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Low-threshold, high-efficiency, high-repetition-rate optical parametric generator based on periodically poled $LiNbO_3$*

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We report a high-repetition-rate optical parametric generator (OPG) with a periodically poled lithium niobate (PPLN) crystal pumped by an acousto-optically Q-switched CW-diode-end-pumped Nd:YVO_4 laser. For the maximum 1064nm pump power of 970mW, the maximum conversion efficiency is 32.9% under the conditions of 250°C, 1064nm pulse repetition rate of 22.6kHz and pulse width of 12ns, and the PPLN OPG threshold in the collinear case is less than 23.7μJ. The output power increases with the increase of the crystal temperature. The 1485–1553nm signal wave and 3383–3754nm idler wave are obtained by changing the temperature and the angle of the PPLN crystal.

Keywords: quasi-phase-matching, periodically poled lithium niobate, optical parametric generator
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1. Introduction

Nowadays, optical parametric oscillators (OPOs) and optical parametric generators (OPGs) are two very effective ways to obtain tunable coherent infrared sources which can be used in the areas of biology, laser remote sensing and spectrum analysis. The OPG is different from OPO due to its operation without optical resonators. So, in contrast to OPO, OPG has no difficulty of dielectric coating technique. Its cavity configuration is simpler and has a better stability. Another advantage of OPG is that it is easier to realize a coherent source with a narrow spectral width by injection seeding than with the OPO. The main limitations of OPG are the higher threshold and the lower conversion efficiency because of its nonresonant structure. However, quasi-phase-matching (QPM) [1−7] nonlinear frequency conversion based on periodically poled crystals enables these problems to be readily solved. For the QPM technique, a periodical modulation of the sign of the second-order nonlinear polarization is used to compensate for the difference of propagation vectors by a grating vector in a nonlinear crystal. Because the phase matching condition for QPM can be satisfied by the grating period irrespective of the inherent properties of the crystal, it can use the largest tensor component which allows high conversion efficiency. Periodically poled lithium niobate (PPLN) is now one of the most popular ferroelectric crystals for QPM due to its large nonlinear coefficient. PPLN OPG [8−14] can be obtained at lower threshold with higher efficiency. Bäder *et al*[8] obtained 1.63W of signal- and 0.76W of idler-radiation for the average 1064nm pump power of 6.8W (repetition rate: 10kHz) with the conversion efficiency of 35.3% by using a 29.75μm period PPLN. To our knowledge, this is the maximum conversion efficiency for high-repetition-rate nanosecond PPLN OPG, though the OPG threshold was as high as 160μJ.

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In this paper, we demonstrate the high-repetition-rate PPLN OPG pumped by a 1064nm CW-diode-pumped acousto-optically Q-switched Nd:YVO_4 laser with 12ns FWHM pulse width at 22.6kHz. The maximum conversion efficiency was 32.9% which was a little less than the experimental result of Bäder *et al.* But the measured threshold in our experiment was less than 23.7μJ. The wavelength of the OPG was tunable in the range of 1485–1553nm and 3383–3754nm by rotating a 29μm period PPLN crystal from 0° to 10° about the crystal z-axis in the x–y plane and by adjusting the PPLN crystal temperature from 80 to 250°C.

2. Theoretical analysis

We consider the quasi-phase-matched configuration conditions such that the PPLN is periodically poled along the crystal z-axis and all interacting waves are polarized parallel to the crystal z-axis too. To maximize the conversion efficiency, the phase matching condition should be satisfied:[1]

$$\Delta \boldsymbol{k} = \boldsymbol{k}_p - \boldsymbol{k}_s - \boldsymbol{k}_i - \boldsymbol{k}_m = 0, \qquad (1)$$

where $\Delta \boldsymbol{k}$ is the phase mismatch, $\boldsymbol{k}_p$, $\boldsymbol{k}_s$, $\boldsymbol{k}_i$ and $\boldsymbol{k}_m$ are the vectors of the pump wave, signal wave, idler wave and the QPM grating, respectively. In the case of collinear configuration, $k_m = 2\pi m/\Lambda$, where Λ is the grating period and m is the QPM order. In general, m is taken to be unity in order to obtain the largest effective nonlinear coefficient for QPM.

