Wavelength tunability of tandem optical parametric oscillator based on single PPMgOLN crystal

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The theoretical analysis and experimental results of the wavelength tunability of a tandem optical parametric oscillator (TOPO) based on a single nonlinear crystal are presented. TOPO is a configuration wherein the signal laser is used as a pump laser to generate secondary optical parametric oscillator (OPO). The cascaded parametric interactions are achieved synchronously in a single-grating-period MgO doped periodically poled lithium niobate (PPMgOLN). Tunable multiple-wavelength mid-infrared (mid-IR) lasers are obtained by changing the temperature of the crystal. When the PPMgOLN crystal with a grating period of 31.2 μm is operated at 148 °C, the dual OPOs generate an identical mid-IR laser of 2.83 μm. The secondary OPO transforms into an optical parametric amplifier, in which different frequency mixing from the signal laser results in the amplification of the idler laser in the first OPO. TOPO is a useful configuration for multiple laser output, broad tuning range, and high-efficiency mid-IR lasers.

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Optical parametric oscillators (OPOs) have been used effectively in obtaining mid-infrared (mid-IR) lasers (3–5 μm) with an output power over 10 W[1]. MgO doped periodically poled lithium niobate (PPMgOLN) has been an outstanding nonlinear crystal for OPO because of its large nonlinear coefficient and wide wavelength tunability. Its largest nonlinear polarization tensor, d_{33}(27.4 pm/V), which is several times larger than other nonlinear crystals, can be utilized through quasi-phase-matching technique. The doping of MgO can significantly enhance its photorefractive damage threshold and effectively reduce its coercive field for fabricating thicker crystals. According to literature, high-power mid-IR OPOs were mainly based on the PPMgOLN crystal, such as 9 W at 3.3 μm by Hirano *et al.*[2], 10 W at 3 μm by Chen *et al.*[3], and 11.8 W at 2.7 μm, and 16.7 W at 3.8 μm by Peng *et al.*[4−7]. With increasing thickness from 0.5 to 5 mm, made available in a laboratory[8] and the 3-mm crystal obtained commercially, PPMgOLN could offer many advantages for high-power mid-IR lasers.

The mid-IR OPO pumped by a 1-μm laser generates a near-IR signal laser around 1.5 μm alongside the mid-IR idler laser at around 3–5 μm. If the mid-IR idler laser is the desired output, the greater power of the near-IR signal laser in a common OPO is rather wasted. The final output power of the mid-IR laser is restricted by the ratio of photon energies and by conversion efficiency. If the signal laser is used as a pump laser to generate a secondary OPO, new wavelength mid-IR lasers can be obtained. This configuration is called the tandem OPO (TOPO).

The frequency diagrams of OPO and TOPO are shown in Fig. 1[9]. The output lasers of the secondary OPO are both in mid-IR range.

TOPO is more appropriate for high pump power and high-efficiency output than common OPOs because the consumption of the signal laser in the secondary OPO can enhance the depletion of the initial pump laser and suppress back conversion in the first OPO. Dearborn *et al.* achieved over 100% photon-conversion efficiency by TOPO configuration with two periodically poled lithium niobate (PPLN) crystals[10].

Usually, two nonlinear crystals (or a single crystal with two grating periods) are needed to achieve the dual OPOs separately[11−13]. In fact, TOPO with a single-grating-period PPMgOLN crystal is possible as long as the energy and momentum conservation equations are satisfied in both parametric interactions. The phase-matching of PPMgOLN-TOPO can be easily achieved by adjusting the grating period and temperature of the crystal. Vaidyanathan *et al.* first observed the phenomenon of TOPO by using a single PPLN crystal in 1997[14]. Subsequently, Moore *et al.* reported the theoretical analysis based on a ring cavity model[15]. However, the wavelength tunability of TOPO with a single-grating-period PPMgOLN has not been fully studied to date.

