Investigation of stimulated rotational Raman scattering of the high-power broadband laser with applied angular dispersion*

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Smoothing by spectral dispersion (SSD) leads to considerable improvement on laser-irradiation uniformity in far field for fusion lasers. Phase modulation in time and spectral angular dispersion (SAD) across the beam introduced by SSD will affect the stimulated rotational Raman scattering (SRRS) gain in the near field. This paper focuses on the influence of SAD on SRRS gain under different laser conditions. Results show that the SAD will aggravate the generation of SRRS when the laser initial additional phase is constant. On the contrary, the SAD can reduce the SRRS gain if appropriate SSD parameters are adopted when the laser initial additional phase is variable. SSD has a certain application prospect in SRRS suppression.

Keywords: spectral angular dispersion, smoothing by spectral dispersion, rotational Raman scattering

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1. Introduction

For laser fusion and many other applications, some high-energy and high-power beams must propagate over long air paths, resulting in the generation of the unwanted nonlinear effect of stimulated rotational Raman scattering (SRRS), which limits the laser intensity and fluence that can be transmitted through the air.[1–7] Therefore, the solutions for suppressing the SRRS process have been pursued.[8–10] Smoothing by spectral dispersion (SSD) is originally a smoothing technique to obtain highly smooth focused laser beams in the far field[11] and has produced considerable improvement in this aspect.[12–15] Skeldon and Bahr[10] proposed that SSD could reduce the SRRS gain in the near field via experiment. Fan *et al.*[16] further studied the mechanism of SSD suppressing SRRS and indicated that the suppression effect was attributed to the pure phase modulation (PPM) in time and the spectral angular dispersion (SAD) across the beam introduced by SSD.

In the light of the application prospect in the far field, SSD will bring a great advantage to the designing and building of the large scale lasers if it can effectively suppress the SRRS process in the near field. However, there are still few research studies in this aspect so far.

In this paper, our contribution is to provide the influences of SAD on SRRS gain under different laser conditions.

The rest of this paper is divided into three sections as follows. In Sections 2, 3, and 4, we give the relevant theories, the simulation results and analyses, and the concluding remarks respectively.

2. Theories

The governing Raman equations under slowly varying envelop approximation are[6]

$$\left(\nabla_{\perp}^{2}+2\mathrm{i}k_{\mathrm{L}}\frac{\partial}{\partial z}\right)E_{\mathrm{L}}=2k_{3}k_{\mathrm{L}}QE_{\mathrm{S}}, \tag{1a}$$

$$\left(\nabla_{\perp}^{2}+2\mathrm{i}k_{\mathrm{S}}\frac{\partial}{\partial z}\right)E_{\mathrm{S}}=2k_{2}k_{\mathrm{S}}Q^{*}E_{\mathrm{L}}, \tag{1b}$$

$$\frac{\partial}{\partial t}Q^{*}=-\Gamma Q^{*}+\mathrm{i}k_{1}E_{\mathrm{L}}^{*}E_{\mathrm{S}}, \tag{1c}$$

where E_{L} and E_{S} are the laser and the Stokes complex amplitudes and their respective wave numbers are k_{L} and k_{S}; Q represents the medium polarization; k_1, k_2, and k_3 are the coupling coefficients; Γ is the Raman bandwidth. Equations (1a) and (1b) contain the influence of diffraction on laser and Stokes transmission. In the following simulation, we only give the one-dimensional variations of physical quantities along the x axis considering the spatial symmetry of the beam.

Generally, inertial confinement fusion (ICF) drivers or other large scale lasers with numerous optical elements, the phase across the output beam is varied or distorted, the distorted phase is named additional phase here and could be expressed as[17,18]

$$\varphi_{0}(x)=\varphi_{0\mathrm{L}}(x)+\varphi_{0\mathrm{H}}(x), \tag{2}$$

where

$$\varphi_{0\mathrm{L}}(x)=A\cdot\mathrm{Random}(-1,1)\otimes\exp\left[-\left(\frac{x}{S_x}\right)^{2}\right], \tag{3}$$

$$\varphi_{0\mathrm{H}}(x)=\sigma\cdot\mathrm{Random}(-1,1). \tag{4}$$

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Here, $\varphi_{0L}(x)$ and $\varphi_{0H}(x)$ represent the low and high frequency additional phase terms respectively. The low frequency term $\varphi_{0L}(x)$ is a random Gaussian distribution generated by convolving a Gaussian function with a uniformly distributed random number sequence. In Eq. (3), A is the low frequency phase amplitude coefficient; S_x is the factor determining the size of phase distortion of the laser beam in the x direction; σ is the disturbing amplitude of the high frequency random phase.

