Appl Phys B (2011) 104:597–601
DOI 10.1007/s00340-011-4477-4

Applied Physics B
Lasers and Optics

High-efficiency mid-infrared laser from synchronous optical parametric oscillation and amplification based on a single MgO:PPLN crystal

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Received: 9 November 2010 / Revised version: 20 January 2011 / Published online: 19 April 2011

Abstract This paper presents a specially designed optical parametric oscillator (OPO) which achieved high-efficiency mid-infrared laser of 2.83 µm. The cascaded nonlinear interactions of OPO and optical parametric amplifier (OPA) were simultaneously realized in a single MgO:PPLN crystal. The signal oscillation of 1.70 µm was used to pump a secondary parametric process that resulted in amplification of the idler laser of 2.83 µm. When the MgO:PPLN crystal with a grating period of 31.2 µm was pumped by a 1.064 µm laser and operated at 148°C, the quasi-phase-matching of both OPO and OPA could be simultaneously achieved. Average output power of 7.68 W at 2.83 µm was obtained for 25 W of pump at 7 kHz. The power conversion efficiency of 2.83 µm laser was 30.7%, which was evidently higher than common OPOs.

1 Introduction

Mid-infrared lasers in the 3–5 µm wavelength region arouse a growing interest due to their potential applications in atmospheric pollution monitoring, leak detection, medical diagnosis of disease, and so on. Optical parametric oscillators (OPOs) are capable of providing broad and continuous wavelength tunability from ultraviolet to far-IR, compact solid-state configuration, high efficiency and practical output power, and can deliver output throughout the entire temporal spectrum from continuous wave to ultrafast femtosecond time-scales [1].

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However, in OPOs, the power conversion efficiency of the mid-IR lasers with respect to the 1 µm pump laser is restricted by the ratio of the idler and signal photon energies. The maximal power conversion efficiency of the 2.83 µm laser is only 35.3% even with 100% quantum conversion efficiency. If the mid-IR idler laser is the desired output, the greater power of the near-IR signal laser will be wasted. A tandem OPO (TOPO) which uses the signal oscillation to pump a secondary nonlinear parametric process is an effective way to improve the efficiency [2, 3]. The pump-to-idler slope efficiency was improved by 52.8% using a dual-grid MgO:PPLN crystal to satisfy the phase matchings of TOPO [4]. With multiple choices of the tuning methods such as grating period tuning, temperature tuning, angle tuning, the cascaded nonlinear interactions could be achieved in a single nonlinear crystal based on quasi-phase-matching (QPM) system [5, 6].

2 Analysis of the TOPO based on a single MgO:PPLN crystal

OPOs based on QPM can utilize the largest nonlinear coefficient of crystals which lead to low threshold, high gain and high efficiency [7]. MgO doped periodically poled lithium niobate (MgO:PPLN) is one of the most widely used nonlinear crystals for generating tunable mid-IR lasers in the 2–5 µm range, owing to its large nonlinear coefficient (d_{33} of 27 pm/V is several times larger than some other crystals), wide transmission range of 330–5000 nm, low absorption and high damage threshold (compared with PPLN without MgO doping). OPOs based on MgO:PPLN have achieved mid-IR lasers with a practical output power over 10 W, such as: 57 W for near-degenerated 2.02 µm and 2.25 µm lasers by Y. Hirano et al. [8]; 18 W for 2.71 µm laser by Xingbin

Wei et al. [9]; 16.7 W for 3.8 μm laser by Yuefeng Peng et al. [10].

High-efficiency mid-IR lasers based on TOPO with two PPLN crystals (or single crystal with dual grating periods along the propagation direction) were reported [5, 11]. M.E. Dearborn et al. achieved greater than 100% photon-efficiency from an OPO with intracavity optical parametric amplification (OPA). The system involved two PPLN crystals to achieve the cascaded nonlinear interactions separately [12]. Gerald T. Moore et al. reported the theoretical analysis of a ring cavity TOPO based on a single crystal, and indicated that high efficiency over a large dynamic range in the pump intensity would be achieved [13]. However, to the best of our knowledge, synchronous OPO and OPA in a single MgO:PPLN crystal with single-grating period have not been realized in experiment yet.

