Investigation of near-collinear degenerated quasi-phase matching optical parametric amplification using PPKTP crystal

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The gain properties of near-collinear degenerated phase-matched optical parametric amplification (OPA) using PPKTP crystal are investigated theoretically. The results indicate that the type-0 phase matching of PPKTP has larger accepted angle and better gain spectrum by tuning crystal temperature or rotating crystal angle.

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In the past decade, chirped-pulse amplification (CPA)[1] has been successfully used in high-field science by achieving unprecedented peak power and focused intensity. However, there exist some defects such as large amplified stimulated emission and amplified prepulse. The optical parametric chirped-pulse amplification (OPCPA) proposed by Dubietis *et al.*[2] has many advantages, such as high gain with broad bandwidth, high signal-to-noise ratio (SNR) and small B integral, which can avoid the disadvantages of CPA. OPCPA systems have been mainly developed to replace regenerative amplifiers or multi-pass preamplifiers of CPA using nonlinear crystals LBO[3], BBO[4], and KDP[5]. Better OPA can be achieved by tuning those crystal angles. However, the small accepted angles are disadvantageous to angle tuning.

Compared with those birefringence crystals, quasi-phase matching (QPM) materials can substantially improve parametric gain properties[6−8]. Firstly, the highest effective nonlinear coefficient can be gotten through QPM technology with type-0 ($\mathrm{e}+\mathrm{e}\rightarrow\mathrm{e}$) scheme. Secondly, it eliminates the limitation of the interaction length with zero walk-off. Compared with PPLN and PPLT, PPKTP exhibits higher damage threshold, weaker photorefractive effect, and lower coercive fields which can fabricate thicker samples[9]. Therefore it is more suitable for generating higher energy in OPCPA system with proper polarized grating period to realize broad gain bandwidth. Jovanovic *et al.*[10] have measured that the accepted angle is large and the gain is not sensitive to crystal angle.

In this letter, the properties of near-collinear degenerated OPA based on PPKTP are investigated theoretically in type-0 phase matching geometry with pump pulse at 532 nm. The properties of phase-matched gain spectrum with the change of noncollinear angle are numerically simulated. When signal and pump lights collinearly propagate along x axis, the gain properties with the change of crystal angle are calculated; where the accepted angle is about ±1.85° in x-y plane and ±1.18° in x-z plane. With the change of crystal angle, the gain center is not shifted. With shorter crystal length and higher pump intensity, the accepted angle becomes larger. The gain center and the center of signal wavelength can be matched through tuning noncollinear angle, and then better gain spectrum can be realized by tuning crystal temperature or rotating crystal angle. The theoretical analysis is very useful to optimize OPCPA system.

In the condition of type-0 phase matching, all the interacting waves are polarized along z axis and propagate along x axis of the crystal in order to utilize the largest noncollinear coefficient ($d_{33} = 16.9$ pm/V) of PPKTP. The effective noncollinear coefficient is[11]

$$d_{\mathrm{eff}} = \frac{2}{m\pi} d_{33} \sin(m\pi D), \tag{1}$$

where $D = l/\Lambda$ is the duty factor, l is the length of a reversed domain and Λ is the grating period of the reversion. The effective nonlinear coefficient with quasi-phase matching is the largest for the first-order process ($m = 1$) with a 50% duty circle. In this case,

$$d_{\mathrm{eff}} = \frac{2}{\pi} d_{33}. \tag{2}$$

The grating vector is

$$k_{\mathrm{g}} = \frac{2\pi}{\Lambda}. \tag{3}$$

OPA is a typical three-wave coupled nonlinear process, conservation of energy and momentum for this process are required as

$$\begin{aligned} \hbar w_{\mathrm{p}} &= \hbar w_{\mathrm{s}} + \hbar w_{\mathrm{i}}, \\ \vec{k}_{\mathrm{p}} &= \vec{k}_{\mathrm{s}} + \vec{k}_{\mathrm{i}} + \vec{k}_{\mathrm{g}}, \end{aligned} \tag{4}$$

