Available online at www.sciencedirect.com
ScienceDirect
MATTER AND RADIATION AT EXTREMES
Matter and Radiation at Extremes 2 (2017) 190–196
www.journals.elsevier.com/matter-and-radiation-at-extremes

Research Article

Stimulated Raman scattering excited by incoherent light in plasma

Yao Zhao [a,b], Suming Weng [a,b], Min Chen [a,b], Jun Zheng [a,b], Hongbin Zhuo [c,b], Zhengming Sheng [a,b,d,*]

[a] Key Laboratory for Laser Plasmas (MoE), School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Collaborative Innovation Center of IFSA (CICIFSA), Shanghai Jiao Tong University, Shanghai 200240, China
[c] College of Science, National University of Defense Technology, Changsha 410073, China
[d] SUPA, Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK

Received 3 March 2017; revised 15 May 2017; accepted 2 June 2017
Available online 8 July 2017

Abstract

Stimulated Raman scattering (SRS) excited by incoherent light is studied via particle-in-cell simulations. It is shown that a large bandwidth of incoherent light can reduce the growth of SRS and electron heating considerably in the linear stage. However, different components of the incoherent light can be coupled by the Langmuir waves, so that stimulated Raman backward scattering can develop. When the bandwidth of incoherent light is larger than the Langmuir wave frequency, forward SRS can be seeded between different components of the incoherent light. The incoherent light can only increase the time duration for nonlinear saturation but cannot diminish the saturation level obviously.

PACS Codes: 52.25.Os; 52.35.-g; 52.38.Bv

Keywords: Stimulated Raman scattering; Instability suppression; Incoherent light; Inertial confinement fusion

1. Introduction

Stimulated Raman scattering (SRS) in plasma is simply a pump laser decay into an electron plasma wave and a scattered light [1]. It may cause significant laser energy loss and hot electron production, where the latter can preheat the fusion targets. Therefore, SRS has been one of the key problems in laser-indirect-driven inertial confinement fusion [2–4]. Several methods have been proposed to suppress the SRS, such as introducing laser bandwidth [5,6] or polarization rotation [7], laser smoothing technique (smoothing by spectral dispersion, induced spatial incoherence and polarization smoothing) [8–11]. It is also shown that initial high temperature of plasma electrons can reduce the SRS growth [12,13].

In our previous work, we have studied the effects of finite bandwidth of incident lasers on SRS [6]. A considerable reduction of linear growth of SRS is found when the bandwidth is much larger than the SRS growth rate. In that work, the finite bandwidth is modeled by a sinusoidal-frequency-modulation around the central laser frequency. Recently, it is shown by theory and simulation that such modulated lasers with large bandwidth may be produced with a type of plasma optical modulators for intense lasers [14]. On the other hand, it is noted that such modulated lasers cannot completely suppress the SRS growth at later stage. Therefore it is necessary to investigate other possible schemes. Here we consider a type of partially incoherent light, which is composed of a large number of beamlets, each of which has different frequencies within a certain range, a random phase, and even a random polarisation. The SRS growth with such light beams is studied via particle-in-cell (PIC) simulations. Comparison of the

* Corresponding author. Key Laboratory for Laser Plasmas (MoE), School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China.

E-mail address: zmsheng@sjtu.edu.cn (Z.M. Sheng).

Peer review under responsibility of Science and Technology Information Center, China Academy of Engineering Physics.

http://dx.doi.org/10.1016/j.mre.2017.06.001
2468-080X/

results with those obtained with frequency modulated lasers of large bandwidth is made. The mechanisms of the SRS development due to the coupling between different frequency components of the incoherent light are analyzed.

2. Model of incoherent light beams

It is proposed that there are several schemes to model an incoherent light beam, such as spectral combining, short pulse stacking, and a mosaic of beamlets [15]. Here we consider a simple case where it is composed of a large number of coherent beamlets, each with a different frequency and a different phase:

$$a_{\mathrm{sum}} = \sum_{i=1}^{N} a_i \cos(\omega_i t + \phi_i), \tag{1}$$

where a_i is the field amplitude of the beamlet i normalised by $m_e\omega_i c/e$, which is related to the laser intensity with $a_i = \sqrt{I_i(\mathrm{W/cm^2})[\lambda_i(\mu\mathrm{m})]^2/1.37\times10^{18}}$. ω_i and λ_i are the corresponding frequency and wavelength, ϕ_i is a random phase in [-π,π], and N is the number of beamlets typically around a few hundreds. The frequency ω_i can be defined within certain bandwidth $\Delta\omega_0$ around a central frequency ω_0. If the frequency of the beamlets ω_i is uniformly distributed, the frequency gap of neighboring beamlets is simply $\delta\omega_i = \Delta\omega_0/(N-1)$. One can also let ω_i be randomly selected within $[\omega_0 - \Delta\omega_0/2, \omega_0 + \Delta\omega_0/2]$ in numerical simulation. Comparing with the model of sinusoidally modulated lasers with certain bandwidth used before [6] in the form of $a(t) = a_0\cos[\omega_0 t + b\sin(\omega_m t)]$, the present model can be considered as an extension now with arbitrary amplitude, frequency, and phase for the beamlets. Fig. 1 shows an example of the temporal structure and corresponding spectrum when taking $a_i = 0.004$, $\Delta\omega_0 = 15\%$, and $N = 100$. It shows that there are some fluctuations in the envelope profile, but overally the amplitude appears around $a_0 = (\sum_{i=1}^{N}|a_i|^2|\omega_i|^2)^{1/2} = 0.04$, which is expected according to energy conservation. Note that the coherence length between different components is just a few laser wavelengths, which is much shorter than that of the conventional laser light.

