

# The optimization of frequency doubling using periodically poled crystal

Junwen Xue<sup>a</sup>, Kaiyong Deng<sup>b</sup>, Yujie Fang<sup>c</sup>, Xuedan Pei<sup>d</sup>, Binghua Su<sup>e</sup>

Beijing Institute of Technology, Zhuhai, 519088, China

<sup>a</sup>email: xuejunwen001@126.com, <sup>b</sup>email: 602829042@qq.com,

<sup>c</sup>email: fyj0202@126.com, <sup>d</sup>email: peixuedan\_2001@163.com, <sup>e</sup>email: bhsu@263.net

**Keywords:** Laser; Periodically Poled Crystals; Frequency Doubling

**Abstract.** Through in-depth analysis of the second harmonic nonlinear conversion efficiency, using periodically poled crystal MgO:SPPLT as the research object, combining the Sellmeier equation and the polar period with temperature thermal expansion relationship, the best matching temperature is obtained when the fundamental laser is normal incidence into the periodically poled crystal. When the fundamental laser tilt incident, equivalent polar period becomes larger, the best matching temperature is reduced. Temperature and wavelength accept bandwidth can be obtained conveniently using the normalized frequency doubling efficiency curves for given length of frequency doubling crystal. The crystal length becomes longer, temperature and wavelength accept bandwidth will become narrower. These conclusions are useful for other periodically poled crystals and are guidances 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.

## Introduction

For the expansion of the existing laser wavelength scope, frequency conversion is an effective means and frequency doubling is one important way. At present, in order to obtain high efficiency continuous laser frequency conversion, the use of intracavity frequency doubling is a general method [1-3]. However, in order to obtain high stability, low noise, even single frequency, it often needs to design the resonant cavity and align carefully [1] [4]. With the development of laser technology, external cavity frequency doubling using high power CW laser by periodically poled nonlinear crystal is drawing more and more attention [5-9]. So it is necessary to optimize the design of frequency doubling characteristics for periodically poled crystals.

In this paper, through in-depth analysis of the second harmonic nonlinear conversion efficiency, using periodically poled crystal MgO:SPPLT as the research object, combining the Sellmeier equation and the polar period with temperature thermal expansion relationship, the best matching temperature is obtained when the fundamental laser is normal incidence into the periodically poled crystal. When the fundamental laser tilt incident, equivalent polar period becomes larger, the best matching temperature is reduced. Temperature and wavelength accept bandwidth can be obtained conveniently using the normalized frequency doubling efficiency curves for given length of frequency doubling crystal. The crystal length becomes longer, temperature and wavelength accept bandwidth will become narrower. These conclusions are useful for other periodically poled crystals and are guidances 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.

## 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]:

$$\eta = \left( \frac{8\pi^2 d_{eff}^2 L^2}{n_{\omega}^2 n_{2\omega} c \varepsilon_0 \lambda_{\omega}^2} \frac{P_{\omega}}{A} \right) \sin^2 \left( \frac{\Delta k L}{2} \right) \quad (1)$$

Of which,  $\eta$  is second harmonic conversion efficiency,  $d_{eff}$  is effective nonlinear coefficient of nonlinear crystal,  $L$  is the length of nonlinear crystal,  $n_{\omega}$  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,  $\varepsilon_0$  is vacuum dielectric constant,  $\lambda_{\omega}$  is the wavelength of the fundamental frequency light in vacuum,  $P_{\omega}$  is fundamental frequency power,  $A$  is the average spot area for fundamental frequency light in the nonlinear crystal,  $\Delta k$  is the phase mismatch factor,  $\sin c(x)$  is expressed as  $\sin(x)/x$ .

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

### Analysis of Phase Mismatch Factor

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

$$\frac{1}{\lambda_{10}} - \frac{1}{\lambda_{20}} - \frac{1}{\lambda_{30}} = 0 \quad (2)$$

$$\frac{n_1}{\lambda_{01}} - \frac{n_2}{\lambda_{02}} - \frac{n_3}{\lambda_{03}} = 0 \quad (3)$$

Of which,  $\lambda_{01}$ ,  $\lambda_{02}$  and  $\lambda_{03}$  are wavelength in vacuum for three light participating in the nonlinear effect.  $n_1$ ,  $n_2$  and  $n_3$  are refractive index corresponding to three light, and the index is the function of temperature and wavelength in general.

