Analysis of Frequency Doubling Characteristics of Periodically Poled Crystal

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Abstract Best matching temperature is obtained when the fundamental laser is of normal incidence in periodically poled crystal. The in- depth analysis of second harmonic nonlinear conversion efficiency uses periodically poled crystal MgO:sPPLT as the research object, and combines the Sellmeier equation and the polar period with temperature thermal expansion relationship. When the fundamental laser tilt is incident, the equivalent polar period becomes larger, and the best matching temperature is reduced. Acceptable temperature and wavelength bandwidth can be obtained conveniently by using the normalized frequency doubling efficiency curves for the given length of frequency doubling crystal. The crystal length becomes longer, and the acceptable temperature and wavelength bandwidth become narrower. As long as the Sellmeier equation and polar period with temperature thermal expansion relationship are known, the method used in this study can be extended to other periodically poled crystals. These conclusions are useful for other periodically poled crystals and guiding continuous wave fiber laser external cavity frequency doubling.

Key words nonlinear optics; laser; periodically poled crystals; nonlinear frequency coversion; frequency doubling

OCIS codes 190.4400; 190.4360; 140.3515; 140.3580; 160.4330

周期极化晶体倍频特性分析

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摘要 通过深入分析二次谐波转换效率,以周期极化晶体 MgO:sPPLT 为研究对象,结合其斯涅耳方程和极化周期随温度的热膨胀关系,得到了基频光正入射时周期极化晶体的最佳匹配温度;当基频光倾斜入射时,极化周期等效变大,最佳匹配温度降低。利用归一化倍频效率图形,可以方便地得到给定晶体长度的温度和波长接收带宽;同时晶体通光长度越长,温度和波长接收带宽越窄。只要更换晶体的斯涅耳方程和极化周期随温度的热膨胀关系,所使用的研究方法可方便地推广到其他周期极化晶体的倍频研究当中。所得到的这些结论对于使用周期极化晶体进行倍频,尤其是连续光纤激光器腔外倍频有一定的指导意义。

关键词 非线性光学; 激光; 周期极化晶体; 非线性频率变换; 倍频

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1 Introduction

Frequency conversion is an effective means to expand the existing laser wavelength scope, and frequency doubling is one important approach. At present, to obtain high efficiency continuous laser frequency conversion, intracavity frequency doubling is a general method[1-3]. However, obtaining high stability, low noise, and single frequency requires a careful design and alignment of the resonant cavity[1,4]. With the development of laser technology, external cavity frequency doubling using high power continuous wave (CW) laser by periodically poled nonlinear crystal is eliciting more attention[5-9]. Hence, optimization is needed for

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the design of frequency doubling characteristics for periodically poled crystals.

Through in-depth analysis of the second harmonic nonlinear conversion efficiency, this study uses periodically poled crystal MgO:sPPLT as the research object and combines the Sellmeier equation and the polar period with temperature thermal expansion relationship. The best matching temperature is obtained when the fundamental laser is in normal incidence into the periodically poled crystal. When the fundamental laser tilt is incident, equivalent polar period becomes larger, and the best matching temperature is reduced. Acceptable temperature and wavelength bandwidth can be obtained conveniently via normalized frequency doubling efficiency curves for the given length of frequency doubling crystal. The crystal length becomes longer, whereasa the acceptable temperature and wavelength bandwidth becomes narrower. These conclusions are useful for other periodically poled crystals and guidance for CW fiber laser external cavity frequency doubling. As long as the Sellmeier equation and polar period with temperature thermal expansion relationship are known, the method used in this study can be extended to other periodically poled crystals.

2 Second harmonic conversion efficiency

The second harmonic conversion efficiency formula for the conditions of the fundamental frequency light is not exhausted and the plane wave approximation is[10]

$$\eta=\left(\frac{8\pi^2 d_{\mathrm{eff}}^2 L^2}{n_\omega^2 n_{2\omega} c\varepsilon_0\lambda_\omega^2}\frac{P_\omega}{A}\right)\mathrm{sinc}^2\left(\frac{\Delta kL}{2}\right), \tag{1}$$

where η is second harmonic conversion efficiency, d_{eff} is effective nonlinear coefficient of nonlinear crystal, L is the length of nonlinear crystal, n_ω is the fundamental frequency light refractive index, $n_{2\omega}$ is the frequency doubling light refractive index, c is the speed of light in vacuum, ε_0 is vacuum dielectric constant, λ_ω is the wavelength of the fundamental frequency light in vacuum, P_ω is fundamental frequency power, A is the average spot area for fundamental frequency light in the nonlinear crystal, Δk is the phase mismatch factor, and $\mathrm{sinc}(x)$ is expressed as $\sin(x)/x$.

