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Residual thermal stress of a mounted KDP crystal after cooling and its effects on second harmonic generation of a high-average-power laser

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ABSTRACT

Thermal problems are huge challenges for solid state lasers that are interested in high output power, cooling of the nonlinear optics is insufficient to completely solve the problem of thermally induced stress, as residual thermal stress remains after cooling, which is first proposed, to the best of our knowledge. In this paper a comprehensive model incorporating principles of thermodynamics, mechanics and optics is proposed, and it is used to study the residual thermal stress of a mounted KDP crystal after cooling process from mechanical perspective, along with the effects of the residual thermal stress on the second harmonic generation (SHG) efficiency of a high-average-power laser. Effects of the structural parameters of the mounting configuration of the KDP crystal on the residual thermal stress are characterized, as well as the SHG efficiency. The numerical results demonstrate the feasibility of solving the problems of residual thermal stress from the perspective on structural design of mounting configuration.

1. Introduction

Second harmonic generation (SHG) is of great interest to the solid state lasers, majority of which use KDP crystal to obtain high-average-power SHG [1–3]. When the laser beam propagates within the KDP crystal and interacts with it, the KDP crystal absorbs part of the laser energy and coverts it to heat as its own. Consequently, temperature of the KDP crystal rises and causes the thermal stress. As a result, the refractive indices of the KDP crystal changed, which further causes a phase mismatch and reduction of the SHG efficiency [4,5].

Generally, there are three kinds of approach to solve thermal problems, which are theoretical analysis, cooling schemes and temperature control. As regard to the theoretical analysis, some kinds of phase mismatch equation is firstly established, based on the change of the refractive index of the crystal induced by the temperature change. Taking advantages of the phase mismatch equation, the thermally induced phase mismatch is solved, and then it is used to solve the SHG efficiency [6]. Since the thermal problem is caused by the absorption of the laser power, which includes the fundamental and the second harmonic waves, both of these two waves are in need of consideration in solving the SHG efficiency. Thus, both the heat equation and coupling wave equations are solved simultaneously to consider the effects of these two waves [7]. Addition to the theoretical calculation, the phase mismatching angle also could be measured, based on which, the Sellmeier formula and thermo-optic dispersion formulas are rebuilt, results of which are used to determine phase matching condition [8]. Regarding to the cooling schemes, appropriate cooling measures are proposed to solve the thermal problems, where temperature is cooled down, as well as phase mismatch is decreased. Liquid cooling is widely applied in solid state lasers, since it is in advantage of easy implementation. However, cooling performance is significantly limited due to poor heat conducting property of crystal, where the demand that employing materials with favorable heat conducting property is required. In advantages of high thermal conductivity and well tested cooling performance, comparing with copper and sapphire, diamond is preferentially applied to make heat conducting element [9]. Usually, one side of the diamond-made heat spreader is bounded to crystal, while the other side is in contact with a kind of heat sink, and with assist of the heat spreader, the heat within the crystal is removed to heat sink completely and frequently, in which way temperature of the crystal descends [10]. Unfortunately, significant birefringence always appears in the case of nature diamond, which arouses the need of using synthetic diamond that is to suppress the birefringence effects [11]. Other than diamond, cooper is also a potential candidate to make heat conducting element, especially in some kinds of special conditions [12]. Apart from liquid cooling, gas is sometimes used as heat conducting element, where sealed

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gas is located between crystal and heat sink and transfers heat to heat sink, which provides the benefit that radial thermal gradient vanishes [13]. Besides, in some cases of gas cooling, temperature, velocity and direction of the gas in inlet and outlet are determined to achieve satisfactory cooling performance [14]. As to the temperature control, oven is always applied to control the temperature for diminishing thermal stress and thermal phase mismatch. In this way, crystal is usually located in an oven, where heaters are installed and temperature-controlled. Long term temperature stability of the oven matters critically, and the method that uses proportion-integral-derivative (PID) controlled heater is demonstrated in this regard [15]. Additionally, a kind of multiple heaters approach is proposed, where heater temperatures are independently controlled [16]. Taking advantages of the multiple heaters approach, negative temperature gradient could be created in the case that heaters have different temperatures, and it is used to compensate the positive temperature gradient induced by absorption [17]. Usually, some kind of thermal conductive paste is used to improve heat conduction between the crystal and the heater, for enhancing the controlling efficiency [18].

