Temperature Modeling of Intracavity Doubling Frequency Nonlinear Crystal*

Li Long[1,2,3], Shi Peng[1], Chen Haowei[3], Jia Sen[3], Bai Jintao[3]

1 *Faculty of Science, Xi'an University of Architecture & Technology, Xi'an* 710055
2 *School of Electronic & Information Engineering, Xi'an Jiaotong University, Xi'an* 710049
3 *The Institute of Photonics & Photo-Technology of Northwest University, Key Laboratory of Photoelectronic Technology of Shaanxi Province, Xi'an* 710069

Abstract In order to improve harmonic conversion efficiency and eliminate walk-off effect, temperature field of nonlinear crystal was accurately calculated. Through work state analysis of KTP crystal with intracavity doubling frequency, a thermal model of rectangle nonlinear crystal was buildt and the radiation eccentricity (RE) of a rectangle crystal was first defined. Based on heat conductive equation, a general analytical solution of temperature model was obtained and the temperature model influenced by eccentric radiated of fundamental wave was first investigated.

Keywords Laser; Nonlinear crystal; Intracavity doubling frequency; Thermal model

CLCN TN248 **Document Code** A

0 Introduction

Second Harmonic Generation (SHG) of infrared laser radiation has many applications, such as, coherent communication, information storage, medicine, active imaging, holography and so on. It is easy to obtain high harmonic conversion efficiency of nonlinear crystal by intracavity doubling frequency due to its high fundamental wave power density[1,2]. Nd : laser with KTP crystal intracavity doubling frequency has attracted much attention for its excellent performance[3,4]. At intracavity doubling frequency, the KTP crystals are with II-type phase match (the PM angle: $\theta = 90°$, $\phi = 23.3°$)[5]. However, intracavity doubled green laser generally suffers from a large noise fuctuation in the output due to the thermal effect of nonlinear crystal[6]. The non-uniform temperature rise would not only destroy intrinsical phase matching condition of nonlinear crystal, but also lead to the depolarization of fundamental wave[7].

In Nd : lasers, the nonlinear crystal is often cut at rectangle with the size $a \times b \times c$ mm^3. In previous research, the rectangle crystals were approximated by the cylinder and the finite-element analysis was used, which inevitably brought many errors in temperature model analysis[8,9]. In the present paper, through work feature analysis of nonlinear crystal with intracavity doubling frequency, a rectangle thermal model was introduced. Based on the heat conductive equation and its boundary condition, a new analytical solution was deduced and the temperature model of nonlinear crystal was obtained. The factors which influenced temperature model were analyzed. Particularly the temperature model of a rectangle nonlinear crystal influenced by the eccentric radiation of fundamental wave was first discussed.

1 Temperature field distribution of nonlinear crystal

1.1 Thermal model of nonlinear crystal and its boundary condition

To counteract the thermal effects, nonlinear crystal must be cooled during the operation. Fig. 1 shows the schematic diagram of nonlinear crystal with intracavity doubling frequency and its thermal sink.

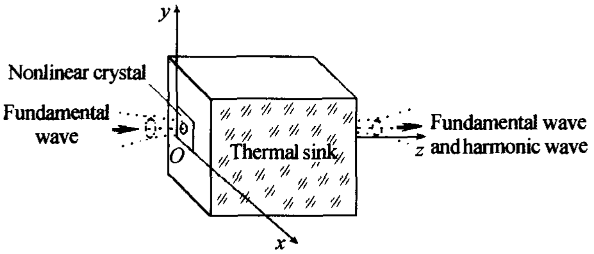

Fig. 1 Schematic diagram of nonlinear crystal with intracivity doubling frequency

Because nonlinear crystal actively was cooled during the operation, heat was conducted to the thermal sink. Through characteristic analysis of KTP crystal at intracavity doubling frequency, a rectangle thermal model was built:

1) In nonlinear crystal, the fundamental wave has TEM$_{00}$ mode distribution. The intensity of fundamental wave was given by

$$I(x, y) = I_0 e^{-2\frac{(x-x_0)^2+(y-y_0)^2}{w^2}} \tag{1}$$

where I_0 was the center power intensity of fundamental wave; x_0 and y_0 were the coordinates of incidence

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*Supported by Special Research of Shaanxi Province Education Department, with the project No. 04JK129

Tel: 029-82205088 Email: lilong7211@ 126. com

Received date: 2004-11-08

point, which can be seen from Fig. 2; and w was the waist spot radius of fundamental wave. The a and b were sides length of nonlinear crystal.

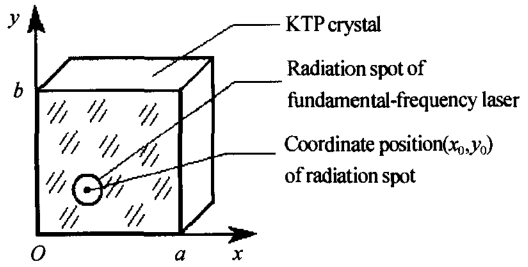

Fig. 2 Thermal model schematic of KTP crystal eccentric-radiated by fundamental wave

2) In nonlinear crystal, the power and waist spot of fundamental wave were assumed as invariability.

As the absorption coefficient of KTP crystal was littler ($\beta = 0.006\ \mathrm{cm}^{-1}$ @ $\lambda = 1064$ nm), the energy attenuation of fundamental wave can be ignored. The length of KTP crystal was about 3~5 mm, the variation of waist spot in crystal also can also be ignored.

3) The temperature rise of nonlinear crystal was mainly caused by fundamental wave.

In cavity power intensity of fundamental wave was much higher than harmonic wave. The temperature rise of KTP crystal was mainly caused by fundamental wave. The thermal power intensity in KTP crystal was described as

$$q_v(x,y) = \beta I(x,y) \tag{2}$$

Here q_v was the heat power density; β was the absorption coefficient of nonlinear crystal.

4) End-faces of KTP crystal were satisfied with the adiabatic condition and the four side-faces had a fix boundary temperature.

Since KTP crystal had a higher thermal conductivity coefficient and the end-faces were connected with air, heat dissipated by convection was less than the heat conduction through the four sides, which was no more than 1%. An approximate solution was introduced that the end-faces of KTP crystal were satisfied with the adiabatic condition.

$$\frac{\partial u}{\partial z}(x,y,0) = 0; \frac{\partial u}{\partial z}(x,y,c) = 0 \tag{3}$$

The boundary temperatures of four-sides were consistent with thermal sink. In mathematic, the temperature of four-sides was assumed as 0. So the boundary conditions of nonlinear crystal were obtained.

$$\begin{aligned} &u(0,y,z) = 0; u(a,y,z) = 0 \\ &u(x,0,z) = 0; u(x,b,z) = 0 \end{aligned} \tag{4}$$

1.2 The heat conductive equation and analytical solution of temperature model

The heat conductive equation of KTP crystal was the Poisson equation

$$\frac{\partial^2 u(x,y,z)}{\partial x^2} + \frac{\partial^2 u(x,y,z)}{\partial y^2} + \frac{\partial^2 u(x,y,z)}{\partial z^2} = -\frac{q_v(x,y,z)}{\lambda} \tag{5}$$

where λ was thermal conductivity of nonlinear crystal.