The wavelengths of the mixing waves in the TOPO are determined by the equations below.

$$\begin{cases} \dfrac{1}{\lambda_{\mathrm{p}}} = \dfrac{1}{\lambda_{\mathrm{i}}} + \dfrac{1}{\lambda_{\mathrm{s}}} \\ \dfrac{n_{\mathrm{p}}(\lambda_{\mathrm{p}},t)}{\lambda_{\mathrm{p}}} - \dfrac{n_{\mathrm{i}}(\lambda_{\mathrm{i}},t)}{\lambda_{\mathrm{i}}} - \dfrac{n_{\mathrm{s}}(\lambda_{\mathrm{s}},t)}{\lambda_{\mathrm{s}}} - \dfrac{1}{\Lambda} = 0 \end{cases}, \qquad (1)$$

$$\begin{cases} \dfrac{1}{\lambda_{\mathrm{s}}} = \dfrac{1}{\lambda_{\mathrm{i'}}} + \dfrac{1}{\lambda_{\mathrm{s'}}} \\ \dfrac{n_{\mathrm{s}}(\lambda_{\mathrm{s}},t)}{\lambda_{\mathrm{s}}} - \dfrac{n_{\mathrm{i'}}(\lambda_{\mathrm{i'}},t)}{\lambda_{\mathrm{i'}}} - \dfrac{n_{\mathrm{s'}}(\lambda_{\mathrm{s'}},t)}{\lambda_{\mathrm{s'}}} - \dfrac{1}{\Lambda} = 0 \end{cases}, \qquad (2)$$

where λ_j, n_j, t, and Λ are the wavelength, refractive index, temperature, and grating period of PPMgOLN, respectively. Equations (1) and (2) are the energy conservation and the phase-matching equations in the first and secondary OPOs, respectively. The pump laser, idler laser in the first OPO, signal laser in the first OPO, idler laser in the secondary OPO, signal laser in the secondary

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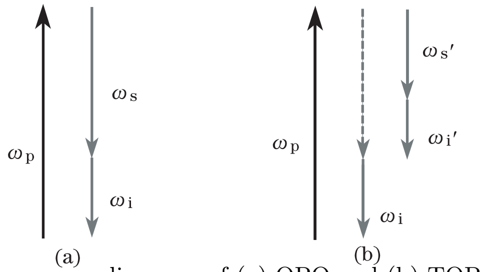

Fig. 1. Frequency diagrams of (a) OPO and (b) TOPO.

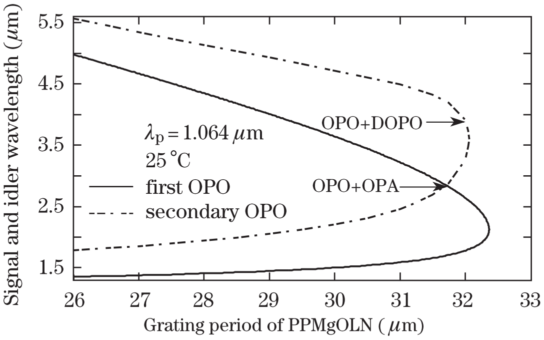

Fig. 2. Calculated wavelength for the first (solid line) and secondary (dashed line) OPO interactions with the tuning of grating period. OPA: optical parametric amplifier.

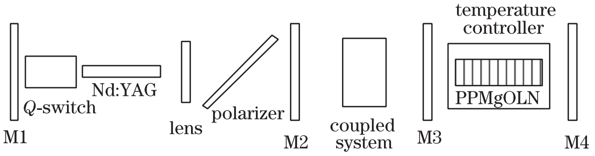

Fig. 3. Schematic of the experimental setup.