where p, s, and i represent pump, signal, and idler lights, respectively. For the near-collinear interaction, the angle between k_{s} and k_{p} is defined as noncollinear angle θ and the angle between k_{i} and k_{p} is defined as ϕ, as shown in Fig. 1. The fundamental expressions in phase matching condition for the noncollinear three-wave mixing can be derived easily as

$$\begin{aligned} &1/\lambda_{\mathrm{p}} = 1/\lambda_{\mathrm{s}} + 1/\lambda_{\mathrm{i}}, \\ &k_{\mathrm{p}} = k_{\mathrm{g}} + k_{\mathrm{s}} \cos\theta + k_{\mathrm{i}} \cos\varphi, \\ &k_{\mathrm{s}} \sin\theta = k_{\mathrm{i}} \sin\varphi, \end{aligned} \tag{5}$$

$$\text{and} \quad k_{\mathrm{g}} = k_{\mathrm{p}} - k_{\mathrm{s}} \cos\theta - \sqrt{k_{\mathrm{i}}^2 - k_{\mathrm{s}}^2 \sin^2\theta}. \tag{6}$$

According to the Sellmeier equations[12,13] of KTP crystal and Eq. (6), a cluster of phase matching curves with different noncollinear angles are plotted in Fig. 2, with pump pulse at 532 nm. From Fig. 2(a), the smaller the noncollinear angle, the larger the phase-matched grating period Λ becomes. It is common that there has an inflexion near 1064 nm. Therefore there exists a broad OPA near 1064 nm. At a fixed grating period ($\Lambda = 8.94$ μm), with the different noncollinear angles, the phase-matched signal wavelength dependent on temperature is shown in Fig. 2(b). When the noncollinear angle becomes larger, the phase-matched temperature corresponding to signal wavelength decreases. And there also exists inflexion near 1064 nm where broad gain spectrum of OPA exists.

For a broad gain bandwidth in OPCPA system, gain spectrum of signal is very important; the properties of gain spectrum we got are very useful to optimize OPA. Here we discuss the gain spectrum in near-degenerated and near-collinear geometries. The parameters used in following simulation are given here. The pump intensity at 532 nm is 40 MW/cm^2 and a 10-mm-long PPKTP is used.

For the mismatching of wave vectors, the mismatching in the direction which is perpendicular to k_p can be neglected due to smaller noncollinear angle. We just consider the mismatching in the direction of k_p as

$$\Delta k = \left|\Delta \vec{k}\right| \approx 2\pi\left(\frac{n_p}{\lambda_p} - \frac{n_s}{\lambda_s}\cos\theta - \frac{n_i}{\lambda_i}\cos\varphi - \frac{1}{\Lambda}\right). \quad (7)$$

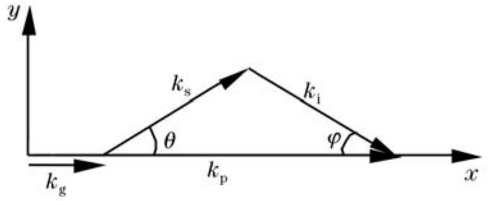

Fig. 1. Geometry of the noncollinear phase matching in x-y plane.

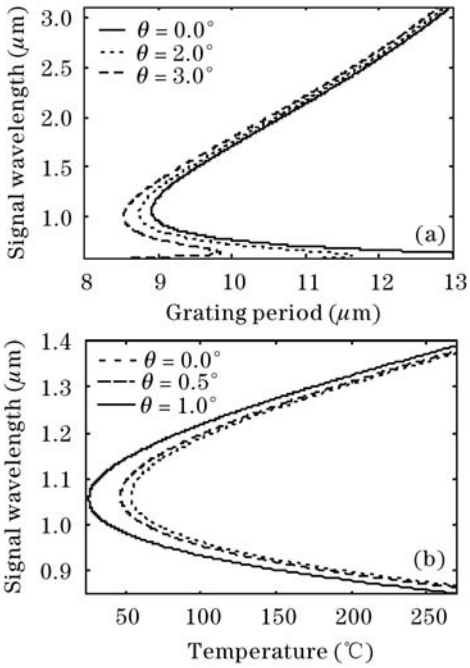

Fig. 2. Phase matching curves with different noncollinear angles ($\lambda_p = 532$ nm). (a) Dependence of signal wavelength on grating period ($T = 53.7$ °C); (b) dependence of signal wavelength on crystal temperature ($\Lambda = 8.94$ μm).

