Anti-Stokes scattering and Stokes scattering of stimulated Brillouin scattering cascade in high-intensity laser–plasma interaction

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Abstract

Anti-Stokes scattering and Stokes scattering in stimulated Brillouin scattering (SBS) cascades have been researched using the Vlasov–Maxwell simulation. In high-intensity laser–plasma interactions, stimulated anti-Stokes Brillouin scattering (SABS) will occur after second stage SBS rescattering. The mechanism of SABS has been put forward to explain this phenomenon. In the early phase of SBS evolution, only first stage SBS appears and total SBS reflectivity comes from first stage SBS. However, when high-stage SBS and SABS occur, SBS reflectivity will display burst behavior and the total reflectivity comes from the SBS cascade and SABS superimposition. The SABS will compete with the SBS rescattering to determine the total SBS reflectivity. Thus, SBS rescattering including SABS is an important saturation mechanism of SBS and should be taken into account in high-intensity laser–plasma interaction.

Keywords: stimulated Brillouin scattering, ion-acoustic waves, inertial confinement fusion, laser–plasma interaction

(Some figures may appear in colour only in the online journal)

1. Introduction

Backward stimulated Brillouin scattering (SBS), i.e., Stokes scattering, is a three-wave interaction process where an incident electromagnetic wave (EMW) decays into a back-scattered EMW and a forward propagating ion-acoustic wave (IAW). Backward SBS leads to great energy loss of the incident laser and is detrimental in inertial confinement fusion (ICF). Many mechanisms for the saturation of SBS have been put forward, including the creation of cavities in plasmas [7–10], frequency detuning due to particle trapping [11–14], coupling with higher harmonics [15, 16], increasing linear Landau damping by kinetic ion heating [17, 18] and so on. However, if the pump light intensity is large enough or the IAW Landau damping is low enough, it is possible for the scattered light to be scattered again. The multi-stage rescattering of SBS is called an SBS cascade [19–21]. In this paper, the rescattering of SBS is observed and found to be an important saturation mechanism of SBS in the high-intensity laser region. Theoretical work on SBS rescattering [19] gives a prediction of reduced SBS reflectivity under the assumption that the incident light is allowed to scatter only twice. In fact, multiple SBS rescattering will occur in the high-intensity laser region [20, 21], and different stage SBS rescatterings will have different
effects on the total reflectivity or total transmissivity of SBS. Therefore, the simulation of an SBS cascade is requisite. This paper will give a detailed analysis of each stage of SBS rescattering evolution with time, and demonstrate how SBS rescatterings compete with each other to affect reflectivity or transmissivity.

In addition to Stokes scattering in the SBS cascade, which is a common scattering mechanism of SBS, there exists a novel scattered light with a higher frequency than the pump light frequency. This novel scattering is called stimulated anti-Stokes Brillouin scattering (SABS). SABS occurs when a pump light (EMW0) couples with an inverse IAW (denoted as IAW2) to produce a backward scattering light (EMW$_{-1}$) with a higher frequency than the pump light, i.e., $\text{EMW}_0 + \text{IAW}_2 \rightarrow \text{EMW}_{-1}$, and the three waves satisfy the frequency and wave vector match conditions, i.e., $\vec{k}_0 + \vec{k}_{\text{IAW}_2} = -\vec{k}_{-1}$, $\omega_0 + \omega_{\text{IAW}_2} = \omega_{-1}$, where $\vec{k}_i$ and $\omega_i$ ($i = 0$, $\text{IAW}_2$, $-1$) are the wave vectors and frequencies of the corresponding waves (EMW0, IAW2, EMW$_{-1}$). Anti-Stokes Raman scattering was researched with intense light interaction with gas [22, 23], liquid [24] and solid [25]. And anti-Stokes scattering of SBS was researched with intense light interaction with liquid [26] and solid [27]. However, research on anti-Stokes scattering in SBS cascades with high-intensity laser–plasma interaction has seldomly been reported.

This paper gives an insight into SBS with high-intensity laser–plasma interaction. We found that only when second stage SBS rescattering (denoted SBS2) occurs can the IAW generated by SBS2 couple with the pump light to generate a higher-frequency scattered light, which is the stimulated anti-Stokes Brillouin scattering (SABS) process. And SABS can be even stronger than third stage SBS rescattering (SBS3), thus SABS should be considered as a competitor with other SBS rescattering processes. The total SBS reflectivity is the result of effects of SBS rescattering and SABS.