The wavelengths of the mixing waves in the TOPO based on a single MgO:PPLN crystal are determined by the following equations. Equation (1) and (2) represent the energy conservation and phase-matching conditions of the first and secondary nonlinear interactions, respectively. Notations λ, n, Λ, t denote the wavelength, refractive index, grating period, temperature, respectively. $j =$ p, s, i, s2, i2 represent the pump, the signal in the first process, the idler in the first process, the signal in the secondary process, and the idler in the secondary process, respectively. The refractive index of the MgO:PPLN crystal is a function of the wavelength and temperature, given by O. Gayer et al. [14].

$$\begin{cases} 1/\lambda_p = 1/\lambda_s + 1/\lambda_i \\ n(\lambda_p, t)/\lambda_p = n(\lambda_s, t)/\lambda_s + n(\lambda_i, t)/\lambda_i + 1/\Lambda \end{cases} \tag{1}$$

$$\begin{cases} 1/\lambda_s = 1/\lambda_{s2} + 1/\lambda_{i2} \\ n(\lambda_s, t)/\lambda_s = n(\lambda_{s2}, t)/\lambda_{s2} + n(\lambda_{i2}, t)/\lambda_{i2} + 1/\Lambda \end{cases} \tag{2}$$

The calculated wavelengths of the mixing waves with the tuning of the temperature are shown in Fig. 1. The tandem optical parametric processes are based on a single MgO:PPLN crystal with a single-grating period of 31.2 μm. The wavelength of the pump laser is 1.064 μm. The solid and dashed lines represent the wavelength tuning in the first and secondary processes, respectively. The two lines intersect at about 150°C, where the dual processes generate the same mid-IR lasers of 2.83 μm. The secondary optical parametric process is equal to an OPA. Difference-frequency mixing from the signal laser results in amplification of the idler laser in the first process. The conversion efficiency of this amplified idler laser is supposed to be much higher than the common OPOs with a single interaction. The wavelength of the amplified laser is tunable by changing the grating period and corresponding operating temperature determined by (1)–(2), or with a tunable pump source.

Figure 2 shows the wavelength of the amplified idler laser with different grating period and operating temperature. Simultaneous OPO and OPA can be achieved with the grating period from 30.5 μm to 31.8 μm, however, the output wavelength of the idler laser is around 2.8 μm. This method can be applied in some other periodically poled crystals (such as periodically poled $LiTaO_3$) to obtain the amplified laser of other wavelengths.

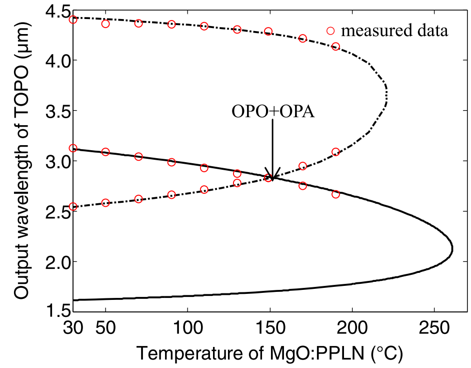


Fig. 1 Output wavelength of the first (*solid line*) and secondary (*dashed line*) optical parametric processes versus the temperature of MgO:PPLN

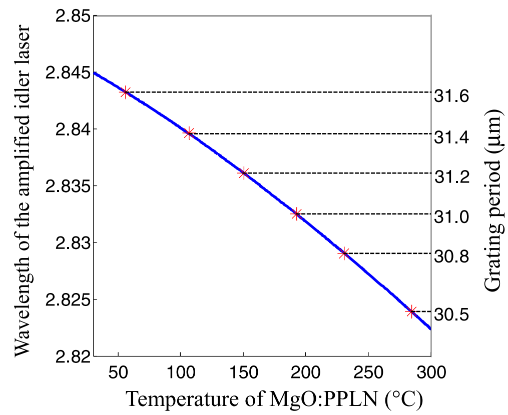


Fig. 2 Wavelength of the amplified idler laser with different grating periods and operating temperature

For a more interesting case, a pump photon could convert to three mid-IR photons of the same wavelength ($\lambda_i = \lambda_{s2} = \lambda_{i2}$). This fully-pump-used TOPO process could achieve even higher efficiency than the case of synchronous OPO + OPA ($\lambda_i = \lambda_{s2} \neq \lambda_{i2}$).

