Angular spectrum characters of high gain non-critical phase match optical parametric oscillators

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The angular spectrum gain characters and the power magnification characters of high gain non-walk-off colinear optical parametric oscillators have been studied using the non-colinear phase match method for the first time. The experimental results of the $KTiOAsO_4$ and the $KTiOPO_4$ crystals are discussed in detail. At the high energy single resonant condition, low reflective ratio of the output mirror for the signal and long non-linear crystal are beneficial for small divergence angles. This method can also be used for other high gain non-walk-off phase match optical parametric processes.

Keywords: optical parametric oscillator, non-critical phase match, angular spectrum, divergence angle

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1. Introduction

Optical parametric oscillator (OPO) is an important way to obtain the lasers with the wavelength of 1.5–1.6 μm and 3–5 μm, which attracts much attention and interest in the fields of remote sensing, radar systems and optical-electronic countering.[1,2] The $KTiOAsO_4$ (KTA) and the $KTiOPO_4$ (KTP) are two of the main non-linear crystals working at high gain condition to obtain high energy parametric waves and are usually used for their non-critical phase match for non-walk-off and large effective nonlinear coefficient.[3−6]

The temperature characters and the acceptance angles have been analyzed by many people,[7−9] while none of them gave the models for the angular spectrum. As the divergence angle is an important parameter for judging the beam quality, it is necessary to study the angular spectrum characters of optical parametric oscillators.

In optical parametric oscillators, the divergence angles of the parametric waves are usually worse than that of the pump,[7] and the parametric waves with smaller divergence angles can be achieved by the OPO+OPA (optical parametric amplifier) method or by the unstable resonators.[8] In 2003, Anstett *et al.* numerically simulated the optical parametric oscillators.[9] However, none of them put forward the models of angular spectrum characters to the parametric waves.

This work, to the best of our knowledge, for the first time, studies the angular spectrum gain characters and the power magnification characters for high gain non-walk-off colinear optical parametric oscillators with the method of non-colinear phase match. Two conceptions, the gain angle width (GAW) and the power magnification angle width (PMAW), are introduced to describe the angle spectrum characters. Comparing the experimental results of the KTA and the KTP crystals with the theoretical ones, we find that they match in general.

2. Theory model

When the divergence angles of the parametric waves are not zero, the three waves couple at the non-colinear condition and the wave vectors match as shown in Fig. 1. The coupled equations for plane waves are[10−13]

$$\begin{aligned}
&\frac{\partial A_{\rm s}}{\partial z}+\frac{\alpha_{\rm s}}{\cos\alpha}A_{\rm s}={\rm i}\,\frac{N_{\rm s}}{\cos\alpha}A_{\rm i}^{*}A_{\rm p}{\rm e}^{{\rm i}\,\Delta kz},\\
&\frac{\partial A_{\rm i}}{\partial z}+\frac{\alpha_{\rm i}}{\cos\beta}A_{\rm i}={\rm i}\,\frac{N_{\rm i}}{\cos\beta}A_{\rm s}^{*}A_{\rm p}{\rm e}^{{\rm i}\,\Delta kz},\\
&\frac{\partial A_{\rm p}}{\partial z}+\alpha_{\rm p}A_{\rm p}={\rm i}\,N_{\rm p}A_{\rm s}A_{\rm i}{\rm e}^{-{\rm i}\,\Delta kz},
\end{aligned}\tag{1}$$

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where N_j (j= p, s, i) is the interaction coefficient, α_j (j= p, s, i) is the absorption coefficient of the nonlinear medium, Δk is the phase mismatch along z direction, A_j (j=p, s, i) is the amplitude of the pump, the signal and the idler, α is the divergence angle of the signal and β is the divergence angle of the idler.