When laser was in a proper operation, the power intensity of fundamental wave kept invariabilitye and the four-sides of crystal had a fix boundary temperature. The heat would be conducted to the thermal sink through four-side faces. Therefore it can be assumed that the heat flow in KTP crystal was along radial, that was, the temperature field was independency of the z-axis. The $u(x,y,z)$ can be simplified as $u(x,y)$. The Poisson equation was simplified as

$$\frac{\partial^2 u(x,y)}{\partial x^2} + \frac{\partial^2 u(x,y)}{\partial y^2} = -\frac{q_v(x,y)}{\lambda} \tag{6}$$

According to the boundary condition, the analytical solution of Eq. (6) was given by

$$u(x,y) = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} A_{nm} \sin\frac{n\pi}{\mathrm{a}}x \sin\frac{m\pi}{b}y \tag{7}$$

Where the coefficient A_{nm} was

$$A_{nm} = \frac{4I_0\beta ab}{\lambda\pi^2(b^2n^2 + a^2m^2)} \int_0^b\int_0^a \mathrm{e}^{-\frac{2[(x-\frac{a}{2})^2 + (y-\frac{b}{2})^2]}{w^2}} \cdot \sin\frac{n\pi}{a}x \sin\frac{m\pi}{b}y\,\mathrm{d}x\mathrm{d}y \tag{8}$$

2 Temperature model of KTP crystal with intracavity doubling frequency

2.1 The temperature model under different power of fundamental wave

The radius of fundamental wave mode inside the nonlinear crystal can be calculated by ABCD matrix. When the power was 120 W and the waist spot radius was 50 μm, Fig. 3 shows temperature model of KTP crystal ($4\times4\times5\ \mathrm{mm}^3$) by center radiated. The maximum relative temperature rise of KTP crystal was 3.88 ℃.

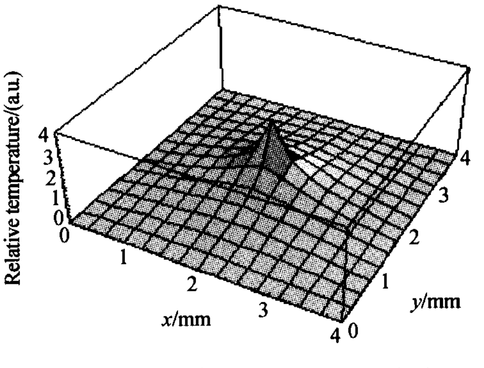

Fig. 3 Three-dimensional temperature model of KTP crystal under center radiated by fundamental wave

When the power of fundamental wave increased, Fig. 4 shows the temperature model on radiated face $z=0$ of KTP crystal.

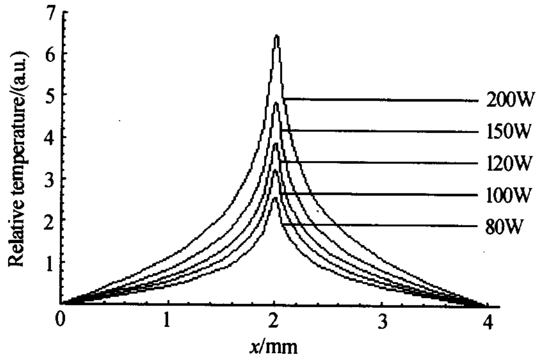

Fig. 4 Radiated face temperature model of KTP crystal under different power of fundamental wave

From Fig. 4, it is known that when the power was 80 W, the maximum relative temperature rise of center radiated point was 2.58 ℃. When power increased to 200 W, the maximum relative temperature rise was 6.46℃.

2.2 The temperature model under different waist spot of fundamental wave

In different cavity, the fundamental wave would have different waist spot radius. Fig. 5 shows the temperature model of KTP crystal when the waist radius was 30 μm, 50 μm, 80 μm, 100 μm and 120 μm respectively.

