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Widely and continuously tunable optical parametric oscillator based on a cylindrical periodically poled $KTiOPO_4$ crystal

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We report on what is to our knowledge the first realization of a quasi-phase-matched optical parametric oscillator (OPO) based on a crystal with a cylindrical shape. The main reason for interest in this device is its broad, continuous tuning. In experiments with a 1064-nm pump, the signal tuning range was equal to 525 nm (1515–2040 nm), and the corresponding idler was continuously tuned over 1340 nm (2220–3560 nm). The angular tuning was 26°, with only a minor variation of the OPO threshold over the entire tuning range.

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Quasi-phase matching is an attractive solution for the realization of efficient optical parametric oscillators (OPOs). Wavelength tuning of the output can be obtained with a tunable pump laser.[1] Another approach is to use a fixed pump wavelength and to change the temperature of the nonlinear crystal. However, this technique gives only limited tuning capabilities. A wider spectral tuning is classically obtained by variation of the grating period. For this purpose, multigrating crystals have been developed, mainly in periodically poled $LiNbO_3$.[2] However, this tuning is discontinuous and should be complemented with thermal tuning. Fan-shaped gratings have been demonstrated as an alternative approach for continuous tuning.[3] However, such a structure has the disadvantage of introducing large spectral heterogeneity into the generated beams, because the grating period is not constant over the pump-beam diameter. Noncollinear geometries have also been used in periodically poled $KTiOPO_4$ PPKTP OPOs to obtain enhanced tunability.[4,5] However, their tuning range was limited by the increasing OPO threshold because of lateral separation of the interacting beams. In this Letter we propose the use of a cylindrically shaped crystal with a single grating in a singly resonant cavity as an alternative approach to simple and widely tunable quasi-phase-matched (QPM) OPOs (Ref. 6) pumped by a fixed wavelength.

The geometry of the present OPO is shown in Fig. 1. Variation of the output wavelengths was obtained by rotation of the cylinder around its revolution axis, which was orthogonal to the cavity axis and to the plane containing the QPM grating vector, $\mathbf{K}_g$ (with $|K_g| = 2\pi/\Lambda$, where Λ denotes the grating period). The tuning in this configuration is achieved by rotation of the cylindrical crystal, whereas the pump and the resonated signal beams remain collinear ($\mathbf{k}_p \parallel \mathbf{k}_s$). It is important to notice that the nonresonant idler beam stays almost collinear to the pump and signal. According to Fig. 1(b), for the crystal's rotation angle, α, from the normal of the grating, the momentum conservation condition gives the idler angle, γ, from the same reference direction:

$$|\sin\gamma| = \left(\frac{k_p - k_s}{k_i}\right)|\sin\alpha|\,. \tag{1}$$

Since the factor in Eq. (1) lies in the interval $1.03 < (k_p - k_s)/k_i < 1.06$ for our configuration, the idler

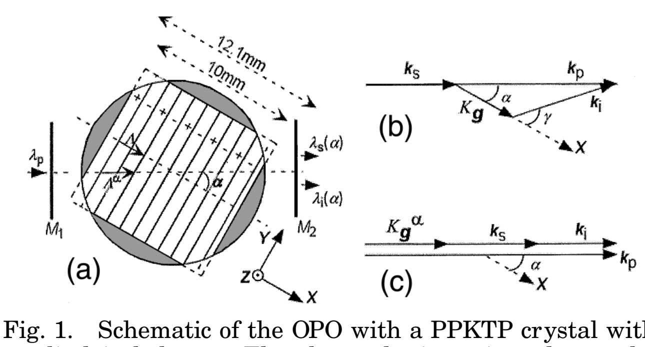

Fig. 1. Schematic of the OPO with a PPKTP crystal with a cylindrical shape. The plus and minus signs denote the polarization directions of the ferroelectric domains. The gray areas are unpoled. x, y, and z are the crystallographic axes, and z is the polar axis. The grating vector is K_g, Λ is the period of the grating, and $\mathbf{k}_{p,s,i}$ are the interacting wave vectors.

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beam remains essentially collinear to the pump and signal beams ($|\alpha| \approx |\gamma|$).

It is also possible to use the approach shown in Fig. 1(c), in which the grating is described by the effective vector, $K_g{}^\alpha$, collinear to the pump and signal, with $|K_g{}^\alpha| = 2\pi/\Lambda_\alpha$ and $\Lambda_\alpha = \Lambda/\cos\alpha$. Under this condition, the generated wavelengths are given by

$$\frac{n_z(\lambda_p)}{\lambda_p} - \frac{n_z(\lambda_s)}{\lambda_s} - \frac{n_z(\lambda_i)}{\lambda_i} - \frac{\cos\alpha}{\Lambda} = 0\,. \qquad (2)$$

The tuning curves that are generated from Eqs. (1) and (2) are very similar, as shown in Fig. 2.

