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., Dr. Robert J. Hull, Vivian E. Titus

Graduate Students

Jeffrey K. Bounds, L. Reginald Brothers, Donald R. Greer, Asuman E. Koksal, Gilbert Leung, Elliott J. Mason, Phillip T. Nee, Joseph Teja, Chen-Pang Yeang

Undergraduate Students

Jennifer C. Kleiman

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

Sponsors

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

Project Staff

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

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.[1] This unique characteristic can lead to a better photodetection system and is potentially useful as a pre-amplifier in coherent optical communication networks.

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 permitted stable cw operation of the OPO with a threshold of 300 mW for a 2.7 percent output coupler. A quantum noise suppression of 3.8 dB for the signal and idler output intensity correlation was measured, which was well below the expected value of $\sim$6 dB, probably due to the large frequency jitter of the pump laser. As a result, we constructed a triply resonant OPO cavity that reduced the threshold to 55 mW and stabilized the krypton ion laser frequency to $\sim$25 kHz rms. We expect that this highly stabilized OPO system should yield a noise suppression in excess of 6 dB and allow us to study the mean-field characteristics, gain saturation, and quantum-noise spectra of an injection-seeded OPA.[2]

In a separate experiment, we investigated a novel OPO configuration that included an intracavity

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

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

quarter-wave plate to achieve self-phase locking at the frequency-degenerate point. The waveplate mixed the two orthogonally polarized subharmonic signal and idler outputs, and provided a means for signal injection for both subharmonics. When the OPO was operated near frequency degeneracy, this mutual signal injection induced self-phase locking.

Self-phase locking was confirmed in a homodyne measurement between the outputs and a local oscillator derived from the YAG laser that was used to generate the second harmonic to pump the OPO. We have obtained very good interference fringes, as shown in figure 1, that confirmed that the outputs had the same frequency as the YAG frequency. We have also observed a π phase shift in the interference fringe when an external acoustical disturbance was applied to momentarily perturb the OPO without unlocking the OPO servo. In this case, both the signal and idler waves underwent a π phase jump so that there was no change in their relative phase difference or their sum phase relative to the pump phase, as required by the OPO equations of motion. This suggests that if a self-phase locked OPO is used for phase-coherent measurements (such as in a frequency chain), this π phase jump can be a potential problem. In addition, there is preliminary evidence that there are two stable self-phase locked regimes, each with a different relative phase between the signal and idler outputs. The self-phase locked OPO is an unusual apparatus that should provide insights into the phase characteristics of an OPO and allows the investigation of the possibility of spontaneous quantum phase jumps.[3]

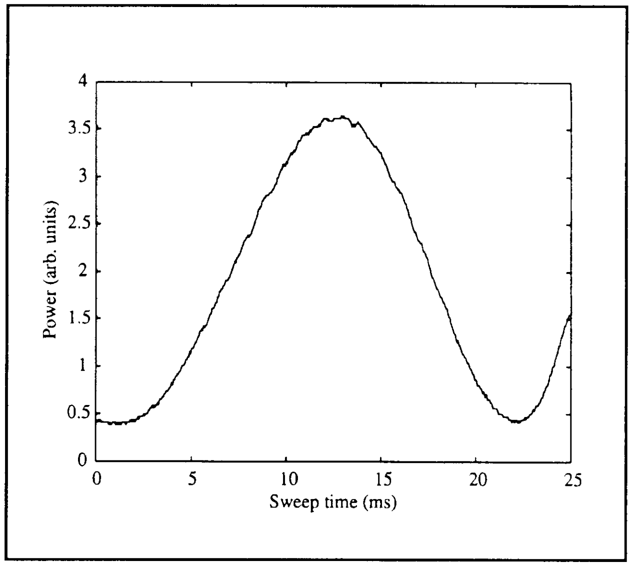

Figure 1. Interference fringe between the equal-amplitude signal output and the YAG-derived local oscillator (LO) as the LO phase is swept, confirming that the signal frequency is the same as the YAG laser.

2.2.2 Quasi-Phase Matched Nonlinear Optics

We have initiated a study of quasi-phase matching (QPM)[4] in periodically poled lithium niobate (PPLN) 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-μm optical communication window. PPLN is becoming the nonlinear material of choice because of its ease of fabrication, large nonlinearity, and room-temperature noncritically phase-matched geometry. Nonlinear optical devices that are fabricated using QPM are potentially useful in many applications such as channel frequency shifting and signal amplification for dense wavelength-division multiplexed (WDM) communication networks.