In addition to introducing random amplitude, frequency, and phase, one may introduce random polarization in the beamlets:

$$\boldsymbol{a}_{\mathrm{sum}} = \sum_{i=1}^{N} a_i\left[\cos(2\pi p_i)\hat{\boldsymbol{e}}_y + \sin(2\pi p_i)\hat{\boldsymbol{e}}_z\right]\cos(\omega_i t + \phi_i), \tag{2}$$

where p_i is a random number in [0,1], $\hat{\boldsymbol{e}}_y$ and $\hat{\boldsymbol{e}}_z$ are unit vectors in the transverse directions, assuming that all the beamlets propagate along the x-direction. Then the light wave can be considered to have two components polarized along the y and z directions, respectively. Averaged over assembly, it is obvious that each component contains half of the total power. This is equivalent to that each component appears with an amplitude of $a_i/\sqrt{2}$ in the y and z directions.

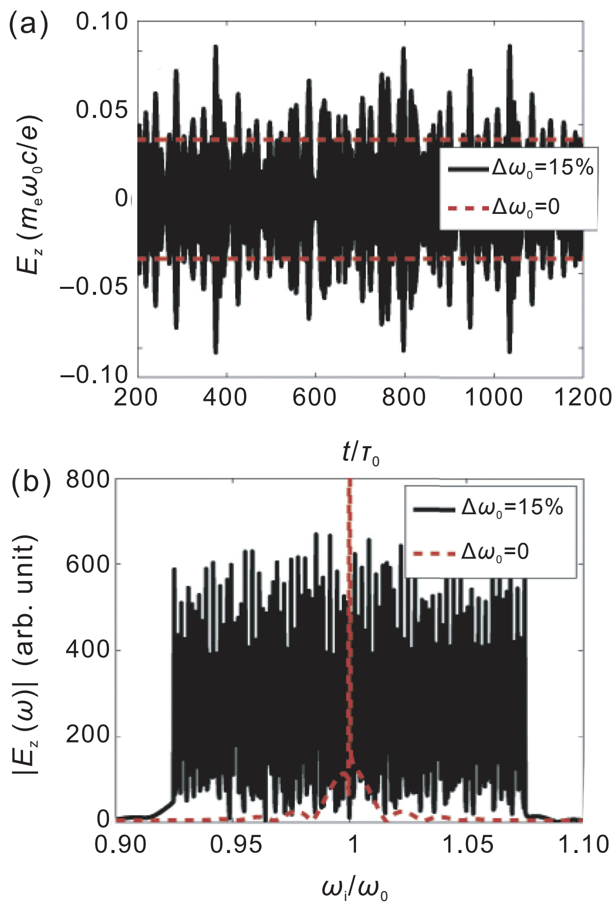

Fig. 1. (a) Temporal envelopes of the incident lights for both coherent and incoherent light, where the bandwidth of incoherent light is 15%, the red lines indicate the laser field amplitude level for coherent light. (b) Fourier transform of the incident light.

In the following, we carry out one dimensional PIC simulation to examine the effects of finite bandwidth and light incoherence on the generation of stimulated Raman scattering in both homogeneous and inhomogeneous plasmas.

3. SRS of incoherent light in homogeneous plasma

Numerical simulations using the PIC code KLAP [16] have been performed firstly in one-dimensional (1D) homogeneous plasma. We write the center frequency of a_{sum} as ω_0, and the corresponding wavelength is λ. In our simulations, we take the number of beamlets $N = 100$. The beamlets are semi-infinite with a 25λ rising edge in the front, each with the peak amplitude $a_i = 0.004$. The bandwidth $\Delta\omega_0$ of the incoherent light beam is normalized by ω_0. Here we take $\Delta\omega_0 = 15\%$. As a comparison, simulations for a coherent or partially coherent laser with sinusoidal modulation and the same laser power are also carried out, where its amplitude is $a = 0.04$ and its bandwidth is taken to be either $\Delta\omega_0 = 0$ or 15%, respectively. The length of the simulation box is 600λ, where the plasma occupies a region from 100λ to 500λ with a linear density ramp 10λ in the front. The homogeneous plasma density is $n_e = 0.08n_c$ with n_c to be the critical density, and the initial temperature is

$T_{e0} = 100$ eV. The ions are stationary with a charge $Z = 1$. We have taken 100 cells per wavelength and 50 particles per cell.

