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# 非共线准相位匹配周期极化 RbTiOAsO<sub>4</sub> 的增益带宽\*

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**摘要:**研究了非共线准相位匹配过程中, 周期极化 RbTiOAsO<sub>4</sub> 晶体同时满足准相位匹配和群速匹配条件的非共线角和相应的极化周期随信号光波长的变化. 分析了满足群速匹配条件时, 非共线准相位匹配的调谐特性. 数值模拟了增益带宽随非共线角、晶体温度和极化周期的变化关系. 对比了群速匹配和最大增益带宽情况下, 周期极化 RbTiOAsO<sub>4</sub> 晶体增益带宽与晶体温度之间的关系.

**关键词:**非共线准相位匹配; 群速匹配; 增益带宽; 周期极化 RbTiOAsO<sub>4</sub>

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## 0 引言

超短脉冲在产生高功率、高强度激光脉冲方面引起越来越多的注意, 而群速失配是限制不同频率成分的脉冲在晶体材料中耦合的一个重要问题, 采用非共线相位匹配成为同时满足相位匹配和群速匹配的一种重要方式<sup>[1-2]</sup>. 相对于双折射相位匹配来说, 准相位匹配可以利用最大的极化张量  $d_{33}$ , 并且原则上可以通过设计极化周期使整个通光波段实现相位匹配<sup>[4-6]</sup>. 基于周期极化 LiNbO<sub>3</sub> (PPLN)、周期极化 KTiOPO<sub>4</sub> (PPKTP) 等周期极化材料的光参量过程获得了广泛的关注<sup>[7-14]</sup>. 相对于 PPLN、PPKTP 等, 周期极化 RbTiOAsO<sub>4</sub> (PPRTA) 晶体的特点为: 极化电压翻转电压低, 可以制作厚度为 3 mm 的大尺寸极化晶体; 电导率低, 有利于生成均匀的极化周期; 抗损伤阈值高; 可以在室温下运转. 此外, PPRTA 晶体的红外透光波段可达 5.3 μm (PPKTP, 4.4 μm), 并且不存在 3.5 μm 处的吸收效应, 因而 PPRTA 晶体比 PPKTP 晶体更加适合 3~5 μm 段的非线性频率变换<sup>[15]</sup>. 本文研究了基于 PPRTA 晶体的非共线光参量准相位匹配 (Quasi Phase Matching, QPM) 过程, 并通过设计合适的非共线角和极化周期使其同时满足 QPM 和群速匹配 (Group Velocity Matching, GVM), 同时研

究了增益带宽和晶体的极化周期、温度、非共线角之间的关系, 指出同时满足 QPM 和 GVM 可以提高波长调谐带宽和温度调谐带宽.

## 1 理论分析

非共线光参量过程必须满足的能量和动量守恒关系式为

$$\frac{1}{\lambda_p} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i} \quad (1)$$

$$\frac{n_p(\lambda_p, T)}{\lambda_p} = \frac{1}{\Lambda(T)} \cos \theta + \frac{n_s(\lambda_s, T)}{\lambda_s} \cos \alpha + \frac{n_i(\lambda_i, T)}{\lambda_i} \cos \beta \quad (2)$$

$$\frac{n_s(\lambda_s, T)}{\lambda_s} \sin \alpha = \frac{n_i(\lambda_i, T)}{\lambda_i} \sin \beta + \frac{1}{\Lambda(T)} \sin \theta \quad (3)$$

式中

$$\Lambda(T) = \Lambda(T_0) [1 + a(T - T_0) + b(T - T_0)^2] \quad (4)$$

$a = 1.4468 \times 10^{-5}$ ,  $b = 1.0454 \times 10^{-8}$  为 PPRTA 晶体的热膨胀系数.

$k_{p,s,i,g}$  依次表示泵浦光、信号光、闲频光和周期极化波矢量, 定义  $k_p$  和  $k_s$  之间的夹角  $\alpha$  为非共线角,  $k_p$  和  $k_i$  之间的夹角为  $\beta$ ,  $k_p$  和  $k_g$  ( $k_g = 2\pi m/\Lambda$ ,  $m$  为阶数, 文中取 1) 之间的夹角为  $\theta$ ,  $\Omega = \alpha + \beta$  为信号光和闲频光之间的夹角.

