Multigrating quasi-phase-matched optical parametric oscillator in periodically poled $LiNbO_3$

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We report a widely tunable quasi-phase-matched optical parametric oscillator that uses periodically poled $LiNbO_3$with a multigrating structure. The device is tuned by translation of the crystal through the resonator and pump beam, with no realignment needed. With a 1.064-μm acousto-optically Q-switched Nd:YAG pump laser, we produced noncritically phase-matched tunable IR output from 1.36 to 4.83 μm. The threshold was 6 μJ for a 26-mm interaction length. The extraordinary polarization of $LiNbO_3$ has better IR transmission than does the ordinary polarization, permitting operation at longer wavelengths with d_{33} quasi-phase matching than with conventional Type I birefringent phase matching. © 1996 Optical Society of America

Optical parametric oscillators (OPO's) are used as sources of tunable coherent radiation.[1] Wide tuning is often limited by the requirement of phase matching. In this Letter we report the demonstration of a quasi-phase-matched (QPM) OPO that is tunable from 1.36 to 4.83 μm, with thresholds of 6 μJ in 7-ns-long 1.064-μm pump pulses. The device consists of a single chip of periodically poled $LiNbO_3$ (PPLN) with multigrating sections, fabricated with lithographically patterned electrodes and electric-field poling. This structure permits noncritical phase matching with high efficiency over its entire tuning range.

For a conventional OPO, the pair of signal and idler frequencies, ω_s and ω_i, respectively, generated for a given pump frequency ω_p is determined by simultaneous satisfaction of the energy conservation condition $\omega_p = \omega_s + \omega_i$ and the phase-matching condition $\Delta k \equiv k_p - k_s - k_i = 0$, where k_p, k_s, and k_i are the wave vectors of the pump, signal, and idler, respectively. In birefringent phase matching, the output wavelengths are controlled with angle or temperature tuning of the refractive indices. These tuning techniques have several limitations. Limitations of tuning by angle are restricted angular acceptance; Poynting vector walk-off, which limits the interaction length; and beam deviation, which complicates alignment. Tuning by temperature depends on the temperature dependence of the refractive indices. Generally the extent of tuning is somewhat limited for reasonable temperature ranges, and tuning is slow to allow for thermal stabilization. In addition, birefringent phase matching constrains the interaction to involve one wave polarized orthogonally to the other two and hence cannot operate with the large diagonal components of the nonlinear susceptibility, such as d_{33} in $LiNbO_3$.

Quasi-phase matching, in which the nonlinear susceptibility is modulated periodically to compensate for dispersion, can relax many of the limitations of birefringent phase matching. In a first-order QPM device, the phase-matching condition is $\Delta k_Q = \Delta k - K_g = k_p - k_s - k_i - 2\pi/\Lambda$, where K_g is the grating vector of the phase-matched Fourier component of the modulated nonlinear susceptibility and Λ is the period of the modulation, assuming that all wave vectors are collinear with the grating vector.[2,3] By appropriate choice of K_g, any interaction can be noncritically phase matched at any temperature, and, as quasi-phase matching does not rely on birefringence, the diagonal components of the nonlinear susceptibility are accessible.

The inclusion of the grating vector in the phase-mismatch expression is a powerful mechanism for achieving phase matching because it can be controlled by the OPO designer. Temperature and angle can also be used for tuning a QPM interaction; however, control of the grating vector means that a QPM interaction does not have to rely on inherent material properties for phase matching because the grating period is chosen to compensate for the effect of material dispersion. Design of QPM devices is not limited to gratings with a single period; more sophisticated structures give specialized phase-matching behavior.[2] In principle any pattern that can be represented with a lithographic mask can be fabricated in the material. Broadening the phase-matching acceptance bandwidth is one example to which this control has been applied.[4] A fanned grating[5] and a segmented step-chirped grating[6] have been used to match various diode laser wavelengths for second-harmonic generation in PPLN waveguides. A 0.532-μm-pumped PPLN OPO has been demonstrated with two grating sections to extend the tuning range around degeneracy.[7] In this Letter we demonstrate a QPM OPO that consists of multigrating sections on a single PPLN chip, which makes tuning across the entire mid-IR transparency range of $LiNbO_3$ possible.

Figure 1 shows a portion of the multigrating device. The PPLN crystals for this study were fabricated from 0.5-mm-thick congruent $LiNbO_3$ wafers by use of the electric-field poling process reported else-

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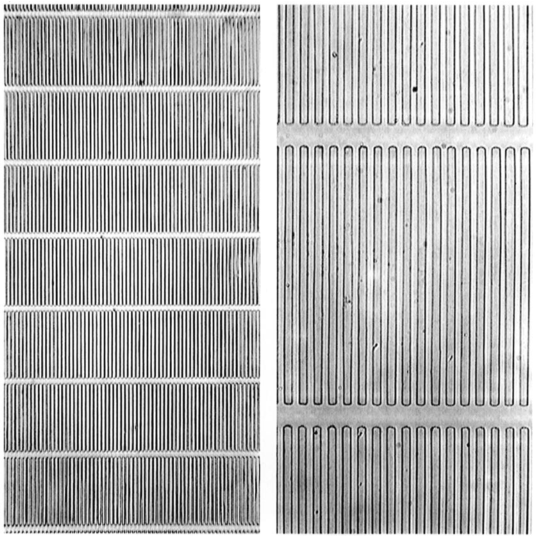