2. Numerical simulations and theoretical analyses

One dimension in space and one dimension in velocity (1D1V) Vlasov–Maxwell code [28–30] is used to simulate the SBS cascade and SABS process. The electron temperature is $T_e = 5 \text{ keV}$. Additionally, the electron density is $n_e = 0.3n_c = 2.72 \times 10^{21} \text{ cm}^{-3}$, where $n_c$ is the critical density for the incident laser ($n_c = 9.08 \times 10^{21} \text{ cm}^{-3}$ for the incident light with a wavelength $\lambda_0 = 0.351 \mu\text{m}$ in our simulation). In this paper, the density is larger than the quarter critical density, thus stimulated Raman scattering does not occur. As a result, we can research the novel scattering in the SBS cascade separately. The C plasma is taken as a typical example, for it is common in ICF [1]. The Landau damping of C plasmas is very low, thus SBS cascades in C plasmas occur more easily. The ion temperature is $T_i = 0.27e$. The wavelength of the linearly polarized laser $\lambda_0 = 0.351 \mu\text{m}$ and the intensity varies. We can see that only when the pump light intensity reaches a certain value, such as $I_0 = 1 \times 10^{16} \text{ W cm}^{-2}$, can the SBS cascade and SABS occur. Thus, the case of the intensity $I_0 = 1 \times 10^{16} \text{ W cm}^{-2}$ will be taken as a typical example. To make the SBS increase more quickly, the seed light at the right boundary has a low intensity of $I_s = 1 \times 10^{10} \text{ W cm}^{-2}$ and a matching frequency $\omega_s = 0.997\omega_0$. In all of the cases in our simulations, the seed light is the same. The spatial scale is $[0, L_s]$ discretized with $N_s = 5000$ spatial grid points. In addition, the spatial length is $L_s = 1000c/\omega_0 \approx 160\lambda_0 = 56 \mu\text{m}$ with $2 \times 5\%L_s$ vacuum layers and $2 \times 5\%L_s$ ion layers in the two sides of the plasma boundaries. The incident laser propagates along the $x$ axis from the left to the right with outgoing boundary conditions. The strong collision damping layers are added into the two sides of the plasma boundaries to damp electrostatic waves such as IAWs at the boundaries. The electron velocity scale $[−0.8c, 0.8c]$, H ion velocity scale $[−0.02c, 0.02c]$ and C ion velocity scale $[−0.01c, 0.01c]$ are discretized with $2N_v + 1$ ($N_v = 512$) grid points. The total simulation time is $t_{\text{end}} = 1 \times 10^5\omega_0^{-1} \approx 1.59 \times 10^3 T_0 = 18.66 \text{ ps}$ (where $T_0 = 1.17 \text{ fs}$ for $\lambda_0 = 0.351 \mu\text{m}$ in our simulation) discretized with $N_t = 5 \times 10^5$ grid points.

Figure 1 shows the dispersion relation of the SBS cascade and SABS. Stokes scattering in SBS is commonly referred to as stimulated Brillouin scattering, and anti-Stokes scattering in SBS is called SABS in this paper. In the first stage of stimulated Brillouin scattering (SBS1), the pump light (EMW0) will resonantly decay into an IAW (denoted as IAW1 in figure 1(b)) and an inverse Stokes-scattered EMW (denoted as SBS1 in figure 1(a)), i.e., SBS1: $\text{EMW}_0 \rightarrow \text{EMW}_1 + \text{IAW}_1$. If the scattered light EMW1 is strong enough and the Landau damping of the IAW is low enough, the second stage of stimulated Brillouin scattering (SBS2) will occur, i.e., SBS2: $\text{EMW}_1 \rightarrow \text{EMW}_2 + \text{IAW}_2$. Similarly, the third stage of stimulated Brillouin scattering (SBS3) is: $\text{EMW}_2 \rightarrow \text{EMW}_3 + \text{IAW}_3$. Thus, stage $n$ of stimulated Brillouin scattering (SBS$n$) is: $\text{EMW}(n−1) \rightarrow \text{EMW}_{n−1}$, $\omega_{n−1} \rightarrow \text{EMW}[k_n, \omega_n] + \text{IAW}[k_{\text{IAW}n}, \omega_{\text{IAW}n}]$, where $[k_n, \omega_n]$ are the wave vector and frequency of the corresponding waves. The matching condition of the waves in the stage $n (n \geq 1)$ of SBS is:

$$\vec{k}_{n−1} = \vec{k}_n + \vec{k}_{\text{IAW}_n}, \quad \omega_{n−1} = \omega_n + \omega_{\text{IAW}_n}. \quad (1)$$

