A tunable optical parametric generator by using a quasi-phase-matched crystal with different wedge angles

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We report a tunable quasi-phase-matched optical parametric generator (OPG) with different wedge angles, pumped by a commercially available Q-switched diode-pumped Nd:YVO$_4$ laser with a repetition of 50 kHz. The nonlinear crystal is a periodically poled MgO-doped LiNbO$_3$ (PPMgOLN) with a period of 30 μm. A congruent bulk LiNbO$_3$ (LN) with three different wedge angles of 0°, 4°, and 9° is placed in front of PPMgOLN. Rapid tuning has been achieved by simply moving the LN crystal along its lateral direction and over 60-mW average signal output power was obtained in the whole wavelength tuning range of 1539—1570 nm.

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It is well known that optical parametric generators (OPGs) and optical parametric oscillators (OPOs) are promising candidates for the tunable infrared coherent source. Recently, the research in this area is focused on the quasi-phase-matching (QPM) technique based on the periodically poled crystal[1−8]. Compared with the conventional birefringent phase matching, the advantages of QPM technique are the availability of the largest nonlinear coefficient and the absence of the walk-off effect between the Poynting vectors and the wave vectors. Furthermore, in the whole transparency range of the crystal, the noncritical phase matching condition can be achieved at a specific temperature.

Nowadays, many wavelength-tuning methods in QPM OPO/OPG are available, such as the grating period tuning[3,4], the angle tuning[3,5,6], the temperature tuning[2,7], and the electro-optic tuning[8]. However, the temperature tuning has low tuning speed and the angle tuning requires the complicated mechanical tuning components. In addition, the grating period tuning and the electro-optic tuning have high costs. These shortages put some limitations on the application of the periodically poled crystals. So in some cases, it is beneficial to find an alternative tuning method that is rapid, simple, and economical.

This paper reports a new tuning method, wedge-angle-tuning method, in which signal and idler wavelengths are tuned by different wedge angles. A small congruent bulk LiNbO$_3$ (LN) with several different wedge angles is used to achieve the wedge-angle tuning. The LN crystal is placed in front of the periodically poled MgO-doped LiNbO$_3$ (PPMgOLN). We can make the pump light propagate into the different wedges by simply moving the LN crystal along its lateral direction. So the wavelength can be changed rapidly. Moreover, the fabrication of the congruent LN with several wedge angles is much easier than that of the multi-grating periodically poled crystal. Because the congruent LN is replaceable, the wedge-angle tuning is more flexible than the grating period tuning. In particular, this wedge-angle-tuning method can be applied with other tuning methods as an efficient compensation for their limitations.

We consider that the PPMgOLN is periodically poled along the z direction and all interacting waves are the extraordinary waves that are polarized parallel to the z-axis. In quasi-phase-matching condition, the energy conservation and the momentum conservation can be described as

$$\omega_{\mathrm{p}} = \omega_{\mathrm{s}} + \omega_{\mathrm{i}}, \tag{1}$$

$$\Delta k = k_{\mathrm{p}} - k_{\mathrm{s}} - k_{\mathrm{i}} - k_{\mathrm{g}} = 0, \tag{2}$$

where Δk is the phase mismatch, and k_j (j = p, s, i) are the wave vectors of pump wave, signal wave, and idler wave. $k_{\mathrm{g}} = 2\pi/\Lambda$ is the grating vector of the periodically poled crystal, where Λ is the grating period.

When the congruent LN with a wedge angle α is placed in front of the PPMgOLN, the direction of the pump light in the crystal is changed according to Snell's law, as shown in Fig. 1. The angle between k_{p} and k_{g} in the crystal is described as θ_{p}. For a small angle θ_{p}, we have $\theta_{\mathrm{s}} \approx \theta_{\mathrm{i}} \approx \theta_{\mathrm{p}} \approx \theta$, where θ_{s} is the angle between k_{s} and k_{g}, θ_{i} represents the angle between k_{i} and k_{g}. Consequently,

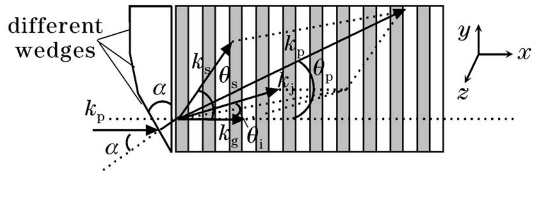

Fig. 1. Geometry of the wedge-angle-tuned OPG.