If the crystal is rotated about the z-axis for a certain angle α, $\boldsymbol{k}_p$, $\boldsymbol{k}_s$ and $\boldsymbol{k}_i$ would be noncollinear in the crystal and the noncollinear QPM would be formed. Figure 1 shows the configuration of the noncollinear PPLN OPG, where θ_s, θ_i and θ_p represent the angles between $\boldsymbol{k}_s$ and $\boldsymbol{k}_m$, $\boldsymbol{k}_i$ and $\boldsymbol{k}_m$, and $\boldsymbol{k}_p$ and $\boldsymbol{k}_m$, respectively; α is the incident angle of the pump outside the PPLN crystal, i.e. the crystal rotation angle. For a smaller α, we have $\theta_s \approx \theta_i \approx \theta_p$. Consequently, we can take the value of the grating period in the direction of $\boldsymbol{k}_p$, $\Lambda_\alpha = \Lambda/\cos(\theta_p)$, as the effective grating period of the noncollinear QPM.[4,10] In this approximation, the phase matching condition can be described as

$$\Delta k = 2\pi \left(\frac{n(\lambda_p,T)}{\lambda_p} - \frac{n(\lambda_s,T)}{\lambda_s} - \frac{n(\lambda_i,T)}{\lambda_i} - \frac{1}{\Lambda(T)} \times \sqrt{1 - \left(\frac{\sin\alpha}{n(\lambda_p,T)} \right)^2} \right) = 0, \qquad (2)$$

where λ_p, λ_s and λ_i represent respectively the wavelengths of the pump, signal and idler, $n\ (\lambda_p,T)$, $n\ (\lambda_s,T)$ and $n\ (\lambda_i,T)$ are determined by the temperature-dependent Sellmeier equations for the refraction index of PPLN,[15] $\Lambda\ (T)$ is the grating period at temperature T which is determined by the thermal expansion equation of $LiNbO_3$,[16] and $\cos(\theta_p)$ is replaced by $[1-(\sin\alpha/n(\lambda_p,T))^2]^{1/2}$ in consideration of the law of refraction. Equation (2) gives the relation between the output wavelength, the crystal temperature and the phase-matched angle of rotation for noncollinear QPM OPG including the case of collinear QPM with α=0°. For a fixed pump wavelength λ_p, grating period Λ, and crystal temperature T, the phase-matched angle for different output wavelengths can be directly calculated by using Eq.(2) and the energy conservation condition ($1/\lambda_p = 1/\lambda_s + 1/\lambda_i$).

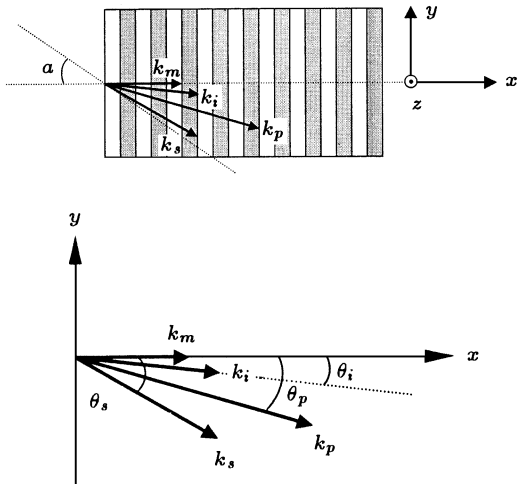


Fig.1. Schematic of the noncollinear QPM OPG with a PPLN crystal. x, y and z are the crystallographic axes, and z is the polar axis.