By employing the electric field poling technique,[5] we have successfully obtained domain reversal in bulk 250-μm-thick lithium niobate samples. Samples with a grating periodicity of 21.5 μm were tested using a Ti:Sapphire laser at ~ 780 nm and a YAG

[3] P.D. Drummond and P. Kinsler, "Quantum tunneling and thermal activation in the parametric oscillator," *Phys. Rev. A* 40: 4813 (1989).

[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): 435-4362 (1993).

laser at 1064 nm to generate a difference-frequency signal at 3 μm. Figure 2 shows the temperature bandwidth of the PPLN sample that indicates the effective length was 90 percent of the physical length of 1 cm. PPLN crystals with different grating periods have been fabricated including one that was used for the generation of tunable 1.6-μm by difference-frequency mixing.

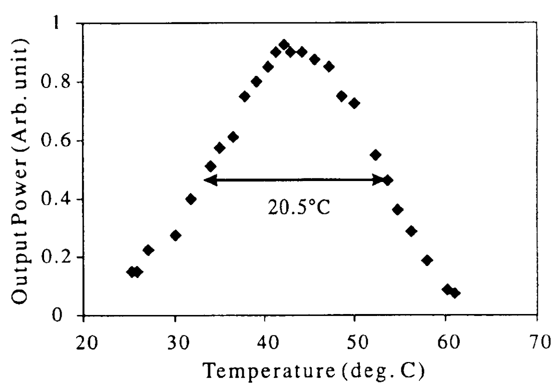

Figure 2. Difference-frequency signal output as a function of the temperature of the periodically poled lithium niobate crystal.

An interesting application is to combine two functional blocks onto a single PPLN crystal with two different gratings, one for each nonlinear function. We have fabricated a 1-cm-long wafer containing two gratings. The first grating, designed for third order QPM, was used to generate 1596 nm signal from inputs at 798 nm and 532 nm. The second grating will be used to generate a second 1596 nm output from the input 798 nm laser and the 1596 nm output obtained from the first grating. By measuring the beat frequency between the two 1596 nm outputs, a 3:1 frequency divider can be obtained. Potentially, multiple nonlinear and linear devices could be fabricated onto a single PPLN crystal wafer for integration and enhanced functionality in nonlinear optical devices.

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.[6] For pulsed experiments, we have developed a general theory for optimal LO selection for quadrature-noise measurements of arbitrary spatio-temporal quantum states.[7] 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. Furthermore, our general theory has revealed a new squeezing mode for cw-source fiber experiments: Raman squeezing. 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. In recent work, we have been applying optimal two-frequency LO theory to examine the possibility of Brillouin squeezing, i.e., detecting quadrature-noise squeezing from stimulated Brillouin scattering in optical fiber.

2.2.4 Quantum Photodetection

The three principal paradigms for high-sensitivity photodetection—direct detection, homodyne detection, and heterodyne detection—all have well accepted continuous-time quantum descriptions as Heisenberg-picture operator measurements.[8] Recently, there has been considerable interest in the single-mode quantum phase problem.[9] One branch of this work has identified single-mode quantum phase as the Fourier-dual wave function

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

7 J.H. Shapiro and A. Shakeel, "Optimizing Homodyne Detection of Quadrature-Noise Squeezing via Local Oscillator Selection," *J. Opt. Soc. Am. B* 14(2): 232-249 (1997).

8 H.P. Yuen and J.H. Shapiro, "Optical Communication with Two-Photon Coherent States—Part III: Quantum Measurements Realizable with Photoemissive Detectors," *IEEE Trans. Inform. Theory* IT-25(1): 78-92 (1979).

9 R. Lynch, "The Quantum Phase Problem: A Critical Review," *Phys. Rep.* 256(6): 367-436 (1995).

to the number-state wave function.[10] Another avenue of single-mode phase research has focused on the phase marginal obtained from heterodyne detection.[11] To generalize these approaches to continuous-time quantum phase, it is desirable to have explicit measurement eigenkets for continuous-time direct detection and continuous-time heterodyne detection. In recent theoretical work, we have accomplished both of these objectives,[12] and we are now proceeding further with their application to the continuous-time quantum phase problem.

2.2.5 Publications

Shapiro, J.H., and A. Shakeel, "Optimizing Homodyne Detection of Quadrature-Noise Squeezing via Local Oscillator Selection." *J. Opt. Soc. Am. B.* 14(2): 232-249 (1997).

Wong, N.C., E. Mason, and P. Nee, "Metrological Applications of Frequency Conversion in $\chi^{(2)}$ Media." Quantum and Semiclass. Opt. Forthcoming (1997).

