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Plasma modulator for high-power intense lasers

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Abstract: A type of plasma-based optical modulator is proposed for the generation of broadband high-power laser pulses. Compared with normal optical components, plasma-based optical components can sustain much higher laser intensities. Here we illustrate via theory and simulation that a high-power sub-relativistic laser pulse can be self-modulated to a broad bandwidth over 100% after it passes through a tenuous plasma. In this scheme, the self-modulation of the incident picoseconds sub-relativistic pulse is realized via stimulated Raman forward rescattering in the quasi-linear regime, where the stimulated Raman backscattering is heavily dampened. The optimal laser and plasma parameters for this self-modulation have been identified. For a laser with asub-relativistic intensity of $I \sim 10^{17}\mathrm{W/cm^2}$, the time scale for the development of self-modulation is around 10^3 light periods when stimulated Raman forward scattering has been fully developed. Consequently, the spatial scale required for such a self-modulation is in the order of millimeters. For a tenuous plasma, the energy conversion efficiency of this self-modulation is around 90%. Theoretical predictions are verified by both one-dimensional and two-dimensional particle-in-cell simulations.

1. Introduction

High-power picosecond (ps) or nanosecond (ns) lasers are mostly used in inertial confinement fusion (ICF) [1–3] and laboratory astrophysics [4,5]. Usually they have narrow bandwidths. High-power intense laser, especially that with broad bandwidth, have many advantages for applications, such as incoherent laser acceleration [6–8], THz radiation generation [9], parametric instability suppression [10–12], shock ignition and related astrophysics study [3,4,13]. Normal optical components are not suitable to modulate intense laser pulse due to their low damage threshold. Plasma-based optical devices have no damage threshold. Presently, plasma optics for the manipulation of high-power laser pulses has garnered much more attention [14–18].

Different from electro-optic modulators [19,20], intense laser modulates itself by its ponderomotive force acting on plasma [21,22]. Self-modulation of short pulses have been widely studied, such as wakefield generation, laser self-focusing and electromagnetic soliton. Mima et al. found that the stimulated photon cascade leads to the condensate of the relativistic laser pulse [23]. Najmudin et al. studied the electron acceleration in the self-modulated wakefield regime, where the wavebreaking results in energetic electrons being accelerated to more than 100 MeV [24]. Yu et al. proposed a scheme to modulate a carrier pulse by use of a drive pulse to excite quasi-linear plasma wave [18]. However, the time-lag between these two pulses must be less than 2ps, and the duration of carrier pulse is less than 3ps. Here we show that the self-modulation of high-power intense laser in tenuous plasma is an efficient and practical approach for laser spectral expansion

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with transmissivity around 90%. A low saturation level of stimulated Raman backward scattering (SRBS) and stimulated Brillouin scattering (SBS) is found in the quasi-linear regime within tenuous plasma, where the stimulated Raman forward scattering (SRFS) is the major instability mode. The optimal laser and plasma parameters for this self-modulation have been discussed in detail. The pump laser required here is achievable in many laser facilities worldwide [25]. This scheme paves a way to experimentally demonstrate some theoretical predictions, such as the suppression of laser plasma instabilities via multi-frequency broad bandwidth laser in ICF [11,12].

2. Theoretical analysis

Stimulated Raman scattering (SRS), the decay of the incident laser into a scattered light and an electron plasma wave [26,27], is an important mechanism in plasma optics [28], and also one of the key concerns in ICF [1,3,29]. SRS in the relativistic regime is described by the following dispersion relation [30,31]

$$\omega_L^2 - \omega_{pe}'^2 = \frac{\omega_{pe}'^2 k_L^2 c^2 a_0^2}{4\gamma^2}\left(\frac{1}{D_+} + \frac{1}{D_-}\right), \tag{1}$$

where k_0, γ, a_0 and c respectively are the wavenumber of incident laser, relativistic factor, pump laser amplitude, and the light speed in vacuum. $\omega_{pe}' = \omega_{pe}/\sqrt{\gamma}$ is the relativistic modification frequency of electron plasma wave. The relation between a_0 and laser intensity I is given by $a_0 = \sqrt{I(\mathrm{W/cm^2})[\lambda(\mu\mathrm{m})]^2/1.37\times10^{18}}$. The Stokes and anti-Stokes components are $D_- = (\omega_L - \omega_0)^2 - (k_L - k_0)^2c^2 - \omega_{pe}'^2$ and $D_+ = (\omega_L + \omega_0)^2 - (k_L + k_0)^2c^2 - \omega_{pe}'^2$, respectively. Waves mixing via stimulated Raman forward rescattering leads to the self-modulation of the pump laser [18,23,24]

