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Optomechanical analysis and performance optimization of large-aperture KDP frequency converter

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HIGHLIGHTS

- Surface textures greatly influence the frequency conversion of large-aperture KDP crystal.
- Optical performances of KDP converter are highly correlated with the external forces.
- Integrated optomechanical method is developed to evaluate mechanical influences on optical performances.
- The edge-adaptive clamping apparatus is significant in improving the crystal's working performance.

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ABSTRACT

Surface characteristics of large-aperture potassium dihydrogen phosphate (KDP) frequency converter have direct and significant impacts on the performance of high-power solid-state laser in Inertial Confinement Fusion (ICF) facility. In this study, we analyze the close relationships between the phase gradient and the optical performances including type-I phase matching capacity and focusability of KDP frequency converter theoretically. Moreover, the influences of external forces are studied with field interferometry and finite element method (FEM). An edge-adaptive clamping apparatus with two-stage preload controllers (TSPCs) is proposed to mitigate the gravitational effect. With the proposed integrated optomechanical method and principle verification experiment, new clamping method is proved to be effective to perform offline precision calibration, improve frequency conversion efficiency and has potential for use in online surface control of this large-aperture transmission optics. The coupled effects of preload and gravity on optical performance are analyzed for identifying the characteristics of new clamping method, and the optimal preloads at typical installation attitudes are determined.

1. Introduction

In virtue of the excellent nonlinear optics property, potassium dihydrogen phosphate (KH_2PO_4/KDP) crystals have been widely used as harmonic conversion component since 1960s [1]. To this day, KDP crystals still serve as the essential frequency converters in the high-power solid-state lasers of Inertial Confinement Fusion (ICF) facilities like NIF in America [2], LMJ in France [3] and SG-III in China [4]. The large size KDP converters take charge of converting 1ω infrared waves to 3ω ultraviolet waves for improving laser energy absorption of deuterium-tritium target capsule. However, practical process conditions, such as cutting operation, mounting configuration and gravitational effect, always make the crystal surface deviate from the ideal state. Surface aberrations have significant impacts on the phase matching condition, which directly determines the harmonic conversion efficiency.

A variety of studies have been done to find surface control method and propose crystal mounting configurations. Li et al. proposed a combinational adaptive optics (AO) system that can effectively correct the wavefront aberrations by controlling the surface of two DMs [5].

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Zacharias and Beer mentioned that NIF also utilized AO system for the wavefront control, which has strengthened the ability to focus each laser beam onto the target capsule [6]. Haber et al. demonstrated a concept for predictive control of thermally induced wavefront aberrations in optical systems [7]. Zhang et al. put forward an AO mounting method that can achieve surface control of KDP converters [8]. In addition, Researchers in NIF have compared crystal deflections under three different mounting structures: corner simple support, edge simple support and edge clamped support [9]. Olivier Lubin et al. introduced the easy operation and low cost mounting system employed in LMJ, meantime, proposed a modeling method of the effects of gravity on third harmonic generation [10]. Chinese researchers, Ruifeng Su et al., analyzed a torque mounting configuration [11]. Li et al. analyzed the dynamic characteristics of a large-aperture optics with adjustable support [12]. Moreover, English et al. put forward the measuring method and parameters of large aperture KDP converters in NIF [13]. The next generation ICF facility with higher output power has more stringent accuracy requirements of mounting configuration and better pertinence requirements of quantitative metric. Besides, real assembly factors are supposed to be taken into account for providing more direct applications or references.

William's work has proved the close tie between the low-frequency surface errors of ICF optics and laser focusability [14]. Based on in-depth study and understanding of KDP surface topographies, we firstly indicate the direct relationship between the phase gradient and phase matching condition in theory, thus defining the root mean square value of phase gradient (GRMS) as the most appropriate specification instead of the most common specifications: peak-to-valley (P-V) and root mean square (RMS) value of surface distortion. Moreover, integral opto-mechanical model is established to combine crystal assembly factors and nonlinear optics properties, thereby providing a numerical tool for analysis, prediction and optimization of nonlinear optic modules. Numerical simulation and field experiment are performed to make clear the influences of preload and gravity on crystal surface respectively. In order to compensate gravity induced aberrations, an edge-adaptive clamping apparatus with two-stage preload controllers (TSPCs) is put forward based on the conception of clamping force counteracting gravity [15]. Further, the optimization performances of novel clamping apparatus are validated with the optomechanical model and principle verification experiment. The changing trends of phase gradient (GRMS) and phase mismatch factor (ΔK) under incremental preloads are presented and analyzed. Finally, coupled effects of preload and gravity on optical performance are studied for identifying the characteristics of new clamping apparatus, and the optimal preloads at typical installation attitudes are worked out.