将相位失配因子  $\Delta k$  在信号光中心频率  $\omega_{s0}$  处泰勒展开

$$\Delta k = \Delta k_0 + \frac{\partial \Delta k}{\partial \omega_s} \Delta \omega_s + \frac{1}{2} \frac{\partial^2 \Delta k}{\partial \omega_s^2} (\Delta \omega_s)^2 + \dots \quad (5)$$

式中

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$$\Delta k_{//} = k_p - k_s \cos \alpha - k_i \cos \beta - k_g \cos \theta \quad (6a)$$

$$\Delta k_{\perp} = k_s \sin \alpha - k_i \sin \beta - k_g \sin \theta \quad (6b)$$

若泵浦光为准单色光时,将式(6a)和(6b)对信号光波长  $\lambda_s$  求导

$$\frac{\partial \Delta k_{//}}{\partial \lambda_s} = -\frac{\partial k_s}{\partial \lambda_s} \cos \alpha - \frac{\partial k_i}{\partial \lambda_s} \cos \beta + k_i \sin \beta \frac{\partial \beta}{\partial \lambda_s} \quad (7a)$$

$$\frac{\partial \Delta k_{\perp}}{\partial \lambda_s} = \frac{\partial k_s}{\partial \lambda_s} \sin \alpha - \frac{\partial k_i}{\partial \lambda_s} \sin \beta - k_i \cos \beta \frac{\partial \beta}{\partial \lambda_s} \quad (7b)$$

宽带光参量过程应满足

$$\frac{\partial \Delta k_{//}}{\partial \lambda_s} - \frac{\partial \Delta k_{//}}{\partial \lambda_s} - \frac{\partial \Delta k_{\perp}}{\partial \lambda_s} = 0 \quad (8)$$

结合群速度的概念,有

$$v_s = v_i \cos \Omega \quad (9)$$

式(9)为获得宽带的参量光输出的必要条件(与  $\theta$  无关,下文取  $\theta=0$ ),即闲频光沿信号光波矢方向的群速度等于信号光的群速度。

## 2 数值模拟

若通过选择合适的非共线角使其满足群速匹配,并选择相应的极化周期以满足准相位匹配,即可以在非共线准相位匹配过程中同时实现准相位匹配和群速匹配,如图 1。通过图 1 可以看出,在非共线参量过程中,如果想同时获得准相位匹配和群速匹配,则不同的信号光波长对应不同的非共线角和极化周期,当泵浦光为 532 nm,若取信号光为 800 nm,

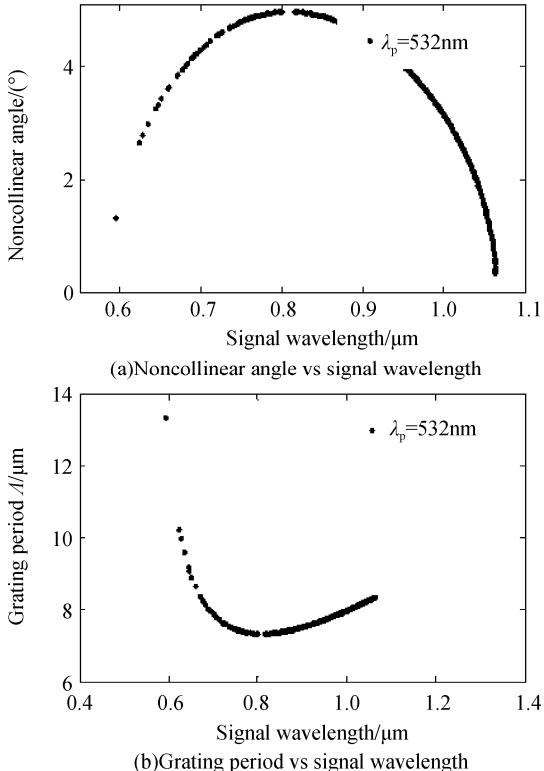


图 1 GVM 下非共线角以及极化周期和信号光波长的关系  
Fig. 1 Noncollinear angle and Grating period vs signal wavelength

