Optical Propagation and Communication

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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.

Nonlinear and Quantum Optics

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Quasi-Phase Matched Nonlinear Optics

Quasi-phase matching (QPM)[1,2] in periodically poled ferroelectric crystals such as lithium niobate is an important technique for nonlinear frequency generation because it allows efficient operation at any user-specified wavelength within the transparency window of the material. Ease of fabrication, large nonlinearity, and room-temperature noncritically phase-matched geometry make periodically-poled nonlinear crystals the material of choice in many applications. Potential device applications include channel frequency conversion and signal amplification for dense wavelength-division multiplexed (DWDM) optical communication networks.

We have previously fabricated periodically-poled lithium niobate (PPLN), for the generation of near-infrared (near-IR) light, with grating periods on the order of 20 μm.[3] In order to generate shorter wavelengths, such as the second-harmonic of Nd:YAG laser, grating periods below 10 μm are necessary. We have investigated and modified our material-processing procedures and fabrication techniques to improve the duty cycle toward the ideal 50/50 ratio and to allow wafers with grating periods of a few microns to be fabricated. To date, PPLN with a 6.5-μm grating period has been fabricated, but the grating lines sometimes merge and the duty cycle is far from the ideal case. We are continuing to refine our techniques to make fabrication of high-quality, short-period, periodically-poled ferroelectric crystals a reliable and routine procedure.

We have also investigated periodic poling of different ferroelectric materials. Periodically-poled lithium tantalate (PPLT) is similar to PPLN, but it affords the advantages of shorter cutoff wavelength (near 300 nm) and a higher damage threshold. PPLT is therefore more suitable for ultraviolet (UV) generation and for high-power applications. We have found that PPLT is easier to fabricate in that the grating lines are better defined and the spread of the grating lines are less than those in PPLN. However, PPLT has the disadvantage of having a nonlinear coefficient that is only half that of PPLN. We plan to test the use of PPLT for high-power nonlinear frequency conversion in the 1.5 and 3 μm IR regions.

For deep-UV generation, we have investigated periodic poling of barium magnesium fluoride ($BaMgF_4$), which is transparent down to 150 nm. We have successfully poled $BaMgF_4$ crystal wafers with grating periods of 21.1 and 19.2 μm. Initial second-harmonic generation of 532 nm, performed at MIT Lincoln Laboratory by Dr. Scott Buchter, indicated a reasonable amount of conversion efficiency that was within 50% of the expected value for the nonlinear *d* coefficient of 0.03 pm/V. Potential applications for periodically-poled $BaMgF_4$ include inspection and sensing for next-generation optical lithography in the deep-UV region.

Quantum Information and Communication

We have embarked on new research in the area of quantum information and communication technology. This work is intended to enable quantum-mechanical information transmission, storage, and processing, for future applications in quantum cryptography, quantum teleportation, quantum networking. Optical realizations of some of these schemes rely on polarization entanglement of a pair of photons. We have initiated research to develop a high-flux source of polarization-entangled photons for use in a variety of quantum-communication experiments, which we intend to perform in the near future.

A parametric downconverter can be used to produce pairs of entangled photons, but the resulting low rate of photon-pair generation has hindered proof-of-principle experiments. This problem is exacerbated if the photon pairs are to transfer their entanglement to a trapped-atom quantum memory, because the relevant pair-generation rate becomes that for photons within the bandwidth of the memory's high-*Q* optical cavity. The best narrowband pair-generation rate, for a parametric downconverter, can be inferred to be at most 15 s^{-1}, within a 30-MHz bandwidth at 702-nm wavelength, using 150 mW of pump power and very high numerical-aperture optics.[4]

We have recently shown, theoretically, that the signals and idlers from a pair of sub-threshold optical parametric oscillators (OPOs) can be combined to produce an ultrabright source of narrowband polarization-entangled photons.[5] For OPOs using periodically-poled potassium titanyl phosphate (PPKTP), we estimate that the pair production rate is 1.5×10^6 s^{-1} within a 30-MHz bandwidth at a 795-nm center wavelength using only 10 mW of pump power. Many quantum information applications will be enabled by development of such a low-power, ultrabright source of entangled photon pairs.