The gain intensity of the amplified signal beam can be obtained by using analytical solution of the coupled wave equations in the slowly varying envelope approximation, assuming no significant pump depletion. The group-velocity mismatching can be neglected in the case that pulse durations of interacting waves are of nanoseconds. The gain intensity G is given by[14]

$$G = 1 + (\xi L)^2(\sinh B/B)^2, \quad (8)$$

where $\xi = 4\pi d_{\mathrm{eff}}\sqrt{I_p/2\varepsilon_0 n_p n_s n_i c\lambda_s\lambda_i}$, $B = \sqrt{(\xi L)^2 - (\Delta k L/2)^2}$, and L is the crystal length, ξ is the effective gain coefficient, d_{eff} is the effective nonlinear coefficient, and I_p is the pump intensity. Based on above expressions, we give dependence of phase-matching gain bandwidth and gain spectrum upon the noncollinear angle as shown in Fig. 3. And the gain bandwidth and gain spectrum with the change of temperature are shown in Fig. 4.

The phase-matched gain bandwidth and gain spectrum with the change of noncollinear angle are shown in Fig. 3, with $T = 53.7$ °C. When the noncollinear angle is 2.0°, there exists the broadest gain bandwidth (81.2 nm). When the noncollinear angle is smaller than 2.0°, the gain bandwidth increases slowly, the gain center shifts to longer wavelength. When the noncollinear angle is larger than 2.0°, the gain bandwidth decreases rapidly, the gain center shifts to shorter wavelength, and the gain center is more concave.

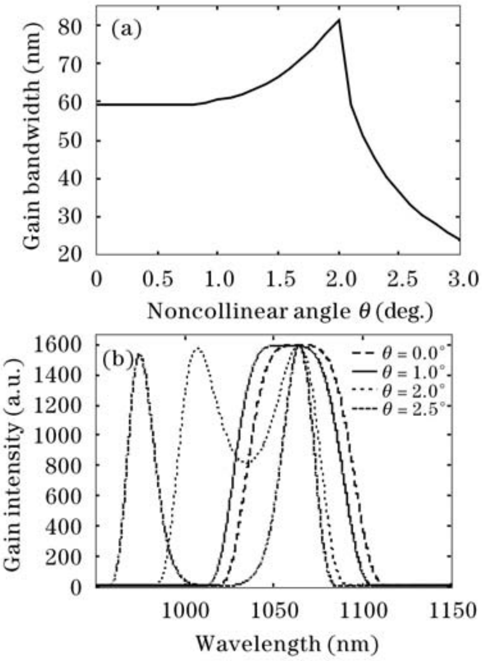

Fig. 3. OPA in phase matching condition at $T = 53.7$ °C. (a) Dependence of gain bandwidth upon noncollinear angle θ; (b) gain spectrum at given noncollinear angle θ.

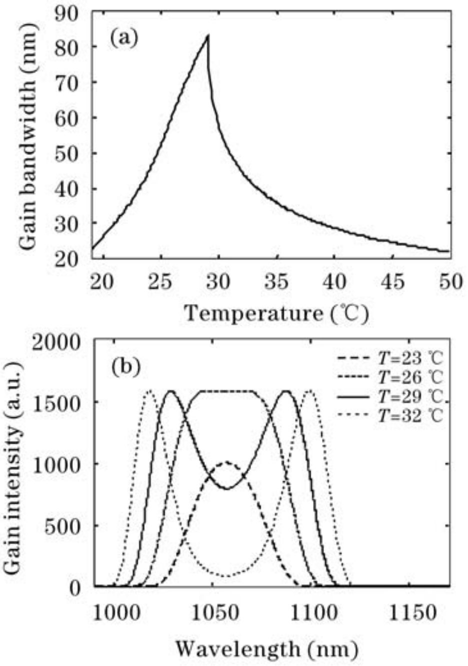

Fig. 4. OPA with $\Lambda = 8.94$ μm and $\theta = 1.0°$. (a) Dependence of gain bandwidth upon temperature; (b) gain spectrum at given temperature.