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the grating vector can be described as an effective grating vector[2,3,6], $k_{\mathrm{geff}} = 2\pi \cdot \cos\theta/\Lambda$ in the direction of k_{p}. So the phase matching can be described as

$$\Delta k = 2\pi\left(\frac{n(\lambda_{\mathrm{p}},T)}{\lambda_{\mathrm{p}}} - \frac{n(\lambda_{\mathrm{s}},T)}{\lambda_{\mathrm{s}}} - \frac{n(\lambda_{\mathrm{i}},T)}{\lambda_{\mathrm{i}}} - \frac{\cos\theta}{\Lambda(T)}\right) = 0, \qquad (3)$$

where λ_j (j = p, s, i) are the wavelengths of pump, signal and idler waves and $\Lambda(T)$ is the grating period determined by the thermal expansion. $n(\lambda_j, T)$ (j = p, s, i), the refractive indexes of the PPMgOLN, are provided by the crystal producer. $\theta = \alpha - \sin^{-1}[\sin\alpha/n'(\lambda_{\mathrm{p}}, T)]$ is based on Snell's law, α is the wedge angle and $n'(\lambda_{\mathrm{p}}, T)$ is the refractive index of the congruent LN. It is obvious that the output wavelength can be effectively tuned by use of the different wedge angles.

The schematic of experimental setup is shown in Fig. 2. The pump laser was a commercially available 1064-nm Q-switched diode-pumped Nd:YVO$_4$ laser (Aion Industrial-V, Bavarian Photonics Corp.) with the beam quality factor $M^2 < 1.3$ and the maximum average power of 6.58 W. The repetition rate of the pump laser was tunable in the range of 1—100 kHz and was fixed at 50 kHz with the pulse duration of 75—80 ns. The pump light was focused with the waist of about 40 μm by a 50-mm focal-length lens. The focal point was located at about 5 mm beyond the PPMgOLN.

The 5-mol% MgO-doped PPLN crystal (HC Photonics Corp.) with a 30-μm period was 50-mm long, 5-mm wide, and 1-mm thick. Both end facets of PPMgOLN were polished and coated antireflection at 1064, 1350—1700, and 2846—5027 nm. To provide different wedge angles, a congruent bulk LN (LN1) with dimensions of 6.85 × 5 × 2 (mm) was used in front of the PPMgOLN. It was cut with wedge angles of 0°, 4°, and 9°. LiNbO$_3$, the material of wedge, could provide a wider wavelength tuning range than other materials like quartz, because it has a bigger refractive index and a wider transmission range. Furthermore, as the refractive index of LiNbO$_3$ was closer to that of PPMgOLN, LiNbO$_3$ was more suitable for reducing the reflective loss between the LN and the PPMgOLN. The PPMgOLN and LN1 were placed in an oven which allowed to adjust the temperature of crystals over the range of 25—190 °C with the precision of ±0.1 °C. In order to avoid the photorefractive effect in PPMgOLN, the normal working temperature was set from 140 to 190 °C. Another congruent LN (LN2) with the same wedge angles as LN1 can be placed behind the PPMgOLN. By moving the LN2 along its lateral direction, we can ensure that the output signal light was parallel to the pump light.

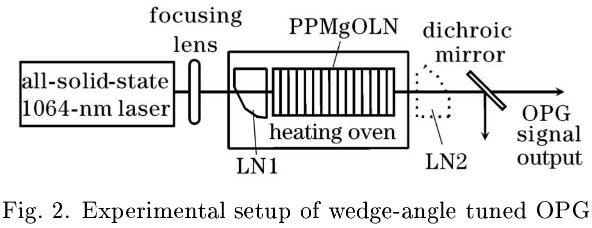

Fig. 2. Experimental setup of wedge-angle tuned OPG.

To measure OPG output power, a dichroic mirror was used to filter the residual 1064-nm pump light. Owing to the absorption of the substrate of the dichroic mirror above 3-μm wavelength range, only the average signal power was measured in the experiment. The signal spectrum was observed by an Agilent 86142B optical spectrum analyzer and the corresponding idler wavelengths were calculated through the energy conservation law.

Figure 3 shows the output wavelength versus the temperature at different wedge angles. Figures 3(a) and (b) is the temperature tuning curves for signal wavelength and the corresponding idler wavelength respectively. The solid lines represent the theoretical tuning curves calculated from Eq. (3) and the dots show the experimental results. Obviously, the experiment results are in good agreement with the theoretical predictions.

The signal wavelength could be tuned from 1537 to 1558 nm by adjusting the temperature from 140 to 190 °C at the 0° wedge, and the corresponding idler wavelength ranged from 3461 to 3359 nm. In the experiment, other wedge angles were also investigated for rapid tuning by moving the LN crystal along its lateral direction. To simplify the experiment, we just fabricated one congruent LN crystal, which provided three different wedge angles. We obtained signal waves from 1540 to 1562 nm for 4° wedge, from 1547 to 1570 nm for 9° wedge, and the corresponding idler wavelengths were from 3445 to 3340 nm for 4° wedge, from 3411 to 3304 nm for 9° wedge, respectively. It is evident that the tuning range over 10 nm (1537—1547 nm at 140 °C) can be obtained by only varying the wedge angle from 0° to 9°. Moreover, more separate output signal wavelengths can be obtained with more different wedge angles on one congruent LN crystal.