Meeting Papers

Shapiro, J.H. "Measurement Eigenkets for Continuous-Time Quantum Photodetection." Paper to be presented at Quantum Electronics and Laser Science Conference, Baltimore, Maryland, May 19-23, 1997.

Wong, N.C. "$\chi^{(2)}$ Interactions for Multi-Wavelength Processing." Invited paper presented at the Workshop on Multiple Wavelengths in Free-Space Optical Interconnects, Taos, New Mexico, February 4-7, 1996.

Wong, N.C., E. Mason, and P. Nee, "Metrological Applications of Frequency Conversion in $\chi^{(2)}$ Media." Invited paper presented at the Les Houches Workshop on Second Order Nonlinear Optics: from Fundamental to Applications, Les Houches, France, April 22-26, 1996.

2.3 Object Detection and Recognition

Sponsors

U.S. Air Force - Office of Scientific Research
Grant F49620-93-1-0604
Grant F49620-96-1-0028
U.S. Army Research Office
Grant DAAH04-95-1-0494

Project Staff

Professor Jeffrey H. Shapiro, Dr. Thomas J. Green, Jr., Dr. Robert J. Hull, Vivian E. Titus, Jeffrey K. Bounds, Donald R. Greer, Asuman E. Koksal, Gilbert Leung, Chen-Pang Yeang

Our work on object detection and recognition includes collaborative research with Professors Alan S. Willsky (from MIT's Laboratory for Information and Decision Systems), W. Eric L. Grimson and Paul A. Viola (from MIT's Artificial Intelligence Laboratory), and their students. Our work is also part of two large multi-university efforts: the Center for Imaging Science (headquartered at Washington University), and a Multiuniversity Research Intitiative (MURI) program (headquartered at Boston University). All of these programs are 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 Multiresolution Laser Radar Range Imaging

We have developed a wavelet-based approach to maximum-likelihood (ML) estimation for laser radar range imaging.[13] 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

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

[11] J.H. Shapiro and S.S. Wagner, "Phase and Amplitude Uncertainties in Heterodyne Detection," *IEEE J. Quantum Electron.* QE-20(7): 803-813 (1984).

[12] J.H. Shapiro, "Measurement Eigenkets for Continuous-Time Quantum Photodetection," paper to be presented at Quantum Electronics and Laser Science Conference, Baltimore, Maryland, May 19-23, 1997.

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

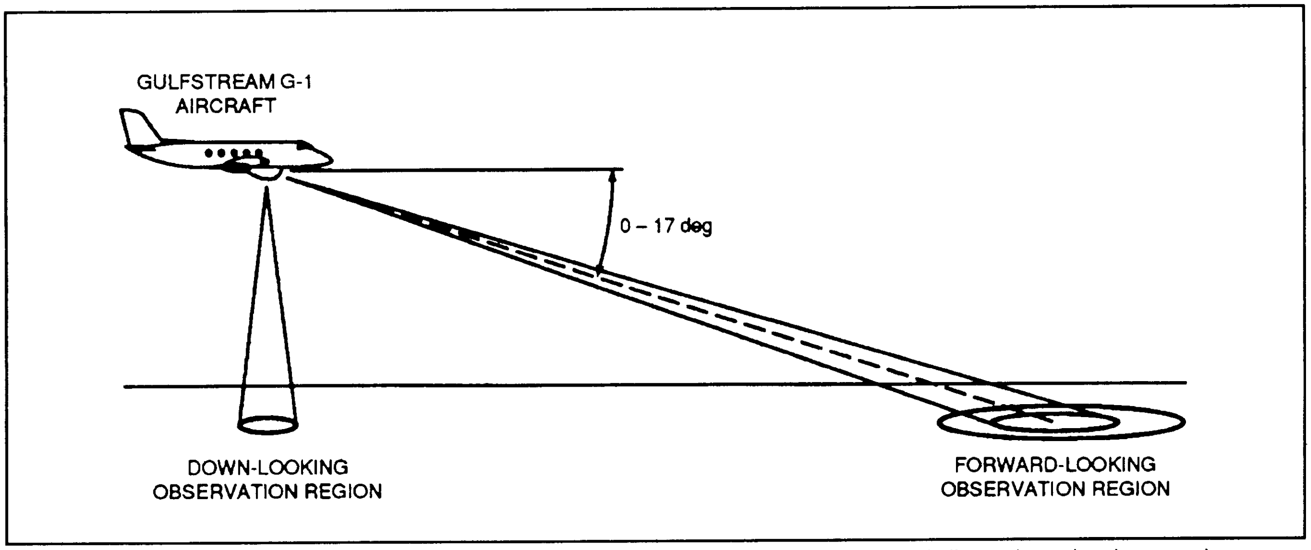

Figure 3. IRAR Sensor suite fields of regard. The downlooking subsystem included direct-detection laser radars operating at near-infrared and mid-infrared wavelengths plus a passive infrared imager. The forwardlooking subsystem included a mid-infrared, coherent-detection laser radar, a passive infrared imager, and a mm-wave radar.

