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Frequency tripling of convergent beam employing crystals tiling in large-aperture high-energy laser facilities

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ABSTRACT

In inertial confinement fusion, ultraviolet laser damage of the fused silica lens is an important limiting factor for load capability of the laser driver. To solve this problem, a new configuration of frequency tripling is proposed in this paper. The frequency tripling crystal is placed on downstream of the focusing lens, thus sum frequency generation of fundamental frequency light and doubling frequency light occurs in the beam convergence path. The focusing lens is only irradiated by fundamental light and doubling frequency lights. Thus, its damage threshold will increase. LiB_3O_5 (LBO) crystals are employed as frequency tripling crystals for its larger acceptance angle and higher damage threshold than KDP/DKDP crystals'. With the limitation of acceptance angle and crystal growth size are taken into account, the tiling scheme of LBO crystals is proposed and designed optimally to adopt to the total convergence angle of 36.0 *mrad*. Theoretical results indicate that 3 LBO crystals titling with different cutting angles in θ direction can meet the phase matching condition. Compared with frequency tripling of parallel beam using one LBO crystal, 83.8% (93.1% with 5 LBO crystals tiling) of the frequency tripling conversion efficiency can be obtained employing this new configuration. The results of a principle experiment also support this scheme. By employing this new design, not only the load capacity of a laser driver will be significantly improved, but also the fused silica lens can be changed to K9 glass lens which has the mature technology and low cost.

1. Introduction

In inertial confinement fusion (ICF) [1], ultraviolet laser induced damage of the fused silica lens is a key restricted factor for further increase of laser energy. To improve the damage threshold of the focusing lens, raising processed quality and laser conditioning technology are two means [2,3] usually used. But the improvement of damage threshold is too limited to meet the engineering needs. In recent years, non-collinear [4] and non-critical phase matching [5] technology are reported as new harmonic generation configurations to avoid ultraviolet laser irradiation on the fused silica lens. Non-collinear phase matching requires spatial separation of the fundamental light and the frequency doubling light. Its structure is huge and complex, especially in ICF laser driver, employing this configuration means more light paths and much larger target chamber. As for non-critical phase matching technology, precise temperature control system is required. It is hard to maintain the temperature for the large aperture of frequency conversion crystal, even vacuum environment is needed. This increase the construction difficulty of laser driver. In this paper, we proposed a new third harmonic generation (THG) configuration. The frequency tripling crystal is placed on the downstream of achromatic focusing lens and the THG occurs in the beam convergence path. Thus, the focusing lens is avoided to be irradiated by ultraviolet laser and its damage threshold will be significantly increased.

LiB_3O_5 (LBO) crystals [6] which have excellent characteristics, especially wide acceptance angle and high damage threshold, are the advisable THG crystals in this new configuration. It had been demonstrated that over 80% of the conversion efficiency [7] from infrared to ultraviolet could be maintained by using type-I KDP doubler in tandem with type-II LBO tripler. To meet the phase matching condition of large angle convergent beam, a tiling scheme [8] of frequency tripling crystals is proposed and designed optimally. Nova [9] had realized 3×3 KDP arrays with 77 cm of total clear aperture in 1980s and fulfilled 70% conversion efficiency. In our new configuration, the incident angle of convergent beam is up to 36.0 *mrad*. Theoretical results indicate that 3 LBO crystals tiling with different cutting angles meet the phase matching condition. The following principle experimental results correspond well with the theoretical results.

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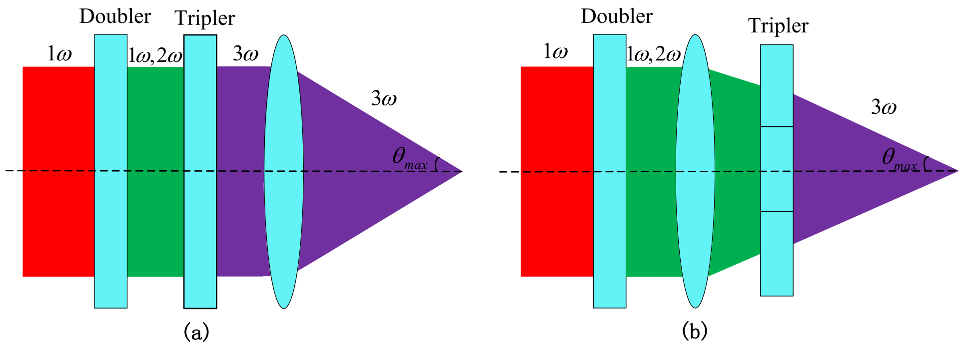

Fig. 1. Frequency conversion configuration. (a) conventional configuration; (b) new configuration.

By employing this new configuration, damage threshold of the focusing lens will be significantly improved and the laser energy can be further increased. Besides that, the limit of growth size of LBO crystals can be broken through by employing tiling technology. K9 glasses which have advantages of lower cost and more mature process technology can be employed as material of the focusing lens instead of fused silica. With energy losses of the tiling gaps being neglected, the average frequency tripling conversion efficiency theoretically reaches 83.8% (or 93.1% with 5 LBO crystals tiling) with 3 LBO crystals tiling in θ direction. Results of a principle experiment are in agreement with the theoretical analysis.

2. Theoretical analysis

The conventional and the new THG configuration are shown in Fig. 1, respectively.

