases.

2.2.4 Publications

Journal Articles

Lee, D., and N.C. Wong. "Tuning Characteristics of a cw Dual-Cavity KTP Optical Parametric Oscillator." *Appl. Phys. B* 66(2): 133-43 (1998).

Mason, E.J., and N.C. Wong. "Observation of Two Distinct Phase States in a Self-Phase Locked Type-II Phase-Matched Optical Parametric Oscillator." *Opt. Lett.* 23(22): 1733-35 (1998).

Nee, P.T., and N.C. Wong. "Optical Frequency Division by 3 of 532 nm in Periodically Poled Lithium Niobate with a Double Grating." *Opt. Lett.* 23(1): 46-48 (1998).

Shapiro, J.H. "Quantum Measurement Eigenkets for Continuous-Time Direct Detection." *Quantum Semiclass. Opt.* 10(3): 567-78 (1998).

Teja, J., and N.C. Wong. "Twin-Beam Generation in a Triply Resonant Dual-Cavity Optical Parametric Oscillator." *Opt. Express.* 2(3): 65-71 (1998).

Meeting Papers Published

Mason, E.J., and N.C. Wong. "Observation of Two Distinct Phase States in a Self-Phase Locked KTP Optical Parametric Oscillator." Paper published in the Digest *of Conference on Lasers and Electro-Optics,* San Francisco, California, May 3-8, 1998.

Nee, P.T., and N.C. Wong. "Three-to-One Optical Frequency Division at 532 nm using a Double-Grating Periodically Poled Lithium Niobate." Paper published in the *Digest of the Conference on Lasers and Electro-Optics,* San Francisco, California, May 3-8, 1998.

2.2.5 Dissertations

Bounds, J.K. *Quantum Noise Propagation in Nonlinear Media*. Ph.D. diss. Department of Electrical Engineering and Computer Science, MIT, 1999.

Nee, P.T. *Optical Frequency Division via Periodically Poled Lithium Niobate-Based Nonlinear Optics*. Ph.D. diss. Department of Electrical Engineering and Computer Science, MIT, 1999.

2.3 Object Detection and Recognition

Sponsors

U.S. Air Force - Office of Scientific Research
Grant F49620-96-1-0028

U.S. Army Research Office
Grant DAAH04-95-1-0494

U.S. Navy - Office of Naval Research
Grant N00014-98-1-0606

Project Staff

Professor Jeffrey H. Shapiro, Dr. Thomas J. Green, Jr., Asuman E. Koksal, Chen-Pang Yeang

Our work on object detection and recognition includes collaborative research with Professors Alan S. Willsky,[8] W. Eric L. Grimson,[9] and Paul A. Viola,[9] and their students. Our work is also part of three large multi-university efforts: the Center for Imaging Science,[10] and two Multidisciplinary University Research Initiatives (MURIs).[11] These programs are all aimed at developing the scientific underpinnings for what has long been a rather ad hoc field: automatic target detection and recognition (ATD/R).

2.3.1 Object Recognition Using Laser Radar Range Imagery

The combined effects of laser speckle and local-oscillator shot noise degrade coherent laser radar range measurements. As a result, laser radar range imagery suffers from both uniformly-distributed range anomalies and Gaussian-distributed local-range

7 J.H. Shapiro and L. Boivin, "Raman-Noise Limit on Squeezing in Continuous-Wave Four-Wave Mixing," *Opt. Lett.* 20(8): 925-27 (1995).

8 MIT Laboratory for Information and Decision Systems, Cambridge, Massachusetts.

9 MIT Artificial Intelligence Laboratory, Cambridge, Massachusetts.

10 At present, headquartered at Johns Hopkins University, Baltimore, Maryland.

11 Headquartered at Boston University, Boston, Massachusetts, and Johns Hopkins University, Baltimore, Maryland, respectively.

errors. We have been working to develop a statistically-optimum approach for doing model-based object recognition using low-resolution, noise-degraded laser radar range images.[12] In particular, we have attempted to build an autonomous end-to-end system that uses raw sensor images as its input and provides recognition decisions as its output.