$$a_m = a_0[1 + m\cos(\omega_{pe}'t)]\cos[\omega_0 t + f_m \sin(\omega_{pe}'t)], \tag{2}$$

where m and f_m are the modulation index for the light envelop and carrier frequency, respectively. The spectrum of the pump laser is broadened to a series of sidebands $\omega_m = \omega_0 \pm n\omega_{pe}'$, where n is a nonzero integer, and ω_{pe}' is the frequency interval.

According to Eq. (1), the phase velocity of the electron plasma wave driven by SRBS in tenuous plasma ($n_e \sim 10^{-3}n_c$) is around $v_B = \omega_{pe}'/2k_0 \sim \omega_{pe}'c/2\omega_0$, and the corresponding energy of trapped electrons in the electrostatic field is in the order of 10^0keV. Different from backscattering, the electrostatic wavenumber of SRFS is $k_F c = \omega_{pe}'$, and the corresponding phase velocity is $v_F \approx v_g$, where v_g is the group velocity of pump laser in plasma.

Large numbers of electrons can be accelerated to hundreds of keV within tens of laser periods in the quasi-linear plasma wave regime, and the electron energy gain satisfies $\Delta\gamma \approx 0.65a_0^2/\gamma_g \gtrsim 1/4$ (i.e., the energy gain is in the order of 10^2keV), where $\gamma_g = \sqrt{1 - v_g^2/c^2}$ [32]. Therefore, the pump laser with amplitude $a_0 \gtrsim 0.2$ is sufficient to drive quasi-linear plasma wave at density $n_e \lesssim 0.01n_c$, where n_c is the critical density for the incident laser. On account of $v_F \gg v_B$, backward SRS is heavily damped while comparing to forward SRS in the quasi-linear regime.

Tenuous plasma $0.001n_c < n_e \lesssim 0.01n_c$ used here is to reduce SRBS and also plasma wavebreaking. Wavebreaking can accelerate numerous electrons to even hundreds MeV and therefore heavily damped the forward SRS [24]. Meanwhile, the kinetic process will detune the phase-matching conditions and result in the weak modulation of laser pulse. The maximum laser amplitude for the self-modulation can be obtained based upon the electron energy gain $\Delta\gamma \lesssim \gamma_g = 10$ at $n_e = 0.01n_c$, i.e., $a_0 \lesssim 1.2$. Therefore, the optimal laser amplitude range for efficient laser phase

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modulation is

$$0.2 \lesssim a_0 \lesssim 1.2. \tag{3}$$

The growth rate of SRFS can be obtained from Eq. (1)

$$\Gamma_{\mathrm{FRS}} = \frac{\omega_{pe}'^2 a_0}{\sqrt{8}\omega_0 \gamma}. \tag{4}$$

Considering an example that a laser $a_0 = 0.3$ interacts with tenuous plasma $n_e = 0.005n_c$, the characteristic time for the development of SRFS is $t_{\mathrm{FRS}} = 1/\Gamma_{\mathrm{FRS}} \approx 327\tau$, where τ is the light period. Pump laser is self-modulated when SRFS has been fully developed. Therefore, the bandwidth and energy conversion efficiency of the carrier pulse can be controlled by the laser amplitude and plasma density according to Eq. (4).

3. Simulation verification

To validate the self-modulation of high-power intense lasers, several one-dimensional (1D) and two-dimensional (2D) particle-in-cell (PIC) simulations have been performed by using the OSIRIS code [33,34]. The space and time given in the following are normalized by the laser wavelength in vacuum λ and the laser period τ. Firstly, we present the 1D simulation results. The length of the simulation box is 15100λ, where the plasma occupies a region from 20λ to 15000λ with homogeneous density $n_e = 0.005n_c$. The initial electron temperature is $T_e = 10$eV. Ion mass is $m_i = 4080m_e$ with an effective charge $Z = 1$. A linear-polarization pump laser is incident from the left boundary of the simulation box with a 2000τ uniform envelope, and 30τ rise and fall edges in the front and end. The uniform envelope holds a peak amplitude $a_0 = 0.35$. We have taken 100 cells per wavelength and 50 particles per cell.