Supposing the beam size is 360 mm × 360 mm [10] and focal length of the achromatic focusing lens is $F = 10000$ mm. The numerical calculation results show that both the size of focused spot and the thickness of focusing lens can be neglected. Taking no account of the above errors, the total beam convergence angle can be calculated as

$$2\theta_{max} = 2 \cdot \arctan\left(\frac{180\ \text{mm}}{10000\ \text{mm}}\right) \approx 36.0\ mrad \tag{1}$$

Where θ_{max} is the half of the whole convergence angle (see Fig. 1).

In ICF laser driver, the tiling LBO crystals should be placed as close as possible to the focusing lens to prevent the irradiated laser energy density exceeding its damage threshold. LBO crystal with growth size of 150 mm × 150 mm × 10 mm had been obtained [11]. However, it should be tiled in a 3 × 3 array at least for the beam size of 360 mm × 360 mm.

By small signal approximation, THG conversion efficiency of three waves interaction can be expressed as [12]

$$\eta = \eta_0 \cdot \left[\frac{\sin\left(\frac{\Delta k \cdot l}{2}\right)}{\frac{\Delta k \cdot l}{2}}\right]^2 \tag{2}$$

Where η_0 is the THG conversion efficiency in optimum phase matching condition, l is the length of LBO crystal and Δk is the phase mismatching factor.

Solving coupling wave equations is a usual method to calculate conversion efficiency. But in this paper, we obtained the relative THG conversion efficiency by calculating the accepted angles of LBO crystals, which is simple and clear. In the new THG configuration, type-II phase matched cutting angle of the central LBO crystal is $\theta_m = 44.7^\circ$, $\varphi_m = 90^\circ$ at 20 °C [13]. Supposing η_0 is equal to 1, the efficiency η as a function of acceptance angle $\Delta\theta$ and $\Delta\varphi$ depending on different crystal lengths [12] are depicted in Fig. 2, respectively.

When the power density reaches 1.5 GW/cm^2, whatever the phase matching is of type-I or type-II, LBO crystal with thickness of 4 mm is needed [14]. Note from the Fig. 2(a) that when the conversion efficiency η drops to 50.05% with the thickness of 4 mm for the margin incident light, the corresponding angle deviating from phase matched angle is $\Delta\theta_h$=4.025*mard*. Assuming the refractive index of air is 1 and taking the inside acceptance angle of LBO crystal as 4.025 *mrad*, as depicted in Fig. 3, the acceptance angle of LBO crystal outside is

$$\Delta\theta'_h = \arcsin\left[n \times \sin\left(\Delta\theta_h\right)\right] \approx 6.44\ mrad \tag{3}$$

Where n is the refractive index of LBO crystals and its typical average value is 1.60 [12].

In φ direction, for the largest convergence angle $\varphi_{\max}(\varphi_{\max} = \theta_{\max} = 18.0 mrad)$, the incident angle inside LBO crystal is $\varphi'_{\max} = \arcsin[1 \times \sin(18.0\ mrad)/n] \approx 11.25\ mrad$ and THG conversion efficiency is still up to 99.86%, as seen in Fig. 2(b). Consequently, a piece of LBO crystal is enough in φ direction if the growth size of the crystal is large enough. But in θ direction, to fulfill more than 50% of the conversion efficiency for margin incident light, the required number of LBO crystals used to tiling is

$$M = \frac{2\theta_{\max}}{2\Delta\theta'_h} = \frac{36.0\ mrad}{2 \times 6.44\ mrad} \approx 3 \tag{4}$$

As shown in Eq. (4), at least 3 crystals are needed in θ direction to fulfill high conversion efficiency. And limited by the growth size, the LBO crystals must be tiled in a 3 × 3 array.

For one of the 3 LBO crystals in θ direction, maximum incident angle outside crystal is $\theta_{s\max} = \theta_{\max}/3 = 6.0\ mrad$. Corresponding incident angle inside the crystal is $\theta'_{s\max} = \arcsin[1 \times \sin(\theta'_{s\max})/n] = 3.75\ mrad$. The THG conversion efficiency η of the margin light drops to 55.2%. When calculating the conversion efficiency, as shown in Fig. 4, the 3 × 3 LBO crystals titling array is handled as a unit. In θ direction, η rises from 55.2% to 100% then down to 55.2% again. As for any of those out of θ direction, taking the light of NF as an example, it can be projected to plane OEF (the projector is EF) firstly and then calculated.

The average conversion efficiency can be calculated as [15]

$$\eta_{tiled} = \frac{1}{2 \cdot \theta'_{smax} \cdot 2 \cdot \varphi'_{max}} \cdot \iint \eta(\Delta\theta) \cdot \cos\left(\varphi'\right) d\Delta\theta d\varphi' \tag{5}$$

Where φ' is the angle between any focused light rays and the plane OEF inside of LBO crystal. The range of values is (−3.75 mrad, 3.75 mrad) for$\Delta\theta$and (−11.25 mard, 11.25 mrad) for φ' for the 3 × 3 LBO crystals tiling array.

From Eq. (5), we obtained that the average THG conversion efficiency was 83.8% with 3 LBO crystals tiling and 93.1% with 5 crystals tiling with other energy losses neglected.

3. Crystal tiling scheme

Fig. 5 shows the tiling scheme of the new THG configuration. A 3 × 3 array of type-II phase matched LBO crystals are represented by A_i, B_i and C_i (i = 1, 2), individually. Their dimensions are140 mm × 140 mm × 4 mm for A_1 and C_1, 120 mm × 140 mm × 4 mm for A_2, B_1 and C_2, and 120 mm × 120 mm × 4 mm for B_2, respectively.