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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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OPO are denoted by $j=p$, $i$, $s$, $i'$, $s'$, respectively. The refractive index of PPMgOLN was previously reported by Gayer et al.\textsuperscript{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 ($\omega_i=\omega_{i'}$). 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 $\omega_{i'}$ and $\omega_{i'}$ are equal. The OPA+OPO and OPA+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 ($\omega_i=\omega_{i'}=\omega_{i''}$), a pump photon can convert to three mid-IR photons of the same wavelength. This fully-pump-converted TOPO is called treble degenerated OPO (TDOP).

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 $\mu$m was formed by a flat mirror M1 (high reflection (HR) at 1.064 $\mu$m), an output coupler flat mirror M2 (reflectivity $R=50\%$ at 1.064 $\mu$m), a continuous wave (CW)-diode-pumped Nd:YAG module, an acousto-optical $Q$-switch, a compensative lens, and a 1.064-$\mu$m laser polarizer. The spot size of the pump beam was adjusted by the coupled system to about 0.7 $\times$ 0.7 (mm) at the center of the crystal. PPMgOLN-TOPO was formed by a 1 $\times$ 5 $\times$ 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 $\mu$m, 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 $\mu$m. The PPMgOLN crystal with a single grating period of 31.2 $\mu$m was placed in an oven with a temperature range of up to 200 $^\circ$C. Oven temperature could be controlled to a precision of 0.1 $^\circ$C. Both end faces of the crystal were coated with AR at 1.064, 1.6–1.8, and 2.5–3.2 $\mu$m. 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 $\mu$m were obtained. The wavelength tunability of 4.4–4.2, 3.1–2.6, and 2.6–3.1 $\mu$m were achieved by adjusting temperature from 30 to 190 $^\circ$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 $^\circ$C are shown in Fig. 5. The central wavelengths of the three mid-IR lasers at 90 $^\circ$C were 2.66, 2.98, and 4.35 $\mu$m. The TOPO processes were 1.064 $\mu$m $\rightarrow$ 2.98 $\mu$m +1.65 $\mu$m and 1.65 $\mu$m $\rightarrow$ 2.66 $\mu$m +4.35 $\mu$m. 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 $\mu$m was much lower than the theoretical calculation of photon-number conservation due to the strong absorption in the crystal. At 148 $^\circ$C, the
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 ω₀ and ω₁, and the frequency sum of ω₀+ω₁ and ω₀+ω₁ 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.

References