The law of momentum conservation equation (3) is actually the phase matching relationship, while for quasi phase matching the relationship is:

$$\frac{n_1}{\lambda_{01}} - \frac{n_2}{\lambda_{02}} - \frac{n_3}{\lambda_{03}} - m \frac{1}{\Lambda} = 0 \quad (4)$$

Of which,  $\Lambda$  is polar period,  $m$  is quasi phase matching order and odd such as 1, 3, 5 etc is 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:

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

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

For frequency doubling, the phase mismatch factor becomes:

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

Of which,  $\lambda_{\omega}$  and  $\lambda_{2\omega}$  are wavelengths in vacuum for the fundamental frequency and frequency doubling light,  $n_e(\lambda_{\omega}, T)$  and  $n_e(\lambda_{2\omega}, T)$  are refractive index for the fundamental frequency and frequency doubling light at the temperature of T.

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

## Parameters of Periodically Poled Crystal

Due to the performance of MgO:sPPLT is excellent currently, its frequency doubling characteristics are analyzed in this study. Sellmeier equation for MgO:sPPLT is [12]:

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

The parameters in the equation are shown in Table 1.

Table 1 The parameters for MgO:sPPLT

Number	Parameters	Values
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	$b(T)$	$3.483933 \times 10^{-8} (T + 273.15)^2$
10	$c(T)$	$1.607839 \times 10^{-8} (T + 273.15)^2$

Formula (7) is valid for wavelength range of 0.39-4.1 $\mu\text{m}$ , the temperature range of 30-200C.

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

$$\Lambda_{th}(T) = \Lambda(25^\circ\text{C})[1 + \alpha(T - 25^\circ\text{C}) + \beta(T - 25^\circ\text{C})^2] \quad (8)$$

Of which,  $\Lambda(25^\circ\text{C})$  is polar period at the temperature of 25C and 7.97 is adopted.  $\alpha$  is  $1.6 \times 10^{-5}$ ,  $\beta$  is  $7 \times 10^{-9}$ .

When  $\Delta k = 0$  is adopted in formula (6) and  $\lambda_{2\omega} = \lambda_\omega / 2$  is taken into account, polar period for complete phase matching is:

$$\Lambda(T) = \frac{\lambda_\omega}{2} [n_e(\lambda_{2\omega}, T) - n_e(\lambda_\omega, T)] \quad (9)$$

## The 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 as shown in Fig.1. By enlarging the graph, the intersection abscissa of these two curves is 55.17C which is the optimum phase matching temperature for normal incident.

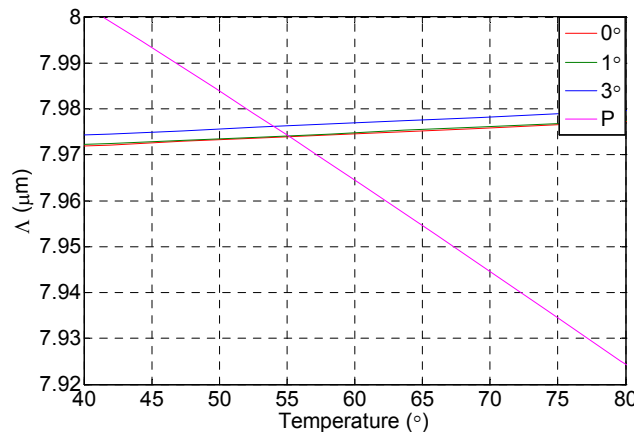


Fig.1. The best matching temperature point graphic display

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

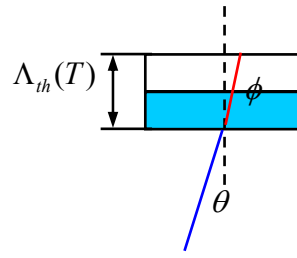


Fig.2 The light tilt incident into the crystal

Equivalent polar period is obtained by refraction law:

$$\Lambda_t(T) = \frac{\Lambda_{th}(T)}{\cos \phi} \quad (10)$$

Of which, refraction angle is:

$$\phi = \arcsin\left(\frac{\sin \theta}{n_e(\lambda, T)}\right), \text{ and } \theta \text{ is incident angle.}$$

