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ABSTRACT
Stimulated Brillouin scattering (SBS) is a basic problem for laser–plasma interactions. In this work, two perpendicular linear polarization lasers with different frequencies are combined to form a new beam. The polarization of the new beam varies between linear and ellipse, while the intensity remains constant. By adopting this method, a significant suppression of SBS is predicted due to the reduction in the effective wave–wave interaction lengths. Additionally, two linearly polarized beams would be easier to use in an experiment than an alternate approach using two circularly polarized beams. The suppression of SBS is modeled with a nonlinear wave–wave coupling model, and the model is verified with 1D particle-in-cell simulations.

I. INTRODUCTION
Stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) are basic problems for laser–plasma interactions. They scatter incident laser energy and cause other harmful effects in both direct and indirect drivers. In indirect inertial confinement fusion (ICF), SRS is dominant for the inner beams, and SBS is dominant for the outer beams. Many methods have been proposed to reduce the effect of laser–plasma interactions by controlling the laser parameters or plasma parameters. Spatial smoothing, spectral dispersion, and polarization smoothing are multiple incident laser manipulation techniques to reduce SBS and SRS. Spike trains of uneven duration and delay (STUD), alternating-polarization light, and polarization rotation are adopted to suppress the growth rate and the reflectivity of SRS or SBS by decreasing the effective interaction length.

In this article, a new form of incident light is proposed, which is a combination of two perpendicular linear polarization lasers with different frequencies. The polarization varies between linear and ellipse due to the relative phase accumulations of the two incident lights, while the intensity of the new incident light is constant. Moreover, it is easier to be set or controlled by two linear polarization lasers than two circularly polarized waves.

This article is organized as follows. The theoretical approach of the suppression of SBS by two perpendicular linear polarization lasers based on the wave–wave model is presented in Sec. II. One-dimension particle-in-cell (PIC) simulation to study the effect of the suppression of SBS caused by different incident lasers is given in Sec. III. Summaries are presented in Sec. IV.

II. THEORY
A. Wave–wave equations
The incident light is a combination of two linear polarization lasers. Consider a vector potential, \( A_0 \), of the form

\[
A_0 = A_y + i A_z = \frac{a_0}{\sqrt{2}} e^{i(k_1 x - \omega_1 t)} y + \frac{a_0}{\sqrt{2}} e^{i(k_2 x - \omega_2 t)} z,
\]

(1)
where $A_0$ and $a_0$ are the vector potential and dimensionless amplitude of the incident light, respectively, with $A_0$ in the unit of $m_e c/e$, $m$ and $e$ are the mass and charge of the electron, respectively, $c$ is the speed of light in vacuum, and $A_i, A_z, \omega_1, \omega_2, k_i, \omega_z$ are the vector potentials, frequencies, and wave vectors of incident lights with the polarization in the y and z direction, respectively. We define $\Omega = \omega_1 - \omega_2$, which is the frequency difference of these two incident lights. A simple schematic of the perpendicular linear polarization laser propagation is shown in Fig. 1. The polarization of this incident light varies between linear and ellipse due to the relative phase accumulations.

The evolution of SBS in one-dimension can be described by the following wave equations:

$$
\left( \frac{\partial}{\partial t} + V'_y \frac{\partial}{\partial x} + \frac{1}{2} \frac{\partial}{\partial x} V'_z \right) \psi_y = -\frac{4\pi c^2}{m_e a'_i} \sqrt{2} e^{i(k_i - k'_i)x - (\omega_1 - \omega'_1)t},
$$

(6)

$$
\left( \frac{\partial}{\partial t} + V'_z \frac{\partial}{\partial x} + \frac{1}{2} \frac{\partial}{\partial x} V'_y \right) \psi_z = -\frac{4\pi c^2}{m_e a'_z} \sqrt{2} e^{i(k_z - k'_z)z - (\omega_2 - \omega'_2)t},
$$

(7)

$$
\left( \frac{\partial}{\partial t} + V'_y' \frac{\partial}{\partial x} + \frac{1}{2} \frac{\partial}{\partial x} V'_z' \right) \psi_y' = -\frac{4\pi c^2}{m_e a'_i} \sqrt{2} e^{i(k_i - k'_i)x - (\omega_1 - \omega'_1)t},
$$