Fig. 2(a) shows the temporal envelops of the backscattering light in three cases. For the sinusoidal-frequency-modulation light with $\Delta\omega_0 = 15\%$, the growth of the backscattered light is significantly reduced under the same power due to its large bandwidth. In the case of the incoherent light with the same bandwidth 15%, the growth rate of backscattered light is much slower than the case of frequency-modulation light. This shows additional suppression effects of the SRS of random phase. However, after certain time about $t = 500\tau$ with $\tau = 2\pi/\omega_0$, the backscattered light starts to grow quickly. Finally at $t = 1000\tau$, the scattered light saturates at the same level as produced by normal coherent lasers.

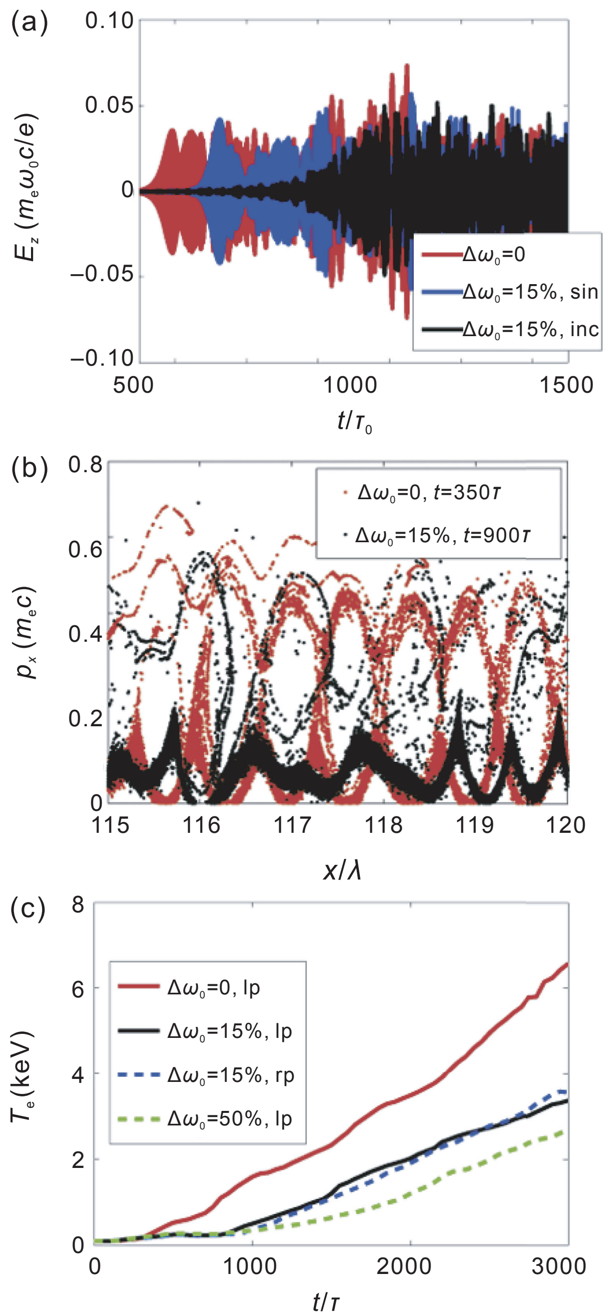

Fig. 2. (a) Temporal profile of the backscattered light waves. The incoherent light and sinusoidal-frequency-modulation light are denoted as "inc" and "sin", respectively. Both of them have the same bandwidth $\Delta\omega_0 = 15\%$. (b) Phase-space plot of electrons for incident light with different bandwidth at different time. (c) Temporal evolutions of the electron temperature for the incident light with different bandwidth or polarization. Linear polarization and random polarization are denoted as "lp" and "rp", respectively.

Since backward SRS can develop a large amplitude Langmuir wave to trap numbers of electrons. The trapped electrons are accelerated to a high temperature, and then SRS evolves into nonlinear stage. One can use the plasma electron temperature to diagnose the strength of nonlinear SRS [12,17]. The phase-space plot of electrons are shown in Fig. 2(b), where large numbers of electrons are trapped by the Langmuir wave at $t = 350\tau$ for coherent light. Due to reduced linear SRS growth, Langmuir wave-breaking occurs at $t = 900\tau$ for incoherent light [1]. The trapped electrons lead to a reduced Langmuir wave frequency [18,19], as discussed later. Re-scattering of Raman will develop at longer time, which can heat the electrons to higher temperature [17].