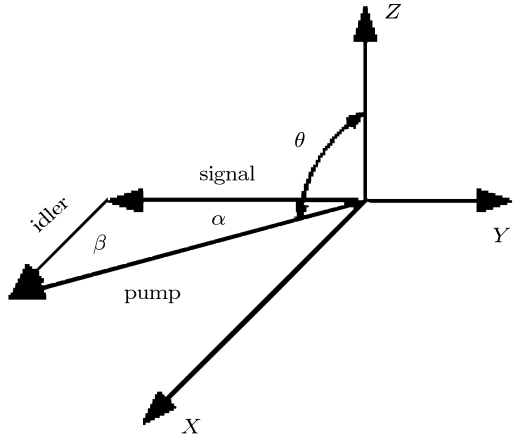


Fig. 1. Vectors for non-colinear phase match.

The gain coefficient is

$$g = \sqrt{\frac{8\pi^2 d_{\rm eff}^2}{n_{\rm p} n_{\rm s} n_{\rm i} \lambda_{\rm s} \lambda_{\rm i} c\varepsilon_0 \cos\alpha \cos\beta} I_{\rm p} - (\Delta k/2)^2}, \quad (2)$$

where $d_{\rm eff}$ is the effective nonlinear coefficient, $I_{\rm p}$ is the power density of the pump, n_j (j=p, s, i) is the refractive index of the pump, the signal and the idler, λ_j (j=s, i) is the refractive index of the signal and the idler, c is the speed of light in the vacuum, q_0 is the dielectric function of the vacuum.

Taking the X-cut KTP crystal (used in many OPOs) as an example, we consider the X–Z plane. The X–Y plane has the same conclusion with a similar deduction. So do the X-cut KTA and the Y-cut KTA.

For the X-cut KTP crystal, the phase match form in the X–Z plane is like that in the positive uniaxial crystals. The pump wave and the signal light are polarized along the Y-axes and the idler wave is in the X–Z plane.

The refractive indexes of the pump and the signal are related to the wavelength. For the pump and the signal, when the divergence angle of the signal changes, the wavelength and the refractive indexes remain nearly the same, the idler wavelength and the idler refractive index can be obtained by

$$\lambda_{\rm i} = (\lambda_{\rm p}^{-1} - \lambda_{\rm s}^{-1})^{-1},$$

$$n_{\rm i} = \left[\left(\frac{\sin\theta}{n_z}\right)^2 + \left(\frac{\cos\theta}{n_x}\right)^2\right]^{-1/2}, \quad (3)$$

where $\theta = 90^\circ + \beta$.

When $\alpha = 0$, the three waves satisfy the phase match conditions. The phase mismatch along z direction is

$$\Delta k = \frac{2\pi n_{\rm p}}{\lambda_{\rm p}} - \frac{2\pi n_{\rm s}}{\lambda_{\rm s}} \cos\alpha - \frac{2\pi n_{\rm i}}{\lambda_{\rm i}} \cos\beta. \quad (4)$$

If $2\pi n_{\rm p}/\lambda_{\rm p} - 2\pi n_{\rm s}/\lambda_{\rm s} - 2\pi n_{\rm i}/\lambda_{\rm i} = 0$, then

$$\Delta k = \frac{2\pi n_{\rm s}}{\lambda_{\rm s}}(1 - \cos\alpha) + \frac{2\pi n_{\rm i}}{\lambda_{\rm i}}(1 - \cos\beta) \geq 0, \quad (5)$$

$$\left|\frac{\partial \Delta k}{\partial \beta}\right| = \left|\frac{2\pi}{\lambda_{\rm i}} \sin\beta \left[\cos^2\beta (n_x^{-2} - n_z^{-2}) + n_{\rm i}\right]\right| \geq 0. \quad (6)$$

During the process of the three waves coupling, the efficiency achieves the highest value when the phase mismatch along z direction is the lowest, which requires $\beta = 0$. And the gain coefficient for the signal is

$$g = \sqrt{\frac{8\pi^2 d_{\rm eff}^2}{n_{\rm p} n_{\rm s} n_{\rm i} \lambda_{\rm s} \lambda_{\rm i} c\varepsilon_0 \cos\alpha} I_{\rm p} - \left[\frac{\pi n_{\rm s}}{\lambda_{\rm s}}(1 - \cos\alpha)\right]^2}. \quad (7)$$

