Quasi-phase-matched optical parametric amplification and oscillation in periodically poled $LiNbO_3$ waveguides

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We report quasi-phase-matched optical parametric amplification and oscillation in a periodically poled $LiNbO_3$ waveguide. Single-pass parametric gains of 4.1 dB, corresponding to 18%/W efficiency, were achieved at a signal wavelength of 1.55 μm with a pump wavelength of 782.2 nm. We formed a low-finesse cavity resonant at both signal and idler wavelengths by attaching mirrors to the waveguide end faces. Parametric oscillation was observed at wavelengths between 1.4 and 1.7 μm with a peak output power of 700 mW for pump wavelengths between 779 and 782 nm.

Over the past several years, rapid advances in the performance of optical parametric oscillators (OPO's) have led to renewed interest in their use as sources of tunable coherent radiation. Doubly resonant OPO's have been demonstrated with thresholds below 100 mW, but the requirement of simultaneous signal and idler resonance usually results in poor stability and complicated tuning characteristics. Singly resonant OPO's have increased stability and simple tuning behavior, but until recently the higher thresholds (>3 W) prevented the operation of a cw singly resonant OPO.[1] By eliminating diffraction effects, a waveguide configuration can increase the parametric gain by several orders of magnitude over bulk interactions. Quasi-phase matching (QPM) permits phase-matched operation at any wavelength and further increases the gain through the use of large effective nonlinear coefficients. In this Letter we report what is to our knowledge the first demonstration of guided-wave quasi-phase-matched optical parametric amplification and oscillation.

The single-pass nearly degenerate parametric gain in a waveguide is larger than that of a confocally focused bulk interaction by a factor of $\lambda_s L/2A_{\mathrm{eff}} n_s$, where λ_s and n_s are the signal wavelength and effective index, L is the interaction length, and A_{eff} is the effective modal overlap area. For $L = 1$ cm, $A_{\mathrm{eff}} = 10\ \mu m^2$, $\lambda_s = 1\ \mu m$, and $n_s = 2.2$, this factor is 230. Both singly[2] and doubly[3] resonant birefringently phase-matched OPO's were previously demonstrated in titanium-diffused $LiNbO_3$ waveguides; however, the material system limited operation to temperatures between 200 and 300 °C and to pump wavelengths near 600 nm, too short to permit laser diode pumping.

QPM has recently emerged as a practical alternative to birefringent phase matching for frequency conversion applications. QPM uses a periodic modulation in the nonlinear coefficient to compensate for refractive-index dispersion.[4] A change of the sign of the nonlinear coefficient accompanies ferroelectric domain reversal in materials such as $LiNbO_3$, $LiTaO_3$, and KTP, so periodic ferroelectric domain inversion, or periodic poling, can be used to form a QPM grating. QPM permits use of the largest diagonal elements of the $\chi^{(2)}$ tensor, since the waves can be polarized in the same direction. In $LiNbO_3$, QPM increases the conversion efficiency over the birefringently phase-matched process by $(2d_{33}/\pi d_{31})^2 \approx 20$. Reference 5 gives a review of quasi-phase-matched second-harmonic generation (SHG). Several nonresonant QPM parametric interactions have been demonstrated in $LiNbO_3$ waveguides.[6,7]

The waveguide QPM OPO was designed to operate at room temperature with a pump wavelength near 780 nm and nearly degenerate signal and idler wavelengths between 1.5 and 1.6 μm. Ferroelectric domain inversion for QPM was accomplished with a Ti-diffusion process.[8] A 10-nm-thick Ti film deposited on the $+z$ surface of $LiNbO_3$ was patterned into a grating with a 15.5-μm period and 3.5-μm lines, followed by heat treatment at 1080 °C for 30 min in a closed Al_2O_3 boat containing congruent $LiNbO_3$ powder. Annealed-proton-exchanged (APE) waveguides for modal confinement were formed by proton exchange in pure benzoic acid at 180 °C for 2 h through a SiO_2 mask with 5.50-μm channel widths, followed by annealing at 333 °C for approximately 10 h. The device was 9 mm long. The 15.5-μm period was chosen to account for the additional material dispersion of APE $LiNbO_3$ and modal dispersion.