The average signal power as a function of the average pump power was measured at three typical working temperatures of 140, 160, and 190 °C for 0° and 9° wedge

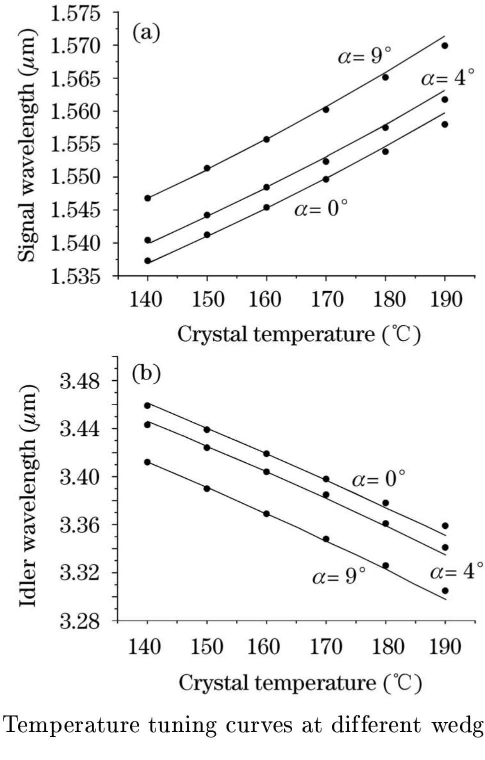

Fig. 3. Temperature tuning curves at different wedge angles.

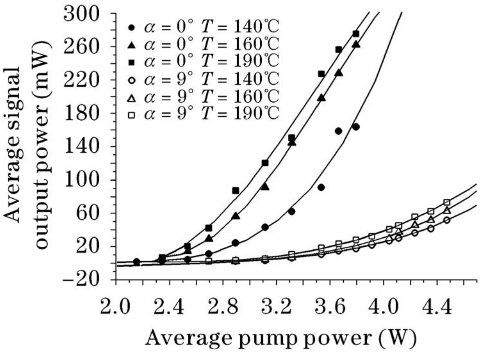

Fig. 4. Average signal output power as a function of the average pump power at different temperature for different wedge angles of 0° and 9°.

angles, as shown in Fig. 4. When the wedge angle was 0°, the maximum average signal power of 274 mW was obtained for the average pump power of 3.8 W at the temperature of 190 °C. In order to avoid the damage of the PPMgOLN, the higher pump power was not applied for 0° wedge. Nevertheless, the higher pump power of 4.48 W for 9° wedge could be applied because about 12.5% of the pump power was reflected by the 9° wedge. Obviously, owing to the reflection loss of the wedge, the average output signal power for 9° wedge was much lower than that for 0° wedge. The maximum average signal power for 9° wedge was 72 mW, which was sufficient for many applications like optical communication. The maximum average signal output powers at different wavelengths are displayed in Table 1. In the experiment, we found that the average signal power increased with the increase of the temperature. This is because $\omega_s\omega_i$, the product of the signal and idler angular frequencies in the gain equation of OPG[10], increases with the temperature increasing. Moreover, the transmission of the signal and idler waves increases as the temperature increases. So the gain of OPG is enhanced. The highest signal conversion efficiency was 7.2% and the corresponding total conversion efficiency was 10.6%, where the average idler power was calculated by the Manley-Rowe relation[11].

Table 1. Maximum Average Signal Power at Different Wavelengths

Wavelength (nm)	Average Signal Power (mW)
1539	162
1543	239
1547	261
1551	251
1555	245
1560	274
1565	64
1570	72

In conclusion, we have demonstrated a new wavelength tuning method, the wedge-angle-tuning method, in nanosecond PPMgOLN OPG at a high repetition rate of 50 kHz. A congruent LN was placed in front of the PPMgOLN to provide three different wedges, 0°, 4°, and 9°. With the incident pump power of 3.8 W, the highest average output signal power was 274 mW for 0° wedge at 190 °C, and the corresponding total conversion efficiency was 10.6%. Owing to the reflection loss of the wedge, the largest average signal power for 9° decreased to 72 mW at 190 °C. The signal wavelength could be tuned from 1537 to 1571 nm by varying the temperature from 140 to 190 °C and changing the wedge angle from 0° to 9°. A rapid wavelength tuning over 10 nm could be achieved by only replacing the wedge angles. Although the wedge-angle tuning is discontinuous, the continuous and wider wavelength tuning can be obtained with the combination of the temperature tuning. In particular, this economical wedge-angle-tuned OPG with over 60-mW signal output power is suitable for many low-power tunable infrared applications.

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