For the chosen nonlinear crystal and certain optical focusing structure, the first term is constant, and does not make any specific analysis. The analysis is focused on the second term. The analysis of second harmonic conversion efficiency is changed into the analysis of the phase mismatch factor.

3 Analysis of phase mismatch factor

Nonlinear frequency conversion must meet conservation of energy and momentum[10]:

$$\frac{1}{\lambda_{01}}-\frac{1}{\lambda_{02}}-\frac{1}{\lambda_{03}}=0, \tag{2}$$

$$\frac{n_1}{\lambda_{01}}-\frac{n_2}{\lambda_{02}}-\frac{n_3}{\lambda_{03}}=0, \tag{3}$$

where λ_{01}, λ_{02}, and λ_{03} refer to the wavelength in vacuum for three light participating in nonlinear effect, n_1, n_2, and n_3 are refractive indexes corresponding to three light, and the index is the function of temperature and wavelength in general.

The law of momentum conservation in Eq.(3) is actually the phase matching relationship; while for quasi phase matching, the relationship is

$$\frac{n_1}{\lambda_{01}}-\frac{n_2}{\lambda_{02}}-\frac{n_3}{\lambda_{03}}-m\frac{1}{\Lambda}=0, \tag{4}$$

where Λ is polar period, m is quasi phase matching order, and odds, such as 1, 3, 5, etc., are adopted[11].

m is 1 in general and temperature change is considered. Meanwhile, the quasi phase matching nonlinear effect in the crystal is usually e light. Then, the phase mismatch factor becomes

$$\Delta k = 2\pi\left[\frac{n_e(\lambda_{01},T)}{\lambda_{01}} - \frac{n_e(\lambda_{02},T)}{\lambda_{02}} - \frac{n_e(\lambda_{03},T)}{\lambda_{03}} - \frac{1}{\Lambda(T)}\right], \tag{5}$$

where $n_e(\lambda,T)$ is the refraction index related to temperature and wavelength, $\Lambda(T)$ is polar period at the temperature of T.

For frequency doubling, the phase mismatch factor becomes

$$\Delta k = 2\pi\left[\frac{n_e(\lambda_{2\omega},T)}{\lambda_{2\omega}} - \frac{2n_e(\lambda_{\omega},T)}{\lambda_{\omega}} - \frac{1}{\Lambda(T)}\right], \tag{6}$$

where $\lambda_{2\omega}$ is wavelength in the vacuum for the frequency doubling light, $n_e(\lambda_\omega,T)$ and $n_e(\lambda_{2\omega},T)$ are refractive indexes for the fundamental frequency and frequency doubling light at temperature T, respectively.

From Eq.(6), one can conclude that the analysis of phase mismatch factor needs the Sellmeier equation of the periodically poled crystal.

4 Parameters of periodically poled crystal

Given the excellent performance of MgO: sPPLT, this study analyzes its frequency doubling characteristics. The Sellmeier equation for MgO:sPPLT is[12]

$$n_e^2(\lambda,T) = A + \frac{B + b(T)}{\lambda^2 - [C + c(T)]^2} + \frac{E}{\lambda^2 - F^2} + \frac{G}{\lambda^2 - H^2} + D\lambda^2 . \tag{7}$$

Table 1 shows the parameters of the equation.

Table 1 Parameters for MgO:sPPLT

Number	Parameter	Value
1	A	4.502483
2	B	0.007294
3	C	0.185087
4	D	−0.02357
5	E	0.073423
6	F	0.199595
7	G	0.001
8	H	7.99724
9	$b(T)$	$3.483933\times10^{-8}(T+273.15)^2$
10	$c(T)$	$1.607839\times10^{-8}(T+273.15)^2$

Equation (7) is valid for the wavelength range of 0.39~4.1 μm, and the temperature range of 300 ℃~200 ℃.

Considering the thermal expansion of the crystal, polar period is the function of temperature[12]:

$$\Lambda_{th}(T) = \Lambda(25\ ℃)[1 + \alpha(T - 25\ ℃) + \beta(T - 25\ ℃)^2], \tag{8}$$

where $\Lambda(25\ ℃)$ is polar period at the temperature of 25 ℃ and 7.97 is adopted, α is 1.6×10^{-5}, and β is 7×10^{-9}.

When $\Delta k = 0$ is adopted in Eq.(6) and $\lambda_{2\omega} = \lambda_\omega/2$ is considered, polar period for the complete phase matching is

$$\Lambda(T) = \frac{\lambda_\omega}{2}\left[n_e(\lambda_{2\omega},T) - n_e(\lambda_\omega,T)\right]. \tag{9}$$

5 Best matching temperature

When the fundamental frequency light is incident into the crystal normally, polar period curves due to thermal expansion (red) and complete phase matching (pink) are drawn in the same graph using Matlab software (Fig.1. P refers to complete phase matching). By enlarging the graph, the intersection abscissa of these two curves is 55.17 ℃, which is the optimum phase matching temperature for normal incident.