Fig. 1. Portion of the $+z$ surface of a 0.5-mm-thick PPLN chip with multigrating regions etched with HF acid to reveal the domain structure. The lithographic mask consists of 25 gratings with periods from 26 to 32 μm in 0.25-μm steps. Each grating is 500 μm wide and separated by 50 μm. The left panel shows a portion with periods of 29 to 30.5 μm; the right panel shows a magnified view of the 29-μm-period grating. The length of the finished crystals is 26 mm.

where.[3,8] The mask design for the device consisted of grating sections that were 500 μm wide and separated by 50 μm. The grating periods ranged from 26 to 32 μm in 0.25-μm increments for a total of 25 sections. This mask was used to pattern a 2-μm-thick photoresist lithographically on the $+z$ surface of the $LiNbO_3$, and the resulting pattern was covered with 100-nm-thick evaporated Al. Periodic poling was performed with a field of ~21 kV/mm at a current of 20 μA for 19 s in a liquid electrode fixture, and the diameter of the poled region was 28 mm. The same recipe, employed previously on smaller pieces of $LiNbO_3$, worked successfully on the larger sizes used here. The voltage was applied in one or several pulses with comparable results. After poling, the PPLN pieces were annealed at 120 °C for 1 h to relax strain at the domain walls and polished on the $\pm x$ end faces normal to the grating vectors. The crystals were not antireflection coated, but the ends were wedged by 0.25° to reduce étalon effects. The finished pieces used in this experiment were 26 mm long.

The experimental setup is shown in Fig. 2. The pump laser was a cw-diode-pumped, acousto-optically Q-switched Nd:YAG laser operating at 1.064 μm. The laser had a pulse width of 7–20 ns when operating at 1–10-kHz Q-switch repetition rates. The laser was focused to a 47-μm spot in the crystal. The OPO cavity mirrors each had a 15-mm radius of curvature and were separated by 30 mm. The mirror reflectivities at the signal wavelength, centered at $\lambda_s = 1.54$ μm with a 200-nm bandwidth, were 99% and 92% for the input and the output coupler, respectively, with ~10% reflectivity for the pump and the idler wavelengths. Losses as a result of Fresnel reflection from the uncoated crystal surfaces were 14% per surface for all wavelengths. Near the center of the mirror bandwidth, the oscillation threshold was 6 μJ with a 7-ns pulse (0.09 J/cm^2). The OPO operated robustly even at these low pump energies; typical pump depletion was 70% at 8 times threshold. We were able to pump as much as 25 times above threshold without damage.

Figure 3 shows the tuning curve at room temperature obtained by translation of the crystal through the resonator so that the pump interacted with different grating periods. The data agree well with the phase matching calculated from the Sellmeier coefficients.[9] Note that the published Sellmeier fit is based on dispersion data for wavelengths shorter than 3.4 μm. Hence the increased deviation between our measured data and the calculation at longer idler wavelengths is expected.

The OPO ran on all grating sections from the 26-μm to the 31.75-μm period. The 32-μm period grating was not phase matched at room temperature. The OPO output tuned from 1.36 to 1.98 μm in the signal branch and correspondingly from 4.83 to 2.30 μm in the idler branch. The OPO cavity mirrors required no realignment during tuning, because no tilting or beam displacement was involved. The implementation described here used 25 discrete grating sections with

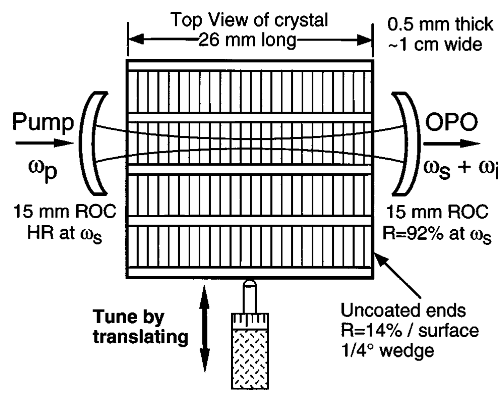

Fig. 2. Experimental setup for the multigrating QPM OPO. For tuning, the PPLN crystal is translated through the resonator so the pump beam interacts with different grating sections. No realignment is necessary. ROC, radius of curvature; HR, highly reflective.