Our object recognition system consists of preprocessing, segmentation, feature-extraction and alignment/scoring steps. The preprocessor we have employed is the fast maximum-likelihood/estimation-maximization (ML/EM) algorithm,[13] which is a quasi-optimal, multiresolution anomaly-suppression scheme that we developed in previous work. The segmentation module we use performs planar range profiling on the ML/EM-processed range image to estimate and isolate the target region from its surrounding background. Our feature-extraction module provides relevant edge-based features that distill the essential characteristics needed to identify the target in the segmented range images. The alignment/scoring step first estimates the pose of the target in the image by means of posterior marginal pose estimation (PMPE), a quasi-optimal statistical technique for matching image features with those from a collection of models for targets that might be present in the image.[14] The alignment/scoring step is completed by comparing the PMPE objective-function values for matching the image to each member of the object-model data base and then declaring the highest-scoring model to be the target that is present in the image.

We have obtained encouraging, preliminary performance results from our object recognition system using laser radar data from the MIT Lincoln Laboratory infrared airborne radar (IRAR) data release[15] together with 3-D CAD models which account for the possible military targets that may have been present on the site imaged by the laser radar. We are continuing work aimed at understanding system performance as a function of the laser radar parameters so as to determine the effect of sensor-physics capabilities on the recognition module.

2.3.2 Multiresolution Synthetic Aperture Radar

Detecting and classifying the signatures of man-made targets in synthetic aperture radar (SAR) imagery continues to be an important issue in image processing. Phenomenological studies using SAR data have demonstrated that multiresolution[16] or adaptive-resolution[17] processing of SAR imagery can lead to improved performance in discriminating artificial targets from natural clutter. Our previous research has indicated that image features exploited by such processors can be derived from the electromagnetic scattering characteristics of the targets and the clutter.[18] Specifically, in the work of Leung[19] we established a fundamental, physics-based understanding of multiresolution SAR-processing schemes for a one-dimensional, continuous-wave, stripmap-mode SAR with a simplified scalar electromagnetic reflection model. In further work by Yeang,[20] we developed a detection scheme for a two-dimensional, pulse-wave, stripmap SAR with a more comprehensive polarimetric electromagnetic scattering model. Both

12 A.E. Koksal, *Using Multiresolution Range-Profiled Real Imagery in a Statistical Object Recognition System,* S.M. thesis, Department of Electrical Engineering and Computer Science, MIT, 1998; A.E. Koksal, J.H. Shapiro, and W.M. Wells, III, “Model-Based Object Recognition Using Laser Radar Range Imagery,” paper presented at SPIE Aero Sense '99, Orlando, Florida, April 5-9, 1999.

13 D.R. Greer, I. Fung, and J.H. Shapiro, “Maximum-Likelihood Multiresolution Laser Radar Range Imaging,” *IEEE Trans. Image Process*. 6(1): 36-46 (1997).

14 W.M. Wells, III, “Statistical Approaches to Feature-Based Object Recognition,” *Int. J. Comput. Vision* 21(1/2): 63-98 (1997).

15 J.K. Bounds, *The Infrared Airborne Radar Sensor Suite*, RLE TR-610 (Cambridge: MIT Research Laboratory of Electronics, 1996); IRAR data release, <http://cis.jhu.edu/mit_cis/laserradar/IRAR/IRARmain.html>.

16 W.W. Irving, L.M. Novak and A.S. Willsky, “A Multiresolution Approach to Discriminating Targets from Clutter in SAR Imagery.” *Proc. SPIE* 2487: 272-99 (1995); N.S. Subotic, B.J. Thelen, J.D. Gorman, and M.F. Reiley, “Multiresolution Detection of Coherent Radar Targets,” *IEEE Trans. on Image Processing* 6(1): 21-35 (1997).

17 R.D. Chaney, A.S. Willsky, and L.M. Novak, “Coherent Aspect-Dependent SAR Image Formulation,” *Proc. SPIE* 2230: 256-74 (1994).

18 G. Leung and J.H. Shapiro, “Toward a Fundamental Understanding of Multiresolution SAR Signatures,” *Proc. SPIE* 3070: 100-09 (1997); C.-P. Yeang and J.H. Shapiro, “Target Detection Theory for Stripmap SAR using Physics-Based Multiresolution Signatures,” *Proc. SPIE* 3370: 646-60 (1998).