SSD is obtained by an electro-optic modulator broadening the bandwidth of the initial narrow-linewidth (NLW) laser and one or two gratings introducing SAD across the transverse direction of the beam without distorting the temporal pulse shape.[11] For the SSD pulse output from large scale lasers, the complex amplitude of the electric field under slowly varying amplitude approximation can be written as[11]

$$E_L(x,t) = E_{L0}(x,t)\exp\left\{i\delta\sin\left[2\pi\left(\nu_m t+\beta\frac{\nu_m}{\nu_0}x\right)\right] + i\varphi_0(x)\right\}, \quad (5)$$

where $E_{L0}(x,t)$ is the real amplitude of the electric field, $\varphi_0(x)$ is the transverse additional phase of the beam, δ and ν_m are the modulation amplitude and frequency of the phase-modulator respectively, $\beta = \Delta\theta/\Delta\lambda$ is the grating dispersion coefficient, ν_0 is the laser central frequency.

3. Simulation results and analyses

In the simulation, the values of physical parameters are given as follows. For the initial laser, both the temporal and the spatial distribution are 18-order super-Gaussian, the central wave length, the intensity, the full width, and the diameter are 1053 nm, 2 GW/cm^2, 3 ns, and 10 cm respectively. For the Stokes light, we assume that it only refers to the spectral line $S(8)$ which has a maximum gain coefficient of 2.5 cm/TW[1] and central wave length of 1061.5 nm obtained from Eq. (1) in Ref. [10]. In addition, the generation threshold for SRRS is defined as the value at which the energy of Stokes light reaches 1% of that of the initial laser, and the corresponding transmission length is defined as threshold distance. For simplicity, the size of divergence angle and the reduction of laser intensity caused by the divergence angle are ignored.

According to the SSD principle described in Ref. [11] and Eq. (5), the variation of the phase in both time and space is the outstanding characteristic of the SSD beam different from other lasers, and we can consider that SSD introduces PPM in time and SAD across the beam into the laser pulse simultaneously. The phase variation, which is determined by the three modulation parameters (modulation amplitude δ, modulation frequency ν_m, and grating dispersion coefficient β) and the additional phase $\varphi_0(x)$, may change the linear and nonlinear characteristics of the laser beam.

Substituting the laser electric field Eq. (5) into the coupled wave Eqs. (1a)–(1c), we simulate the variations of the Stokes energy conversion efficiency η with the transmission distance z under different modulation parameters as shown in Fig. 1. Here, figures 1(a) and 1(b) respectively represent the laser initial additional phase $\varphi_0(x)$ constant (let $\varphi_0(x) = 0$) and variable (where $A = 2$, $S_x = 5$ cm, $\sigma = 0.2$). The modulation parameters of pulse 1, 2, and 3 are $\delta = 0$, $\nu_m = 0$, $\beta = 0$; $\delta = 2$, $\nu_m = 20$ GHz, $\beta = 0$; $\delta = 2$, $\nu_m = 20$ GHz, $\beta = 1.5$ mrad/nm ($\Delta\lambda = 0.3$ nm) respectively, and they represent NLW, PPM, and SSD pulses respectively.