Because $\omega_{\text{IAW}_n} \ll \omega_n$ and the direction of the wave vectors of the pump light and the scattered light are inverse for backward SBS discussed here, equation (1) can be written as:

$$k_n \simeq -k_{n−1}, \quad k_{\text{IAW}_n} \simeq 2k_{n−1}. \quad (2)$$

In addition to Stokes scattering in the SBS cascade, there exist some novel scattered lights with higher frequencies than the pump light frequency as shown in figure 1(a). These novel scattered lights come from SABS. The first stage anti-Stokes scattering process in SBS is that the pump light (EMW0) couples with inverse strong IAW fluctuations (IAW2) to produce higher-frequency scattered light (EMW$_{-1}$), i.e., SABS1:

$$\text{EMW}_0 + \text{IAW}_2 \rightarrow \text{EMW}_{−1}. \quad (3)$$
\[ k_0, \omega_0 ] + [k_{IAW2}, \omega_{IAW2}] = [k_{-1}, \omega_{-1}]. \] (4)

Therefore, the IAW2 must be produced before the SABS1 and the intensity of the pump light and IAW2 should be strong enough. If the anti-Stokes-scattered light (EMW_1) produced in SABS1 is also strong enough, second stage SABS will occur, i.e. SABS2:

\[ \text{EMW}_1 + \text{IAW1} \rightarrow \text{EMW}_2, \]

\[ [k_{-1}, \omega_{-1}] + [k_{IAW1}, \omega_{IAW1}] = [k_{-2}, \omega_{-2}]. \] (5)

The dispersion relation of EMW_n is:

\[ \omega_n^2 = \omega_{pe}^2 + k_n^2 c^2, \] (7)

where \( c \) is the light speed in vacuum, \( \omega_{pe} \) is the electron plasma frequency, \( n = 0 \) represents the pump incident light, \( n = 1, 2, 3, \ldots \) represent the Stokes scattered lights and \( n = -1, -2 \) represent the anti-Stokes scattered lights. In single-species plasmas, the dispersion relation of the IAW is:

\[ \omega_{IAW_n} = |k_{IAW_n}| * c_s. \] (8)

The linear frequency, thus the sound velocity \( c_s \), and Landau damping of IAW can be obtained by solving the equation \([31-33]):\]

\[ \epsilon_L(\omega, k_{IAW} = 2k_0) = 1 + \text{species} \sum_j \left( \frac{1}{(k_j \lambda_{DJ})^2} \right) \times (1 + \xi_j Z(\xi_j)) = 0, \] (9)

where \( j \) represents electrons or C ions, \( Z(\xi_j) = \frac{1}{4\pi} \int_{-\infty}^{+\infty} e^{-\xi} / (v - \xi) d\nu \) is the dispersion function, \( \xi_j = \omega_j / (\sqrt{2} k_{IAW} * v_{ji}) \) is complex and \( \omega_j = Re(\omega_j) + i \gamma_j \) is the linear Landau damping of IAW; \( v_{ji} = \sqrt{T_j/m_j} \), \( \lambda_{DJ} = \sqrt{T_j/4\pi n_j Z_j^2 e^2} \) is the thermal velocity and the Debye length of species \( j \). And \( m_j, T_j, n_j, Z_j \) are the mass, temperature, density and charge number of species \( j \), respectively.

From equation (7), one can obtain the wave number of the pump incident light \( k_0 = 0.8367 \omega_0 / c = 0.1510 \lambda_{De} \) in the condition of \( n_e = 0.3 n_c, T_e = 5 \text{ keV} \). From equation (2), the wave numbers of IAWs are: \( k_{IAW1} = k_{IAW3} = \ldots = k_{IAW(2n-1)} = 2k_0 \) and \( k_{IAW2} = k_{IAW4} = \ldots = k_{IAW(2n)} = -2k_0 \).

