Widely continuous-tunable 2.789−4.957 μm twin-MgO:PPLN cascaded optical parametric oscillator

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An all-solid-state mid-infrared optical parametric oscillator with wide tunability by using two identical multi-grating periodically poled 5-mol.-% MgO-doped lithium niobate cascaded is reported. The pump laser is an acousto-optically Q-switched Nd:YAG laser with 150-ns pulse width at repetition rate of 10 kHz. Wide tunability from 2.789 to 4.957 μm at the idler wavelength is achieved by varying the temperature from 40 to 200 °C and translating the grating periods from 26 to 31 μm with a step of 0.5 μm. When the incident pump average power is 8.15 W, the maximum idler output average power is 2.23 W at 3.344 μm and the optic-optic conversion efficiency is about 27.4%.

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Optical parametric oscillators (OPOs) are attractive options for emitting widely continuous-tunable coherent radiation with narrow line-width at high average power. In OPOs systems, in order to meet the conditions of phase-matching, the quasi-phase-matched (QPM) technology is usually adopted[1−5]. Among the commercial nonlinear materials, $LiNbO_3$ (LN) is one of the most suitable materials to be the carrier of QPM, due to its high nonlinear coefficient, wide transparency range (from 0.35 to 5 μm), and good mechanical robustness[6,7]. However, high coercive field and lower photorefractive damage have limited the application of LN crystals. Magnesium oxide doped $LiNbO_3$ (MgO:LN) crystals have been verified to be an effective method to eliminate the above drawbacks. The coercive field of the MgO:LN is only about a quarter of the LN's. And the crystal has a lower photorefractive damage which makes it possible to construct a reliable OPO at room temperature[8]. Guo *et al.*[9] reported a 1.064-μm laser pumped mid-infrared QPM-OPO by using periodically poled MgO:LN (MgO:PPLN) crystal. In this OPO system, the pulse width of the pump source was 100 ns and the obtained maximum optic (pump light)-optic (idler light) conversion efficiency was about 11.53%. Kong *et al.*[10] obtained an optic (pump light)-optic (signal light) conversion efficiency of 29.5% in a singly resonant OPO based on MgO:PPLN crystal. The pump source of the OPO was a Q-switched $Nd:GdVO_4$ laser which could produce 3-ns laser pulses. In 2008, Zhang *et al.*[11] demonstrated a 1.047-μm Q-switched Nd:YLF laser pumped mid-infrared intracavity MgO:PPLN OPO. The pulse width of the pump source was about 20 ns. And the obtained optic (pump light)-optic (idler light) conversion efficiency was about 5.2%.

In this letter, a QPM-OPO based on two identical MgO:PPLN (twin-MgO:PPLN) crystals cascaded is experimentally demonstrated. The OPO is pumped by a 1.064-μm Q-switched Nd:YAG laser, which could produce 150-ns laser pulses with a repetition rate of 10 kHz. By using this new OPO structure, the idler output average power can be improved. The obtained maximum optic (pump light)-optic (idler light) conversion efficiency is about 27.4%. And a 2.789−4.957 μm continuous-tunable high power mid-infrared laser is realized.

Figure 1 shows a schematic of the experimental setup for a QPM-OPO. The pump source of the OPO system is a commercially acousto-optically Q-switched Nd:YAG laser. Its output wavelength is 1.064 μm with pulse duration of 150 ns at a repetition rate of 10 kHz. The polarized prism is used to allow the polarized light which is parallel to the direction of the largest nonlinear coefficient of the MgO:PPLN crystal to through out. L is a focusing lens with 150-mm focal length. It is used to focus the pump beam into the cavity. The focal point is located in the middle of the cavity, the length of which is 100 mm. The OPO is singly resonant at the signal wave and composed of two plane-concave mirrors M_1 and M_2. The curvature radii of the cavity mirrors (M_1 and M_2) are 100 mm. M_1 is used as the input mirror of the cavity, which was coated with high transmission for the pump wave ($T > 90\%$), high reflectivity for the signal wave ($R > 99.8\%$ from 1.4 to 2 μm), and low transmission for the idler wave ($T > 10\%$ from 2.5 to 5 μm). M_2 is used as the output mirror of the cavity, which was coated with high transmission for the idler wave ($T > 90\%$ from 2.5 to 5 μm), high reflectivity for the signal wave ($R > 99.8\%$ from 1.4 to 2 μm), and low transmission for the pump wave ($T > 10\%$). A filter with high transmission for the idler wave ($T > 90\%$ from 2.5 to 5 μm) and high reflectivity for the signal wave ($R > 98\%$ from 1.4 to 2 μm) is used as a cutoff filter for the signal and any residual pump light. In the experiment, D is a detector for power meter (Gentec-EO SOLO) or spectrometer (Tensor 27).