the expectation-maximization (EM) algorithm for this problem, together with the special properties of the Haar wavelet basis.[14] ML/EM range processing of typical 128 X 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 disseminated our ML/EM processor through the Web site of the Center for Imaging Science (CIS). In particular, on the CIS Web site (http://cis.wustl.edu), we have included: sample imagery, software, and a user manual, providing a complete technical transfer of our work in this area. We are now proceeding to apply our ML/EM algorithm as a front-end processor for a model-based object recognition module.

2.3.2 Infrared Airborne Radar Data Release

During the past year, we have obtained the release and documented the contents of a substantial body of imaging data relevant to ATD/R research: the IRAR data base. Under DARPA sponsorship, MIT Lincoln Laboratory developed and deployed the infrared airborne radar (IRAR). IRAR, which was flown aboard a Gulfstream G-1 aircraft, was used to collect multispectral ground image data using active (laser radar) subsystems operating at long-wave and near-visible infrared wavelengths, passive optical subsystems operating in the long-wave infrared band, and a millimeter-wave radar, see figure 3. Nearly 500 Mbytes of actual sensor data files have been released for unlimited use and disseminated to members of the Center for Imaging Science. The data release consists of: the data files in NATO format on Exabyte tape plus C routines for reading these files; and a simple database cross-referencing the data files to their contents, based on the original flight logs. In addition, a substantial number of sample images, with commentary, have been mounted on the CIS Web site (http://cis.wustl.edu), along with a tutorial description of the IRAR sensor suite.[15]

2.3.3 Multiresolution Synthetic Aperture Radar

Synthetic aperture radars (SARs) provide the coverage rate and all-weather operability needed for wide-area surveillance. SAR-based automatic target recognition (ATR) systems need fast and effective discriminators to suppress vast amounts of natural clutter from, while admitting the much more

[14] 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 Multresolution Laser Radar Range Imaging," *IEEE Trans. Image Process.* 6(1): 36-46 (1997).

[15] J.K. Bounds, *The Infrared Airborne Radar Sensor Suite,* RLE TR-610 (Cambridge: MIT Research Laboratory of Electronics, 1996).

limited set of man-made object data, to their classification processors. Recent research, using mm-wave SAR data, has demonstrated that multiresolution processing offers a useful discriminant in this regard. Other work, with ultra-wide-band foliage-penetrating SAR data, has shown that adaptive-resolution imaging can exploit the aspect-dependent reflectivity of man-made objects Our effort is aimed at providing a principled approach to multiresolution SAR image formation and its use in detection.

We have considered multiresolution SAR image formation for a 1-D SAR, i.e., a continuous-wave down-looking sensor, using a physical optics formulation.[16] We find that the carrier-to-noise ratios (CNRs) for diffuse, specular, dihedral, and trihedral reflectors have different multiresolution signatures. For example, a diffuse reflector and a specular reflector of the same size have identical normalized CNRs when their SAR returns are processed over the full dwell time. However, these reflectors show substantially different behavior when processed over shorter time intervals. Moreover, this specular CNR behavior directly impacts the structure and performance of the Neyman-Pearson optimal detector for such a reflector. We are presently working on the extension of our framework to full stripmap (2-D SAR) operation against composite (multiple-reflector) targets.

2.3.4 Publications

Bounds, J.K. *The Infrared Airborne Radar Sensor Suite,* RLE TR-610 Cambridge: MIT Research Laboratory of Electronics, 1996.

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 Multresolution Laser Radar Range Imaging." *IEEE Trans. Image Process.* 6(1): 36-46 (1997).

Leung, G. *Synthetic Aperture Radar Discrimination of Diffuse and Specular Target Returns,* M.Eng. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1997.

Leung, G., and J.H. Shapiro, Toward a Fundamental Understanding of Multiresolution SAR Signatures," to be presented at SPIE Aero Sense '97, Orlando, Florida, April 20-25, 1997.

2.4 Optical Frequency Metrology

Sponsors

U.S. Air Force - Office of Scientific Research
Grant F49620-95-I-0505
Grant F49620-96-1-0126
U.S. Army Research Office
Grant DAAH04-93-G-0399
Grant DAAH04-93-G-0187

Project Staff

Professor Jeffrey H. Shapiro, Dr. Ngai C. Wong, L. Reginald Brothers, Jennifer Kleiman

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 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 technology such as wide-band optical frequency comb generation,[17] tunable cw OPOs, and techniques for operating a parallel network of OPOs.