The gain coefficient for the idler is

$$g = \sqrt{\frac{8\pi^2 d_{\rm eff}^2}{n_{\rm p} n_{\rm s} n_{\rm i} \lambda_{\rm s} \lambda_{\rm i} c\varepsilon_0 \cos\beta} I_{\rm p} - \left[\frac{\pi n_{\rm i}}{\lambda_{\rm i}}(1 - \cos\beta)\right]^2}. \quad (8)$$

With the small signal gain condition, $\partial A_{\rm p}/\partial z \approx 0$, and when $A_{\rm i}(0) = 0$, the power magnification of the signal wave with divergence angle of α is

$$G(\alpha) = \left|\frac{A_{\rm s}(l)}{A_{\rm s}(0)}\right|^2 = {\rm e}^{-\frac{2\alpha_{\rm s} l}{\cos\alpha}} \left[\cosh^2(gl) + \left(\frac{\Delta k}{2g}\right)^2 \sinh^2(gl)\right], \quad (9)$$

where l is the length of the crystal. The power magnification of the idler with divergence angle of β is

$$G(\beta) = \left|\frac{A_{\rm i}(l)}{A_{\rm s}(0)}\right|^2 = {\rm e}^{-\frac{2\alpha_{\rm i} l}{\cos\beta}} \left(\frac{N_{\rm i} A_{\rm p}}{g\cos\beta}\right)^2 \sinh^2(gl). \quad (10)$$

The gain angle width (GAW) is defined as the divergence angle range when the gain coefficient exceeds half of the maximum and the power magnification angle width (PMAW) is defined as the divergence angle range when the power magnification exceeds half of the maximum. The GAW is the inherent character of a certain phase match type with a certain type of crystal and pump source. The divergence angles of the output parametric waves are mainly determined by the PMAWs.

3. Experiment

For the three-wave-coupled equations used at the plane wave condition, the nominally flat-topped pump source was chosen for the OPO. The pump wavelength was 1064 nm and the non-linear crystals were Y-cut KTA and X-cut KTP. The OPO was designed as a plane–plane single resonant oscillator to minimize the cavity's contribution to the divergence angle. The cavity length was 30 mm (Fig. 2). The crystal lengths of both KTA and KTP were 20 mm to reduce the back conversion in the OPO. Both ends of each crystal were anti-reflection coated for 1.064 μm, 1.5–1.6 μm and 3–5 μm. The input mirror of the OPO was high transparent (HT) for 1.064 μm and high reflective (HR) for 1.5–1.6 μm, while the output mirror was HR for 1.064 μm and HT for 3–5 μm. The transmission for the signal was $T = 0.3$ for the KTA OPO and $T = 0.2$ for the KTP OPO.

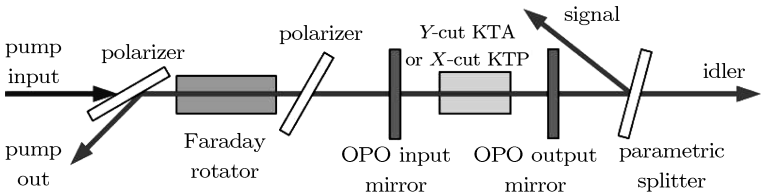


Fig. 2. Experimental scheme of the Y-cut KTA / X-cut KTP OPO.

For the Y-cut KTA crystal, the pump pulse was 10 ns in width with a diameter of 10 mm, a pump pulse energy of 1 J and a pump divergence angle of less than 1 mrad. While for the X-cut KTP crystal, the pump pulse was 13.5 ns in width with a diameter of 4 mm, a pump pulse energy of 102 mJ and a pump divergence angle of less than 2 mrad.

4. Results and analysis

For the Y-cut KTA crystal, the idler divergence angle was nearly 34 mrad in the experiment. The calculated PMAW is 20 mrad, which is near the experimental one. The beam radius of the idler wave as a function of the transfer distance is shown in Fig. 3.

For the X-cut KTP crystal, the signal divergence angle is 11.2 mrad which is in better agreement with the theory result of 13.6 mrad.

In the experiments, the distribution of the pump energy was not strictly flat-topped (especially there were bright uneven spots in the beam spot), which made the experimental results not match the theory very well.