Cylindrical crystals in a birefringent phase-matched OPO (Ref. 7) offer two important advantages: The interacting beams always propagate at normal incidence to the crystal surface for every direction of propagation, which permits very large angular tuning with no degradation of the beam quality, and the short focal distance of the crystal placed in the cavity induces a spatial filtering effect that prevents oscillation of beams with large M^2.[8] It is reasonable to expect these advantages to be preserved in the case of a QPM OPO with a cylindrical crystal.

A 0.5-mm-thick PPKTP crystal was used in the present experiments. It was poled[9] with a period $\Lambda = 35.0\ \mu$m, over a 10 mm $\times$ 10 mm area; the overall dimensions of the crystal were 12.5 mm $\times$ 12.5 mm. Preliminary OPO experiments were performed before the crystal was ground to a cylinder shape, and only small variations in the measured threshold were observed when the sample was translated in the pump beam. The calculated effective nonlinear coefficient from these experiments was $d_{\text{eff}} = (2/\pi)d_{33} = 5.8 \pm 1.4$ pm/V, which is somewhat lower than previously published values.[10]

The crystal was cut and polished to a cylinder after poling. A technique similar to that reported in Ref. 7 was used. The diameter of the cylinder was 12.16 mm. The average roughness of the lateral surface was measured to be 5.0 ± 0.6 nm rms over a 186 μm $\times$ 176 μm surface, which is two times better than the roughness of the large KTP cylinder in Ref. 7. Most of this surface is a nonpoled area, as shown in Fig. 1(a); no difference in the measured roughness could be observed where the ferroelectric domains reached the lateral surface. The crystal surface was left uncoated.

A Nd:YAG laser at $\lambda_p = 1064$ nm was used as the pump source for the OPO. The laser was in the longitudinal multimode with a 10-Hz repetition rate, and the pulse duration was 5.1 ns ($I = I_0/e^2$). The spatial profile was measured to be almost perfectly Gaussian, with $M^2 = 1.1 \pm 0.1$, and the beam was polarized along the z axis, allowing us to make use of the largest nonlinear coefficient of KTP, i.e., d_{33}.

Proper focusing of the pump beam is necessary to obtain a large beam waist at the center of the cylinder and to ensure parallel beams in the crystal.[7,8] Two cylindrical lenses were used to focus the pump beam in the plane orthogonal to the cylinder axis. Along the z axis, adequate beam size was obtained by use of a 300-μm aperture. The pump-beam radius measured before the cylinder was $45 \pm 1\ \mu$m $\times$ $230 \pm 5\ \mu$m. This corresponds to a calculated pump waist refracted at the center of the cylinder, with a radius of $47 \pm 5\ \mu$m $\times$ $225 \pm 25\ \mu$m. The pump-beam profile at the exit of the cylinder exhibited a clear diffraction pattern along the z axis because the beam size was very close to that of the crystal aperture along this dimension. This closeness in size caused substantial losses in the cavity and reduced the efficiency of the OPO. However, it did not change the spectral tuning characteristics, and the problem may be overcome in the future with a thicker PPKTP crystal (3-mm-thick samples have already been reported[10]).

The cavity of the OPO consisted of two plane mirrors, M_1 and M_2 in Fig. 1, with a cavity length $L_c = 13.5$ mm, constant for all experiments. Two mirrors sets, A and B, were used that had the following characteristics: The pump beam was completely reflected by mirror M_2 for both sets. Their reflectivity at λ_s is shown in Fig. 3. For set B, the reflectivity of M_2 was $R_s > 90\%$ from 1650 to 2100 nm and then rapidly decreased for shorter wavelengths. The measured and calculated signal wavelengths and their corresponding idlers as a function of revolution angle α are shown in Fig. 2. The Sellmeier equation according to Fradkin *et al.* was used for the calculation.[11] The measured wavelengths were in very good agreement with calculations from Eq. (1) or (2). The maximum crystal rotation was 26° from either side of the x axis. The cavity needed only negligible realignment during tuning, which indicates very good precision in the grinding of the cylindrical shape. The signal wavelength, λ_s, was tuned from 1517 ± 5 to 2040 ± 15 nm. The corresponding idler was then tuned from 3560 ± 20 to 2220 ± 15 nm. This spectral

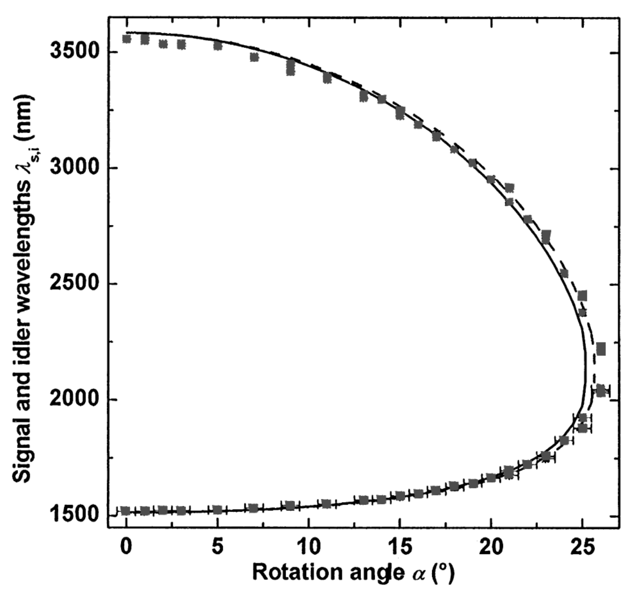

Fig. 2. Spectral-tuning curve as a function of the revolution angle, α. The filled squares are the experimental points. We calculated the solid curve by taking into account that $\gamma \neq \alpha$, and the dashed curve was calculated with Eq. (2); both were calculated with refractive indices from Ref. 11.