3 Experimental setup

The main purpose of the experiment is to validate the higher efficiency of the simultaneous OPO + OPA compared with a single OPO. The experimental setup of the simultaneous OPO + OPA based on a single MgO:PPLN crystal is shown in Fig. 3. The pump laser of 1.064 μm was formed by flat mirror M1 (HR@1.064 μm), output coupler flat mirror M2 ($R = 50\%$@1.064 μm), a cw-diode-pumped Nd:YAG module, an acousto-optical Q-switch, a compensative lens, and a

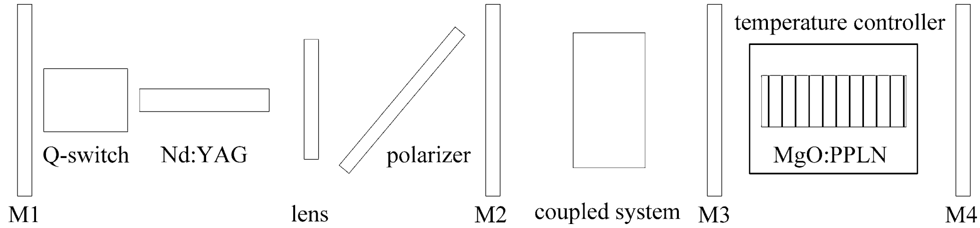


Fig. 3 Setup of the simultaneous OPO + OPA based on a single MgO:PPLN crystal

1.064 μm laser polarizer. The repetition rate of the Nd:YAG laser can be tuned from 1 to 10 kHz. The beam polarization matched the e → e + e interaction in the crystal, thus the maximal nonlinear coefficient d_{33} is available and walk-off of the beams can be avoided. The spot size of the pump beam was adjusted by the coupling system to about 0.7×0.7 mm^2 at the center of the crystal. The simultaneous OPO + OPA cavity was formed by a $1 \times 5 \times 50$ mm^3 MgO:PPLN crystal, a temperature controller, together with flat mirrors M3 and M4. M3 was coated with AR@1.064 μm, HR@1.6–1.8 μm and 2.5–3.2 μm, while M4 was coated with HR@1.6–1.8 μm and 1.064 μm, AR@2.5–3.2 μm. The cavity length was about 60 mm. The MgO:PPLN crystal with a single-grating period of 31.2 μm was staged in an oven with the temperature range up to 200°C. The temperature of the oven can be controlled to a precision of 0.1°C. Both end faces of the crystal were coated with AR@1.064 μm, 1.6–1.8 μm and 2.5–3.2 μm.