Equivalent polar periods for  $1^\circ$  and  $3^\circ$  as the function of temperature are shown in Fig.1. Phase matching temperature can be read  $55.04^\circ\text{C}$  and  $54.01^\circ\text{C}$  by enlarging the graph. With the increasing of the tilt angle, the refraction angle will increase. And the increasing of the equivalent polar period will lead to the drop of phase matching temperature. According to this characteristic, one can adjust the temperature to the correct direction. The experiments also proved this point [7] [9].

### The Relationship Between Accept Bandwidth and Crystal Length

The direct relationship between the normalized frequency doubling efficiency and temperature and wavelength is drawn as shown in Fig.3 and Fig.4 for different length of the crystal.

From Fig.3, one can obtain the best phase matching temperature  $55.17^\circ\text{C}$  which is agreement with the result of Fig.1.

From Fig.4, one can obtain the best phase matching wavelength is  $1064\text{nm}$ .

For different length of crystal, the results of temperature and wavelength accept bandwidths are shown in table 2. The crystal is longer, the accept bandwidth of temperature and wavelength is narrower. The longer crystal means high frequency doubling efficiency from equation (1), however, it will need high temperature control precision and narrow line width fundamental laser.

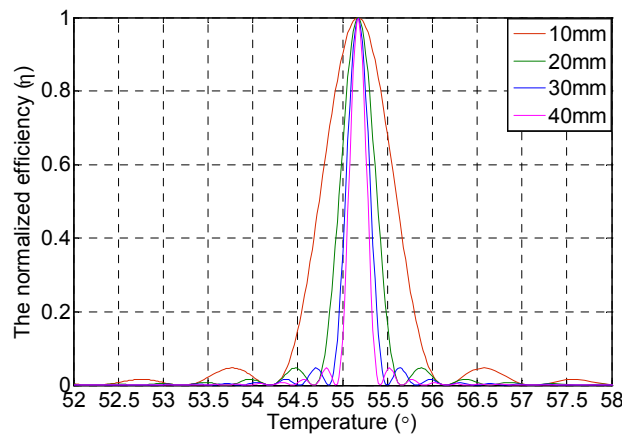


Fig.3 The direct relationship between the normalized efficiency and temperature

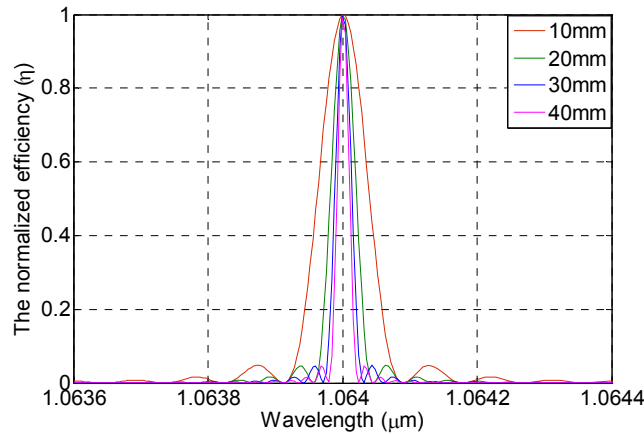


Fig.4 The direct relationship between the normalized efficiency and wavelength

Table 2 The temperature and wavelength accept bandwidth

Number	Crystal length(mm)	Temperature bandwidth (C)	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

## Conclusion

According to the second harmonic nonlinear conversion efficiency, using periodically poled crystal MgO:sPPLT as the research object, combining the Sellmeier equation and the polar period with temperature thermal expansion relationship, the best matching temperature is obtained when the fundamental laser is normal incidence into the periodically poled crystal. When the fundamental laser tilt incident, equivalent polar period becomes larger, the best matching temperature is reduced. Temperature and wavelength accept bandwidth can be obtained conveniently using the normalized frequency doubling efficiency curves for given length of frequency doubling crystal. The crystal length becomes longer, temperature and wavelength accept bandwidth will become narrower. These conclusions are useful for other periodically poled crystals and are guidances 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.