(8)

where $V'_y = \frac{k'_y}{\omega'_y}, V'_z = \frac{k'_z}{\omega'_z}$, and $V'_y' = \frac{k'_y}{\omega'_y}$ are the group velocities of the waves, and they can be neglected in the homogeneous plasma. The matching relations are

$$
\omega_1 = \omega'_1 + \omega_i, \quad k_i = k'_i + k_1, \quad \omega_2 = \omega'_2 + \omega_z, \quad k_2 = k'_2 + k_2.
$$

(9)

(10)

(11)

(12)

### B. The growth rate of SBS

In the simulation, a hydrogen plasma is used, and the electron (ion) temperature is $T_e = 1000$ eV ($T_i = 50$ eV). The Landau damp can be calculated by the following equation in a harmonic plasma:

$$
v_{li} = \sqrt{\frac{\pi}{8}} \omega_i \left[ m_e \left( \frac{e}{m} \right) \frac{1}{1 + \left( \frac{2Z}{\omega_i} \right)^2} \right].
$$

(13)

The Landau damping is $v_{li} = 0.0146a_{li}$. The threshold of the SBS absolute growth rate can be calculated through $\gamma_0 = \frac{\omega_i^2}{2} \left( V' \right) = 1.75 \times 10^3 s^{-1}$. In the simulation, the growth rate of SBS is $\gamma_0 = 1.9 \times 10^2 s^{-1}$, which is much bigger than $\gamma_0$.

Thus, $\delta n_1$ and $\delta n_2$ are mainly determined by $t$ only. $\delta n_1$ and $\delta n_2$ can be solved by Eqs. (7) and (8),

$$
\delta n_1 = \frac{iZn_0 e^2 a'_i b'_i k^2}{4\sqrt{2m_e m_i c^2 \omega_1} \gamma_y},
$$

(14)

$$
\delta n_2 = \frac{iZn_0 e^2 a'_z b'_z k^2}{4\sqrt{2m_e m_i c^2 \omega_2} \gamma_y},
$$

(15)

$\gamma_y$ and $\gamma_z$ are the growth rates of SBS from different directions, respectively. When SBS is saturated and for a hydrogen plasma, $\gamma_y$ can be solved by Eq. (5) through $\delta n_1$ and $\delta n_2$,

$$
\gamma_y^2 = \frac{n_e^2 a'_i b'_i k^2}{4m_e m_i c^2} \frac{4\pi c^2}{m_e a'_i} \left( 1 + \cos \Omega t \right)
$$

$$
= \frac{n_e^2 a'_i b'_i k^2}{4m_e m_i c^2} \frac{4\pi c^2}{m_e a'_i} \left( 2 \cos^2 \frac{\Omega t}{2} \right)
$$

$$
= \gamma_y^2 \cos^2 \frac{\Omega t}{2}.
$$

(16)
function, and the minimum is determined by \( t \) when \( \Omega \) increases because of the monotonicity of the function 

\[
y_{\gamma} = y_{0} \cos \left( \frac{\Omega}{2^t} \right)
\]

Similarly, \( y_{\gamma} \) can be solved by Eq. 6,

\[
y_{\gamma} = \frac{Z_{m} c^2 \delta^{\gamma} \rho_0^2}{4 m_{e} m_{p} c^2 \omega_2} \left( 2 \cos^2 \frac{\Omega}{2} \right)^{\frac{1}{2}} = y_{0} \cos^2 \frac{\Omega}{2}. 
\]

In one direction, the growth of SBS is synchronous in the whole simulation space. Before saturation, SBS would increase in a growth interval, and the growth interval \( t_{sat} \) is determined by the temporal growth rate of SBS. When \( \Omega \) changes, \( y_{\gamma} \) varies with different \( \Omega \) and \( t \), but the growth time of SBS is still limited in the growth interval. Thus, the growth rate of SBS can be calculated by the time average of \( y_{\gamma} \) or \( y_{\gamma} \) in the growth interval,

\[
I_{\text{back}} = I_{\text{seed}} e^{y_{\gamma} t_{sat}},
\]

where \( I_{\text{back}} \) and \( I_{\text{seed}} \) are the intensities of the backscattering light when \( \Omega = 0 \) and the seed light, respectively,

\[
\bar{y}_{\gamma} = \frac{y_{0}}{y_{\gamma}} \int_{0}^{t_{sat}} \cos \left( \frac{\Omega}{2^t} \right) dt.
\]

Thus, the intensity of the backscattering light can be accumulated by \( \bar{y}_{\gamma} = I_{\text{seed}} e^{y_{\gamma} t_{sat}} \), where \( I_{\gamma} \) is the intensity of the backscattering light.

