Laser and Particle Beams

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Using polarization control plate to suppress transverse stimulated Raman scattering in large-aperture KDP crystal

Xinmin Fan[1], Sensen Li[2], Xiaodong Huang[1], Jianxin Zhang[1], Chunyan Wang[1], Hourong Li[1], Yongzhi Sun[1] and Haizhu Sun[1]

[1]School of Physics and Optoelectronic Engineering & Institute of New Electromagnetic Materials, Weifang University, Weifang 261061, China and [2]Science and Technology on Electro-Optical Information Security Control Laboratory, Tianjin 300308, China

Research Article

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Author for correspondence:
Xinmin Fan, School of Physics and Optoelectronic Engineering & Institute of New Electromagnetic Materials, Weifang University, Weifang 261061, China. E-mail: xinminfan@163.com

Abstract

Transverse stimulated Raman scattering (TSRS) is strongly generated in the third-harmonic-generation crystal potassium dihydrogen phosphate (KDP) and can even damage the KDP crystal in inertial confinement fusion drivers. In this work, a method to suppress TSRS is proposed in which the polarization control plate (PCP) is moved to a new position in the existing optical path. The proposed method can suppress TSRS significantly and doubles the laser threshold intensity in KDP crystal when the order of the PCP is 16. This result is attributed to the reduction of the gain length for the Stokes radiation. The proposed method may also be used to suppress other nonlinear effects, including transverse stimulated Brillouin scattering in large-aperture optical components.

Introduction

The aperture of the third-harmonic-generation crystal potassium dihydrogen phosphate (KDP) in inertial confinement fusion (ICF) drivers is very large (about 40 cm) compared with the thickness (about 1 cm). Therefore, the transverse stimulated Raman scattering (TSRS) is strongly generated and can damage a thin, large-aperture KDP crystal when used to generate a high-intensity 3ω laser (with a center wavelength of 351 nm) (Barker *et al*., 1995; Wang, 2011). TSRS is one of the key factors limiting the intensity of 3ω lasers for ICF drivers (Raymer and Mostowski, 1981; Smith *et al*., 1984; Bel'kov *et al*., 1995; Dixit *et al*., 2005). Therefore, suppressing TSRS is an important scientific and technical challenge, and particularly for research on ICF drivers (Sacks *et al*., 1992; Barker *et al*., 1995; Novikov *et al*., 1999; Carr *et al*., 2006; Zhang *et al*., 2010; Demos *et al*., 2011; Fan *et al*., 2013; Guo *et al*., 2013; Han *et al*., 2013*a*, 2013*b*; Han *et al*., 2016).

If a large-aperture KDP crystal is divided into several smaller ones, the TSRS will be reduced because of the reduction of the Stokes gain length; however, this method is very difficult to implement (Sacks *et al*., 1992). The edges of the KDP crystal may be beveled to reduce the edge reflectivity and further reduce the Stokes intensity, but this effect is very limited (Barker *et al*., 1995; Zhang *et al*., 2010). A deuterated KDP crystal can reduce the TSRS gain coefficient, but it cannot fully meet the requirements of engineering applications (Sacks *et al*., 1992; Barker *et al*., 1995; Novikov *et al*., 1999; Carr *et al*., 2006; Demos *et al*., 2011; Guo *et al*., 2013). TSRS can also be significantly suppressed by the laser-induced damage array in the KDP crystal to block the propagation of the TSRS photons (Han *et al*., 2013*a*, 2013*b*). In this work, we propose a method to suppress TSRS in a large-aperture KDP crystal by reconstructing the polarization direction of 1ω laser (with a center wavelength of 1053 nm) by using a polarization control plate (PCP). The method can also smooth the far-field focal spot of the 3ω laser beam. We believe the method can be of great enlightening significance to the nonlinear effects suppression in high power laser systems.

Suppression scheme design

TSRS in KDP crystal

In ICF drivers, the speckle pattern (random intensity distribution) is formed when the laser is either reflected from a rough surface or propagates through a medium with random refractive index fluctuations. The driver laser with the speckle pattern cannot irradiate the target uniformly. The irradiation nonuniformity disturbs the production of a uniform ablation layer on the target surface, consequently, prevents an efficient compression of the fuel and requires much more incident energy of the fusion driver laser. Therefore, the terminal optical system of the ICF driver should smooth the focal spot in addition to converting the frequency and