By solving equation (9), the frequency of the IAW1 generated by first stage SBS in C plasmas is \( \omega_{IAW1} = \omega_{IAW3} = \ldots = 6.27 \times 10^{-3} \omega_{pe} = 3.4 \times 10^3 \omega_0 \), thus \( c_s = \omega_{IAW1}/k_{IAW1} = 0.0208v_p \). And the frequencies of IAWs are: \( \omega_{IAW1} = \omega_{IAW3} = \ldots = \omega_{IAW(2n-1)} = \omega_{IAW2} = \omega_{IAW4} = \ldots = \omega_{IAW(2n)} \). Thus, we can think that \( \text{IAW1} = \text{IAW3} = \ldots = \omega_{IAW(2n-1)} \) and \( \text{IAW2} = \text{IAW4} = \ldots = \omega_{IAW(2n)} \).

From equation (1), one can further obtain the frequencies of the scattered lights: \( \omega_n = \omega_{n-1} - \omega_{IAW_n} \), \( n = 1, 2, 3, \ldots \), i.e., \( \omega_1 = \omega_0 - \omega_{IAW1} = 0.9966 \omega_0, \omega_2 = \omega_1 - \omega_{IAW2} = 0.9932 \omega_0, \omega_3 = \omega_2 - \omega_{IAW3} = 0.9898 \omega_0, \omega_4 = \omega_3 - \omega_{IAW4} = 0.9864 \omega_0, \ldots \). Through simultaneous equations (1), (7), (8) and an iterative method, assuming the sound velocity of IAW \( c_s = 0.0208v_p \) obtained from equation (9) keeps constant, one can obtain the precise wave numbers and frequencies of the pump light and scattered lights:

\[ [k_0, k_1, k_2, k_3, k_4, k_5, \ldots] = [0.8367, -0.8326, 0.8285, -0.8244, 0.8204, -0.8163, \ldots] * \omega_0 / c, \] (10)

\[ [\omega_0, \omega_1, \omega_2, \omega_3, \omega_4, \omega_5, \ldots] = [1.0000, 0.9966, 0.9932, 0.9898, 0.9864, 0.9830, \ldots] * \omega_0. \] (11)

The results through the iterative method are consistent with the approximate method above.
The frequency spectra of (a) reflective EMW electric field $E_R$ at the left boundary (incident boundary) and (b) transmitting EMW electric field $E_T$ at the right boundary (transmitting boundary). The parameters are $n_e = 0.3n_c$, $T_e = 5$ keV, $I_0 = 1 \times 10^{16} \text{ W cm}^{-2}$ in C plasmas as in figure 1 and the spectra analysis time is the total simulation time $[0, 1 \times 10^5 \omega_i^{-1}]$ (i.e., $[0, 18.6 \text{ ps}]$).

Figure 2 shows the frequency spectra of the reflective EMW and the transmitting EMW. The frequencies of the Stokes scattered lights (denoted as SBS1, SBS2, SBS3, SBS4, SBS5, ... as shown in figure 2) are listed in table 1.

The simulation results are close to the theoretical values as shown in table 1. In the same way, the frequency of anti-Stokes scattered light $\omega_{-1}$ in SABS1 is: $\omega_{-1} = \omega_0 + \omega_{\text{AW1}} = \omega_0 + 3.4 \times 10^{-3} \omega_0 = 1.0034 \omega_0$. And the frequency of anti-Stokes scattered light $\omega_{-2}$ in SABS2 is: $\omega_{-2} = \omega_{-1} + \omega_{\text{AW1}} = 1.0034 \omega_0 + 0.0034 \omega_0 = 1.0068 \omega_0$. Thus, $\omega_{-n} = \omega_0 + n \omega_{\text{AW1}} = (1 + 3.4 \times 10^{-3} + n) \omega_0$, i.e.,

$$\omega_{-1}, \omega_{-2}, \omega_{-3}, \omega_{-4}, \ldots = [1.0034, 1.0068, 1.0102, 1.0136, \ldots] \omega_0.$$  (12)

The simulation results from figure 2 are also listed in table 1. The simulation results are consistent to the theoretical analyses above.