19 G. Leung and J.H. Shapiro, “Toward a Fundamental Understanding of Multiresolution SAR Signatures,” *Proc. SPIE* 3070: 100-09 (1997).

20 C.-P. Yeang and J.H. Shapiro, “Target Detection Theory for Stripmap SAR using Physics-Based Multiresolution Signatures,” *Proc. SPIE* 3370: 646-60 (1998).

of these physics-based studies, however, treated a restricted and simplified scenario: binary detection of the presence of a single-component target in a stripmap-mode SAR image. None of these assumptions is satisfactory in realistic SAR-based target-discrimination scenarios.

Recently we have been extending the preceding physics-based approach to spotlight-mode SAR operation and to multiple-component target detection and classification.[21] We have constructed models for spotlight-mode polarimetric radar returns for targets and clutter using physical optics theory. Using these models, we have developed a multiresolution detection theory finding a single-component target in a spotlight-mode SAR image. We are now in the process of extending our analysis to include the detection of multiple-component targets in stripmap-mode and spotlight-mode SAR images.

2.3.3 Multisensor Fusion for Object Pose Estimation

In previous work, our collaborators from the Center for Imaging Science have established a theory, based on the Hilbert-Schmidt performance bound, for optimal pose estimation of ground-based targets.[22] We have been working to turn this group-theoretic approach into a performance evaluation tool for multisensor fusion. Using physics-based statistical models for high-range-resolution radar (HRR), plus video, forward-looking infrared (FLIR), and laser radar range imagers, we have been quantifying the sensor fusion advantages afforded by combining various subsets of these sensors.[23] Our immediate task is to produce sensor fusion performance curves for pose estimation analogous to our earlier sensor fusion work on FLIR/laser-radar object detection.[24] The tradeoff curves for pose estimation—like our earlier work on target detection—will be cast in terms of the signal-to-noise ratios (SNRs) of the passive sensors (video and FLIR) and the carrier-to-noise ratio (CNR) of the active sensors (HRR, laser radar). Our longer term objective is to use our understanding of the sensor physics to break through the SNR/CNR abstraction barriers and show that pose estimation performance can be understood as a function of operational scenario, i.e., in terms of the sensor, atmosphere, and object parameters that determine these intermediate performance metrics. We have previously accomplished such scenario-based performance evaluation for simple single-pixel laser radar target detection,[25] so we have reason to be optimistic about realizing the present, much more challenging goal.

2.3.4 Publications

Journal Articles

Shapiro, J.H. “Bounds on the Area under the ROC Curve.” *J. Opt. Soc. Am. A* 16(1): 53-57 (1999).

Shapiro, J.H. “An Extended Version of Van Trees's Receiver Operating Characteristic Approximation.” *IEEE Trans. Aerosp. Electron. Syst.* Forthcoming.

Meeting Papers

Koksal, A.E., J.H. Shapiro, and W.M. Wells, III, “Model-Based Object Recognition Using Laser Radar Range Imagery.” Paper presented at SPIE Aero Sense ’99, Orlando, Florida, April 5-9, 1999.

Kostakis, J., M. Cooper, T.J. Green, Jr., M.I. Miller, J.A. O'Sullivan, J.H. Shapiro, and D.L. Snyder, “Multispectral Active-Passive Sensor Fusion for Ground-Based Target Orientation Estimation.” *Proc. SPIE* 3371: 500-07 (1998).

Kostakis, J., M. Cooper, T.J. Green, Jr., M.I. Miller, J.A. O'Sullivan, J.H. Shapiro, and D.L. Snyder. “Multispectral Sensor Fusion for Ground-Based Target Orientation Estimation: FLIR, LADAR, HRR.” Paper presented at SPIE Aero Sense ’99, Orlando, Florida, April 5-9, 1999.

---

21 C.-P. Yeang and J.H. Shapiro, “Target Identification for Stripmap- and Spotlight-mode SARs Using Physics-Based Signatures,” paper presented at SPIE Aero Sense ’99, Orlando, Florida, April 5-9, 1999.

22 U. Grenander, M.I. Miller, and A. Srivastava, “Hilbert-Schmidt Lower Bounds for Estimators on Matrix Lie Groups,” *IEEE Trans. Pattern Anal. Machine Intell.* 20(8): 790-802 (1998).