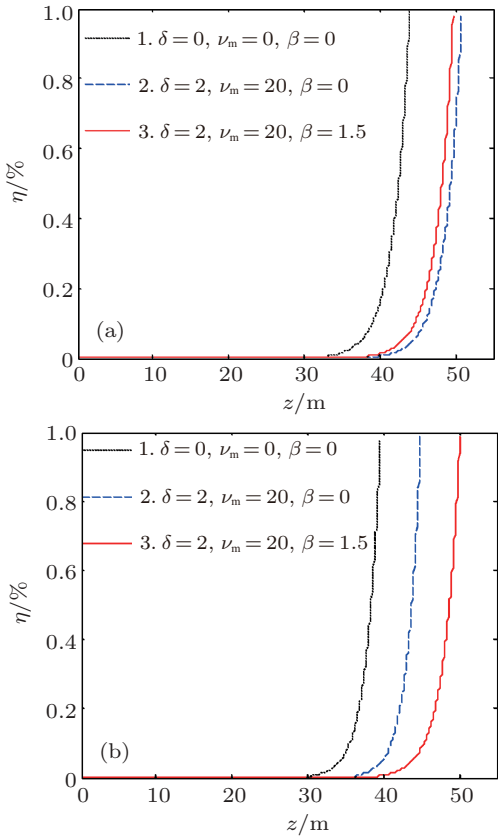


Fig. 1. (color online) Plots of Stokes energy conversion efficiency η versus propagation distance z when the transverse additional phase $\varphi_0(x)$ of initial laser pulse is (a) constant (let $\varphi_0(x) = 0$) and (b) variable (where $A = 2$, $S_x = 5$ cm, $\sigma = 0.2$).

From Fig. 1(a), it can be seen that the SRRS threshold distances of pulse 1, 2, and 3 vary with modulation parameter when the laser initial additional phase is constant, and they are $z_{tha1} = 44.0$ m, $z_{tha2} = 50.8$ m, $z_{tha3} = 49.7$ m respectively, their magnitudes are in order of $z_{tha2} > z_{tha3} > z_{tha1}$. When the laser initial additional phase is variable, the SRRS threshold distances become $z_{thb1} = 39.6$ m, $z_{thb2} = 44.9$ m, and $z_{thb3} = 50.1$ m respectively as shown in Fig. 1(b), and their magnitudes become the order of $z_{thb3} > z_{thb2} > z_{thb1}$. Comparing Fig. 1(a) with Fig. 1(b), it is not hard to find that the threshold distance of NLW and PPM pulses decreases while

that of SSD pulse increases when the laser initial additional phase changes from constant to variable.

From the above simulation, it can be inferred that both PPM in time and SAD across the beam of the SSD pulse affect the SRRS gain. From the threshold distances relation $z_{\mathrm{tha2}} > z_{\mathrm{tha1}}$ and $z_{\mathrm{thb2}} > z_{\mathrm{thb1}}$, we can deduce that PPM can suppress the SRRS process, and the suppression effect is hardly affected by the distribution of the laser additional phase, and we think that the characteristic phase restoration length[19] of PPM pulse is longer than that of NLW pulse, which is the root cause of the suppression effect. However, reference [10] indicated that PPM could hardly suppress the SRRS process, which could be caused by the complicated intensity and phase distribution of the laser (such as hotspots[10,20]). The influence of SAD on SRRS gain is affected by the laser additional phase because $z_{\mathrm{tha3}} < z_{\mathrm{tha2}}$ while $z_{\mathrm{thb3}} > z_{\mathrm{thb2}}$: the SAD will aggravate the production of SRRS when the laser initial additional phase is constant; on the contrary, the SAD can reduce the SRRS gain if appropriate SSD parameters are adopted, when the laser initial additional phase is variable. Therefore, it is necessary to study the distribution of the laser additional phase if we use SSD to suppress the SRRS process.

The detailed explanation of the influence of SAD on SRRS gain can be described as follows. Under the combined action of PPM and SAD, at each instant of time of the SSD pulse, the phase varies across the beam (i.e., in the direction transverse to the beam) and along a sine curve when the initial additional phase $\varphi_0(x)$ is constant according to Eq. (5), which leads to the intensity modulation across the beam caused by diffraction effect during propagation, so the SRRS gain of SSD pulse is larger than that of PPM pulse ($z_{\mathrm{tha3}} < z_{\mathrm{tha2}}$) in Fig. 1(a). However, the variation curves of the phase at each instant are similar within the whole pulse, and they move slightly along the same direction across the beam as time goes by, which causes the position of the peak intensity at any instant to hardly coincide with that at any other instant. Consequently, the laser fluence modulation degree will be reduced if appropriate SSD parameters are adopted when the laser initial phase is variable, resulting in the SRRS gain of SSD pulse, which is smaller than those of NLW and PPM pulses ($z_{\mathrm{thb3}} > z_{\mathrm{thb2}} > z_{\mathrm{thb1}}$), for example, in Fig. 1(b).