The heated electrons typically show quasi-thermal distributions with an effective temperature. In the linear stage of SRS, little growth of the electron temperature can be found. When the SRS enters the nonlinear stage, the temperature appears to grow almost linearly. In the case with a coherent laser, this occurs after $t = 400\tau$ as shown in Fig. 2(c). On the contrary, in the case with incoherent light, the nonlinear SRS is delayed until $t = 900\tau$ for $\Delta\omega_0 = 15\%$ and $t = 1300\tau$ for $\Delta\omega_0 = 50\%$. Here we take $N = 333$ and $a_i = 0.0022$ for the incident laser with $\Delta\omega_0 = 50\%$, to keep the same energy and $\delta\omega_i$ with $\Delta\omega_0 = 15\%$ case. The temporal evolution of the electron temperature is thus consistent with the results shown in Fig. 2(b) that the growth rate of backward SRS is reduced with incoherent light. On the other hand, the continued increase of the electron temperature suggests that nonlinear SRS cannot be suppressed by incoherent light even if a large bandwidth is adopted. Note that this is similar to our previous work with modulated lasers with finite bandwidth [6], where the finite bandwidth is introduced by the sinusoidal modulation of the carrier wave frequency.

As mentioned in Sec. 2, pure incoherent light has also random polarizations described by Eq. (2). We compare the case of randomly polarized incoherent light with the case of linear polarized incoherent light under the same light intensity and the bandwidth. It turns out that the development of SRS instabilities in these two cases is similar, as shown by the scattered light waves, the electron density perturbations and the electron temperatures. The latter is shown in Fig. 2(c) from our PIC simulation. This may be attributed to the fact that the ponderomotive forces are comparable for the two cases under the same light intensity. As a result, the random polarization does not lead to additional suppression effects on the SRS instability.

To understand the physical mechanism responsible for SRS with incoherent light, it is necessary to examine the Langmuir wave structure. Fig. 3 shows the distribution of wavenumber-frequency space (k_L,ω_L) under different driving laser

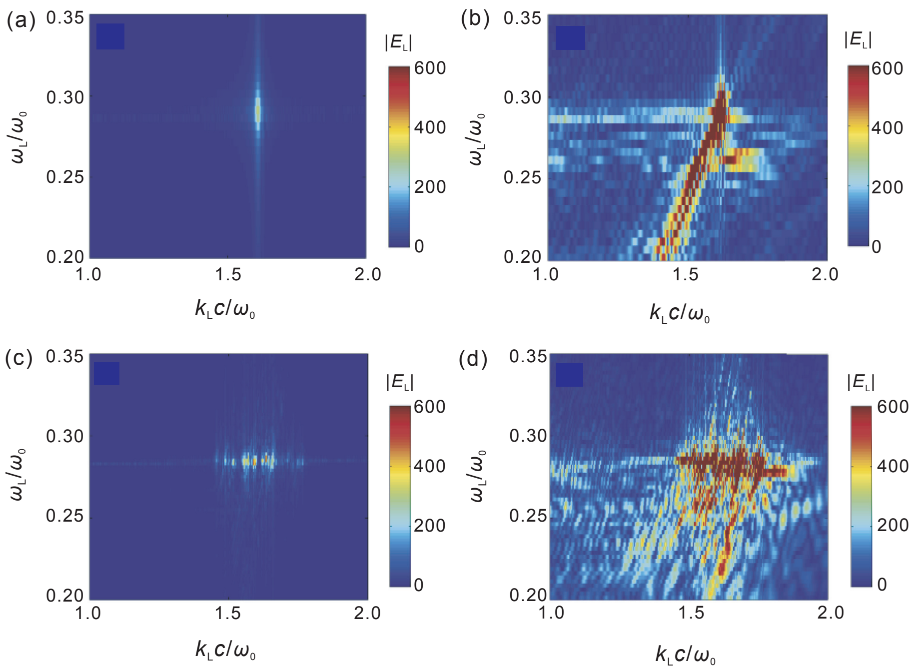

Fig. 3. Phase-space distributions of the Langmuir wave associated with SRS excitation under different driving laser light. (a) and (b) are backscattering driven by ideal coherent laser light with zero bandwidth, which are obtained for the time windows [101,300]τ and [301,600]τ, respectively. (c) and (d) are backscattering driven by incoherent light with $\Delta\omega_0 = 15\%$, which are obtained for the time windows [201,600]τ and [601,1000]τ, respectively. The initial electron temperature for (a)−(d) is $T_{e0} = 100$ eV.

conditions, where ω_L and k_L are respectively the frequency and wavenumber of the Langmuir wave. Note that the electron plasma frequency at the given plasma density is $\omega_{pe} = 0.283$ and the Langmuir wave frequency is given by $\omega_L = \sqrt{\omega_{pe}^2 + 3k_L^2 v_e^2}$ with v_e the thermal velocity of electrons. In the case with a coherent laser at $a_0 = 0.04$, the backward SRS instability (indicated by the peaks at $k_L = 1.62$) has been developed from $t = 101\tau$ to $t = 300\tau$ as shown in Fig. 3(a). From $t = 301\tau$ to $t = 600\tau$, electron trapping (related to the nonlinear Landau damping) and subsequent electron heating lead to the down-shift of the Langmuir wave frequency as shown in Fig. 3(b) [12,13,18−20]. When a large number of electrons are heated to high energy, the relativistic electron-mass increase can also contribute to the frequency down-shift [12,13].