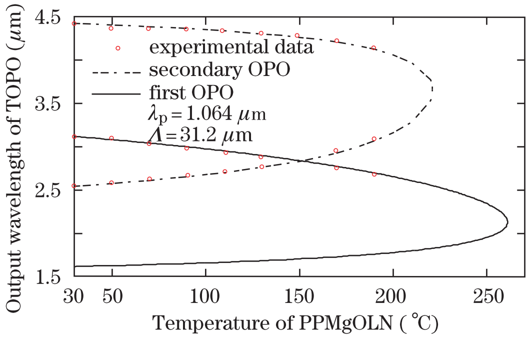

Fig. 4. Output wavelength of the PPMgOLN-TOPO versus the temperature of the crystal. The experimental results (circle dots) generally accord with the theoretical calculation (solid line for the first OPO and dashed line for the secondary OPO).

OPO are denoted by j=p, i, s, i$'$, s$'$, respectively. The refractive index of PPMgOLN was previously reported by Gayer *et al.*[16].

The calculated wavelength of the TOPO based on a single PPMgOLN crystal is shown in Fig. 2. Apart from wider tunability, the TOPO usually contains three mid-IR lasers with different wavelengths, which are quite different from common OPOs. At a particular grating period, dual OPOs generated mid-IR lasers of the same wavelength ($\omega_i = \omega_{s'}$). The secondary OPO turned onto an optical parametric amplifier (OPA), in which different frequencies mixing from the signal laser resulted in amplification of the idler laser in the first OPO. At another particular grating period, the secondary OPO turned onto a degenerated OPO (DOPO), where $\omega_{s'}$ and $\omega_{i'}$ are equal. The OPO+OPA and OPO+DOPO are focal topics in mid-IR literature due to their power-increasing possibilities.

To highlight this finding, if the DOPO generates mid-IR lasers with the same wavelength of the idler laser in the first OPO ($\omega_i = \omega_{i'} = \omega_{s'}$), a pump photon can convert to three mid-IR photons of the same wavelength. This fully-pump-converted TOPO is called treble degenerated OPO (TDOPO).

The wavelength tuning of PPMgOLN-TOPO can be achieved by changing the temperature or the grating period of the crystal. This experimental study focused on temperature change, as it can be adjusted conveniently, continuously, and precisely during the experiment.

The experimental setup is shown in Fig. 3. The pump laser of 1.064 μm was formed by a flat mirror M1 (high reflection (HR) at 1.064 μm), an output coupler flat mirror M2 (reflectivity R=50% at 1.064 μm), a continuous wave (CW)-diode-pumped Nd:YAG module, an acousto-optical Q-switch, a compensative lens, and a 1.064-μm laser polarizer. The spot size of the pump beam was adjusted by the coupled system to about 0.7×0.7 (mm) at the center of the crystal. PPMgOLN-TOPO was formed by a 1×5×50 (mm) PPMgOLN crystal, a temperature controller, and flat mirrors (M3 and M4). M3 was coated with anti-reflection (AR) at 1.064, HR at 1.6–1.8, 2.5–3.2, and 4.2–4.5 μm, while M4 was coated with HR at 1.6–1.8, R≈60% at 2.5–3.2, and AR at 4.2–4.5 μm. The PPMgOLN crystal with a single grating period of 31.2 μm was placed in an oven with a temperature range of up to 200 °C. Oven temperature could be controlled to a precision of 0.1 °C. Both end faces of the crystal were coated with AR at 1.064, 1.6–1.8, and 2.5–3.2 μm. To ensure that the secondary OPO was above the threshold and to avoid damaging the optics, pump intensity was controlled at about 8 MW/cm^2 at 7 kHz.

The output wavelength of the PPMgOLN-TOPO versus the temperature of the crystal is shown in Fig. 4. The experimental results were almost similar with the theoretical calculation. Multiple wavelengths of around 4.4, 3.0, and 2.7 μm were obtained. The wavelength tunability of 4.4–4.2, 3.1–2.6, and 2.6–3.1 μm were achieved by adjusting temperature from 30 to 190 °C. The error between experimental results and theoretical calculation might have been caused by thermal problems, which induced thermal gradient, temperature asymmetry, and heat expansion of the crystal.