The gain bandwidth and gain spectrum with the change of temperature are shown in Fig. 4, with $\Lambda = 8.94$ μm and $\theta = 1.0°$. When the temperature is 29.0 °C, the broadest gain bandwidth can be gotten (81.7 nm). When the temperature is below 29.0 °C, the gain bandwidth and gain intensity become small. When the temperature is above 29.0 °C, the gain center dips more and even results in splitting of the OPA spectrum, the gain bandwidth becomes small. But the wavelength of gain center is constant. OPA of PPKTP is very sensitive to temperature and it is advantageous to temperature tuning. Therefore we can get wanted gain center by changing noncollinear angle and better gain spectrum through tuning temperature.

In practice, the accepted angle of crystal is a primary factor for OPA. Birefringence crystals such as BBO usually have smaller accepted angle which is disadvantageous to tuning OPA. The gain spectrum of QPM crystal can also be tuned by changing crystal angle. Here we calculate the gain properties with the change of crystal angle, where the signal and pump pulse are collinear. The gain spectrum is calculated using Eq. (8), with the different noncollinear angles between pump pulse and x axis. When the gain intensity reaches the half of phase-matched gain intensity, the deviated angle is defined as accepted angle.

Suppose that the signal at 1064 nm and pump pulse propagate along x axis under QPM with $T = 53.7$ °C and $\Lambda = 8.94$ μm. The wave vectors relationship is shown in Fig. 5, the noncollinear angle β between pump pulse and x axis is defined as crystal angle, and the angle between idler pulse and x axis is defined as γ, where the crystal angle is changed in x-y plane or x-z plane, respectively.

In x-y plane, the mismatching is derived,

$$\Delta k = k_{\mathrm{p}} - k_{\mathrm{s}} - k_{\mathrm{g}} \cos\beta - k_{\mathrm{i}} \cos\gamma. \qquad (9)$$

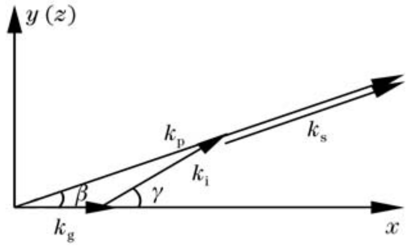

Fig. 5. Geometry of the collinear OPA after rotating crystal angle in x-y plane or in x-z plane.

In x-z plane, vector k_{i} is supposed collinearly with the phase-matched vector k_{io}. The refractive indices of pump and signal are

$$n_{\mathrm{p}} = \sqrt{\frac{1}{\frac{\cos^2\beta}{n_{\mathrm{op}}^2} + \frac{\sin^2\beta}{n_{\mathrm{ep}}^2}}}, \quad n_{\mathrm{s}} = \sqrt{\frac{1}{\frac{\cos^2\beta}{n_{\mathrm{os}}^2} + \frac{\sin^2\beta}{n_{\mathrm{es}}^2}}}, \qquad (10)$$

where the subscripts o and e refer to o-light and e-light.

According to the demand of QPM, we can get

$$k_{\mathrm{io}} = \sqrt{(k_{\mathrm{p}} - k_{\mathrm{s}})^2 + k_{\mathrm{g}}^2 - 2(k_{\mathrm{p}} - k_{\mathrm{s}})k_{\mathrm{g}} \cos\beta}, \qquad (11)$$

$$\gamma = \sin^{-1}\left(\frac{(k_{\mathrm{p}} - k_{\mathrm{s}})\sin\beta}{k_{\mathrm{io}}}\right), \qquad (12)$$

$$n_{\mathrm{i}} = \sqrt{\frac{1}{\frac{\cos^2\gamma}{n_{\mathrm{oi}}^2} + \frac{\sin^2\gamma}{n_{\mathrm{ei}}^2}}}. \qquad (13)$$

Therefore, the mismatching is derived as[15]

$$\Delta k = k_{\mathrm{io}} - k_{\mathrm{i}} = k_{\mathrm{io}} - \frac{2\pi n_{\mathrm{i}}}{\lambda_{\mathrm{i}}}. \qquad (14)$$

From Eqs. (8), (9), and (14), the accepted angle and the gain spectrum following the change of crystal angle β in x-y plane and in x-z plane are shown in Fig. 6, respectively.