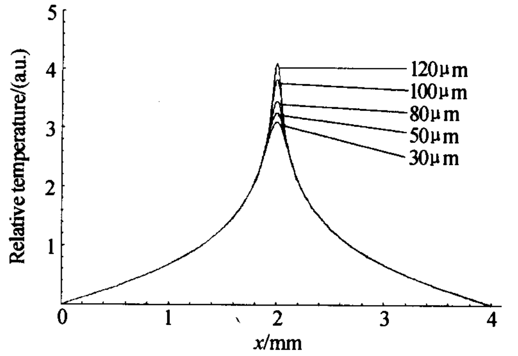

Fig. 5 Temperature model of KTP crystal on radiated face under different waist spot of fundamental wave

In Fig. 5, it is known that when the power was 120 W and the waist radius was 30 μm, the maximum relative temperature rise was 4.15℃. When the waist radius increased to 120 μm, the maximum relative temperature rise of KTP crystal decreased to 3.16℃.

2.3 The temperature model by different radiation eccentricity of fundamental wave

Radiated by fundamental wave, the coating face of KTP crystal would unavoidable be damaged, which would cause the output power decrease. Fig. 6 shows the temperature model of KTP crystal by eccentric radiated, which the coordinate of incident point was $x_0 = a/3$ and $y_0 = b/2$. When the power was 120 W and the waist spot radius was 50 μm, the maximum relative temperature rise on radiated point was 3.79℃.

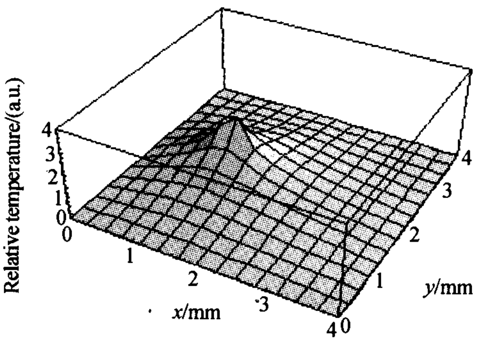

Fig. 6 Temperature model of KTP crystal under the eccentric radiated by fundamental wave

In order to study temperature model influenced by eccentric radiated, a radiation eccentricity (*RE*) of rectangle crystal was introduced. The *RE* can be defined as a ratio between the distance L_0 and L, described as L_0/L. Here the L_0 was the length from the radiation spot center to the geometric center of rectangle, and the L was the length of extension line through the geometric center and the radiation spot center to the side of rectangle. Fig. 7 shows the definition of radiation eccentricity.

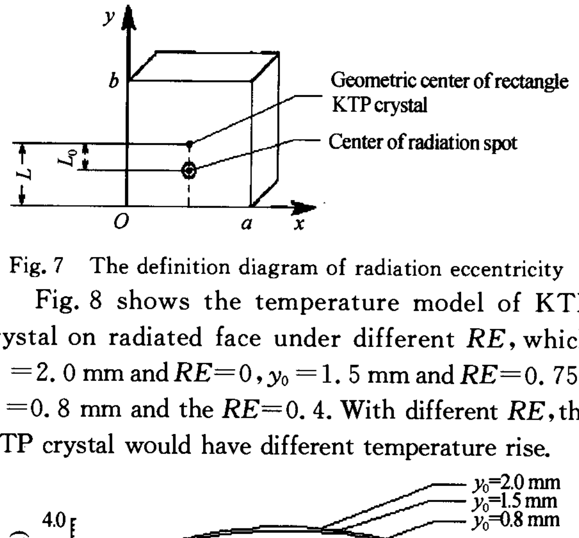

Fig. 7 The definition diagram of radiation eccentricity

Fig. 8 shows the temperature model of KTP crystal on radiated face under different *RE*, which $y_0 = 2.0$ mm and $RE = 0$, $y_0 = 1.5$ mm and $RE = 0.75$, $y_0 = 0.8$ mm and the $RE = 0.4$. With different *RE*, the KTP crystal would have different temperature rise.