In most cases, previous work generally focuses on temperature reduction and stress decrease of the crystal in the cooling process, while the stress after cooling process was not assessed, as well as its effects on the SHG efficiency of subsequent shots. In this paper, it is first proposed, according to our knowledge, that because of the mechanical mounting, not all the thermally induced stress evanish as the temperature drops in the cooling process. As a result, a part of the thermal stress remains after the cooling process, even though the temperature has been cooled down to the initial value, the remained stress is called as residual thermal stress as proposed in this paper. Due to the effects of the residual thermal stress, the SHG efficiency of the subsequent shots after cooling decreases. Regarding to a multiple-plus laser beam, with cooling at shooting interval, as studied in this paper, the residual thermal stress is caused by the previous shots and affects the SHG efficiency of the subsequent ones. It is interesting to know how the residual thermal stress occurs and how it affects the SHG efficiency of the subsequent shots. These questions are clarified getting through a comprehensive analysis, which includes thermal, mechanical and optical analyses. Firstly, temperature rise of the KDP crystal caused by optical absorption is theoretically investigated. Absorption and cooling processes are then successively theoretically analyzed and simulated using the finite element method (FEM), based on which residual thermal stress after cooling is determined. Thirdly, the changes of the refractive indices of the KDP crystal caused by the residual thermal stress are theoretically calculated, results of which are then used to study the induced phase mismatch. By means of solving the coupling wave equations that takes both phase mismatch and linear absorption into account, the SHG efficiency is obtained. Furthermore, a comprehensive model is built based on the three analyses mentioned above, taking advantages of which the effects of the structural parameters of the mounting configuration on the residual thermal stress and the SHG efficiency are investigated.

2. Optical and mechanical configurations

2.1. SHG configuration

The optical configuration of the SHG consists of a type I KDP crystal and a laser beam, as shown in Fig. 1. The KDP crystal has a large aperture with dimensions of 430 mm × 430 mm × 12 mm, and it is arranged in type I phase matching configuration ($o + o \rightarrow e$), with the phase matching and azimuth angles are 41.19° and 45°, respectively. Note that these two angles are determined by additionally considering the third harmonic generation using a DKDP crystal that locates after the KDP crystal, which is beyond the scope of this paper. The laser beam is a plan wave with an aperture of 400 mm × 400 mm, and its intensity is in the order of magnitude of GW cm^{-2} within the whole aperture. The laser beam irradiates onto the KDP crystal and propagates (–Z direction) within the KDP crystal along the phase matching angle, interacting with the KDP crystal within the irradiation zone, which is the central portion of 400 mm × 400 mm × 12 mm of the KDP crystal. The incident fundamental wave (1ω, 1.064 μm) linearly polarizes along the ordinary (O) axis of the KDP crystal, and due to the nonlinearity of the KDP crystal, the optical fields of the fundamental wave interact, leading to an irradiation of second harmonic wave (2ω, 0.532 μm), which polarizes along the extraordinary (E) axis. Besides, part of the fundamental wave remains and propagates polarizing along the O axis, which is mainly due to the phase matching angle setting as mentioned above.

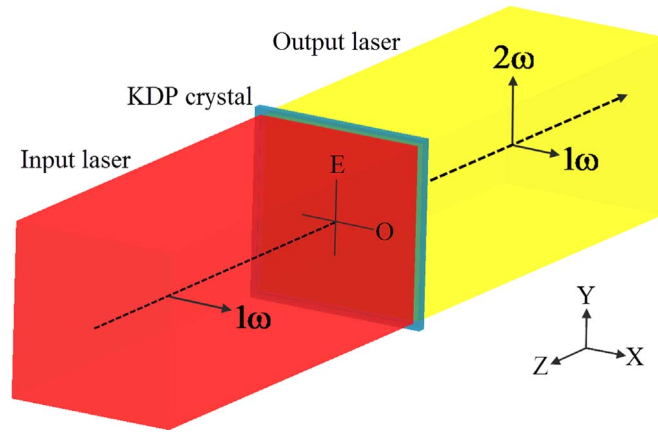

Fig. 1. Schematic diagram of the SHG scheme.

2.2. Mechanical mounting configuration

In consideration of a stable SHG, the KDP crystal is mounted in a mounting set, which mainly consists of frame, locating block, plastic staple, flexible sheet, rigid sheet, loading screw and locating screw, as shown in Fig. 2. The frame is in geometry of window structure, supporting the KDP crystal axially (Z direction) at the supporting region, which is the area of 5 mm wide along the edges of the bottom surface of the KDP crystal. Surrounding the KDP crystal, the locating block is fixed to the frame using the locating screw. Open hole runs through the block, and the plastic staple is installed in it, supporting the KDP crystal in radial directions (X and Y directions) at the constraint region, which is the side face of the KDP crystal that contacts with the staple. Both the rigid and flexible sheets are fixed to the block by means of the loading screw, and the flexible sheet closely contacts with the KDP crystal at the loading region, which is the area of 5 mm wide along the edges of the top surface of the KDP crystal. When the loading screw is tightened, it moves to -Z direction, driving the sheets to squeeze the KDP crystal, in which way a kind of preload applies on the KDP crystal, generating a holding action for the KDP crystal. With regard to installation and positioning of the KDP crystal, the frame is fixed to certain structure that is affiliated to the solid state lasers, taking advantages of which the KDP crystal is fixed at the appointed location of the optical path. The local environment where the mounting set is settled keeps vacuum, for the consideration of the clearness maintaining that is related to crystal damage. Besides, the temperature is set to ambient value of 20 °C, for the convenience of temperature control.