则同时满足准相位匹配和群速匹配的非共线角为  $4.98^\circ$ ,相应的极化周期为  $7.32 \mu\text{m}$ ,虽然非共线角大,不利于光束之间的耦合,但是在此极化周期附近有较宽的信号光范围。

结合 PPRTA 晶体的色散方程,可以得到泵浦光为 532 nm 时,不同极化周期下,信号光和闲频光随非共线角的变化,如图 2。当极化周期为  $7.32 \mu\text{m}$ ,非共线角在  $4.9^\circ$  附近时,可以获得信号光  $0.7417 \sim 0.8931 \mu\text{m}$  的宽带调谐,与上文中同时满足准相位匹配和群速匹配的结果基本一致。

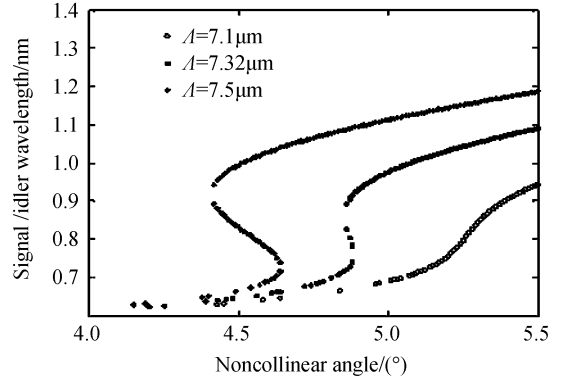


图 2 不同极化周期下,信号光和闲频光随非共线角的变化  
Fig. 2 Dependence of signal and idler wavelength on noncollinear angle for different grating periods

在慢变振幅和忽略泵浦强度衰减的近似下,增益强度可以表示为<sup>[16]</sup>

$$G = 1 + (\xi L)^2 (\sinh B/B)^2 \quad (10)$$

式中  $\xi = 4\pi d_{\text{eff}} (I_p / 2\epsilon_0 n_p n_s n_i c \lambda_s \lambda_i)^{1/2}$ ,  $B = [(\xi L)^2 - (\Delta k L/2)^2]^{1/2}$ ,  $\xi$  为有效增益系数.  $L$  为晶体长度 ( $L=10 \text{ mm}$ ),  $d_{\text{eff}}$  为有效非线性系数 ( $d_{\text{eff}}=9.0 \text{ pm/V}$ )<sup>[17]</sup>,  $I_p$  为泵浦强度 ( $I_p=60 \text{ mW/cm}^2$ ). 定义增益带宽为  $G=G_0/2$  范围内的信号光波长的差值。

取泵浦光波长为 532 nm (Nd:YAG 激光器的倍频光),信号光波长为 800 nm (Ti:sapphire 激光器的中心波长),可以得到增益带宽随非共线角和极化周期及晶体温度的变化,如图 3 和图 4。由图 3 可

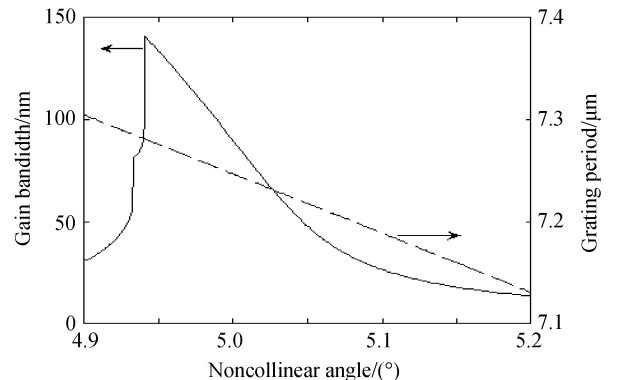


图 3 增益带宽和极化周期随非共线角的变化  
Fig. 3 Dependence of gain bandwidth and grating periods on noncollinear angle