As shown in Fig. 6(a), the accepted angle is ±1.85° in x-y plane and ±1.18° in x-z plane. The accepted angle is symmetrical and larger, which is advantageous to OPA. As the noncollinear angle β becomes large, the gain center dips more and even splits into two parts. But the gain center does not shift at the same time. When the crystal angle is ±1.85° in x-y plane (±1.18° in x-z plane), the gain intensity is half of the phase-matched gain intensity as shown in Fig. 6(b1) and (b2). From Fig. 6(c), the accepted angle becomes small when the crystal length increases with fixed pump intensity. From Fig. 6(d), the accepted angle becomes large when the pump intensity increases with fixed crystal length. And the accepted angle in x-y plane is always larger than that in x-z plane. Therefore, the larger accepted angle can be realized by properly decreasing crystal length or increasing pump intensity. For larger accepted angle, it is beneficial to angle tuning.

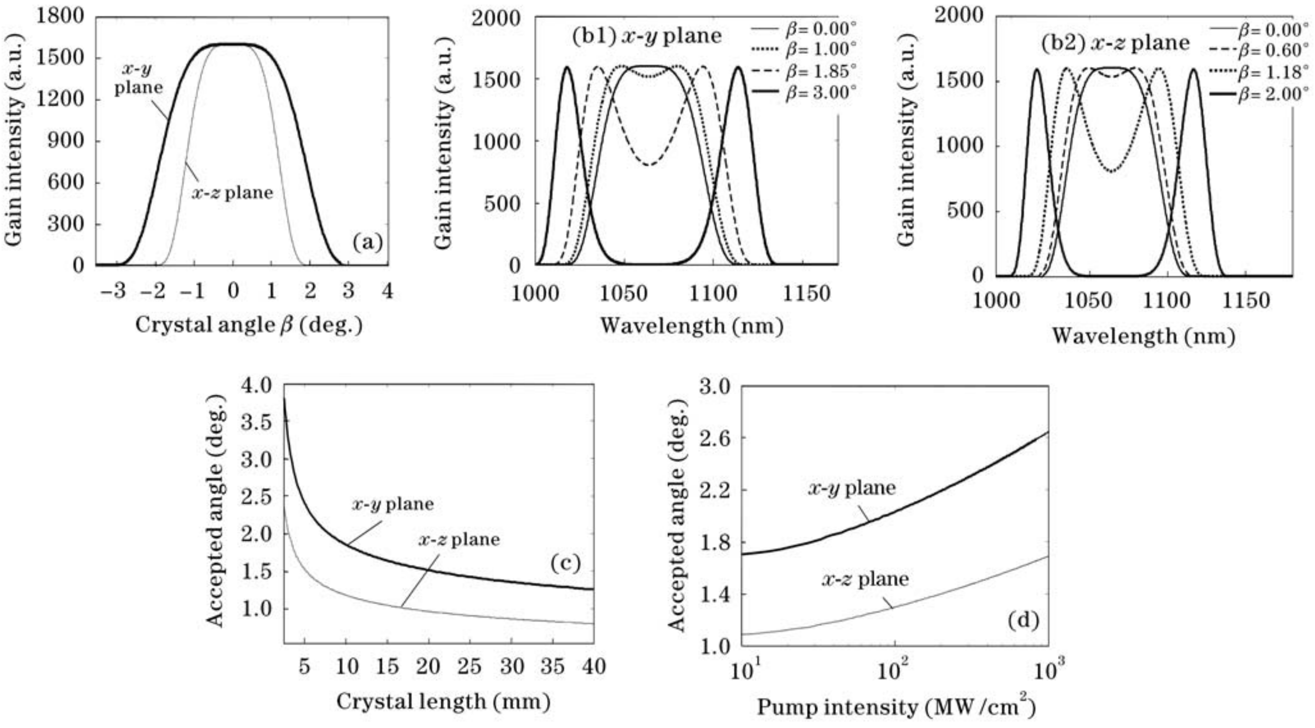

Fig. 6. Accepted angle and gain spectrum in x-y plane and x-z plane, with $T = 53.7$ °C and $\Lambda = 8.94$ μm. (a) Dependence of the gain intensity upon of crystal angle β at 1064 nm; (b1) the gain spectrum with different crystal angles β in x-y plane; (b2) the gain spectrum with different crystal angles β in x-z plane; (c) dependence of accepted angle upon crystal length with pump intensity of 40 MW/cm^2; (d) dependence of accepted angle upon pump intensity with $L = 10.0$ mm.

In summary the properties of near-degenerated OPA based on PPKTP are investigated theoretically, in type-0 phase matching geometry with pump pulse at 532 nm, under collinear and near-collinear conditions. PPKTP has larger accepted angle in x-y plane and x-z plane; it is advantageous to get better gain spectrum through rotating crystal angle. With the shorter crystal length and more intensity of pump pulse, the accepted angle becomes larger. The gain center and the center of signal wavelength can be realized through tuning noncollinear angle, and then better gain spectrum can be realized by tuning crystal temperature and rotating crystal angle. It is very useful to broaden gain of OPCPA.