23 J. Kostakis, M. Cooper, T.J. Green, Jr., M.I. Miller, J.A. O'Sullivan, J.H. Shapiro, and D.L. Snyder, “Multispectral Active-Passive Sensor Fusion for Ground-Based Target Orientation Estimation,” *Proc. SPIE* 3371: 500-07 (1998); J. Kostakis, M. Cooper, T.J. Green, Jr., M.I. Miller, J.A. O'Sullivan, J.H. Shapiro, and D.L. Snyder, “Multispectral Sensor Fusion for Ground-Based Target Orientation Estimation: FLIR, LADAR, HRR,” paper to be presented at SPIE Aero Sense ’99, Orlando, Florida, April 5-9, 1999.

24 S.M. Hannon and J.H. Shapiro, “Active-Passive Detection of Multipixel Targets,'' *Proc. SPIE* 1222: 2-23 (1990).

25 J.H. Shapiro, B.A. Capron, and R.C. Harney, “Imaging and Target Detection with a Heterodyne-Reception Optical Radar,'' *Appl. Opt.* 20(19): 3292-313 (1981).

Yeang, C.-P., and J.H. Shapiro. "Target Detection Theory for Stripmap SAR using Physics-Based Multiresolution Signatures." *Proc. SPIE* 3370: 646-60 (1998).

2.3.5 Thesis

Koksal, A.E. *Using Multiresolution Range-Profiled Real Imagery in a Statistical Object Recognition System.* S.M. thesis. Department of Electrical Engineering and Computer Science, MIT, 1998.

2.4 Optical Frequency Comb Generation

Sponsor

U.S. Air Force - Office of Scientific Research
Grant F49620-96-1-0126

Project Staff

Professor Jeffrey H. Shapiro, Dr. Ngai C. Wong, Elisa C. Pasquali

2.4.1 Terahertz Optical Frequency Comb Generation

In order to provide precisely known wavelength channels for characterizing the spectral performance of channel-dropping filters and 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 lithium niobate or lithium tantalate electro-optic modulator, the phase velocities of the microwave and optical fields can be matched, thus maximizing the electro-optic modulation at a user-specified microwave frequency. Placing the modulator inside an optical cavity that is resonant for the input optical beam and the generated sidebands further enhances the modulation. Previously, we have obtained an optical frequency comb with a 3 THz span for 1 W of microwave power at 17 GHz.[26] However, the span was limited by the material dispersion of and photorefractive damage to the lithium niobate modulator material.

We have recently constructed a new optical frequency comb generator that utilizes lithium tantalate.[27] We produced an output spectral bandwidth of 3.0 THz (11 nm), when the lithium tantalate wavelength generator was operated at 1064-nm-wavelength, with a channel spacing of 15.5 GHz. This measured bandwidth is consistent with calculations for our device, and it is similar to that of our previous lithium niobate wavelength generator. No photorefractive damage was observed in the lithium tantalate device, which makes it a significant improvement over previous lithium niobate devices. Further bandwidth improvement was limited by heating effects when microwave modulation powers greater than 1 W were used. We have developed numerical codes to calculate the output spectral lineshape for a given set of operating parameters in the presence of dispersion. These codes should facilitate optimization of the wavelength generator. We have also explored using chirped mirrors to correct for the material dispersion of lithium tantalate, but we found that the dispersion is too large to be fully compensated by this method. We are in the process of optimizing the wavelength generator to increase its spectral bandwidth and evaluating its performance at 1550 nm.

2.4.2 Thesis

Pasquali, E.C. *Wideband Optical Frequency Comb Generator using a Phase Velocity-Matched Lithium Tantalate Electro-Optic Modulator.* M.Eng. thesis. Department of Electrical Engineering and Computer Science, MIT, 1998.

26 L.R. Brothers and N.C. Wong, "Dispersion Compensation for Terahertz Optical Frequency Comb Generation," *Opt. Lett.* 22(13): 1015-17 (1997).

27 E.C. Pasquali, *Wideband Optical Frequency Comb Generator using a Phase Velocity-Matched Lithium Tantalate Electro-Optic Modulator*, M.Eng. thesis, Department of Electrical Engineering and Computer Science, MIT, 1998.