From the above analyses, it can be seen that the intensity distribution of the laser will be modulated in both time and space during propagation, whichever will affect the SRRS process. However, the SRRS gain is directly determined by the laser fluence modulation, and the SAD has different effects on the laser fluence modulation under different laser conditions. The SAD will increase the laser fluence modulation degree when the laser initial additional phase is constant, on the contrary, the SAD can reduce the laser fluence modulation degree if appropriate SSD parameters are adopted when the laser initial additional phase is variable. Therefore, SSD has a certain application prospect in SRRS suppression for the ICF driver or other large scale lasers whose output laser beams generally have larger phase distortions.

Figure 2(a) shows the variations of the laser fluence modulation degree M_{F} with the transmission distance z without SRRS and other nonlinear effects, the black dotted and red solid line represent the cases of NLW and SSD pulses respectively, and the initial additional phase distribution of the laser is the same as that in Fig. 1(b). It can be seen from Fig. 2(a) that in the case of NLW pulse, with the increase of distance, the laser fluence modulation degree varies dramatically with an overall uptrend. It can be deduced that the fluence modulation degree of NLW beam is very unstable so even sudden changes can appear during propagation when the laser initial additional phase is variable; in the case of SSD pulse, the fluence modulation degree and the fluctuation are always smaller than those of NLW beam over the whole transmission path. The fluence modulation degrees of NLW and SSD beam are 1.9 and 1.4 respectively at the destination of 40 m as shown in Fig. 2(b). Obviously, the SSD can significantly suppress the laser fluence modulation in the near field if appropriate SSD parameters are adopted when the laser initial

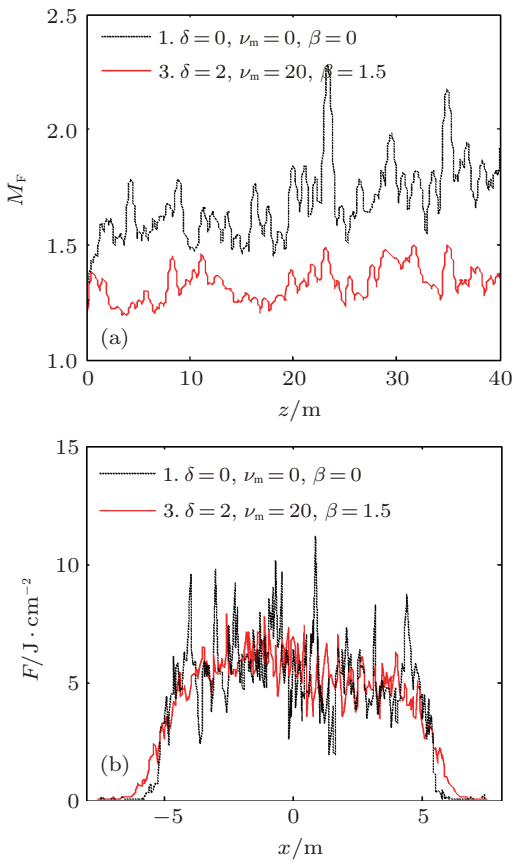


Fig. 2. (color online) (a) Variations of laser fluence modulation M_F with transmission distance z and (b) the laser fluence distributions along x axis at the destination of 40 m in the cases of NLW (black dotted line) and SSD (red solid line).

additional phase is variable. In addition, the simulation results prove that the fluence modulation degrees of PPM and NLW pulse are the same during transmission. Therefore, the PPM in time does not change the linear transmission characteristic of the beam, which once again proves that SAD affects the laser fluence modulation degree.

4. Conclusion

In this paper we study the influences of SAD on SRRS gain under different laser conditions. It is demonstrated that the SAD will aggravate the generation of SRRS when the laser initial additional phase is constant, on the contrary, the SAD can reduce the SRRS gain if appropriate SSD parameters are adopted when the laser initial additional phase is variable, which is attributed to the influence of the SAD on the laser fluence modulation degree. Therefore, it is necessary to study the distribution of the laser additional phase if we use SSD to suppress the SRRS process. The SSD also has a certain application prospect in nonlinear effect suppression in the near field for large scale lasers besides in laser-irradiation uniformity in the far field.

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