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

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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.[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 in a dual-cavity triply resonant configuration with a threshold of ~50 mW for a 2.7% output coupler. The two coupled cavities, one that resonated the signal and idler waves and the other the pump field, permitted separate tuning, feedback control, and optimization for the pump input and the two subharmonic outputs. A quantum noise suppression of 5.5 dB for the signal and idler output intensity correlation was measured and shown in Figure 1, in good agreement with theory.[2] The inferred quantum noise correlation for the system is 7.4 dB for unity detection quantum efficiency. The highly correlated triply resonant OPO is a good starting point for the study of the mean-field characteristics, gain saturation, and quantum-noise spectra of an injection-seeded OPA.[3]

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

[2] J. Teja and N.C. Wong, "Twin-beam Generation in a Triply Resonant Dual-cavity Optical Parametric Oscillator," *Opt. Express* 2(3): 65-71 (1998); K.X. Sun, *Classical and Quantized Fields in Optical Parametric Interactions*, Ph.D. diss., Department of Physics, MIT, 1993.

[3] J. Teja, *Intensity Noise Correlation in a Triply Resonant Optical Parametric Oscillator*, S.M. thesis, Department of Electrical Engineering and Computer Science, MIT, 1997.

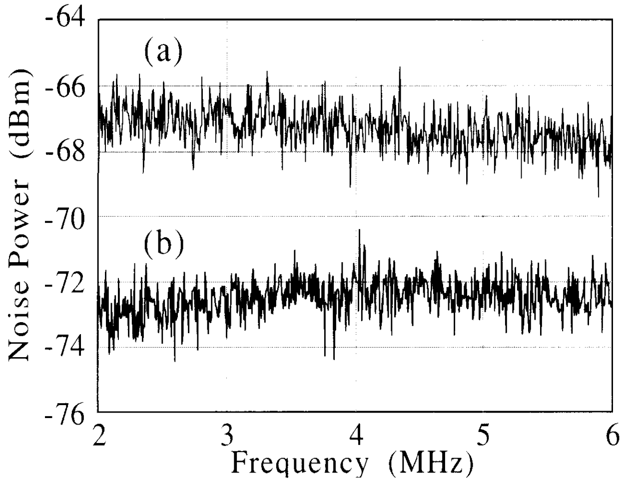

Figure 1. Noise power spectrum of: (a) shot noise, and (b) signal-idler output difference-intensity correlation, with an observed maximum noise suppression of 5.5 dB at 3 MHz.

In a separate experiment, we investigated a novel OPO configuration that included an intracavity quarter-wave plate to achieve self-phase locking at the frequency-degenerate point. The quarter-wave plate mixed the two orthogonally polarized subharmonic signal and idler outputs, and provided a means for mutual injection for both subharmonics. When the OPO was operated near frequency degeneracy within the capture range, this mutual signal injection induced self-phase locking.

Self-phase locking was confirmed in a homodyne measurement between the outputs and a local oscillator (LO) derived from the YAG laser that was frequency doubled to pump the OPO. We have obtained very good interference fringes, as shown in Figure 2, that confirmed that the outputs had the same frequency as the YAG frequency. We have observed two distinct phase states under self-phase locking conditions that differed in their thresholds and signal-idler phase differences.[4] Figure 2 shows the signal-LO interference for the two states, clearly indicating the relative phase shift of the signal output. This suggests that if a self-phase locked OPO is used for phase-coherent measurements (such as in a frequency chain), the existence of the two phase states can be a potential problem. The self-phase locked OPO is an unusual apparatus that should provide insights into the phase characteristics of an OPO and allow the investigation of the possibility of spontaneous quantum phase jumps.[5]