Because the degenerate parametric gain and the SHG efficiencies are equal, SHG of a cw, tunable, multilongitudinal-mode Er fiber laser could be used for initial device characterization. The waveguide supported a single transverse mode at the fundamental wavelength. QPM SHG was observed at $\lambda = 1.5642\ \mu$m. All powers for single-pass interactions were measured at the exit face of the sample and were corrected for Fresnel effects at the waveguide exit end face. We observed SHG efficiencies exceeding 44%/W and nearly ideal sinc^2 tuning curves with FWHM bandwidths of 1.3 nm, in good agreement with the 1.2 nm cm bandwidth–length product predicted from the total dispersion. SHG with a highly multimoded fundamental source results in a conversion efficiency twice the single-mode effi-

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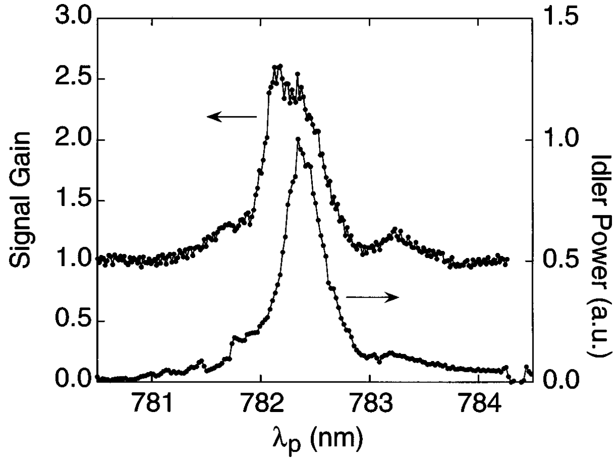

Fig. 1. Quasi-phase-matched parametric gain at $\lambda_s = 1.55\ \mu m$ and associated difference frequency generation near $\lambda_i \approx 1.58\ \mu m$ versus pump wavelength.

ciency because of sum frequency mixing effects[9]; thus the single-mode SHG efficiency for this device was $\eta = 22\%/W$.

The pump source for parametric amplification and oscillation was an acousto-optically Q-switched Ti:Al_2O_3 laser with a 100-ns FWHM pulse duration, 100-Hz repetition rate, and 0.6-nm FWHM (time-averaged) bandwidth. We performed parametric amplification by simultaneously coupling the $\lambda_s = 1.55\ \mu m$ signal and the $\lambda_p \approx 782$ nm pump into the lowest-order transverse mode of the waveguide (at each wavelength). Power measurements were performed with a calibrated Ge detector and a boxcar averager.

Figure 1 shows the pump wavelength dependence of the peak parametric gain $[G = P_s(L)/P_s(0)]$ for $\lambda_s = 1.55\ \mu m$ and the associated difference frequency generation of the idler near $\lambda_i \approx 1.58\ \mu m$. The parametric gain increased with pump power approximately as $(1 + \eta P_p/2)^2$, and the maximum gain at $\lambda_p = 782.2$ nm was $G = 2.6$ for 6.4 W of pump power in the waveguide. This corresponds to an efficiency of $\eta = 18\%/W$ and a normalized efficiency $\eta_{nor} = 22\%/W\ cm^2$. The wavelength, efficiency, and bandwidth observed for pulsed parametric amplification are in good agreement with the cw SHG results.