2.4.1 Terahertz Optical Frequency Comb Generation

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 $LiNbO_3$ electro-optic modulator, the phase velocities of the microwave and optical fields can be

[16] G. Leung, *Synthetic Aperture Radar Discrimination of Diffuse and Specular Target Returns,* M.Eng. thesis, Dept. of Electr. Eng. and Comput. Sci., MIT, 1997; G. Leung and J.H. Shapiro, "Toward a Fundamental Understanding of Multiresolution SAR Signatures," paper to be presented at SPIE Aero Sense '97, Orlando, Florida, April 20-25, 1997.

[17] 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).

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 3.0-THz span.[17] However, the span is limited by the material dispersion of the lithium niobate modulator material.

In order to overcome the dispersion limitations, we employed a pair of dispersion compensating prisms, similar to its usage in ultrafast mode locked lasers. With partial compensation we have increased the span of the comb from an uncompensated 3.0 THz to a span of 4.3 THz,[18] as shown in figure 4. A number of improvements are underway to increase the span to 5-10 THz, including the use of lithium tantalate instead of lithium niobate to increase the damage threshold level and the replacement of the prism pair with a specially coated dielectric mirror.

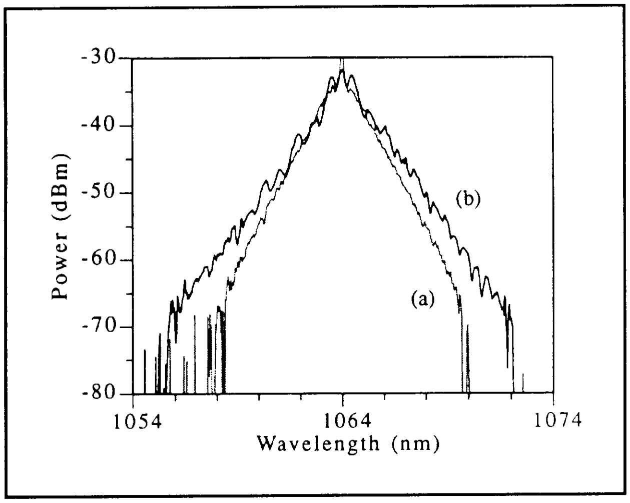

Figure 4. Optical frequency comb spectra for two cases of dispersion compensation: (a) uncompensated, span = 3.0 THz; (b) partially compensated, span = 4.3 THz.

2.4.2 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 + δ to yield a difference frequency of f - δ. A second step involves a second-stage three wave mixing of the input 2f + δ and the output f - δ to yield a second output at f + 2δ. By measuring the beat frequency between the two outputs at 3δ and setting δ to zero, an exact 3:1 frequency ratio is obtained.

We have previously used the nonlinear optical crystal cesium titanyl arsenate (CTA) for generating ~3:1 frequency ratio by three-wave difference frequency mixing.[19] More recently we have used a periodically poled lithium niobate (PPLN) crystal under third-order quasi-phase matched conditions and obtained higher power for the first difference-frequency mixing stage. The second difference-frequency mixing stage is integrated into the same PPLN to simplify the setup and work is progressing to measure the δ beat frequency.

2.4.3 Publications

Wong, N.C., E. Mason, and P. Nee, "Metrological Applications of Frequency Conversion in $\chi^{(2)}$ Media." *Quantum Semiclass. Opt.* Forthcoming.

Conference Papers

Wong, N.C., "$\chi^{(2)}$ Interactions for Multi-Wavelength Processing." Invited paper presented at the Workshop on Multiple Wavelengths in Free-Space Optical Interconnects, Taos, New Mexico, February 4-7, 1996.

Wong, N.C., E. Mason, and P. Nee, "Metrological Applications of Frequency Conversion in $\chi^{(2)}$ Media." Invited paper presented at the Les Houches Workshop on Second Order Nonlinear Optics: from Fundamental to Applications, Les Houches, France, April 22-26, 1996.

18 L.R. Brothers and N.C. Wong, "Dispersion Compensation for Terahertz Optical Frequency Comb Generation," submitted to *Opt. Lett.*

19 B. Lai, N.C. Wong, and L.K. Cheng, "Continuous-Wave Tunable Light Source at 1.6 μm by Difference-Frequency Mixing in $CsTiOAsO_4$," *Opt. Lett.* 20(17): 1779-1781 (1995).