Fig. 3(c) and (d) present the (k_L,ω_L) distributions in the linear and nonlinear stage for incoherent light, respectively. Drastic nonlinear frequency shift occurs during [601,1000]τ. The frequency down-shift is found both for coherent and incoherent light, where the mechanisms are similar as due to electron trapping (or nonlinear Landau damping) and electron heating. However, the backward SRS has not been strongly developed during [201,600]τ. The frequency of the Langmuir waves is mainly around 0.29 expected for linear waves. The bandwidth of Langmuir wave $\delta\omega_L$ is small. On the other hand, the distribution for k_L is relatively broad. According to the phase matching conditions for the backscattered SRS, the wavenumber of the Langmuir waves is given by

$$k_{iL} = k_i + c^{-1}\sqrt{\omega_i^2 - 2\omega_i\omega_L} \tag{3}$$

with $k_i = c^{-1}\sqrt{\omega_i^2 - \omega_{pe}^2}$ for an incident beamlet with light (k_i,ω_i). When the incident light frequency changes between $[0.925,\ 1.075]\omega_0$, one finds that k_{iL} changes between $[1.46,\ 1.78]\omega_0/c$, taking $\omega_L = 0.29$. This can explain the instability-region in k space shown in Fig. 3(c).

One critical issue is whether there is coupling between different beamlets during the SRS development. In this case, the coupling between different beamlets is weak if there is no bandwidth of the Langmuir wave $\delta\omega_L = 0$. However, if there is a finite bandwidth of the Langmuir waves with $\delta\omega_L \neq 0$, the beamlets of incoherent light could be coupled with each other to develop backward SRS. According to the expression of k_{iL} given above, its change with frequency is given by

$$\frac{dk_{iL}}{d\omega_i} = \frac{\omega_i}{c\sqrt{\omega_i^2 - \omega_{pe}^2}} + \frac{\omega_i - \omega_L}{c\sqrt{\omega_i^2 - 2\omega_i\omega_L}}, \tag{4}$$

$$\frac{dk_{iL}}{d\omega_L} = -\frac{\omega_i}{c\sqrt{\omega_i^2 - 2\omega_i\omega_L}}. \tag{5}$$

When $\delta\omega_L \gtrsim 2\delta\omega_i$, there may be $\delta k_{iL} = (dk_{iL}/d\omega_i)\delta\omega_i + (dk_{iL}/d\omega_L)\delta\omega_L = 0$. Under this condition, neighboring beamlets of the incoherent light can be coupled with the same Langmuir wave.

For the coupling between two beamlets, one may consider the simplest case, where two lasers with the same amplitude

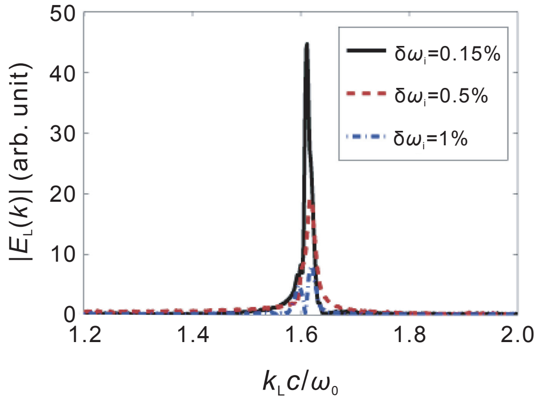

Fig. 4. The wavenumber distributions of the Langmuir wave for driving by two laser beamlets with different frequency $\delta\omega_i$ at $t = 400\tau$, where each laser beamlet has the amplitude $a_i = 0.02$.

$a_i = 0.02$ (for $i = 1$,2) with some frequency difference $\delta\omega_i$ to interact with plasma under the same conditions. When $\delta\omega_i = 0.15\%$, they are easier to be coupled with each other than $\delta\omega_i = 1\%$, as shown in Fig. 4. With a smaller frequency difference of the driving lasers, the produced Langmuir waves are easier to serve as the common density perturbations for wave scattering.