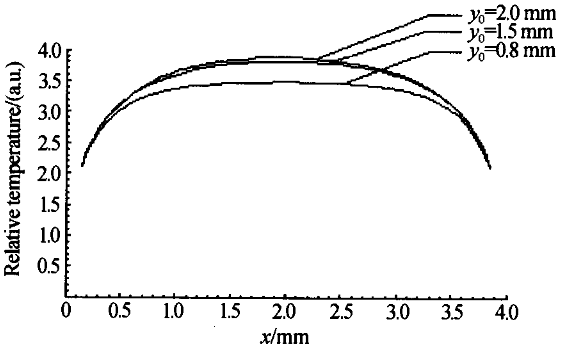

Fig. 8 Temperature model of KTP crystal on radiated face with different RE

2.4 The temperature model with different sectional dimension

At the same boundary temperature, the KTP crystals have different temperature model with different size. In experiments, four pieces of KTP crystals with the sizes of $2.5\times2.5\times5.0\ \mathrm{mm}^3$, $3.0\times3.0\times5.0\ \mathrm{mm}^3$, $3.5\times3.5\times5.0\ \mathrm{mm}^3$, $4.0\times4.0\times5.0\ \mathrm{mm}^3$ were selected. Fig. 9 shows the temperature model of KTP crystal with different sizes.

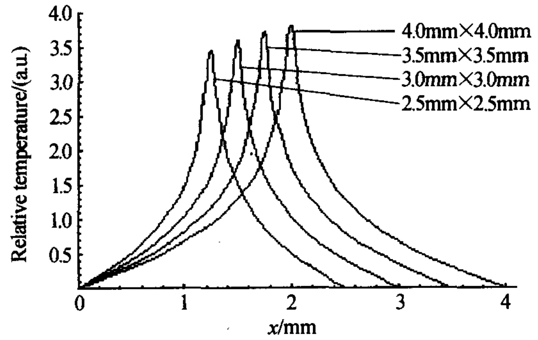

Fig. 9 Temperature model of KTP crystal with different sectional dimension

On the same radiated condition of Fig. 3, the maximum relative temperature rise of KTP crystal with $2.5\times2.5\times5.0\ \mathrm{mm}^3$ was 3.46℃, the $3.0\times3.0\times5.0\ \mathrm{mm}^3$ was 3.62℃ and the $3.5\times3.5\times5.0\ \mathrm{mm}^3$ was 3.78℃.

3 Conclusions

The temperature model of rectangle KTP crystal was required by Nd: laser. The temperature model influenced by different radiation eccentricity was more favored to the maintenance of Nd∶YVO_4/KTP green lasers. The analytical solution of temperature model of KTP crystal would be theoretical foundation for further research, such as phase mismatching and walk off induced by non-uniform temperature rise. The solution has ordinary character and can be applied to the models with inner heat source with a fix boundary temperature.

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非线性晶体内腔倍频的温度模式分布

李 隆[1,2,3] 史 彭[1] 陈浩伟[3] 贾 森[3] 白晋涛[3]
(1 西安建筑科技大学理学院,西安 710055)
(2 西安交通大学电子与信息工程学院,陕西省信息光子技术重点实验室,西安 710049)
(3 西北大学光子学与光子技术研究所,西北大学光电子省级重点开放实验室,西安 710069)

收稿日期:2004-11-08

摘 要 为了提高谐波转换效率和消除温升引起的晶体走离效应,对于非线性晶体温度场分布特点进行了分析与计算.同时研究了基波偏心辐射对KTP晶体温度场的影响.通过对腔内倍频KTP晶体工作特点的分析,建立了方形非线性晶体热模型并首次引入了方形晶体辐射偏心度的定义.基于热传导方程,得到了温度场分布的一般解析表达式.

关键词 激光器;非线性晶体;内腔倍频;温度场模式

Li Long was born in 1972. He received the B. S. degree in 1995 and the M. S. degree in 2001 from Shaanxi Normal University. He is an instructor at Xi′an University of Architecture & Technology. He now is studying for his Ph. D. degree in Xi′an Jiaotong University. He works at Institute of Photonics & Photo-Technology, and Provincial Key Laboratory of Photoelectronic Technology in Northwest University. His major research is research LD pumped all-solid-state lasers.