Two identical MgO:PPLN crystals with 40-mm length, 10-mm width, and 2-mm thickness are cascaded in the experiment. The grating periods of the MgO:PPLN crystals are changed from 26 to 31 μm in 0.5-μm increment. Figure 2 shows the amplified image of the MgO:PPLN crystal with the periods of 26 and

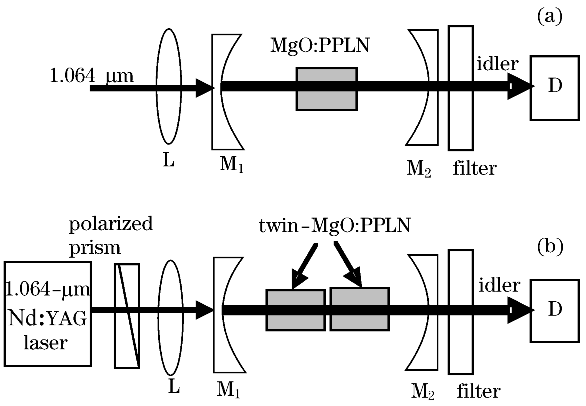

Fig. 1. Experimental setup of the QPM-OPO based on (a) MgO:PPLN or (b) twin-MgO:PPLN cascaded.

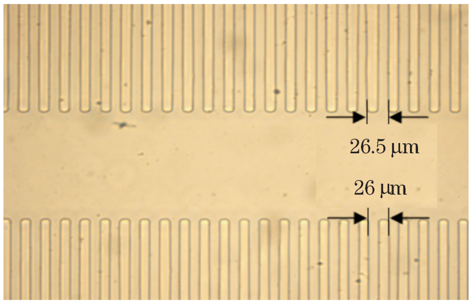

Fig. 2. Amplified image of the $+z$ surface of the multi-grating MgO:PPLN crystal showing portion with periods of 26 and 26.5 μm.

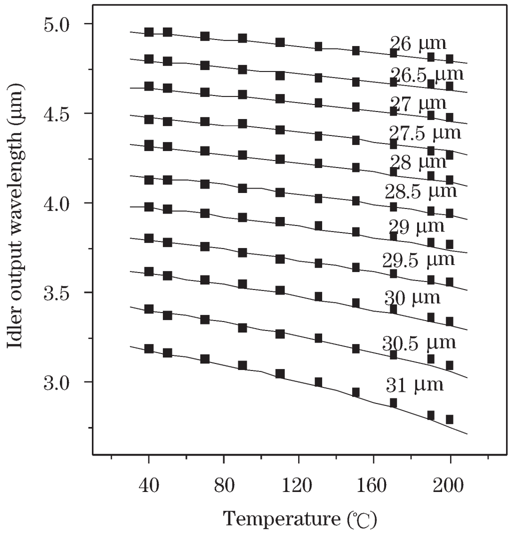

Fig. 3. Temperature tuning curves for 1.064-μm pumped OPO based on twin-MgO:PPLN cascaded with different grating periods.

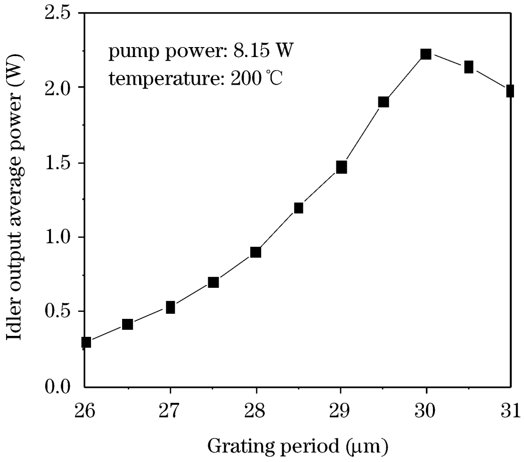

Fig. 4. Idler output average power versus the grating period.