## Acknowledgement

In this paper, the research was sponsored by The Training Plan of Guangdong Province Young Teachers in Higher Education Institutions (Project No. Yq2013208), Seedling Cultivation Project Plan of Colleges and Universities in Guangdong Province (Natural Science) (Project No. 2013LYM\_0101) and Scientific Research Foundation of Beijing Institute of Technology Zhuhai (Project No. 2013JS02).

## References

- [1] Yaohui Zheng, Yajun Wang, Changde Xie, and Kunchi Peng. Single-Frequency Nd:YVO<sub>4</sub> Laser at 671 nm With High-Output Power of 2.8 W[J]. IEEE Journal of Quantum Electronics, 2012, 48(1): 67-72
- [2] J. Yi, H. J. Moon, and J. Lee. Diode-pumped 100-W green Nd:YAG rod laser[J]. Applied Optics, 2004, 43: 3732-3737

- [3] Q. H. Xue, Q. Zheng, Y. K. Bu, F. Q. Jia, and L. S. Qian. High-power efficient diode-pumped Nd:YVO<sub>4</sub>/LiB<sub>3</sub>O<sub>5</sub> 457 nm blue laser with 4.6 W of output power[J]. Optics Letters, 2006, 31(8): 1070-1072
- [4] Zheng Yaohui, Li Fengqin, Zhang Kuanshou, Peng Kunchi. Progress of All-Solid-State Single-Frequency Lasers[J]. Chinese Journal of Lasers, 2009, 36(7): 1635-1642
- [5] D. Georgiev, V. P. Gapontsev, A. G. Dronov, M. Y. Vyatkin, A. B. Rulkov, S. V. Popov, J. R. Taylor. Watts-level frequency doubling of a narrow line linearly polarized Raman fiber laser to 589 nm[J]. Optics Express, 2005, 13(8): 6772-6776
- [6] A. B. Rulkov<sup>1</sup>, A. A. Ferin, S. V. Popov and J. R. Taylor, I. Razdobreev, L. Bigot and G. Bouwmans. Narrow-line, 1178nm CW bismuth-doped fiber laser with 6.4W output for direct frequency doubling[J]. Optics Express, 2007, 15(9): 5473-5476
- [7] S. Sinha, D. S. Hum, K. E. Urbanek, Y. Lee, M. J. F. Digonnet, M. M. Fejer, and R. L. Byer. Room-temperature stable generation of 19 watts of single-frequency 532-nm radiation in a periodically poled lithium tantalate crystal[J]. Journal of Lightwave Technology, 2008, 26(24): 3866-3871
- [8] S. Chaitanya Kumar, G. K. Samanta, Kavita Devi, and M. Ebrahim-Zadeh. High-efficiency, multicrystal, single-pass, continuous-wave second harmonic generation[J]. Optics Express, 2011, 19(12): 11152-11169
- [9] Hao Liyun, Su Cen, Qi Yunfeng, Liu Chi, Zhou Jun. Second Harmonic Generation Characteristics of Continuous Wave All-Fiber Laser Oscillator in PPMgO:LN[J]. Chinese Journal of Lasers, 2013, 40(6): 0602007-1-0602007-6
- [10] G. D. Boyd and D. A. Kleinman. Parametric interaction of focused Gaussian light beams[J]. Journal of Applied Physics, 1968: 39(8): 3597-3639
- [11] Martin M. Fejer, G. A. Magel, Dieter H.Jundt, and Robert L. Byer. Quasi-Phase-Matched Second Harmonic Generation: Tuning and Tolerances[J]. IEEE Journal of Quantum Electronics, 1992, 28(11): 2631-2654
- [12] Ariel Bruner, David Eger, Moshe B. Oron, Pinhas Blau, and Moti Katz. Temperature-dependent Sellmeier equation for the refractive index of stoichiometric lithium tantalate[J]. Optics Letters, 2003, 28(3): 194-196