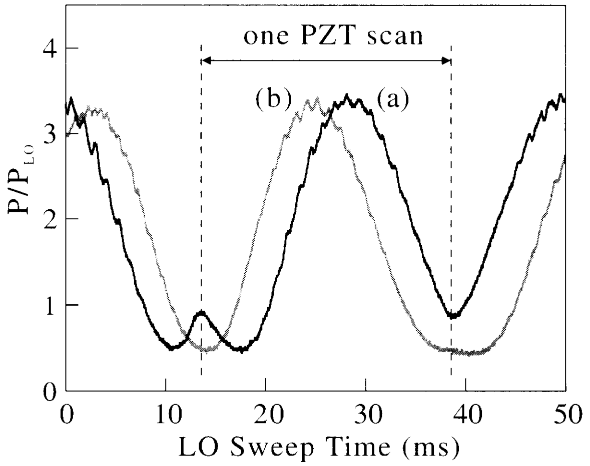

Figure 2. Interference between the equal-amplitude (power = 1 unit) signal output and the YAG-derived local oscillator (LO) as the LO phase is swept, confirming that the signal frequency is the same as the YAG laser. Traces (a) and (b) correspond to two different phase states with different thresholds and signal-idler phase difference.

2.2.2 Quasi-Phase Matched Nonlinear Optics

Quasi-phase matching (QPM)[6] 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. 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 (WDM) optical communication networks.

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[4] 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," forthcoming.

[5] P.D. Drummond and P. Kinsler, "Quantum Tunneling and Thermal Activation in the Parametric Oscillator," *Phys. Rev. A* 40(8): 4813-16 (1989).

[6] 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).

By employing the electric field poling technique,[7] we have successfully obtained domain reversal in bulk 500-μm-thick lithium niobate samples. The thicker samples (compared to our previous 250-μm thickness) allow longer PPLN devices to be made and easier beam alignment. 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 with a double grating. The first grating, designed for third order QPM, was used to generate a 1596-nm signal from inputs at 798 nm and 532 nm. The second grating was 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-to-1 optical frequency divider was demonstrated.[8] Potentially, multiple nonlinear and linear devices can be fabricated onto a single PPLN crystal wafer for integration and enhanced functionality in nonlinear optical devices.

2.2.3 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.[9] Recently, there has been considerable interest in the single-mode quantum phase problem.[10] One branch of this work has identified single-mode quantum phase as the Fourier-dual wave function to the number-state wave function.[11] Another avenue of single-mode phase research has focused on the phase marginal obtained from heterodyne detection.[12] 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.[13] Furthermore, we have used our direct detection results to establish a Fourier duality between the eigenkets for continuous-time photon counting and those for quantum frequency-spectrum measurement.[14]

2.2.4 Publications

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.* Forthcoming.

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

Mason, E.J., and N.C. Wong. "Self-Phase Locking in a Type-II Phase-Matched Optical Parametric Oscillator." *Digest of Conference on Lasers and Electro-Optics,* Baltimore, Maryland, May 19-23, 1997.

Nee, P., and N.C. Wong. "3:1 Optical Frequency Division by Difference-Frequency Mixing in Periodically Poled Lithium Niobate." *Proceedings of the 1997 IEEE Frequency Control Symposium,* Orlando, Florida, May 28-30, 1997.

Shapiro, J.H. "Measurement Eigenkets for Continuous-Time Quantum Photodetection." *Digest of Quantum Electronics and Laser Science Conference,* Baltimore, Maryland, May 19-23, 1997.

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[7] 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): 435-37 (1993).

[8] P.T. Nee 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).

[9] 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).

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

[11] J.H. Shapiro and S.R. Shepard, "Quantum Phase Measurement: A System-Theory Perspective," *Phys. Rev. A* 43(7): 3795-817 (1991).

[12] J.H. Shapiro and S.S. Wagner, "Phase and Amplitude Uncertainties in Heterodyne Detection," *IEEE J. Quantum Electron.* QE-20(7): 803-13 (1984).

[13] J.H. Shapiro, "Measurement Eigenkets for Continuous-Time Quantum Photodetection," *Digest of Quantum Electronics and Laser Science Conference,* Baltimore, Maryland, May 19-23, 1997.

[14] J.H. Shapiro, "Quantum Measurement Eigenkets for Continuous-Time Direct Detection," *Quantum Semiclass. Opt.*, forthcoming.