26.5 μm. Both end facets of the crystals are polished and antireflection-coated for 1.064 μm, 1.4−2 μm, and 2.5−5 μm. The crystals are mounted in heating ovens which make it possible to adjust the temperature of the crystals over a range of 30−200 °C with a precision of ± 0.1 °C.

Figure 3 shows the tuning performance of the idler beam in the twin-MgO:PPLN crystals cascaded OPO by changing temperature and grating periods. With the temperature changing from 40 to 200 °C and grating periods translating from 26 to 31 μm, the OPO system can achieve wide and smooth wavelength tuning from 2.789 to 4.957 μm at the idler beam. In Fig. 3, the filled squares are the experimental data which are measured by a spectrometer, and the solid curves are the theoretical fitting curves which are calculated by using the Sellmeier equations[12,13] for the 5-mol.-% MgO:PPLN crystal. It is seen that the measured data show good consistency with the theoretical calculated results. Furthermore, we can observe that the tuning range becomes narrower with a decrease in the grating periods. So the tuning ability of long grating period is better than that of short grating period. The idler output average power for each grating period has been measured at a pump power of 8.15 W when the temperature of the MgO:PPLN crystal is controlled at 200 °C, which is shown in Fig. 4. The idler output average power firstly enhances with an increase of the grating period, but decreases after the grating period over 30 μm. The curve of Fig. 4 is not like that in Ref. [14]. Myers *et al.* theoretically predicted that the curve should increase over the whole range. It resulted from the difference of coating at different wavelengths on both the cavity mirrors and the end faces of the MgO:PPLN crystals. Furthermore, the incompleteness of the domain structure of the crystals is the other important reason.

Due to the limit of the fabrication techniques, the thicker the fabricated thickness of the MgO:PPLN crystal is, the shorter the fabricated length of the MgO:PPLN crystal is. Therefore, to extend the interaction length, the way that twin-MgO:PPLN crystals are cascaded in the OPO system is adopted. When the OPO system is based on one MgO:PPLN crystal, the maximum idler output average power of 1.88 W at 3.344 μm is achieved at the pump power of 8.15 W. The obtained optic (pump light)-optic (idler light) conversion efficiency is about 23.1%. Compared with the above OPO system, the maximum idler output average power of the OPO system based on twin-MgO:PPLN crystals cascaded is increased by 18.6%. Now the idler output average power is 2.23 W

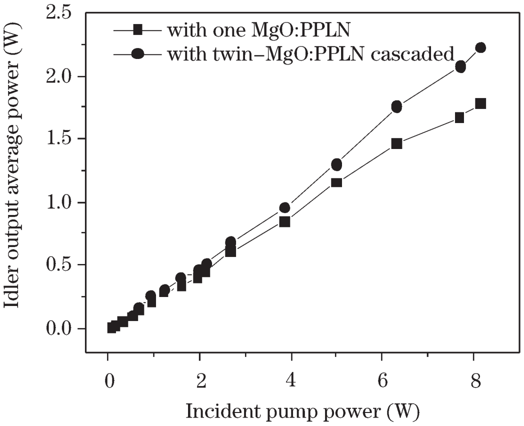

Fig. 5. Idler output average power versus the incident pump power in OPO systems based on one MgO:PPLN or twin-MgO:PPLN cascaded.

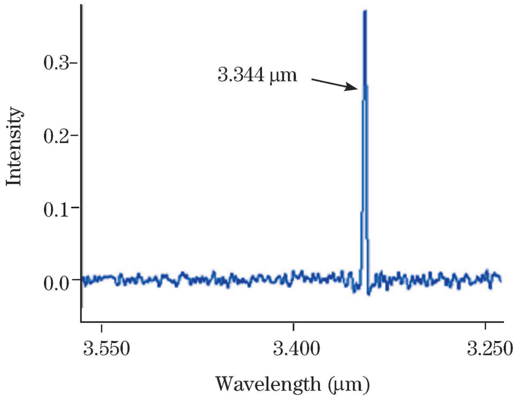

Fig. 6. Spectrum of the output idler wave.