We formed a symmetric OPO cavity by attaching 2 mm × 6 mm × 150 μm mirrors to the end faces of the waveguide using an ≈10-μm-thick Fluorinet FC-70 liquid film. The dielectric mirrors had a nominal 90% reflectivity band extending from 1.4 to 1.7 μm. We determined the waveguide propagation losses by measuring the wavelength dependence of the transmission of a tunable single-longitudinal-mode 1.55-μm laser through the waveguide and observing the amplitude variation of the Fabry–Perot resonances. The data points in Fig. 2 show the measured transmission versus wavelength for the cavity before and after the mirrors are attached. The solid curves show a curve fitting with waveguide propagation losses of 0.4 dB/cm (8%/pass) and total round-trip OPO cavity losses (including 20% output coupling) of 35%. The effective mirror reflectivity of 87.5% at $\lambda_s = 1.55\ \mu m$ implies some additional loss resulting from the simple mounting procedure. The propagation losses reported here are typical for APE $LiNbO_3$ waveguides; periodic poling does not appreciably increase propagation loss.

The expression for the nearly degenerate parametric oscillation threshold is given by[10]

$$P_{th} = \frac{1}{\eta_{nor}}\left[\frac{\alpha_p}{1 - \exp(-\alpha_p L)}\ \ln(Q + \sqrt{Q^2 - 1}\,)\right]^2, \tag{1}$$

with

$$Q = \frac{1 + R_s R_i \exp(-4\alpha L)}{(R_s + R_i)\exp(-2\alpha L)}, \tag{2}$$

where α_p is the field loss coefficient at the pump wavelength and $R_{s,i}$ and α are effective mirror reflectivities and field loss coefficients at the oscillation wavelengths. Assuming that the pump, signal, and idler modes have similar propagation losses, the observed parametric gain yields a calculated doubly resonant ($R_s = R_i$) OPO threshold of 0.28 W and a singly resonant ($R_i \approx 0$) threshold of 2.8 W for this device.

We observed parametric oscillation with peak pump powers exiting the waveguide cavity exceeding 4.0 W. Accounting for the 80% mirror transmission and assumed propagation losses at λ_p, the power coupled into the waveguide at threshold was 5.5 W. Figure 3 shows the OPO output pulse and the pump pulse coupled into and out of the waveguide OPO. The pump pulse shows a maximum depletion of approximately 25–30%, and the peak total OPO output was over 700 mW. Since the mirrors were uniformly reflecting across the signal/idler oscillation band it is likely that this OPO was operating in the doubly resonant regime, utilizing only one mode of the highly multimoded pump. The observed threshold of 5.5 W, though significantly higher than the predicted

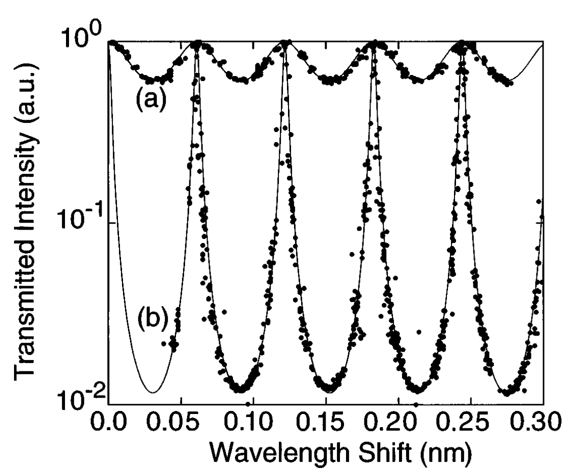

Fig. 2. Wavelength dependence of the transmission of a single-mode, 1.5-μm laser through the waveguide cavity before [curve (a)] and after [curve (b)] the mirrors are attached. The data are independently normalized to unity peak transmission.