Figure 3 gives a clear demonstration of the evolution of Stokes scattering and anti-Stokes scattering in SBS cascades. We can see that the burst behaviors of the total reflectivity and transmissivity are due to the occurrence of SBS cascades and SABS. Before $t \approx 6000T_0 = 7.02 \text{ ps}$, only SBS1 ($\omega_1 \in [0.993\omega_0, 0.999\omega_0]$) occurs, thus the total SBS reflectivity ($\omega \in [0.9\omega_0, 0.999\omega_0]$) is entirely from SBS1 as shown in figure 3(a), and total SBS transmissivity ($\omega \in [0.9\omega_0, 1.2\omega_0]$) is entirely from the transmissions of the pump light (SBS0, $\omega_0 \in [0.997\omega_0, 1.004\omega_0]$) as shown in figure 3(b). After $6000T_0 = 7.02 \text{ ps}$, SBS2 ($\omega_2 \in [0.989\omega_0, 0.997\omega_0]$) will occur and the strength of SBS2 is much larger than other higher stage SBS or SABS as shown in figure 3(d). As a result, strong IAW2 fluctuations will be produced by SBS2. Once IAW2 is generated, the strong pump light will couple with IAW2 to produce a novel scattered light with a frequency larger than the pump light frequency, i.e., EMW1 $+$ IAW2 $\rightarrow$ EMW2, which is called stimulated anti-Stokes Brillouin scattering (SABS). As shown in figure 3(c), the SABS1 ($\omega_1 \in [1.0\omega_0, 1.008\omega_0]$) peak occurs during the time $[8000T_0, 10000T_0]$ (i.e., $[9.36 \text{ ps}, 11.7 \text{ ps}]$), which is even larger than SBS3. After $t \approx 12000T_0 = 14.04 \text{ ps}$, the SBS3, SBS4, SBS5 will develop and will compete with each other. However, second stage SABS (SABS2, $\omega_2 \in [1.004\omega_0, 1.012\omega_0]$) is very weak, and as a result, SABS3 and SABS4 are weaker than SABS2 and their effects on reflectivity and transmissivity can be neglected.

Figure 4 gives a comparison of the cases in the condition of $I_0 = 1 \times 10^{16} \text{ W cm}^{-2}$ and $I_0 = 5 \times 10^{15} \text{ W cm}^{-2}$. As we can see, the dispersion relation of longitudinal electrostatic waves in the condition of $I_0 = 1 \times 10^{16} \text{ W cm}^{-2}$ (figure 4(a)) demonstrates two branches of IAWs, while that in the condition of $I_0 = 5 \times 10^{15} \text{ W cm}^{-2}$ (figure 4(e)) demonstrates only one branch of IAW. This illustrates that only when the pump light intensity reaches a certain value, such as $I_0 = 1 \times 10^{16} \text{ W cm}^{-2}$, can the SBS cascade and SABS occur. The broadening of frequency is due to the nonlinear

**Table 1.** The wave numbers and frequencies of IAWs and EMWs generated by SBS cascade and SABS in C plasmas. (The wave numbers $k$ are normalized to $\omega_0/c$, the frequencies $\omega$ are normalized to $\omega_0$.)

| SBS  | SBS0 | SBS1 | SBS2 | SBS3 | SBS4 |
|------|------|------|------|------|------|
| $\omega_0$ | $\omega_1$ | $\omega_2$ | $\omega_3$ | $\omega_4$ |
| Theory | 1.0000 | 0.9966 | 0.9932 | 0.9898 | 0.9864 |
| Simulation | 1.0000 | 0.9970 | 0.9926 | 0.9882 | 0.9847 |
| SABS | SBS0 | SBS1 | SBS2 | SBS3 | SBS4 |
| $\omega_0$ | $\omega_1$ | $\omega_2$ | $\omega_3$ | $\omega_4$ |
| Theory | 1.0000 | 1.0034 | 1.0068 | 1.0102 | 1.0136 |
| Simulation | 1.0000 | 1.004 | 1.007 | 1.011 | 1.015 |
frequency shift of IAWs \[32, 34\]. Figures 4(b)–(d) give a snapshot of the C ion distribution evolution with time in the condition of \(I_0 = 1 \times 10^{16} \text{ W cm}^{-2}\). At the time \(t = 40000\omega_0^{-1} = 636670 = 7.45 \text{ ps}\) (figure 4(b)), the IAW1 generated by SBS1 has reached a large amplitude, thus the trapping width \(\Delta v_t = 2\sqrt{q_i\phi/m_i}\) (\(i\) represents C ions, \(q_i, m_i\) are the charge and mass of C ions, and \(\phi\) is the electric potential of the IAW) will reach a large value. At the same time, the
IAW2 generated by SBS2 starts to develop as shown in figure 3(d) after \( t \approx 6000 \text{fs} = 7.02 \text{ps} \). Figures 4(b)–(d) show the development of IAW2. As time increases, the ion trapping width generated by IAW2 increases in an obvious manner; this illustrates that the IAW2 amplitude increases in an obvious way. At the time \( t = 60000 \frac{\text{fs}}{\omega_0^1} = 9549 \text{fs} = 11.16 \text{ps} \), the IAW2 reaches a certain amplitude as shown in figure 4(c); thus, the strong pump light can couple with IAW2 to produce a higher frequency scattered light called stimulated anti-Stokes Brillouin scattering (SABS1, as shown in figure 3(c)). After \( t \approx 12000 \text{fs} = 14.04 \text{ps} \), SBS3, SBS4 and SBS5 will develop as shown in figure 3; thus, positive propagating IAWs as the same as IAW1 will be generated by SBS3 and SBS5, while negative propagating IAWs, the same as IAW2, will be generated by SBS4. Therefore, the IAW1 and IAW2 amplitudes will further increase as shown in figure 4(d) at the time \( t = 80000 \frac{\text{fs}}{\omega_0^1} = 12732 \text{fs} = 14.88 \text{ps} \). However, if the pump light intensity decreases, such as \( I_0 = 5 \times 10^{15} \text{ W cm}^{-2} \), IAW2 will not be generated, thus the SBS cascade and SABS will not occur. Figures 4(f)–(h) demonstrate that the C ions will be trapped only by positive propagating IAW1, but not negative propagating IAW2 in the condition of \( I_0 = 5 \times 10^{15} \text{ W cm}^{-2} \). Thus, we believe that if the pump light intensity is lower than \( 5 \times 10^{15} \text{ W cm}^{-2} \), the SBS cascade and SABS can almost not occur in our simulation system.