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References

1. D.Strickland and G. Mourou, Opt. Commun. **56,** 219 (1985).
2. A. Dubietis, G. Jonuauskas, and A. Piskarskas, Opt. Commun. **88,** 437 (1992).
3. X. Yang, Z.-Z. Xu, Y.-X. Leng, H.-H. Lu, L.-H. Lin, Z.-Q. Zhang, R.-X. Li, W.-Q. Zhang, D.-J. Yin, and B. Tang, Opt. Lett. **27,** 1135 (2002).
4. I. Jovanovic, C. A. Ebbers, and C. P. J. Barty, Opt. Lett. **27,** 1622 (2002).
5. Z. Xu, X. Yang, Y. Leng, H. Lu, L. Lin, Z. Zhang, R. Li, W. Zhang, D. Yin, S. Jin, J. Peng, B. Tang, and B. Zhao, Chin. Opt. Lett. **1,** 24(2003).
6. A. Piskarskas, V. Smilgevicius, A. Stabinis, V. Jarutis, V. Pasiskevicius, S. Wang, J. Tellefsen, and F. Laurell, Opt. Lett. **24,** 1053(1999).
7. A. Galvanauskas, A. Hariharan, D. Harter, M. A. Arbore, and M. M. Fejer, Opt. Lett. **23,** 210 (1998).
8. A. Fragemann, V. Pasiskevicius, G. Karlsson, and F. Laurell, Opt. Exp. **11,** 1297 (2003).
9. J. Hellstrm, V. Pasiskevicius, H. Karlsson, and F. Laurell, Opt. Lett. **25,** 174 (2000).
10. I. Jovanovic, J. R. Schmidt, and C. A. Ebbers, Appl. Phy. Lett. **83,** 4125 (2003).
11. M. M. Fejer, G. A. Magel, D. H. Jundt, and R. L. Byer, IEEE J. Quantum. Electron. **28,** 2631 (1992).
12. W. Wiechmann, S. Kubota, T. Fukui, and H. Masuda, Opt. Lett. **18,** 1208 (1993).
13. T. Y. Fan, C. E. Huang, B. Q. Hu, R. C. Eckardt, Y. X. Fan, R. L. Byer, and R. S. Feigelson, Appl. Opt. **26,** 2390 (1987).
14. I. N. Ross, P. Matousek, M. Towrie, A. J. Langley, and J. L. Collier, Opt. Commun. **144,** 125 (1997).
15. X. Yang, Z. Xu, Z. Zhang, Y. Leng, J. Peng, J. Wang, S. Jin, W. Zhang, and R. Li, Appl. Phys. B **73,** 219 (2001).