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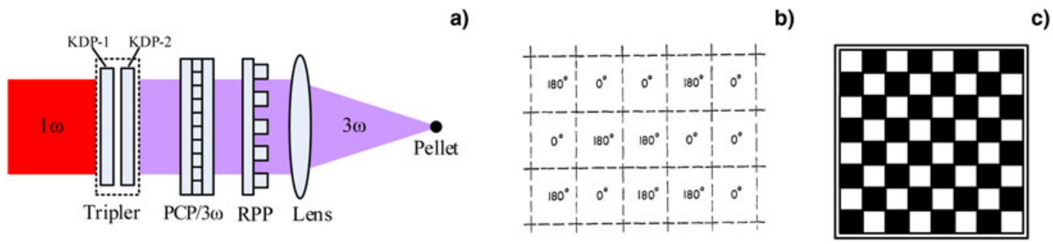

Fig. 1. (a) Schematic diagram of the terminal optical system of ICF driver (Lv, 1999). (b) Portion of the RPP (Burckhardt, 1970). (c) Square PCP with 8 × 8 array (Lv, 1999).

focusing the beam, as shown in Figure 1a. The tripler converts the 1ω laser beam into a 3ω laser beam and includes two KDP crystals. The first crystal, KDP-1, is a frequency-doubling crystal that partly converts 1ω to 2ω, and the second crystal, KDP-2, implements the sum-frequency conversion of 1ω and 2ω into 3ω. The lens is used to focus the laser beam onto the pellet. The RPP (Random Phase Plate, shown in Fig. 1b) consists of an array of square areas of transmitting material each of which applies a phase shift randomly chosen between 0° and 180° to the light incident on it, this will improve the laser beam incoherence and smooth the interference fringes at the far-field focal spot (Burckhardt, 1970). PCP/3ω (shown in Fig. 1c) is used to divide the 3ω laser beam into several small-cross-section sub-beams with the polarization directions of adjacent sub-beams being perpendicular to each other, obviously, the sub-beams with the mutually perpendicular polarization directions are incoherent. Therefore, the PCP can further improve the laser irradiation uniformity on the target surface (Tsubakimoto *et al*., 1992; Lv, 1999).

The gain coefficient of TSRS in KDP is inversely proportional to the lasing wavelength, so the Stokes radiation is more intense in KDP-2 than in KDP-1, which means that KDP-2 is more likely than KDP-1 to suffer damage from TSRS. In KDP-2, the Stokes radiation with the same polarization direction as the 3ω beam gets the maximum gain, so its intensity distribution is symmetric (Sacks *et al*., 1992; Barker *et al*., 1995). For example, in Figure 2, the polarization of the 3ω beam is perpendicular to the paper, so the Stokes radiation grows fastest in the upward and downward directions. When the Stokes radiation makes one trip up (or down) across the crystal, it is amplified by the 3ω laser, so the TSRS process can be regarded as a steady-state process and the Stokes radiation is amplified and becomes very intensive (Sacks *et al*., 1992). TSRS follows the coupled wave equations (Raymer, *et al*., 1979; Sacks *et al*., 1992):

$$\frac{\partial}{\partial x}E_{\mathrm{S}} = -\mathrm{i}k_2 Q^* E_{\mathrm{L}}, \tag{1}$$

$$\frac{\partial}{\partial t}Q^* = -\Gamma Q^* + \mathrm{i}k_1 E_{\mathrm{L}}^* E_{\mathrm{S}}, \tag{2}$$

where E_{L} and E_{S} are the complex amplitudes of the laser and the Stokes radiation. Q represents the medium polarization, k_1 and k_2 are the coupling coefficients

$$k_1 = \sqrt{\frac{\Gamma c^2 g}{8\pi^2 n\hbar\,\omega_{\mathrm{S}}}}, \tag{3}$$

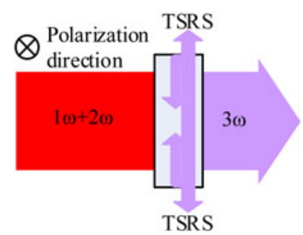

Fig. 2. Schematic diagram of TSRS amplification in KDP crystal.

$$k_2 = \frac{2\pi n\hbar\,\omega_{\mathrm{S}}}{c}k_1^*, \tag{4}$$

Γ is the Raman bandwidth, c is the speed of light in vacuum, n is the medium refractivity, g is the TSRS gain coefficient, ω_{S} is the angular frequency of Stokes. In addition, the reflection of the Stokes radiation from the KDP crystal face further increases the amplification of the Stokes radiation. Therefore, the Stokes radiation is likely to damage the KDP crystal. The TSRS fluence damage threshold for KDP crystals is $F_{\mathrm{th}} = 6\sqrt{\tau}\mathrm{J/cm^2}$, where τ is 3ω laser pulse width (Sacks *et al*., 1992).