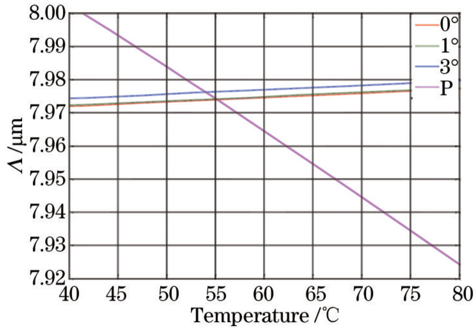

Fig.1 Best matching temperature point graphic display

However, light will deviate from the normal incident in experiments as shown in Fig.2.

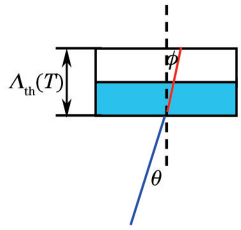

Fig.2 Light tilt incident into the crystal

Equivalent polar period is obtained by refraction law:

$$\Lambda_{t}(T)=\frac{\Lambda_{th}(T)}{\cos\phi}, \tag{10}$$

where refraction angle $\phi=\arcsin\left[\frac{\sin\theta}{n_{e}(\lambda,T)}\right]$, and θ is incident angle.

Equivalent polar periods for 1° and 3° as the function of temperature are shown in Fig.1. Phase matching temperature can be read as 55.04 ℃ and 54.01 ℃ by enlarging the graph. With increasing tilt angle results in increased refraction angle. The increase in the equivalent polar period will lead to the drop of phase matching temperature. Based on this characteristic, one can adjust the temperature to the correct direction. The experimental results also proved this point[7,9].

6 Relationship between acceptable bandwidth and crystal length

The direct relationship between the normalized frequency doubling efficiency and temperature and wavelength is shown in Figs.3 and 4 for different lengths of the crystal.

From Fig.3, the best phase matching temperature is 55.17 ℃, which agrees with the result in Fig.1.

From Fig.4, the best phase matching wavelength is 1064 nm.

For different lengths of crystal, the results of temperature and wavelength acceptable bandwidths are

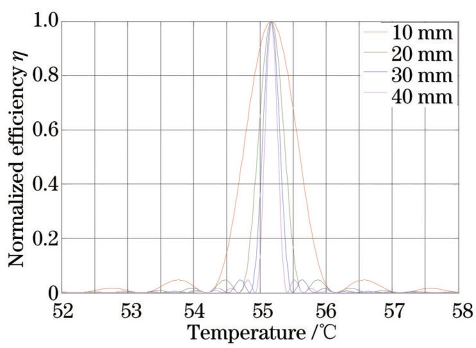

Fig.3 Direct relationship between normalized efficiency and temperature

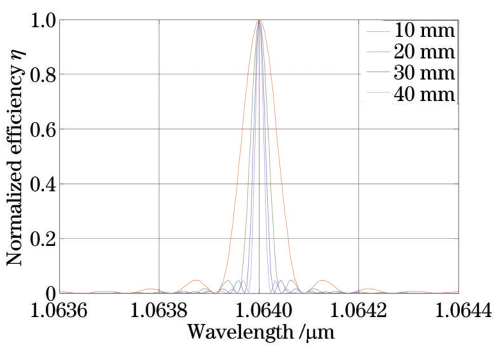

Fig.4 Direct relationship between normalized efficiency and wavelength

shown in Table 2. The crystal is longer, and the acceptable bandwidth of temperature and wavelength is narrower. While longer crystal indicates high frequency doubling efficiency from Eq.(1), the process will need high temperature control precision and narrow line width fundamental laser.

Table 2 Temperature and wavelength bandwidth

Number	Crystal length /mm	Temperature bandwidth /℃	Wavelength bandwidth /nm
1	10	0.8	0.1
2	20	0.5	0.05
3	30	0.3	0.03
4	40	0.25	0.02

7 Conclusion

Based on the second harmonic nonlinear conversion efficiency, using periodically poled crystal MgO: sPPLT as the research object, combined with the Sellmeier equation and the polar period with temperature thermal expansion relationship, the best matching temperature can be obtained when the fundamental laser is in normal incidence to the periodically poled crystal. When the fundamental laser tilt is incident, equivalent polar period becomes larger, and the best matching temperature is reduced. Temperature and wavelength accept bandwidth can be obtained conveniently by using normalized frequency doubling efficiency curves for given lengths of frequency doubling crystal. When crystal length becomes longer, acceptable temperature and wavelength bandwidth become narrower. These conclusions are useful for other periodically poled crystals and in guiding cw fiber laser external cavity frequency doubling. As long as the Sellmeier equation and polar period with temperature thermal expansion relationship are known, the method used in this study can be extended to other periodically poled crystals.

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