Obviously, continuous output wavelength tuning is available by rotating PPLN about the crystal z-axis in the x–y plane or by adjusting the PPLN crystal temperature. The differences between the two methods lie in the following aspects. Firstly, the wavelength tuning range of the angle tuning is less than that of the temperature tuning because the crystal rotation angle cannot be very large for the limitation of the transverse size of the bulk periodically poled crystal. Secondly, some additional loss would appear when the crystal is rotated for a certain angle with oblique incidence of the pump wave on the periodically poled crystal. However, in comparisons with the temperature tuning, the angle tuning allows one to construct a more rapidly tunable source for QPM OPG.

In the case of low-conversion, the single-pass power gain of a QPM parametric amplifier in a periodically poled crystal is given by [8]

$$G(L) \approx \frac{8\pi^2 d_Q^2 I_P}{n(\lambda_p)n(\lambda_s)n(\lambda_i)\lambda_s\lambda_i\varepsilon_0 c} L^2 \times \left(\frac{\sin\left(\frac{\Delta kL}{2}\right)}{\frac{\Delta kL}{2}} \right)^2 , \quad (3)$$

where $I_{\rm P}$ is the pump intensity, L is the length of the crystal, d_Q is the effective nonlinear coefficient for the QPM interaction, c is the speed of light in vacuum and ε_0 is the absolute permittivity. The central frequency of the output is determined by the condition that the gain $G(L)$ reaches the maximum value where Δk=0, and the spectral width is determined by the value of $|\Delta kL|=\pi$, where the gain $G(L)$ is $4/\pi^2$ (about 40%) of the maximum value.

3. Results of PPLN OPG

A schematic diagram of the PPLN OPG setup is shown in Fig.2.

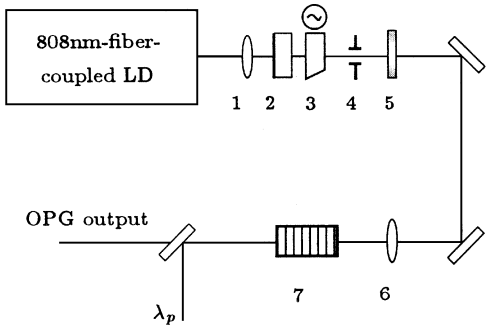


Fig.2. Schematic diagram of the PPLN OPG. 1: an 808nm coupling system; 2: the crystal of Nd:YVO_4; 3: a Q-switch; 4: an aperture; 5: the 1064nm output coupler; 6: a 1064nm coupling system; 7: the PPLN crystal and its heating oven.

The pumping source for PPLN OPG is a 1064nm acousto-optically Q-switched CW-diode-pumped Nd:YVO_4 laser. The central wavelength of the fibre-coupled CW diode is 808nm. The maximum power of the diode is 16.5W and the diameter of the output beam is 400μm with the numerical aperture of 0.22. Two lenses are used to focus the 808nm laser beam into the Nd:YVO_4 crystal, which has a size of 3mm×3mm×5mm with a Nd concentration of 0.5%. The input pump face of the crystal is antireflection coated at 808nm and coated for high reflectivity at 1064nm. The 1064nm laser output coupler is coated with a transmission of 20%. An aperture is put at the front of the output coupler in the 1064nm cavity in order to increase the diffraction loss of the cavity and obtain the lower-order mode. The Nd:YVO_4 crystal is kept at 21.2°C with water cooler and the 808nm diode laser is kept at 23.7°C with wind cooling. A coupling system focus the 1064nm pump laser to a 100μm beam radius at the centre of the PPLN crystal. In the experiment, we found that it has an evident effect on reducing the threshold and increasing the conversion efficiency for PPLN OPG to arrange the size of the aperture, as well as the location of the focus point and the PPLN crystal.

The PPLN crystal has a 29μm grating period (at room temperature) which is periodically poled along the crystal z-axis with dimensions of 50mm×5mm×1mm. Both of the end faces of the PPLN crystal are antireflection-coated at signal, idler and pump wavelengths in order to ensure the single-pass OPG process. The PPLN crystal is placed in a heating oven with the operating range from room temperature to 250°C and with a long-term stability of ±0.1°C. We adjust the temperature in the range of 80–250°C to avoid the photorefractive effect of PPLN.