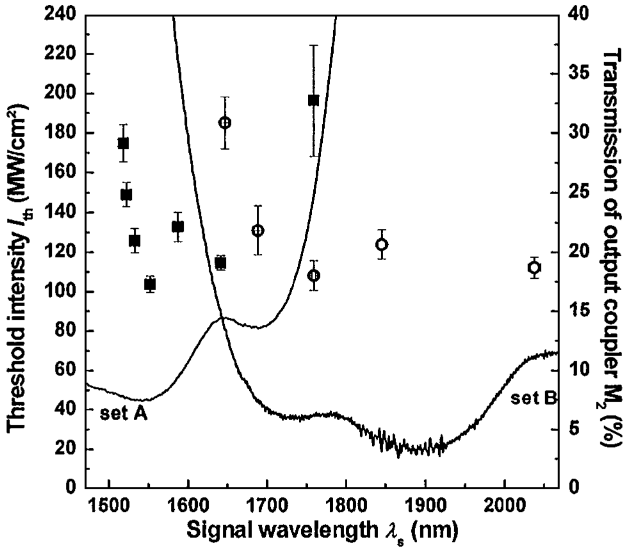

Fig. 3. OPO peak intensity threshold for mirrors sets A (filled squares) and B (open circles) versus signal wavelength. The solid curves are the transmission of output coupler M_2 for each mirror set.

tuning is to our knowledge the largest ever reported for PPKTP OPOs. It is quite similar to that obtained with multigrating $LiNbO_3$,[2] but with the important advantage of continuous tuning in the present experiments. A weak blue beam near 450 nm and at angle $\alpha = 11°$ was also observed. This was attributed to a seventh-order sum-frequency mixing of the pump wavelength, λ_p, the second harmonic of the signal beam $\lambda_s/2$ for the particular values $\lambda_s = 1545$ nm and $\alpha = 11.1°$. The efficiency of the OPO was not affected by the sum-frequency mixing. In agreement with calculations, no other parasitic interaction was found.

The measured spectral bandwidth of the signal beam was rather constant, $\Delta\lambda_s = 1.1 \pm 0.4$ nm, for propagation angles α from 0° to 20°. This bandwidth is 1 order of magnitude smaller than the value reported for a previously published PPKTP OPO[10] because the finesse of the present cavity was higher, leading to a larger number of cavity round trips and to a larger effective interaction length,[12] and because the spatial quality of the present pump beam was better. The measured spectral bandwidth was enlarged for propagation angles larger than 20° because the interaction became more sensitive to the angle of propagation, and multipeak behavior was observed when the signal wavelength came close to degeneracy where the OPO became doubly resonant.

The measured OPO thresholds corresponding to mirrors sets A and B are shown in Fig. 3. The variations in thresholds were correlated mainly with the measured transmission of the cavity mirrors, also shown in Fig. 3. As can be seen even for remarkably large angles α, the threshold intensity did not exhibit any particular increase. This, once again, shows that large lateral walk-off of the signal and idler beams was avoided. It also shows that the periodic poling was homogeneous over the entire volume. The larger thresholds for α close to 0° were related to poorer surface quality for these particular directions. For comparison, we calculated the OPO threshold at $\lambda_s = 1700$ nm, using the expression in Ref. 13 and considering an average mirror transmission $T_s = 10\%$ and an effective nonlinear coefficient $d_{\text{eff}} = 5.8 \pm 1.4$ pm/V. The calculated threshold intensity was 24 ± 6 MW/cm^2, well below the experimental value of 130 ± 10 MW/cm^2. The discrepancy is attributed to large pump-power losses owing to diffraction along the z axis caused by the limited aperture of the PPKTP crystal. The maximum value of energy conversion at $\alpha = 26°$ was 17.3%, corresponding to a pump energy of 0.43 mJ, i.e., 3.5 times above threshold. The output energy of this OPO was low compared with previously published values (e.g., in Ref. 10) for OPOs based on PPKTP. Optimized focusing of the pump beam or a thicker crystal will increase the efficiency of the cylindrical OPO further.

In conclusion, we have demonstrated, for the first time to our knowledge, that a periodically poled, cylindrical crystal can be used for building continuous and widely tunable OPOs. The tuning range of the OPO employing PPKTP extended over 520 nm for the signal wavelength. Considering the efficient QPM OPOs that have already been reported[10] and the good M^2 factor obtained with a cylindrical crystal in a birefringent phase-matched OPO, we believe that the cylindrical periodically poled crystal has the potential to be a very simple and promising solution for the realization of efficient and widely tunable OPOs with good beam quality.

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