To date, the TSRS effect has damaged KDP crystals in several ICF laser drivers, such as Nova (Sacks *et al*., 1992), and Shen Guang-III (Han *et al*., 2013*a*, 2013*b*; Han *et al*., 2016). Figure 3a shows the pattern of destruction in a KDP crystal caused by TSRS in the Shen Guang-III prototype. The destruction pattern is symmetric and is consistent with the theoretical analysis in the references of Barker *et al*., 1995 and Sacks *et al*., 1992. The upper and lower regions do not have exactly the same shape because of the intensity modulation or inhomogeneity in the incident laser beam. Figure 3b shows the calculated distribution of TSRS fluence in KDP near the damage threshold. The 3D simulation is obtained from the coupled wave Eqs (1) and (2) by using the finite difference method. To compare with Figure 3a, 3b shows the top view of the 3D simulation. In the figure, the different colors represent different Stokes fluence. The bar graph on the left in Figure 3b shows that the ranges of Stokes fluence from 0 to around 12 J/cm^2. In the numerical calculation, the center wavelength, the average laser intensity, the pulse width and the beam diameter of 3 ω laser are 351 nm, 1.34 GW/cm^2, 3 ns, 29 cm, respectively; the diameter and edge reflectivity of the KDP crystal are 33 cm and 4%, respectively; the center wavelength and gain coefficient of the Stokes radiation in KDP are 362.6 nm (at frequency shift of 913 cm^{-1}) and 0.345 cm/GW (Sacks *et al*., 1992), respectively. The parameters and conditions are basically the same as in Figure 3a, except for the intensity modulation.

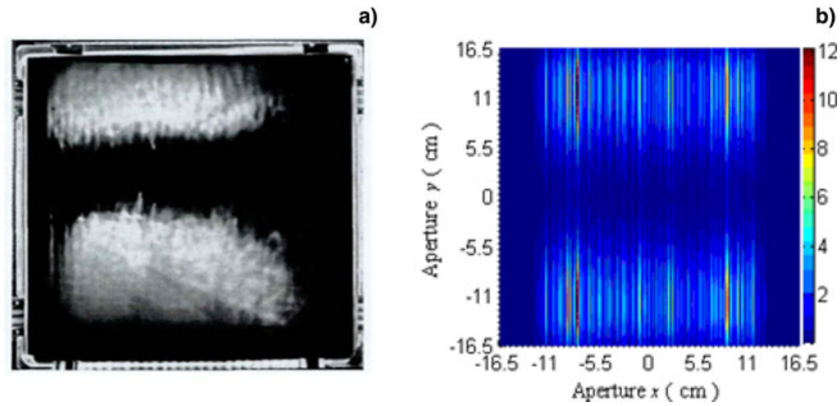

Fig. 3. (a) Dark-field images of damage to KDP induced by TSRS in Shen Guang-III (Wang, 2011) and (b) calculated distribution of TSRS fluence near damage threshold of KDP.

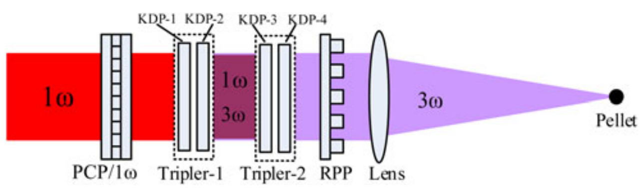

Fig. 4. Sketch of TSRS suppression in KDP third-harmonic-generation crystal by using PCP/1ω.

Suppression scheme design and the suppression effects

To protect KDP from TSRS damage, we propose a method to suppress TSRS based on Figure 1a by reconstructing the 1ω laser beam using the PCP. In addition, the proposed method can also smooth the 3ω focal spot, as indicated in Figure 4. Unlike Figure 1a, the polarization control plate is inserted in the 1ω-beam path to divide the 1ω laser beam into several sub-beams, with the polarization directions of adjacent sub-beams perpendicular to each other. The two types of sub-beams need two frequency triplers: Tripler-1 transforms the 1ω sub-beams with the vertical polarization into 3ω sub-beams, and tripler-2 transforms the 1ω sub-beams with horizontal polarization into 3ω sub-beams. Thus, tripler-1 and tripler-2 have the same physical parameters but their optical axes are oriented differently. The terminal 3ω laser beam behind tripler-2 is also constructed from sub-beams and the polarizations of adjacent sub-beams are perpendicular to each other. Therefore, the 3ω laser uniformly irradiates the pellet after passing through the random phase plate and the lens, as shown in Figure 4.