The output spectra of PPMgOLN-TOPO at 90, 148, and 190 °C are shown in Fig. 5. The central wavelengths of the three mid-IR lasers at 90 °C were 2.66, 2.98, and 4.35 μm. The TOPO processes were 1.064 μm→2.98 μm +1.65 μm and 1.65 μm→2.66 μm+4.35 μm. The relative intensities of these lasers were mainly determined by their photon energies, as well as by the conversion efficiencies of the dual OPO; they were also influenced by the different absorption coefficients of PPMgOLN. The intensity of the lasers beyond 4 μm was much lower than the theoretical calculation of photon-number conservation due to the strong absorption in the crystal. At 148 °C, the

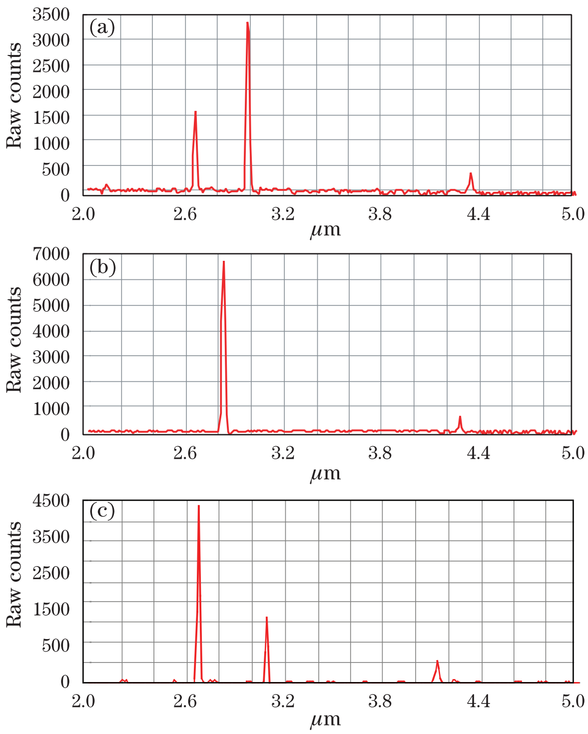

Fig. 5. Output spectra at (a) 90, (b) 148, and (c) 190 °C.

dual OPO generated the same wavelength mid-IR lasers as with the following processes: 1.064 μm→2.83 μm+ 1.70 μm and 1.70 μm→2.83 μm+4.28 μm. The secondary optical parametric interaction was equal to an OPA, in which the signal laser of 1.70 μm amplified the idler laser of 2.83 μm. The conversion efficiency of this amplified mid-IR laser was supposedly much higher than common OPOs. The coincident wavelength tended to separate at higher temperatures, such as at 190 °C, where the TOPO processes were 1.064 μm→2.67 μm+1.77 μm and 1.77 μm→3.09 μm+4.13 μm.

The multiple-wavelength output ability of PPMgOLN-TOPO can be utilized by some special applications. The desired output wavelengths of these mid-IR lasers can be achieved by designing the grating period and the operating temperature of PPMgOLN.

The output spectra in the other ranges were also measured. The frequency doubling of ω_p and ω_s, and the frequency sum of $\omega_\mathrm{p}+\omega_\mathrm{s}$ and $\omega_\mathrm{p}+\omega_\mathrm{i}$ were obtained. The intensities of these visible lasers were much weaker compared with the mid-IR lasers.

In conclusion, the wavelength tunability of a TOPO based on a single PPMgOLN crystal is studied. The TOPO achieves cascaded parametric interactions in such a way that the signal oscillation can pump a secondary OPO. By adjusting the temperature of the crystal, multiple-wavelength tuning of mid-IR lasers is achieved. The experimental results are almost similar with theoretical calculations. The tunability of TOPO can be enhanced with a tunable pump source. Apart from its better wavelength tunability, the higher efficiency output property of TOPO is also deemed attractive compared with common OPOs.

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