We define \( R = \frac{I_{\text{back}}}{I_{\gamma}} \), where \( I_{\gamma} \) is the intensity of the incident light. The reflectivity can be calculated through \( R_{\Omega_{\gamma}} \),

\[
R = \frac{I_{\text{back}}}{I_{\gamma}} = \frac{I_{\Omega_{\gamma}}}{I_{\gamma}} = R_{\Omega_{\gamma}} e^{y_{\gamma} t_{sat}}.
\]

From these expressions, it is predicted that SBS is suppressed when \( \Omega \) increases because of the monotonicity of the function \( e^{y_{\gamma} t_{sat}} \). When \( \bar{y}_{\gamma} = y_{\gamma} \), \( R_{\gamma} = R_{\Omega_{\gamma}} e^{y_{\gamma} t_{sat}} \), which is the first smallest value of reflectivity for the periodicity of the cosine function, and the minimum is determined by \( t_{sat} = \frac{y_{\gamma}}{y_{\gamma} \Omega_{\gamma}} \). When \( \Omega \) is big enough, many cycles would be involved in the growth interval, and SBS can only grow in every cycle separately. In one cycle, the reflectivity of SBS can be derived from \( \bar{y}_{\gamma} \) and \( \Delta \),

\[
\Delta \gamma = 1 - \frac{1}{2} \left( 2 \cos^2 \frac{\Omega}{2} \right) = y_{0} \cos^2 \frac{\Omega}{2}.
\]

Thus, \( R \) will be saturated when \( \Omega \) is too big and it will equal \( \Delta \).
The relations of the reflectivity of SBS versus different frequency differences are obtained and plotted in Fig. 5. The reflectivity reduced monotonically before the lowest reflectivity when $\Omega = 400$ GHz which is near the value predicted by theoretical equations, $\frac{\pi}{2} t_{sat} = 360$ GHz. The smallest reflectivity $R = 0.04$ is also consistent with the theoretical value, $R = 0.0448$. In theory, the saturation will appear after $\frac{\pi}{2} t_{sat}/2\pi = 360$ GHz, and the simulation is consistent with it. The reflectivity increases a little after 360 GHz because more than one cycle is involved in the growth interval and the SBS returns to be resonant.

Moreover, a series of simulations with different plasma lengths are performed. The plasma length is set to $L = 0.175$ mm, about $500\lambda$, and the lowest reflectivity appears at about $\Omega = 400$ GHz, as shown in Fig. 6, which is near the value of $\Omega = 469$ GHz, which proves the correctness of the theory.

The variation in reflectivity versus $\Omega$ can be explained physically as well. SBS will increase when the backscattering light and polarization direction are in the same direction. The variation in polarization between linear and ellipse will reduce the effective interaction length of SBS. When $\Omega = 0$, the backscattering light and polarization direction are in the same direction all the time, and the reflectivity of SBS reaches the highest value. When $\Omega$ is small, polarization of some incident lights is not in the same direction as the backscattering light, and the growth of SBS is suppressed. When $\Omega$ is big enough, the polarization changes fast enough where many cycles are involved in the growth interval. The growth of SBS is the same as in a single cycle, and the reflectivity will saturate at a low level all the time.

IV. CONCLUSIONS

In order to suppress SBS, a new form of incident light, which is a combination of two perpendicular linear polarization lasers with different frequencies, is proposed. A new theory of it...
is proposed and proved. The reflectivity of SBS is suppressed from 0.16 to 0.04, which is about four times smaller than that of the single linear incident light with a suitable choice of frequency difference. The reflectivity of SBS reduces monotonically before saturation, and it will saturate when the frequency difference is too large. The lowest reflectivity can be predicted by theory when \( \Omega = \frac{\pi}{t_{\text{sat}}} \), and the variation in reflectivity can be described precisely as well. Additionally, two linearly polarized beams would be easier to use in an experiment than an alternate approach using two circularly polarized beams.

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