4 Results and discussion

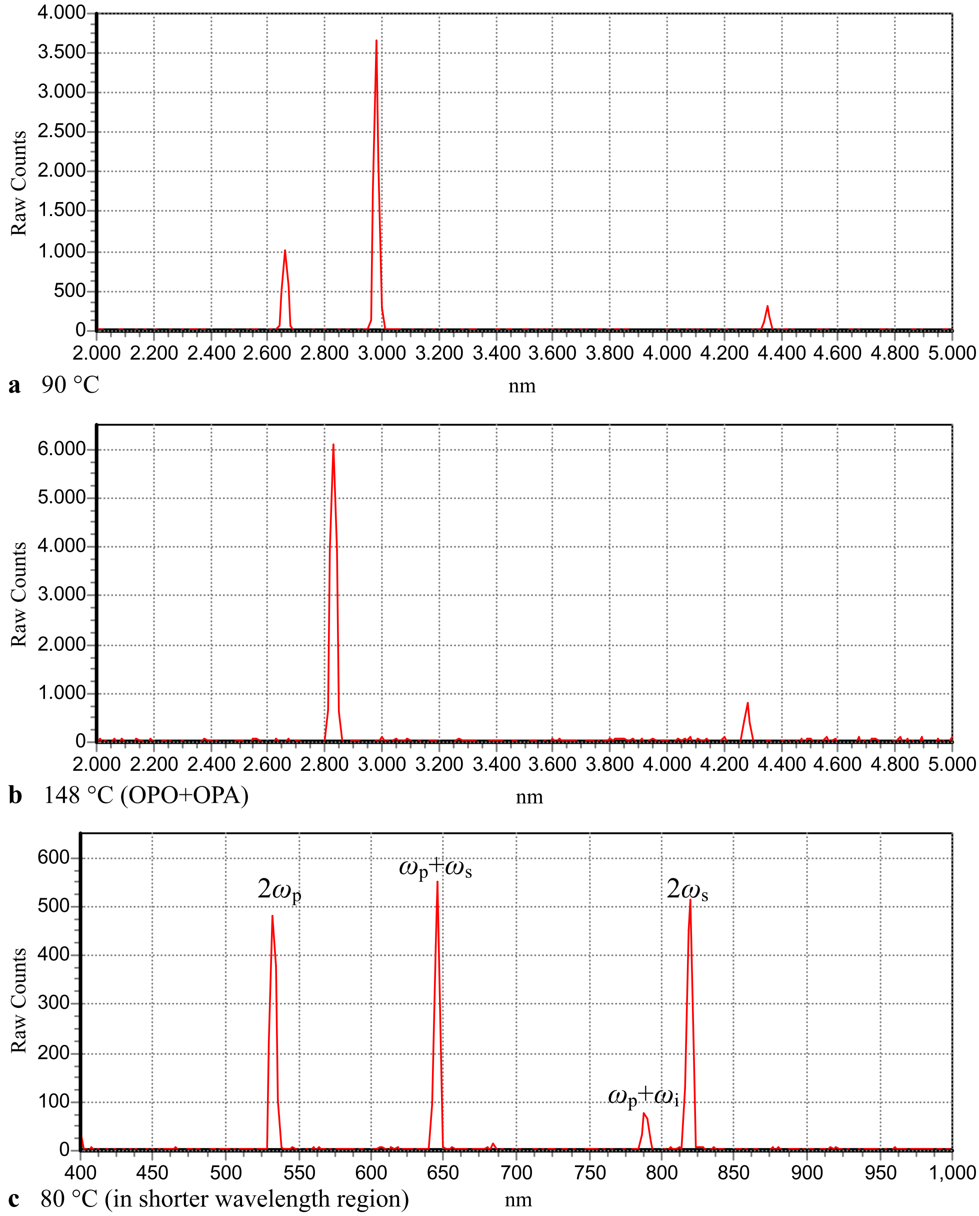
By changing the temperature of the MgO:PPLN crystal, different cascaded nonlinear interactions with different output wavelength were achieved. The experimental results shown in Fig. 1 (red circle) accorded well with the theoretical calculation. Multiple output wavelengths around 4.4 μm, 3.0 μm and 2.7 μm were obtained. The wavelength tunability of 4.4–4.2 μm, 3.1–2.6 μm and 2.6–3.1 μm could be achieved by adjusting the temperature from 30°C to 190°C. The error between the experiment results and theory calculation might be caused by the heat expansion of the crystal and the thermal problems which induced temperature asymmetry.

The output spectra at 90°C, 148°C and 80°C are shown in Fig. 4. The central wavelengths of the three mid-IR lasers at 90°C were 2.66 μm, 2.98 μm and 4.35 μm, respectively. The tandem optical parametric processes were: 1.064 μm → 2.98 μm + 1.65 μm, and 1.65 μm → 2.66 μm + 4.35 μm, respectively. The relative intensity of these lasers was mainly determined by their photon energies and conversion efficiencies, and was also influenced by the different absorption coefficients of the MgO:PPLN crystal. 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. By adjusting the temperature in a step of 0.1°C, the phase-matching of simultaneous OPO and OPA could be achieved. At about 148°C, the cascaded nonlinear interactions generated the same wavelength mid-IR lasers of 2.83 μm as the following processes: 1.064 μm → 2.83 μm + 1.70 μm (OPO), and 1.70 μm → 2.83 μm + 4.28 μm (OPA). The second process was equal to an OPA in which the signal laser of 1.70 μm amplified the idler laser of 2.83 μm. The output spectra in other range were also measured, the frequency doubling of ω_p and ω_s, frequency summing of $\omega_p + \omega_s$ and $\omega_p + \omega_i$ were found as shown in Fig. 4(c). But the intensities of these visible lasers were much weaker than the mid-IR lasers.