To research the effect of SBS cascade and SABS on reflectivity and transmissivity, the other conditions are invariant and we change the pump light intensity, which is a common intensity scale in ICF experiments. As shown in figure 5, if the pump light intensity is not larger than \( 5 \times 10^{15} \text{ W cm}^{-2} \), only first stage stimulate Brillouin scattering (SBS1) will occur as discussed above. As the pump light intensity increases from \( 1 \times 10^{14} \text{ W cm}^{-2} \) to \( 5 \times 10^{15} \text{ W cm}^{-2} \), the reflectivity of SBS will obviously increase and the transmissivity will decrease. As we can see, the absorptivity in the SBS process is very low (not larger than 3%), thus the reflectivity and transmissivity is inversely correlated. To our surprise, when the pump intensity reaches \( 1 \times 10^{16} \text{ W cm}^{-2} \), the total reflectivity will decrease and be lower than that in the condition of \( I_0 = 5 \times 10^{15} \text{ W cm}^{-2} \). This interesting phenomenon is due to the SBS cascade and SABS discussed above. Although SBS1 is the strongest scattering and dominates in the SBS cascade and SABS, a part energy of scattered light of SBS1 will transfer to the other stage SBS and SABS, especially SBS2. As shown in figure 3, SBS2 is much stronger than other higher stage SBS and SABS, thus SBS2 will obtain the most energy from SBS1, and the scattered light of SBS2 will transmit from the right boundary. Therefore, SBS2 will increase transmissivity and decrease reflectivity.

### 3. Discussions

Several related SRS rescatterings have been reported [35, 36] in the field of LPI. We can divide the regions by the temperature and density of electrons and the intensity of the incident laser:

1. In the low density region of the indirect-drive ignition [1–3, 37], which is a common ignition-hohlraum plasmas region, such as \( n_e \lesssim 0.1 n_c \), \( T_e \sim 2.5 \text{ keV} \sim 5 \text{ keV} \), in addition to backward stimulated Raman scattering (BSRS), forward stimulated Raman scattering (FSRS), and backward stimulated Brillouin scattering (BSBS), there also exist several rescatterings of SRS, such as BSRS of BSRS, BSRS of FSRS [35, 36].

2. In the moderate density region of the shock ignition [41, 42], such as \( n_e \sim 0.2 n_c \), \( T_e \sim 3 \text{ keV} \), \( I_0 \sim 2.5 \times 10^{15} \text{ W cm}^{-2} \), the strongest instability is the backward stimulated Raman scattering (BSRS), and the BSRS is mainly saturated by Langmuir decay instability (LDI) [13, 38].