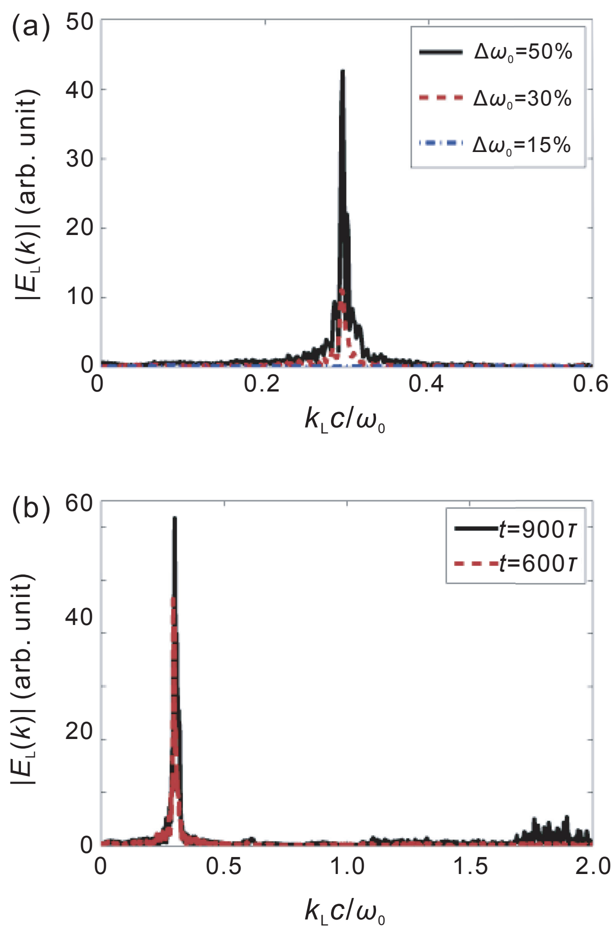

Fig. 5. The distributions of the Langmuir waves in the k space. (a) for incoherent light with different bandwidth at $t = 400\tau$. (b) for incoherent light with $\Delta\omega_0 = 50\%$ at $t = 600\tau$ and $t = 900\tau$.

Fig. 5(a) presents the wavenumber of forward SRS for incoherent light with different bandwidth. Here we take $N = 200$ and $a_i = 0.0028$ for incident laser with $\Delta\omega_0 = 30\%$, to keep the same energy and $\delta\omega_i$ with the other two bandwidths. One should note that the wavenumber of forward SRS is mainly decided by the plasma parameters, i.e., $k_L c = \omega_{pe}$. At $t = 400\tau$, no forward SRS spectrum can be found for the bandwidth $\Delta\omega_0 = 15\% < \omega_{pe}$, as shown in Fig. 5(a). As a comparison, when the whole bandwidth of incident light is larger than the frequency of plasma wave, i.e., $\Delta\omega_0 \geq \omega_{pe} = 28.3\%$, seed forward SRS can be stimulated. For a larger bandwidth, more components of the incoherent light are coupled to seed the forward SRS, so the intensity of Langmuir wave is much stronger for $\Delta\omega_0 = 50\%$. The phase velocity of the Langmuir wave developed by forward SRS is close to light, and it is difficult to accelerate the electrons as shown in Fig. 2(b). Forward SRS plays a dominant role in the long time interactions, since it is difficult to be damped. At $t = 600\tau$, we can find a peak at $k_L c = \omega_{pe} = 0.283$ for the seed forward SRS, but there is no backward SRS mode shown in Fig. 5(b). At $t = 900\tau$, the mode $k_L = 0.283$ grows larger, and the backward SRS is developed.

4. Incoherent light in inhomogeneous plasma

In inhomogeneous plasma, the plasma density gradients introduce additional intensity threshold of the driving laser for the development of SRS. This adds to further reduction of the SRS. In particular, for inhomogeneous plasma, the wave vectors for incident and scattered light are functions of the spatial coordinates. Therefore the parametric instability is always convective, i.e., it initially grows exponentially with local phase match conditions satisfied, and finally it is saturated due to the phase mismatching [21,22]. When incoherent light incident with certain bandwidth, different frequency components may still be coupled with each other locally. But the growth rate and saturation level could be reduced as compared to those in homogeneous plasma. In our 1D simulations where the length of the simulation box is 1500λ, the plasma occupies a region from 150λ to 1150λ with a linear density profile $n_e(x) = 0.05[1 + (x - 150)/200]n_c$, and an initial electron temperature $T_{e0} = 100$ eV.

For any incident light (ω_i, k_i), the linear instability region is plotted in Fig. 6(a) with the white line, which is obtained by substituting the $\omega_{pe}(x)$ into the function k_L given by Eq. (3). For the coherent laser, broad k spectra have been developed along the linear-instability region, as the convective instability moves in the longitudinal direction. As a comparison, Fig. 6(b) plots the instability region produced by incoherent light during the same period of time. It shows that the intensity of SRS has been reduced by incoherent light during this time. One way to measure the strength of SRS is to study the energy of the electrostatic fields stored in the plasma, i.e., $\mathscr{E} = \int |E_L|^2 dx$. After t=600τ, an obvious reduction of $\mathscr{E}$ with incoherent light can be seen in Fig. 7(a). The corresponding electron temperature is plotted in Fig. 7(b), which shows a reduction of electron heating by use of incoherent light. These results