Webb and Moulton[5] gave the results for the X-cut KTA crystal. The signal divergence angle was 7.3 mrad [$\theta \approx 4M^2\lambda/(\pi D)$] under a low energy and long pulse duration laser pumping and was 10 mrad under a high energy and short pulse duration laser pumping. The theoretical results obtained by our model are 7.8 mrad and 8.4 mrad, respectively.

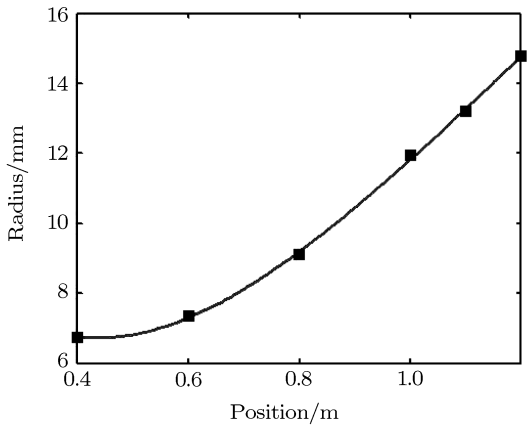


Fig. 3. The beam radius of the idler wave as a function of the transfer distance for the Y-cut KTA. The idler divergence angle is 34 mrad.

In both our and Webb's experiments, the high energy high gain pumps were used, so the divergence angles of the parametric waves were higher than the numerical results given by the SNLO software. The wide GAW expresses that the parametric wave with large divergence angle can be magnified more easily. The GAW is related to the pump conditions and the nonlinear crystal characters. If the pump pulse is 10 ns in width, with the wavelength of 1064 nm and the diameter of 10 mm and the pump reaches the peak power,

the gain coefficient for the Y-cut KTA is shown in Fig. 4 according to our theory.

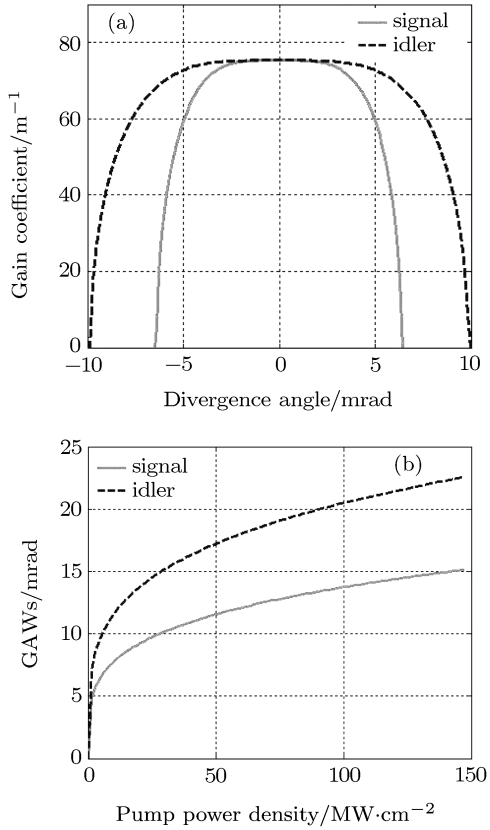


Fig. 4. The gain coefficient and the gain angle width for the Y-cut KTA. (a) Gain coefficient versus divergence angle, (b) GAWs versus pump power density.

At the same pump condition, the signal divergence angle is smaller than the idler one and both are bigger than the pump one. The main effective range of gain is the angles within the GAW, while the gain coefficient decreases sharply out of the range. The GAW is proportional to the square root of the pump power density. When the pump works around the threshold, the GAW is small and the divergence angles of the parametric waves are determined mainly by the pump beam quality and the cavity type. When the pump power density is high enough, the effects of the gain on the divergence angles become obvious, which occurred in our and Webb's experiments.

The divergence angles of the output parametric waves are mainly determined by the PMAW, which is related by the gain coefficient and the crystal length. The normalized power magnifications according to our theory are shown in Fig. 5. The length of the X-cut KTA are 10, 20, 40 and 80 mm, respectively and the pump pulse is 10 ns in width, with the wavelength of 1064 nm and the diameter of 10 mm.