and the optic (pump light)-optic (idler light) conversion efficiency is about 27.4%. The results clearly indicate that it is more favorable for increasing optic (pump light)-optic (idler light) conversion efficiency by using twin-MgO:PPLN crystals cascaded to extend the interaction length in OPO systems. However, we can find that the increased idler output average power is un-conspicuous. The possible reasons for this condition are partly from the loss of the joint between the two end faces of the two MgO:PPLN crystals. At the same time, the absorption of the idler beam cannot be neglected when it passes through the second MgO:PPLN crystal. As we know, the three waves (pump light, signal light, and idler light) must obey the energy conservation law ($\omega_{\rm p} = \omega_{\rm s}+\omega_{\rm i}$) in the OPO systems. Based on the energy conservation law, we can conclude that the theory limitation of the conversion efficiency is about 31.9% when the idler wavelength is 3.344 μm. Whereas the conversion efficiency can reach 23.1% by using one MgO:PPLN crystal. So we can conclude that the depletion of the pump power is very large when the pump light through the first MgO:PPLN crystal in the twin-MgO:PPLN crystals cascaded OPO system. Now the residual pump power is weak when it passes through the second MgO:PPLN crystal. In general, the weaker the pump power is, the lower the conversion efficiency is.

Figure 5 shows the measured characteristics of idler output average power based on one MgO:PPLN crystal or twin-MgO:PPLN crystals cascaded in OPO. In Fig. 5, the used grating period is 30 μm and the temperature of the crystal is controlled at 200 °C. And now the obtained idler wavelength is 3.344 μm, and the linewidth of the idler wave at 3.344 μm is about 2.3 nm, as shown in Fig. 6.

In summary, we have demonstrated an efficient singly resonant optical parametric oscillator based on twin-MgO:PPLN crystals cascaded. A commercially acousto-optically Q-switched Nd:YAG laser is used as the pump source, which can produce 150-ns laser pulse with a repetition rate of 10 kHz. By changing the crystal temperature and grating periods, the OPO can generate idler output in the range from 2.789 to 4.957 μm. The maximum output average power is measured to be 2.23 W with an 8.15-W pump power at the idler wavelength of 3.344 μm. Now the optic (pump light)-optic (idler light) conversion efficiency is about 27.4%. And the experimental results obviously prove that the optic (pump light)-optic (idler light) conversion efficiency would be improved by using twin-MgO:PPLN crystals cascaded in the OPO system.

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References

1. H. Ishizuki, I. Shoji, and T. Taira, Opt. Lett. **29,** 2527 (2004).
2. X. Zhang, B. Yao, Y. Ju, and Y. Wang, Chin. Phys. Lett. **24,** 1953 (2007).
3. B. Zhang, J. Yao, T. Zhang, F. Ji, Y. Lu, and P. Zhao, Opt. Commun. **270,** 368 (2007).
4. X. Zhang, Y. Ju, Y. Wang, B. Yao, and Y. Zhang, Chin. Opt. Lett. **6,** 286 (2008).
5. X. Zhang, Y. Wang, Y. Ju, B. Yao, and Y. Zhang, Chin. Opt. Lett. **6,** 204 (2008).
6. X. Lin, Y. Zhang, Y. Kong, J. Zhang, A. Yao, W. Hou, D. Cui, R. Li, Z. Xu, and J. Li, Chin. Phys. Lett. **21,** 98 (2004).
7. H. P. Li, D. Y. Tang, S. P. Ng, and J. Kong, Opt. Laser Technol. **38,** 192 (2006).
8. S. Haidar, Y. Sasaki, E. Niwa, K. Masumoto, and H. Ito, Opt. Commun. **229,** 325 (2004).
9. H. Guo, S. Tang, Z. Gao, Y. Qin, S. Zhu, and Y. Zhu, J. Appl. Phys. **101,** 113112 (2007).
10. J. Kong, C. C. Chan, N. Ni, B. Zhao, and D. Y. Tang, Opt. Eng. **46,** 014205 (2007).
11. X. Zhang, B. Yao, Y. Wang, Y. Ju, and Y. Zhang, Chin. Opt. Lett. **5,** 426 (2007).
12. D. H. Jundt, Opt. Lett. **22,** 1553 (1997).
13. O. Paul, A. Quosig, T. Bauer, M. Nittmann, J. Bartschke, G. Anstett, and J. A. L'huillier, Appl. Phys. B **86,** 111 (2007).
14. L. E. Myers, R. C. Eckardt, M. M. Fejer, R. L. Byer, W. R. Bosenberg, and J. W. Pierce, J. Opt. Soc. Am. B **12,** 2102 (1995).