3. In the field of high energy density science (HEDS), an intense laser propagates through high-temperature \( (T_e \geq 10 \text{ keV}) \) plasmas, such as \( T_e = 20 \text{ keV} \), \( n_e = 0.2 n_c \) and \( I_0 = 1 \times 10^{16} \text{ W cm}^{-2} \) [35], the saturation mechanism is rescattering rather than LDI. In this region, the BSRS is the dominant scattering process, and the saturation mechanism of FSRS is the BSBS of FSRS, which is found by Langdon [35].

4. In addition to the regions discussed above, we research high-intensity laser and high-density plasma interaction, which is common in direct-drive ignition [39, 40] or shock ignition [41, 42]. In our simulation, the electron density is \( n_e = 0.3 n_c \) which is higher than the quarter-critical density, thus the SRS, the corresponding rescattering of SRS and LDI are excluded. And the multiple rescatterings of SBS, called the SBS cascade, are found under the condition of

![Figure 5](image-url)
interaction. This paper focuses on a high-density C plasma, which is of relevance to direct-drive ICF or shock ignition. However, in indirect-drive ICF hohlraum fills, such as He, H or HeH plasmas, since the density $n_e \approx 0.1n_c$ is low, SRS and corresponding SRS rescatterings are dominant as discussed above. These interesting results give an advance and of important significance to the field of high-intensity laser plasma interaction in ICF.

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References

[1] He X T, Liu J W, Fan Z F, Wang L F, Liu J, Lan K, Wu J F and Ye W H 2016 Phys. Plasmas 23 082706
[2] Gienzer S H et al 2010 Science 327 228
[3] Gienzer S H et al 2007 Nat. Phys. 3 716
[4] Lan K et al 2017 Phys. Rev. E 95 031202
[5] Lan K et al 2016 Matter and Radiation at Extremes 1 8
[6] Huo W Y et al 2016 Phys. Rev. Lett. 117 025002
[7] Liu Z J, He X T, Zheng C Y and Wang Y G 2009 Phys. Plasmas 16 093108
[8] Weber S, Riconda C and Tikhonchuk V T 2005 Phys. Rev. Lett. 94 055005
[9] Weber S, Riconda C and Tikhonchuk V T 2005 Phys. Plasmas 12 043101
[10] Weber S, Lontano M, Passoni M, Riconda C and Tikhonchuk V T 2005 Phys. Plasmas 12 112107
[11] Froula D H, Divol L and Gienzer S H 2002 Phys. Rev. Lett. 88 105003
[12] Giacone R E and Yu H X 1998 Phys. Plasmas 5 1455
[13] Vu H X, DuBois D F and Bezzereides B 2001 Phys. Rev. Lett. 86 4306
[14] Albright B J, Yin L, Bowers K J and Bergen B 2016 Phys. Plasmas 23 032703
[15] Cohen B I, Lasinski B F, Langdon A B and Williams E A 1997 Phys. Fluids B 4 576
[16] Rozmus W, Casanova L, Pesme D, Heron A and Adam J 1992 Phys. Plasmas 4 956
[17] Rambo P W, Wilks S C and Kruer W L 1997 Phys. Rev. Lett. 79 83
[18] Pawley C J, Huey H E and Luhmann N C 1982 Phys. Rev. Lett. 49 877
[19] Speziale T, McGrath J F and Berger R L 1980 The Physics of Fluids 23 1275
[20] Zhan-Jun L, Xian-Tu H, Chun-Yang Z and Yu-Gang W 2012 Chin. Phys. B 21 015202
[21] Turner R E and Goldman L M 1981 The Physics of Fluids 24 184
[22] Reginier P R and Taran J P E 1973 Appl. Phys. Lett. 22 240
[23] Hickman A P and Bischel W K 1988 Phys. Rev. A 37 2516
[24] Manz T, Schwarz U and Maier M 2004 Opt. Commun. 235 201
[25] Kneipp K et al 2000 Phys. Rev. Lett. 84 3470
[26] Goldblatt N and Hercher M 1968 Phys. Rev. Lett. 20 310

4. Conclusions

In conclusion, detailed research into anti-Stokes scattering and Stokes scattering in SBS cascades in C plasmas has been carried out. An insight into the mechanism of SABS in SBS cascades is given. The evolution of SABS and high stage SBS have been demonstrated for the first time. When the SBS cascade and SABS occur, the reflectivity and transmissivity will display a burst behavior. Since the effect of SBS2 is the strongest in the higher stage SBS and SABS, the reflectivity will decrease and the transmissivity will increase. The SBS cascade including SABS is an important saturation mechanism of SBS, especially in high-intensity laser–plasma