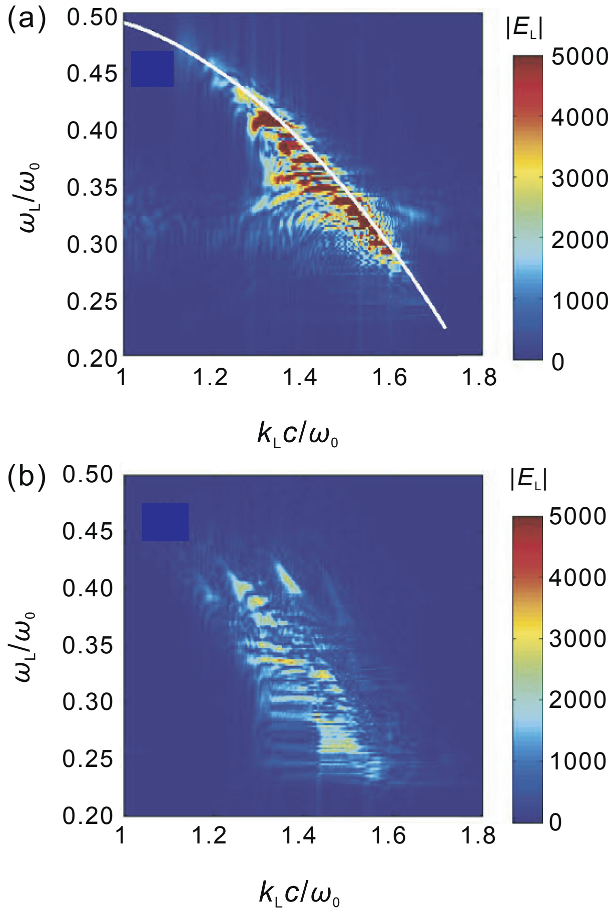

Fig. 6. The k_L–ω_L distributions of the Langmuir wave for (a) coherent light with $\Delta\omega_0 = 0$ and (b) incoherent light with a whole bandwidth $\Delta\omega_0 = 15\%$. The time and space windows are taken to be [500,1000]τ and [150,1150]λ, respectively. The white line is the theoretical linear-instability region for backward SRS.

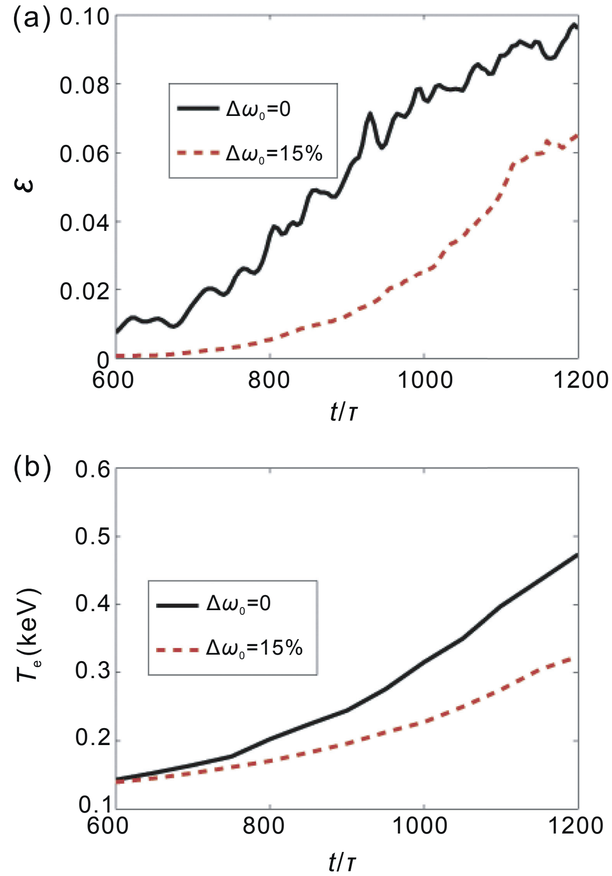

Fig. 7. Temporal evolutions of (a) electrostatic energy and (b) plasma temperature for coherent and incoherent incident light.

indicate that the linear convective SRS and electron heating can be suppressed by incoherent light in the inhomogeneous plasma due to its large bandwidth.

5. Summary

Stimulated Raman scattering excited by incoherent light have been investigated using PIC simulations, where the incoherent light is modelled as composed of many beamlets with random phases and different frequencies within certain bandwidth. Our simulations indicate that the growth of SRS and electron temperature can be reduced considerably in the linear stage due to the large bandwidth of incoherent light. This suppression effect is even stronger than that with a sinusoidally modulated laser light under the same bandwidth. The coupling between different beamlets with sharing the Langmuir wave can excite the backward SRS. When the bandwidth of incoherent light is larger than the frequency of Langmuir wave, seeded forward SRS can be developed easily. The incoherent light can only increase the time duration for linear growth but cannot diminish the instability completely. When large amplitude of Langmuir wave has been developed, the instability process evolves into nonlinear stage, and the suppressions of SRS and electron heating are weakened. The incoherent light interacts with inhomogeneous plasma is also studied, which shows a reduction of linear convective SRS and electron heating as compared with the case of coherent laser light.