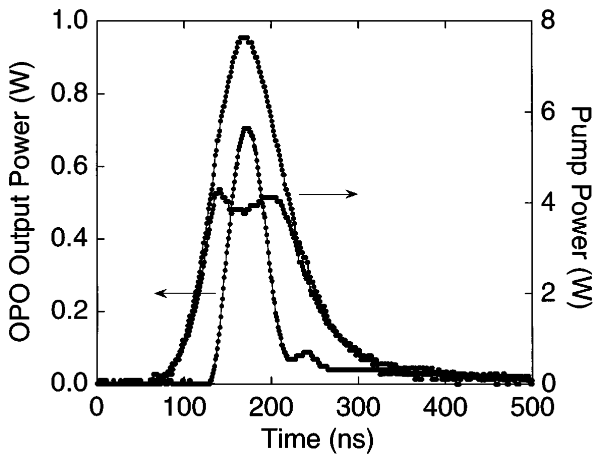

Fig. 3. OPO output pulse and pump pulse coupled into and out of the OPO. The total OPO output power exceeded 700 mW, with a peak pump power coupled into the waveguide of 7.7 W.

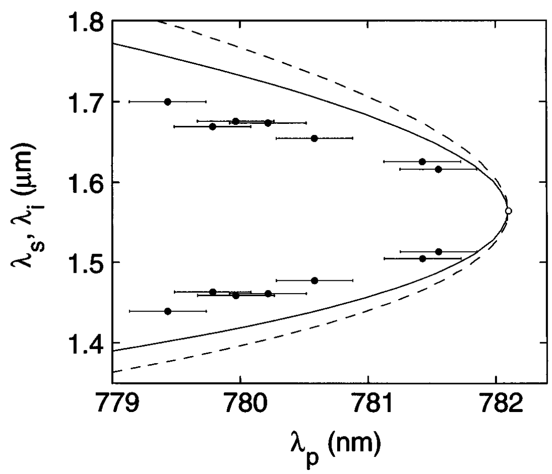

Fig. 4. OPO signal and idler wavelengths versus pump wavelength.

single-frequency-pumped doubly resonant oscillation threshold of 0.28 W, is consistent with this mode of operation. Because of the broadband nature of the pump source it is also possible that the OPO was operating as a singly resonant oscillator, using the entire pump bandwidth and again exhibiting a threshold in reasonable agreement with theory. The transition between singly and doubly resonant OPO's in low-finesse cavities has been analyzed elsewhere.[11] Use of a well-characterized, single-mode pump source should clarify the mode of operation and reduce the observed threshold to value closer to that predicted based on the measured parametric gain and cavity loss.

We accomplished tuning by varying the pump wavelength. The filled data points in Fig. 4 show the OPO wavelengths measured with a grating spectrometer as a function of pump tuning between 779 and 782 nm, and the open data point is the degeneracy point measured by cw SHG. Output wavelengths could be varied by several hundred nanometers between 1.4 and 1.7 μm with a few nanometers of pump tuning. The dashed curve is the QPM OPO tuning curve calculated with the bulk $LiNbO_3$ refractive-index dispersion, assuming a parametric interaction degenerate at 782.1 nm, and the solid curve is the tuning curve incorporating the full effects of the material dispersion of APE $LiNbO_3$ and modal waveguide dispersion.[12] The material dispersion of APE $LiNbO_3$ was measured in the visible and extrapolated to the infrared.

The QPM OPO thresholds in optimized waveguide devices could be significantly reduced from the experimental and theoretical values reported here. APE $LiNbO_3$ waveguide propagation losses of 0.2 dB/cm (4.5%/cm) have been reported,[13] half those measured for this device. Also, the parametric gain could be increased by approximately a factor of 6 with better overlap of the ferroelectric domain grating and guided field modes. These improvements, along with direct deposition of mirrors onto the waveguide end faces, could result in 1–2-cm-long singly resonant OPO's with sub-100-mW oscillation thresholds, accessible with commercial laser diodes.

In conclusion, we have demonstrated quasi-phase-matched optical parametric amplification and oscillation in a periodically poled $LiNbO_3$ waveguide. Parametric gains at $\lambda_s = 1.55$ μm of 4.1 dB were observed. Output wavelength tuning from 1.4 to 1.7 μm with several nanometers of pump tuning near 780 nm indicates that waveguide QPM OPO's could be useful sources of tunable radiation across the important infrared communications wavelengths that use available near-infrared laser diode pump sources.

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