2.3 Object Detection and Recognition

Sponsors

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Project Staff

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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 Multdisciplinary University Research Intitiative (MURI) program (headquartered at Boston University). 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 Object Recognition Using Laser Radar Range Imagery

In previous work, we developed a wavelet-based approach to maximum-likelihood (ML) estimation for laser radar range imaging.[15] 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.[16] 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.

In current work,[17] we have used the fast ML/EM algorithm as a preprocessor for model-based object recognition based on Wells' posterior marginal pose estimation (PMPE) objective function.[18] The ultimate purpose of this work is to build a quasi-optimum end-to-end system for object recognition in which *all* the processing steps are based on principled choices accompanied by quantified performance behavior. To date, we have completed the segmentation/feature-selection steps needed to link the output of ML/EM preprocessing to PMPE scoring using 3D CAD models for a variety of target vehicles. Performance evaluation for the object recognition step is underway.

2.3.2 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 their classification processors while admitting the much more limited set of man-made object data. 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.

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[15] D.R. Greer, *Multiresolution Laser Radar Range Profiling of Real Imagery,* M.Eng. thesis, Department of Electrical Engineering and Computer Science, MIT, 1996.

[16] D.R. Greer, *Multiresolution Laser Radar Range Profiling of Real Imagery,* M.Eng. thesis, Department of Electrical Engineering and Computer Science, 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).

[17] A. 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.

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

In our initial work on multiresolution SAR image formation, we considered 1D SAR operation, i.e., a continuous-wave down-looking sensor, using a scalar-wave physical optics formulation.[19] We found that the carrier-to-noise ratios (CNRs) for diffuse, specular, dihedral, and trihedral reflectors have different multiresolution signatures, and we showed that this specular CNR behavior directly impacts the structure and performance of the Neyman-Pearson optimal detectors for such reflectors. Since then, we have extend ed our framework to full polarimetric stripmap (2D SAR) operation, using a scattering-function formulation for target interaction.[20] While many of the characteristics seen in the 1D SAR case carry over naturally to the 2D analysis, some do not. We are beginning to advance our analysis to the case of composite (multicomponent) reflectors.

2.3.3 Multisensor Fusion for Object Pose Estimation

In previous work, our collaborators from the Center for Imaging Science at Washington University have established a theory, based on the Hilbert-Schmidt performance bound, for optimal pose estimation of ground-based targets.[21] We have been working to turn this group-theoretic approach into a performance evaluation tool for multisensor fusion. Using physics-based statistical models for 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.[22] Our immediate task is to produce sensor fusion performance curves for pose estimation analagous to our earlier sensor fusion work on FLIR/laser-radar object detection.[23] 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 sensor (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,[24] so we have reason to be optimistic about realizing the present, much more challenging goal.

2.3.4 Publication

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).

Meeting Papers

Kostakis, J., M. Cooper, T.J. Green, Jr., M.I. Miller, J.A. O'Sullivan, J.H. Shapiro, D.L. Snyder, and A. Srivastava. "Multispectral Active-Passive Sensor Fusion for Ground-Based Target Orientation Estimation." Paper to be presented at SPIE Aero Sense '98, Orlando, Florida, April 13-17, 1998.

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

Yeang, C-P., and J.H. Shapiro. "Target Detection Theory for Stripmap SAR using Physics-Based Multiresolution Signatures." Paper to be presented at SPIE Aero Sense '98, Orlando, Florida, April 13-17, 1998.

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[19] G. Leung, *Synthetic Aperture Radar Discrimination of Diffuse and Specular Target Returns*, M.Eng. thesis, Department of Electrical Engineering and Computer Science, MIT, 1997; G. Leung and J.H. Shapiro, "Toward a Fundamental Understanding of Multiresolution SAR Signatures," paper presented at SPIE Aero Sense '97, Orlando, Florida, April 20-25, 1997.

[20] C.-P. Yeang and J.H. Shapiro, "Target Detection Theory for Stripmap SAR using Physics-Based Multiresolution Signatures," paper to be presented at SPIE Aero Sense '98, Orlando, Florida, April 13-17, 1998.