Compared with Figure 1a, Figure 4 has two triplers instead of one, and the gain region for the Stokes radiation changes from the large cross-section of the whole beam to the small cross-section of a sub-beam. Thus, the proposed method remarkably suppresses TSRS. For example, assume that PCP/1ω is a 4×4 matrix and divides the 1ω beam into 16 sub-beams; the polarization is then either horizontal or vertical, as shown in Fig. 5a. The 1ω laser sub-beams of elements A, C, F, H, I, K, N, and P with vertical polarization are converted into 3ω laser sub-beams in elements A, C, F, H, I, K, N, and P of KDP-2, and the Stokes radiation is transmitted and amplified in the horizontal direction in these regions, as shown in Fig. 5b. Clearly, the Stokes intensity will be greatly reduced thus the laser threshold intensity in KDP crystal is increased, because the cross-section of the sub-beams is reduced to a quarter of that of the original beam incident on KDP-2 in Fig. 1a. However, the gain length of TSRS does not decrease to 1/4 rather than to about 1/2. Because the Stokes will also be amplified further when they passing through the regions where have the laser with the same polarization directions. For example, the Stokes coming from A region will also be amplified further in the C region. Using equations (1) and (2), it can be calculated that the growth rate of the laser threshold intensity in KDP crystal is 1.83 after using the scheme with 4-order PCP/1ω. The growth rate reaches 2 when using the 16-order PCP/1ω, the growth rate of the laser threshold intensity M increases with increasing the order of the PCP/1ω N, as shown in Figure 6. The same is true for KDP-4 (see Fig. 5c). It should be noted that the PCP/1ω can still smooth the 3ω far-field focal spot.

Summary and conclusion

The results of this analysis show that large-aperture KDP crystals are easily damaged by TSRS in ICF drives. This work thus proposes a method to suppress TSRS by changing the position of the PCP in the existing optical path. The results show that the

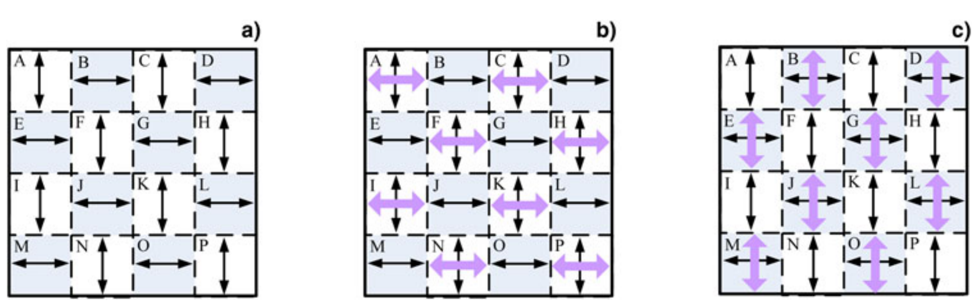

Fig. 5. (a) Polarization of 1ω laser beam in PCP/1ω. The Stokes light generated in (b) KDP-2 and (c) KDP-4 when the 3ω radiation is generated.

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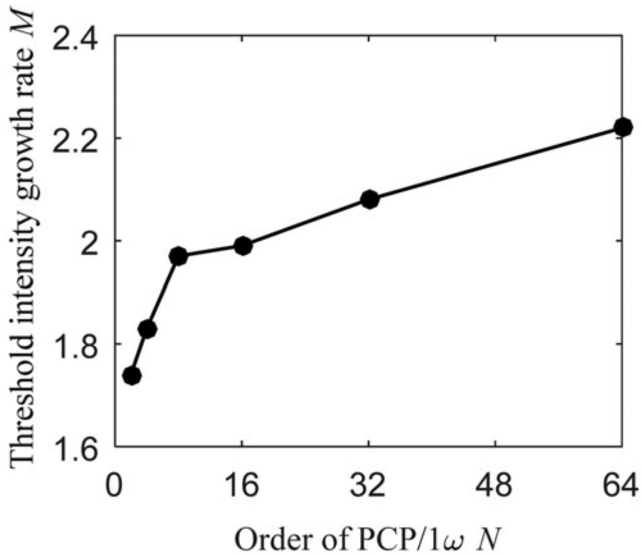

Fig. 6. Variation of the laser threshold intensity growth rate *M* with the order of PCP/1ω *N*.

proposed method can suppress TSRS significantly and doubles the laser threshold intensity in KDP crystal when the order of the PCP/1ω is 16, and the laser threshold intensity increases with increasing the order of the PCP/1ω. Meanwhile, the PCP/1ω can still smooth the 3ω far-field focal spot. In addition, the proposed method can also suppress transverse stimulated Brillouin scattering and other nonlinear effects in large-aperture optical components.

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Author ORCIDs. Xinmin Fan 0000-0001-6208-9520.

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