We have been setting up an experiment to demonstrate the use of a bulk-KTP OPO for the generation of high-brightness entangled-photon pairs at 1.06 μm. The ring-cavity dual-OPO system will be pumped in two counter-propagating directions by the second-harmonic of a diode-pumped YAG laser at 532 nm. The entangled photon pairs will be detected using a pair of Si avalanche photodiodes operated in the geiger mode for single-photon detection. The 1.06 μm source serves as a test system for the next-generation PPKTP-based source at 795 nm, the wavelength of an ^{87}Rb trapped-atom quantum memory.

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. This comb generator is based on an efficient design for an electro-optic phase modulator. 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 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. Previously we have obtained an optical frequency comb with a 3-THz span for 1 W of microwave power at 17 GHz.[6] However, the span was limited by the material dispersion of and photorefractive damage to the lithium niobate modulator material. By partial dispersion compensation, we were able to increase the span to 4.3 THz centered at 1064 nm.[7] In addition, we have recently tested a lithium tantalate-based comb generator that was found to have a higher damage threshold than lithium niobate.

An interesting comb-generator configuration encloses the modulator crystal inside an OPO. The properly phase-matched OPO provides parametric gain at the generated sidebands, so that the output comb has a higher output power and a wider spectral width, as demonstrated recently by Hall et al.[8] We intend to set up a similar configuration at 1550 nm, but with two important improvements. First, we will use quasi-phase matched PPLN or PPLT as both the nonlinear crystal and the modulator, thus allowing the OPO to be pumped at a lower level at a wavelength of 775 nm and permitting better phase-matching conditions. Then, by adding dispersion compensation to the OPO-based comb generator, we hope to significantly increase the comb generation span.

Self-Phase Locked Optical Parametric Oscillator

In a type-II phase matched optical parametric oscillator the signal and idler outputs are orthogonally polarized such that 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, making mutual injection locking 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.[9] We have made a surprising discovery that there were two distinct self-phase locked states that differed in their thresholds and signal-idler phase differences.

In collaboration with Dr. Claude Fabre, we have theoretically investigated the operating conditions that are required for achieving self-phase locking and the characteristics of the two mode-locked states.[10] The two mode-locked states have different thresholds and different signal-idler phase differences, as observed in our experiment. We also find that as the linear coupling between the signal and idler modes is increased, the minimum threshold remains the same, but it occurs at a larger cavity detuning. This work improves our understanding of OPO operation and is useful for implementing OPO-based optical frequency dividers.

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Object Detection and Recognition

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Our work on object detection and recognition includes collaborative research with Professors Alan S. Willsky and Sanjoy K. Mitter from MIT's Laboratory for Information and Decision Systems. Our work is also part of three large multi-university efforts: the Center for Imaging Science (headquartered at Johns Hopkins University), and two Multidisciplinary University Research

Initiatives (headquartered at Boston University and Johns Hopkins University, respectively). 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).

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 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.[1,2] 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,[3] 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.[4] 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[5,6] 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. In our continuing work we have been developing a quasi-analytic approach to target classification performance in the high carrier-to-noise ratio, good-performance regime. This effort is an outgrowth of our research, described below, on multi-sensor fusion for object pose estimation.

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[7,8] or adaptive-resolution[9] 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.[10,11] Specifically, in the work of Leung[10] 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[11] we developed a detection scheme for a two-dimensional, pulse-wave, stripmap SAR with a more comprehensive polarimetric electromagnetic scattering model. Both 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. In more recent research[12,13] we have extended the preceding physics-based approach to spotlight-mode SAR operation and to multiple-component target detection and classification. We are now in the process of developing performance-theory results for optimum, multiresolution SAR processors.

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.[14] 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.[15,16] Our first task was to produce sensor fusion performance curves for pose estimation analogous to our earlier sensor fusion work on FLIR/laser-radar object detection.[17] The tradeoff curves for pose estimation---like our earlier work on target detection---were 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.[18] so we have reason to be optimistic about realizing the present, much more challenging goal. Toward that end, we have used simplified blocks-world models and Cramér-Rao bound asymptotic performance results to replace CAD-model simulations with analytical predictions for FLIR and LADAR target-orientation performance.[19] We are currently working to include HRR within our analytical performance-estimation framework, and have begun an asymptotic approach to classification performance (with pose uncertainty) that is a natural outgrowth of our pose-estimation theory.

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