According to Eq. (4), the growth rate of stimulated Raman forward scattering under $a_0 = 0.35$ and $n_e = 0.005n_c$ is $\Gamma_{\mathrm{FRS}} = 5.5 \times 10^{-4}\omega_0$, i.e., the characteristic time for the SRFS development is $t_{\mathrm{FRS}} = 1/\Gamma_{\mathrm{FRS}} \sim 300\tau$. Therefore, SRFS has been fully developed at $t = 2100\tau$ as shown in Fig. 1(a). One finds an intense SRFS mode around $k_x c = 0.071\omega_0$. As a comparison, the SRBS mode is much weaker around $k_x c = 1.93\omega_0$. Note that the intensity of SBS at $k_x c = 1.995\omega_0$ is also much lower than SRFS mode. Therefore, SRFS is the major instability mode in the quasi-linear regime within tenuous plasma. The Stocks and anti-Stocks modes developed by SRFS can be found on either side of the central frequency ω_0 according to the wave-number distribution of electromagnetic wave displayed in Fig. 1(b). The electrostatic wave developed by SRFS is an initial perturbation for the rescatter of SRFS. Each scattering light develops its own secondary sidebands via stimulated Raman forward rescattering. As a result, sidebands are broadened at latter time $t = 3000\tau$ as shown in Fig. 1(c).

We diagnose the laser at $x = 3600\lambda$, where the energy transformation rate is 93.58%. According to Eq. (2) one knows that self-modulation also leads to the envelop modulation. The fluctuation of whole envelop is presented in Fig. 1(d). The spectra of the first half pulse (duration from $t = 3501\tau$ to $t = 4600\tau$) and the second half pulse (duration from $t = 4601\tau$ to $t = 5700\tau$) shown in Fig. 1(e) indicate that the whole pulse have been deeply modulated. We calculate the bandwidth only considering the sidebands with the intensities larger than 1% (-40dB) of the intensity of the unmodulated mode [18]. From the frequency spectrum exhibited in Fig. 1(f), we obtain the bandwidth of the whole laser $\Delta\omega_0 = 77.6\%\omega_0$. The full width at half maximum (FWHM) of the amplitude spectrum is $\Delta\omega_{\mathrm{FWHM}} \sim 31.68\%\omega_0$, which is important for the parametric inhibition. Note that the whole spectrum is symmetric for the Stokes and anti-Stokes in the early stage. We find a strongly nonlinear evolution of the output spectrum at $x = 15020\lambda$ as shown in Fig. 1(g). After propagating in the plasma over $10^4\tau$, the nonlinear frequency shifts of the electrostatic field lead to the many sidebands of each Stokes and anti-Stokes peak, and the spectrum is down shifted. Note that the maximum spectrum is no longer the original