2. Theory

Multi-scale surface topographies of machined optics will generate different types of impacts on laser system performance. On the one hand, the high spatial frequency aberrations ($> 0.03\,\text{mm}^{-1}$) like the waviness and the roughness could induce near-field beam modulation which determines the damage threshold of KDP crystals [16]. On the other hand, the low spatial frequency aberrations ($0\text{–}0.03\,\text{mm}^{-1}$) could determine the shape and size of the focal spot which directly affect the ability to meet the energy requirement of ICF missions. As for the KDP crystal, we believe low frequency surface aberrations ($0\text{–}0.03\,\text{mm}^{-1}$) also have direct impacts on its second harmonic generation (SHG) efficiency.

2.1. Phase gradient

After passing through a non-ideal mirror surface, the original flat wavefront will be superposed with the complex surface topography and turns to the distorted wavefront with different phase at different position. According to the measurement results from NIF [17], the optical

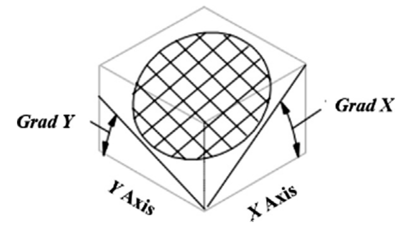

Fig. 1. Schematic showing the concept of phase gradient.

surface with low frequency aberrations could be represented by a random Gaussian phase screen following Eq. (1).

$$z(x, y) = g\cdot random(-1, 1)*\exp\left\{-\left[\left(\frac{x}{S_{gx}}\right)^2 + \left(\frac{y}{S_{gy}}\right)^2\right]\right\} \tag{1}$$

where g is the gradient factor, S_{gx} and S_{gy} are scale lengths a long X and Y axis respectively [14].

Differentiating $z(x, y)$ generates the mathematic expression of phase gradient which is used to describe the spatial variation of the crystal surface as shown in Fig. 1.

$$\nabla z(x, y) = \hat{x}\frac{\partial z}{\partial x} + \hat{y}\frac{\partial z}{\partial y} \tag{2}$$

where $\hat{x}$ and $\hat{y}$ are unit vectors along X and Y axis respectively, $\nabla z(x, y)$ is a vector field whose direction represents the fastest increasing orientation at the certain point (x, y) and the magnitude represents the spatial variation rate along this orientation.

2.2. Simulated focusing

To make clear the close relation between the focal spot and crystals' phase gradient, we set up a simplified focusing system in which a Gaussian beam is transported through the surface $z(x, y)$ and converged by an ideal focusing lens.

Firstly, the incident beam is assumed to be an ideal Gaussian beam whose intensity distribution could be described as Eq. (3),

$$I_\omega(x, y) = I_0\exp\left\{-\left[\left(\frac{x}{R_0}\right)^2 + \left(\frac{y}{R_0}\right)^2\right]\right\} \tag{3}$$

where R_0 is the beam waist. After passing through the focus lens, the optical field could be expressed as Eq. (4).

$$E_1(x_1, y_1) = \sqrt{I_\omega(x, y)}\exp[iz(x, y)]\exp\left[-\frac{ik}{2F}(x^2 + y^2)\right] \tag{4}$$

where F is the focal length of the focusing lens, k denotes the wave number. Fresnel diffraction integral formula could be used to describe the optical field on the focal plane as Eq. (5) without regard to the nonlinear effects like self-focus of laser beam [13].

$$E_2(x_2, y_2) = \frac{\exp(ik(F + \Delta F))}{i\lambda(F + \Delta F)}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_1(x_1, y_1)\exp[iz(x, y)]\exp\left[-\frac{ik}{2F}(x^2 + y^2)\right] \tag{5}$$

where ΔF is the defocusing amount and λ is the wavelength.

2.3. Phase mismatching model

As a widely used negative uniaxial crystal, KDP material can generate second harmonics when the base frequency laser incidents. In this process, harmonic generation efficiency entirely depends on the phase matching condition which is always affected by the incident surface figure and the temperature. As shown in Fig. 2, the radiation intensity of second harmonic on the output end is $I_{2\omega}$ whose magnitude achieves