Acknowledgments

This work was supported in part by the National Science Foundation of China (Grant Nos. 11421064, 11374209, 11405107 and 11374210). Simulations have been carried out on the PI supercomputer at Shanghai Jiao Tong University.

References

[1] W.L. Kruer, The Physics of Laser Plasma Interactions, vol. 70, Addison-Wesley, New York, 1988.
[2] J. Lindl, Development of the indirect-drive approach to inertial confinement fusion and the target physics basis for ignition and gain, Phys. Plasmas 2 (1995) 3933.
[3] J.D. Lindl, P. Amendt, R.L. Berger, S.G. Glendinning, S.H. Glenzer, et al., The physics basis for ignition using indirect-drive targets on the National Ignition Facility, Phys. Plasmas 11 (2004) 339.
[4] S. Glenzer, B.M. Gowan, P. Michel, N. Meezan, L. Suter, et al., Symmetric inertial confinement fusion implosions at ultra-high laser energies, Science 327 (2010) 1228.
[5] J. Thomson, J.I. Karush, Effects of finite-bandwidth driver on the parametric instability, Phys. Fluids 17 (1974) 1608.

[6] Y. Zhao, L.-L. Yu, J. Zheng, S.-M. Weng, C. Ren, et al., Effects of large laser bandwidth on stimulated Raman scattering instability in underdense plasma, Phys. Plasmas 22 (2015) 052119.
[7] I. Barth, N.J. Fisch, Reducing parametric backscattering by polarization rotation, Phys. Plasmas 23 (2016) 103001.
[8] S. Skupsky, R. Short, T. Kessler, R. Craxton, S. Letzring, et al., Improved laser-beam uniformity using the angular dispersion of frequency-modulated light, J. Appl. Phys. 66 (1989) 3456.
[9] R. Lehmberg, S. Obenschain, Use of induced spatial incoherence for uniform illumination on laser fusion targets, Tech. Rep. (1983). DTIC Document.
[10] D. Froula, L. Divol, R. London, R. Berger, T. Döppner, et al., Experimental basis for laser-plasma interactions in ignition hohlraums at the National Ignition Facilitya, Phys. Plasmas 17 (2010) 056302.
[11] J. Moody, B. MacGowan, J. Rothenberg, R. Berger, L. Divol, et al., Backscatter reduction using combined spatial, temporal, and polarization beam smoothing in a long-scale-length laser plasma, Phys. Rev. Lett. 86 (2001) 2810.
[12] Y. Zhao, J. Zheng, M. Chen, L.-L. Yu, S.-M. Weng, et al., Effects of relativistic electron temperature on parametric instabilities for intense laser propagation in underdense plasma, Phys. Plasmas 21 (2014) 112114.
[13] Z.-M. Sheng, K. Mima, Y. Sentoku, K. Nishihara, Parametric instabilities of intense lasers from interaction with relativistic hot plasmas, Phys. Rev. E 61 (2000) 4362.
[14] L.-L. Yu, Y. Zhao, L.-J. Qian, M. Chen, S.-M. Weng, et al., Plasma optical modulators for intense lasers, Nat. Commun. 7 (2016) 11893.
[15] C. Benedetti, C. Schroeder, E. Esarey, W. Leemans, Plasma wakefields driven by an incoherent combination of laser pulses: a path towards high-average power laser-plasma accelerators, Phys. Plasmas 21 (2014) 056706.
[16] M. Chen, Z.-M. Sheng, J. Zheng, Y.-Y. Ma, J. Zhang, Development and application of multi-dimensional particle-in-cell codes for investigation of laser plasma interactions, Chin. J. Comput. Phys. 25 (2008) 43.
[17] B. Winjum, J. Fahlen, F. Tsung, W. Mori, Anomalously hot electrons due to rescatter of stimulated Raman scattering in the kinetic regime, Phys. Rev. Lett. 110 (2013) 165001.
[18] T. O'Neil, Collisionless damping of nonlinear plasma oscillations, Phys. Fluids 8 (1965) 2255.
[19] D.S. Montgomery, Two decades of progress in understanding and control of laser plasma instabilities in indirect drive inertial fusion, Phys. Plasmas 23 (2016) 055601.
[20] N.A. Yampolsky, N.J. Fisch, Simplified model of nonlinear Landau damping, Phys. Plasmas 16 (2009) 072104.
[21] C. Liu, M.N. Rosenbluth, R.B. White, Raman and Brillouin scattering of electromagnetic waves in inhomogeneous plasmas, Phys. Fluids 17 (1974) 1211.
[22] M. Rosenbluth, R. White, C. Liu, Temporal evolution of a three-wave parametric instability, Phys. Rev. Lett. 31 (1973) 1190.