A fast-response photo detector and a TEKTRONIX TDS-620B oscilloscope were used to measure the pulse width. An Agilent 86142B optical spectrum analyser was used to measure the spectrum in the range of 600–1700nm. A Molectron PM500A-2 power meter measured the pump laser and OPG output average power.

Figure 3 shows the PPLN OPG output wavelengths versus the temperature for different crystal rotation angles. The solid dots represent the experimental results, and the continuous curve is the theoretical tuning curve calculated by using Eq.(2). The measured results are in good agreement with the calculated results using Eq.(2).

We tuned the signal wavelength of the PPLN OPG from 1485 to 1541nm by adjusting the temperature from 80 to 250°C at α=0° and the corresponding idler wavelength was from 3754 to 3438nm. Under the same conditions, the 1488–1544nm signal wave and the 3739–3422nm idler wave were obtained at α=5°, and the 1491–1553nm signal wave and the 3716–3383nm idler wave were obtained at α=10°. On the other hand, the signal tuning from 1500 to 1507nm was observed by rotating the PPLN crystal from 0° to 10° about the crystal z-axis at T=140°C and the corresponding idler wavelength was from 3666 to 3621nm.

We also obtained 1520–1528nm signal wave and 3549–3507nm idler wave by rotating the PPLN crystal from 0° to 10°at T=200°C. It is obvious that the wavelength tuning range of the angle tuning is much less than that of the temperature tuning. As a result, for the QPM OPG angle tuning is suitable for the case in which higher tuning speed and smaller tuning range are needed, and temperature tuning is suitable for the case in which lower tuning speed and larger tuning range are needed.

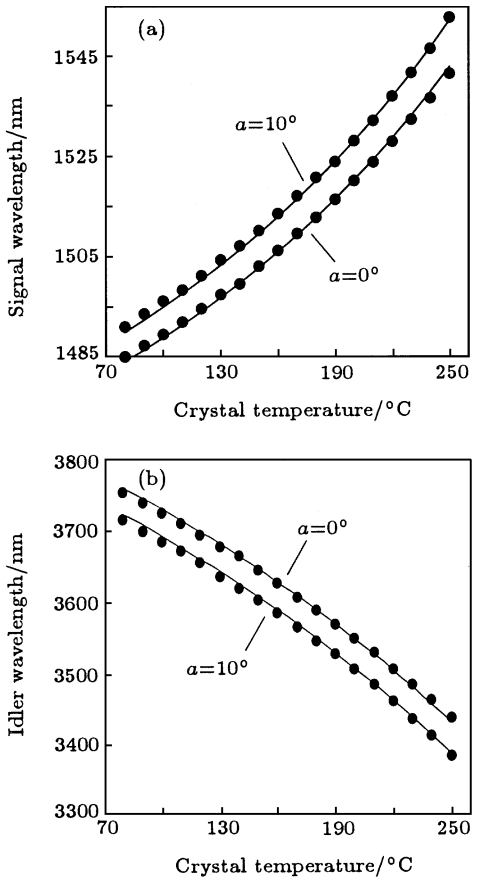


Fig.3. Temperature tuning curves for different angles of rotation of 1064nm Nd:YVO_4 laser pumped PPLN OPG. Solid dots represent the experimental results and the continuous curve is the theoretical tuning curve. In order to characterize the clearer feature, the signal tuning curve a and the idler tuning curve b are shown separately.

When measuring the OPG output power, a filter was used to reflect the residual 1064nm pump laser. Because the substrate of the filter absorbed the OPG idler wave in the range of 3–4μm, we only measured the average signal power, and then used the theoretical ratio between the power of the signal and idler wave, i.e. the ratio of the quantum energy of signal and idler photons,[8] to calculate the average idler power, as well as the average total power. Figure 4 shows the external signal, idler and total output average powers as functions of the PPLN temperature in the collinear case. With increasing temperature, the idler wavelength decreases gradually but the transmission of the idler wave increases. It may be the reason why the output power increases with increasing temperature, as shown in Fig.4.