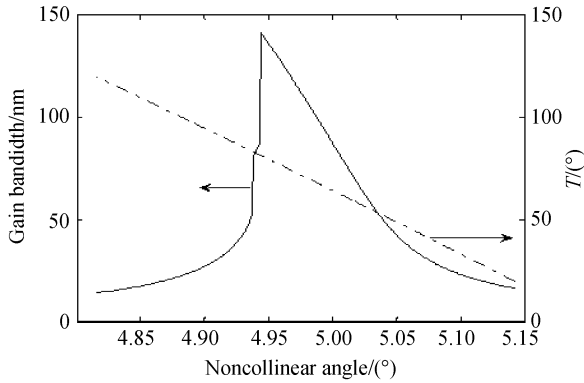


图4 增益带宽和晶体温度随非共线角的变化  
Fig. 4 Dependence of gain bandwidth and crystal temperature on noncollinear angle

以看出,随着非共线角的增大,极化周期将减小以满足准相位匹配.当非共线角为 $4.94^\circ$ 时,可以获得最大的增益带宽 $140.7\text{ nm}$ ,相应的极化周期为 $7.28\text{ }\mu\text{m}$ ,与同时满足准相位匹配和群速匹配的条件非常接近.由图4可以看出,随着非共线角的增大,晶体温度将减小以满足准相位匹配.当晶体温度为 $81.3^\circ$ 时,最大增益带宽为 $141.2\text{ nm}$ .

图5给出了对应不同的非共线角和极化周期,满足最大增益带宽( $\theta=4.94^\circ, \Lambda=7.28\text{ }\mu\text{m}$ )和群速匹配情况( $\theta=4.98^\circ, \Lambda=7.32\text{ }\mu\text{m}$ )下,温度增益带宽的比较.当满足最大增益带宽时,相应的温度带宽很小,不利于温度调谐的实现;当满足群速匹配条件时,增益带宽在 $66.7^\circ$ 和 $72.6^\circ$ 之间没有太大的改变.通过比较可以发现,满足群速匹配时的非共线角和极化周期比较适合于温度调谐.

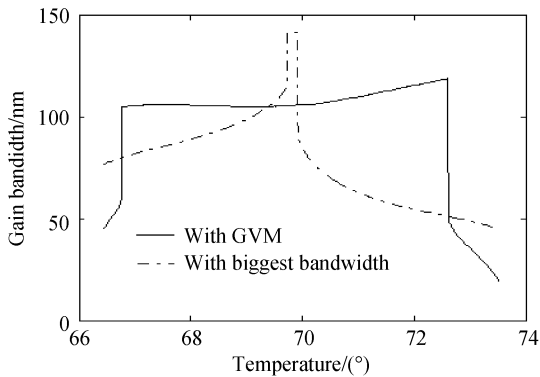


图5 满足最大增益带宽和GVM时,增益带宽和温度的关系  
Fig. 5 Comparison of the dependence on temperature with GVM or with the biggest bandwidth

### 3 结论

通过设计合适的非共线角和极化周期可以获得PPRTA晶体同时满足准相位匹配和群速匹配的参量过程,有利于超短脉冲运转,并讨论了非共线准相位匹配过程增益带宽与非共线角、极化周期和晶体温度的关系,得到同时满足准相位匹配不但可以增

大参量调谐带宽而且可以增大温度调谐过程的温度带宽.

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## Gain Bandwidth of Periodically Poled RbTiOAsO<sub>4</sub> in Noncollinear Quasi-Phase Matching

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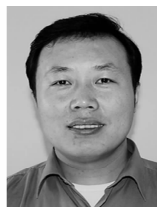
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**Abstract:** The dependence of noncollinear angle and the corresponding grating periods on signal wavelength for satisfying quasi phase-matching and group velocity matching simultaneously of periodically poled RbTiOAsO<sub>4</sub> in noncollinear quasi phase-matched are carried out. The tuning characteristic of noncollinear interaction in group velocity matching situation is analyzed. The dependence of the gain bandwidth on the noncollinear angle, temperature, crystal angle and grating periods are simulated in detail. The dependence of gain bandwidth on crystal temperature for the biggest gain bandwidth and group velocity matching is compared in detail.

**Key words:** Noncollinear quasi phase-matching; Group velocity matching; Gain bandwidth; Periodically poled RbTiOAsO<sub>4</sub>



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