To verify the high conversion efficiency output of the simultaneous OPO + OPA, we have done some comparison experiments. A singly resonated OPO (SRO) was studied. The setup of SRO was similar with the simultaneous OPO + OPA except the output coupler mirror M4. Mirror M4 in the SRO was coated with HR@1.064 μm, AR@1.6–1.8 μm and $R = 60\%$@2.5–3.2 μm, thus the cavity was singly resonated at the idler waves. The MgO:PPLN crystal was still operated at 148°C. The output wavelengths of the signal and idler lasers were 1.70 μm and 2.83 μm, respectively.

The output power of the 2.83 μm laser versus the pump power is shown in Fig. 5. The 1.064 μm pump laser had a repetition rate of 7 kHz and a pulse duration of about 120 ns. The output power of the simultaneous OPO + OPA (filled squares) was evidently higher than the SRO (filled circles). When the pump power was 25 W, the average power of the 2.83 μm laser was 7.68 W for the simultaneous OPO + OPA and 4.72 W for SRO, the corresponding power conversion efficiency was 30.7% and 18.9%, respectively. The consumption of the signal laser (1.70 μm) in the OPA process enhanced the depletion of the pump laser (1.064 μm) and suppressed the back conversion in the OPO process. So the reason for the higher efficiency of the simultaneous OPO + OPA contains two basic parts: the amplification in OPA and the enhanced efficiency in OPO. The output power of the 4.28 μm simultaneously obtained from the difference-frequency mixing in the OPA process was as low as 0.5 W because of the strong absorption in the MgO:PPLN crystal and the limitation of the coating parameters.

Fig. 4 Output spectra at different operating temperature



The near-field intensity distribution of the 2.83 μm laser beam from the simultaneous OPO + OPA is also shown in Fig. 5. The beam quality M^2 factors with the pump power of 25 W were about 2.3 in the parallel direction and 2.8 in the perpendicular direction, respectively.

The phase-matching condition of simultaneous OPO and OPA in a single MgO:PPLN crystal was sensitive with the temperature. A stable and precise temperature controller is required for a stable output. The thermal problem could be ignored at this pump level. Simultaneous OPO and OPA based on a single crystal is an effective way to obtain high-efficiency mid-IR lasers, and has the potentiality of high output power once the thermal problem is solved for high pump power.

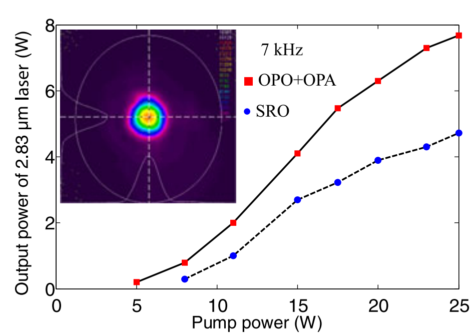


Fig. 5 Output powers of the 2.83 μm laser versus the pump power for the simultaneous OPO + OPA (*filled squares*) and the SRO (*filled circles*). The inner section is the near-field intensity distribution

5 Conclusion

High-efficiency mid-IR laser of 2.83 μm was achieved by simultaneous optical parametric oscillation and amplification based on a single MgO:PPLN crystal. The signal oscillation of 1.70 μm was used to amplify the idler laser of 2.83 μm. The phase-matching conditions of the cascaded nonlinear interactions were simultaneously satisfied when the MgO:PPLN crystal with a single-grating period of 31.2 μm was operated at 148°C and pumped by 1.064 μm laser. The output power of the amplified 2.83 μm laser was 7.68 W for 25 W of pump at 7 kHz. The power conversion efficiency of the 2.83 μm laser was 30.7%, which is evidently higher than a similar singly resonated OPO. The beam quality M^2 factors in the parallel and perpendicular direction were about 2.3 and 2.8, respectively. The thermal problem should be carefully considered to obtain mid-IR lasers with higher power and more stable output.

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