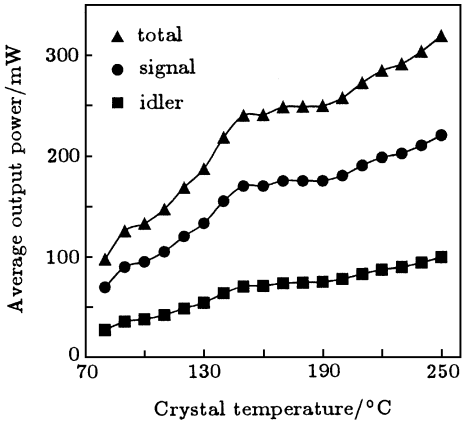


Fig.4. Average PPLN OPG output power as a function of the crystal temperature in the collinear case. The average pump power is kept at 970mW and the pump laser has a 12ns FWHM pulse width at 22.6kHz.

The PPLN OPG threshold (which is defined by the detection of an OPG output pulse energy of 0.1μJ[8]) in the collinear case was less than 535mW (23.7μJ) with an output signal wavelength of 1541nm under the conditions of 250°C, 1064nm pulse repetition rate of 22.6kHz and pulse width of 12ns. For the maximum average pump power of 970mW, the maximum average power of 1541nm was 220mW and the theoretical average idler power was 99mW with the maximum conversion efficiency 32.9%.

Figure 5 shows the signal spectrum of the PPLN OPG signal wave at 250°C in the collinear case. The experimental spectral width of the signal wave was about 1.3nm. We have calculated numerically the signal spectral width with the PPLN grating period of 29 μm and the pump wavelength of 1064nm for a 50mm long PPLN crystal at 250°C by using Eqs.(2) and (3) and $|\Delta kL|=\pi$. The theoretical spectral width of the signal wave was 1.6nm. Considering that Eq.(3) is valid for the low-conversion approximation, we thought that the measured result is consistent with the calculated value for single-pass parametric gain.

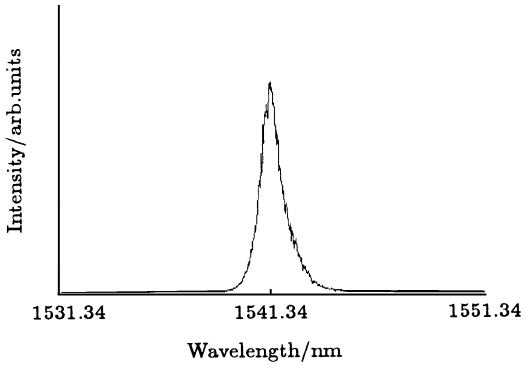


Fig.5. Spectrum of the signal wave of the PPLN OPG at 250°C in the collinear case. The average pump power is kept at 970mW and the pump laser has a 12ns FWHM pulse width at 22.6kHz.

4. Conclusion

In summary, we have demonstrated a low-threshold, high-efficiency and high-repetition-rate PPLN OPG pumped by an acousto-optically Q-switched CW-diode-end-pumped Nd:YVO_4 laser. Widely wavelength tunable outputs (1485–1553nm and 3383–3754nm) have been obtained by adjusting the temperature and by rotating the angle of the PPLN crystal, which show good agreement with our theoretical results. The output power increases with the increase of the crystal temperature. The PPLN OPG threshold in the collinear case is less than 23.7μJ under the conditions of 250°C, 1064nm pulse repetition rate of 22.6kHz and pulse width of 12ns. For the maximum 1064nm pump power of 970mW, the maximum conversion efficiency is 32.9% with the 1541nm signal spectral width of 1.3nm. We have not obtained a 1064nm laser with higher power (>1W) due to the lower energy-storing efficiency of the Q switch used in this experiment, which prevents us from obtaining higher output power and higher conversion efficiency of OPG. With the QPM technique it is now possible to realize low-threshold, high-efficiency and high-repetition-rate OPG, and our research has demonstrated this possibility in PPLN.

Acknowledgments

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