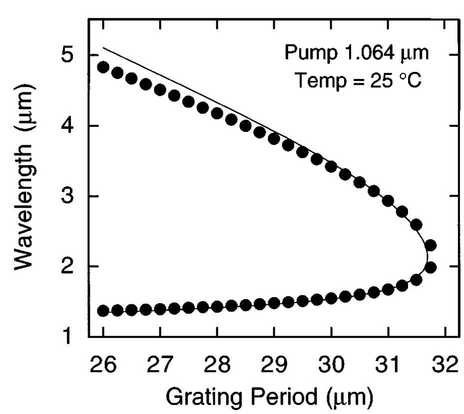

Fig. 3. OPO tuning as a function of grating period, achieved by translation of the PPLN crystal ~1 cm through 24 different grating sections. Phase matching is noncritical for all points. Temperature adjustment permits fine tuning. The theoretical curve is calculated from dispersion.[9]

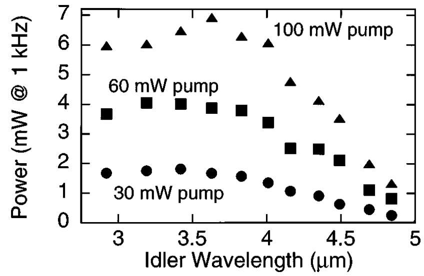

Fig. 4. Idler power for an uncoated PPLN OPO crystal pumped with 7-ns pulses at 1 kHz. The decrease in power at longer wavelengths is due to idler absorption in the PPLN crystal, reflectances of the cavity mirrors, and operation far from degeneracy.

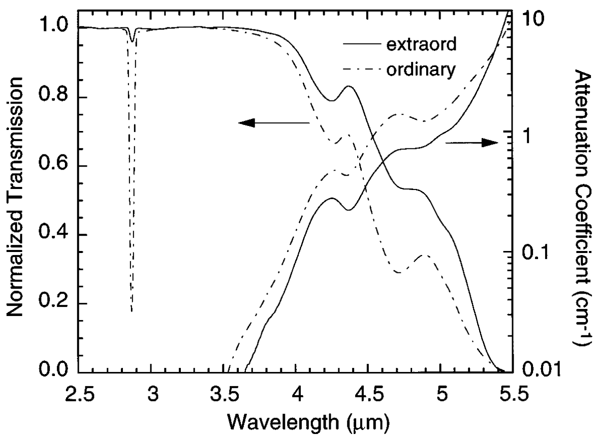

Fig. 5. Power transmission T and attenuation coefficient α of congruent $LiNbO_3$, where $T = \exp(-\alpha L)$ for crystal length L. Transmission data are normalized by the Fresnel reflections to give internal transmission of a 9-mm-thick sample. Attenuation coefficient is a fit to the normalized transmission of 0.5-, 1-, and 9-mm-long pieces, plus a 25-mm-long piece for the ordinary case. (The peak in the attenuation coefficient at ~2.9 μm is omitted for clarity.)

periods from 26 to 32 μm in 0.25-μm steps. If continuous tuning is desired, a fanned grating can be fabricated, or the intermediate frequencies can be filled in with temperature fine tuning, as was previously demonstrated.[7,8]

The idler power as a function of tuning is shown in Fig. 4. We generated up to 6 mW_{av} (average power) at 4.0 μm with a 100-mW_{av} pump and 2 mW_{av} at 4.83 μm with a 150-mW_{av} pump. The modest "in-the-bucket" conversion efficiency is due to the losses of the uncoated crystal. Much of the decrease in the output power at wavelengths greater than 4 μm is due to absorption in the $LiNbO_3$. Other factors contributing to this decrease are the mirror reflectances and the reduction in the idler photon energy far from degeneracy according to the Manley–Rowe relation. The performance presented here can be improved with straightforward changes; for example, antireflection coatings on the crystal surfaces will lower the threshold and increase conversion efficiency. Output power can be increased by an increase in the pulse repetition rate. We previously generated up to 34 mW_{av} of power at 4.0 μm in a 9-mm-long PPLN crystal by pumping with 1 W_{av} at 10 kHz.[3]

The IR transmission and the absorption coefficient of congruent $LiNbO_3$ are shown in Fig. 5. The extraordinary polarization has a longer IR cutoff than the ordinary polarization. In contrast to birefringently phase matched OPO's, QPM OPO's can take advantage of the large d_{33} and thus operate with extraordinary polarization for the long-wavelength idler. The result is that QPM OPO's in PPLN have better IR performance than would be expected from past research. In addition, the extraordinary polarization is much less affected by OH absorption near 2.8 μm.

In conclusion, we have demonstrated a widely tunable QPM OPO using multigrating sections fabricated lithographically on a single PPLN chip. This device has 6-μJ threshold with a Q-switched Nd:YAG pump laser and 70% pump conversion at eight times greater than threshold. The OPO is tuned by translation of the crystal through the resonator, and no cavity realignment is required. This design permits noncritical phase matching over the entire mid-IR transparency range of $LiNbO_3$ from 1.36 to 4.83 μm in a single device. This experiment illustrates the control of ferroelectric domain patterning that is now possible in electric-field-poled bulk PPLN. Complex structures can be fabricated readily by use of microlithography as a tool. We expect that these techniques will lead to devices with tailored gain profiles and other combinations of nonlinear interactions in single devices, such as internal generation of sum frequency, difference frequency, and the second harmonic from an OPO signal and idler.

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