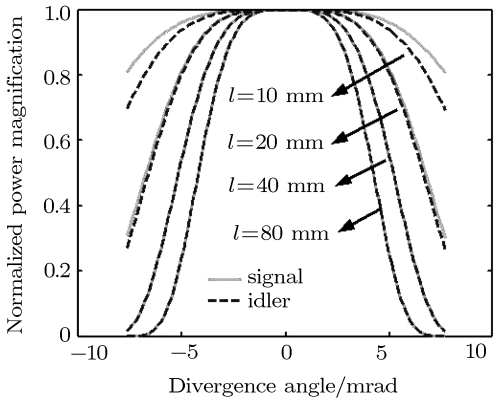


Fig. 5. Normalized power magnification versus divergence angle for the X-cut KTA.

When the crystal length is longer, the PMAW becomes smaller and so do the divergence angles of the parametric lights. In Webb's experiment, the effective gain length of the crystal was 80 mm, which was beneficial to the small divergence angles of the signal waves.

In optical parametric oscillators, the optimal crystal lengthes are related to the cavity parameters and the large optimal length of the crystal is favorable for parametric waves with small divergence angles. Low reflective ratio of the output mirror results in a large number of oscillations for the signal, which works like long crystal length and is helpful for reducing the divergence angles of the parametric waves. In the experiments, the optimum crystal length was designed to reduce the back conversion and to improve the convention efficiency and the optimum length was estimated by the method in Ref. [14].

We will explain the critical phase-match and why the divergence angle in the phase-match plane is smaller than that perpendicular to the plane[15,16] in future work.

5. Conclusion

The angular spectrum characters of high gain non-walk-off colinear optical parametric oscillators are studied with the method of non-colinear phase match and the gain characters and the power magnification characters are analyzed. The experimental results match the theoretical ones.

References

[1] Koechner W 1999 *Solid-State Laser Engineering* (5th ed) (Berlin: springer-Verlag)

[2] Vodopyanov K 2003 *Solid-State Mid-Infrared Laser Sources* (Berlin / Heidelberg: Springer-Verlag) p. 144

[3] Zhang B T, Dong X L, He J L, Huang H T, Yang K J, Zuo C H, Xu J L and Zhao S 2008 *Laser Phys. Lett.* **5** 869

[4] Liu F Q, Xia H R, Zhong Y, Sun S Q, Ling Z C, Ran D G, Gao W L, He J L, Zhang H J and Wang J Y 2008 *Laser Phys. Lett.* **5** 585

[5] Webb M S and Moulton P F 1998 *Opt. Lett.* **23** 1161

[6] Rines G A, Rhes D M and Moulton P F 1994 *OSA Proceedings on Advanced Solid-State lasers* **20** 461

[7] Anstett G, Borsutzky A and Wallenstein R 2003 *Appl. Phys.* **76** 541

[8] Debuisschert T, Mathieu D, Raffy J, Becouarn L, Lallier E and Pocholle J P 1998 *Proc. SPIE* **3267** 157

[9] Anstett G, Nittmann M, Borsutzky A and Wallenstein R 2003 *Appl. Phys.* B **76** 833

[10] Gong M, Zou S, Chen G, Yan P, Liu Q and Huang L 2004 *Opt. Express* **12** 2932

[11] Dou S X, Josse D and Zyss J 1992 *J. Opt. Soc. Am.* B **9** 1312

[12] Jiang X, Wei F and Zhang Y 2000 *Acta Phys. Sin.* **49** 256 (in Chinese)

[13] Zheng J and Zacharias H 2009 *Appl. Phys.* B **97** 765

[14] Liu J, Liu Q and Gong M 2010 *Opt. Commun.* **283** 3773

[15] Yao B,Wang Y, Liu Q and Wang Q 2001 *Chin. J. Lasers* **28** 693 (in Chinese)

[16] Arisholm G, Nordseth Φ and Rustad G 2004 *Opt. Express* **12** 4189