[21] U. Grenander, M.I. Miller, and A. Srivastava, "Hilbert-Schmidt Lower Bounds for Estimators on Matrix Lie Groups," *IEEE Trans. Pattern Analysis and Machine Intell.*, forthcoming.

[22] J. Kostakis, M. Cooper, T.J. Green, Jr., M.I. Miller, J.A. O'Sullivan, J.H. Shapiro, D.L. Snyder, and A. Srivastava, "Multispectral Active-Passive Sensor Fusion for Ground-Based Target Orientation Estimation," paper to be presented at SPIE Aero Sense '98, Orlando, Florida, April 13-17, 1998.

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

[24] J.H. Shapiro, B.A. Capron, and R.C. Harney, "Imaging and Target Detection with a Heterodyne-Reception Optical Radar," *Appl. Opt.* 20(19): 3292-3313 (1981).

2.4 Optical Frequency Metrology

Sponsors

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Optical frequency measurements and synthesis 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 and synthesizer based on a parallel network of phase locked optical parametric oscillators (OPOs) and terahertz optical frequency combs and to apply it to precision measurements and dense wavelength division multiplexed (WDM) communication networks. An OPO-based optical frequency counter can be used to measure, compare, and synthesize frequencies from optical to microwave, with high precision and accuracy. Through the use of optical frequency combs, a precisely spaced network of channels at 1.55-μm can be obtained using only a single input laser. Our research includes the development of a number of enabling technologies such as wideband optical frequency comb generation,[25] 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 matched to maximize 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. For 1 W of microwave power at 17 GHz, we have obtained an optical frequency comb with a 3.0-THz span.[26] 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.[27] For further improvements, we have fabricated modulators using lithium tantalate instead of lithium niobate to increase the damage threshold level. In addition, we are in the process of replacing the prism pair with a chirped mirror that would be more compact and efficient.

2.4.2 3:1 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 δ and setting δ to zero, an exact 3:1 frequency ratio is obtained.

We have employed a periodically poled lithium niobate (PPLN) crystal with a double grating for achieving efficient nonlinear frequency generation for the two steps.[28] The first difference frequency mixing was accomplished under third-order quasi-phase matched conditions to generate 1596-nm light from input lasers at 798 nm and 532 nm. The second difference-frequency mixing stage was integrated into the same PPLN to simplify the setup. Figure 3 shows the measured beat frequency 3δ between the two

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[25] 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): 245-47 (1994).

[26] Ibid.

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

[28] P.T. Nee 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).

1596-nm outputs which was used to frequency lock the 798-nm laser to obtain a 3:1 frequency ratio between the two input lasers.

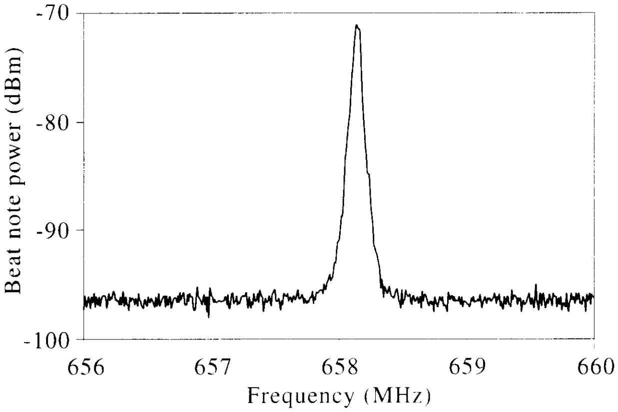

Figure 3. Spectrum of beat note 3δ averaged over 100 traces. Resolution and video bandwidth, 30 kHz.

2.4.3 Publications

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

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).

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).

Meeting Papers

Brothers, L.R., and N.C. Wong. "Dispersion Compensation of a Terahertz-Span Optical Frequency Comb Generator." *Digest of Quantum Electronics and Laser Science Conference*, Baltimore, Maryland, May 19-23, 1997.

Nee, P., and N.C. Wong. "3:1 Optical Frequency Division by Difference-Frequency Mixing in Periodically Poled Lithium Niobate." *Proceedings of the 1997 IEEE Frequency Control Symposium,* Orlando, Florida, May 28-30, 1997.