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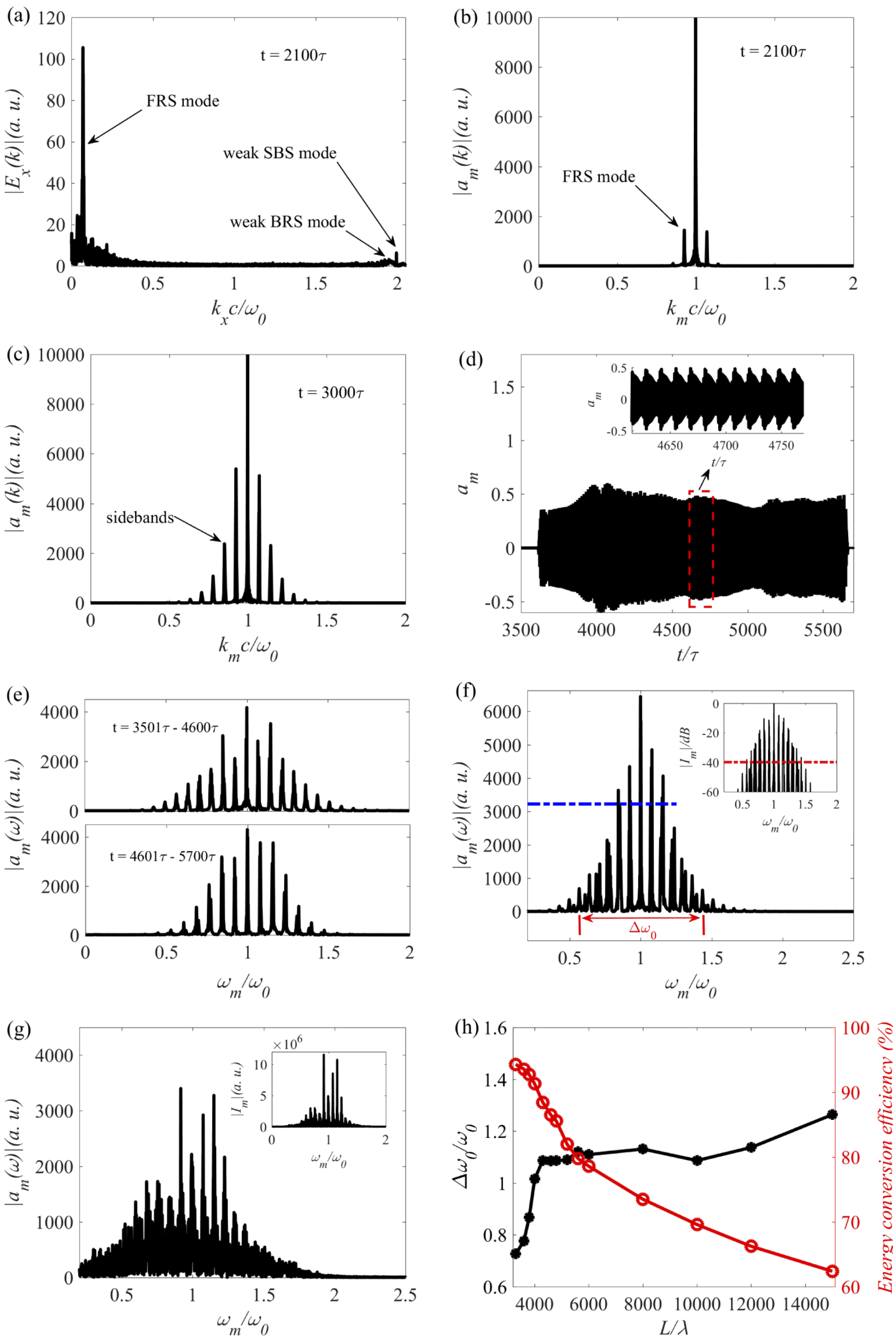

Fig. 1. (a) The wave-number distribution of electrostatic wave at $t = 2100\tau$. The wave-number distributions of electromagnetic wave at (b) $t = 2100\tau$ and (c) $t = 3000\tau$. (d) Temporal envelop of the self-modulated pulse diagnosed at $x = 3600\lambda$. (e) Spectra of the first half (the above one) and the second half (the below one) of (d). (f) Spectrum of the whole self-modulated pulse diagnosed at $x = 3600\lambda$. (g) Spectrum of the whole self-modulated pulse diagnosed at $x = 15020\lambda$. (h) Bandwidth and energy conversion efficiency of the self-modulated light though different plasma length. The insets of (f) and (g) are the intensity spectra. The pump laser amplitude is $a_0 = 0.35$, and plasma density is $n_e = 0.005n_c$.

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frequency ω_0. The evolutions of the laser bandwidth and transmissivity though different plasma length are displayed in Fig. 1(h). The bandwidth saturates at $\Delta\omega_0 = 110\%\omega_0$ after passing though 4300λ. The coupling of different Stokes and anti-Stokes modes $a_m(\omega)$ are weakened due to the large frequency interval ω'_{pe} [11], therefore, forward SRS is reduced by the broad bandwidth $\Delta\omega_{\mathrm{FWHM}}>0.3\omega_0 \gg \Gamma_{\mathrm{FRS}} = 5.5\times10^{-4}\omega_0$ [10,35], which lead to the saturation of the self-modulation. The energy conversion efficiency decreases slowly after the saturation of self-modulation. The bandwidth is weakly enhanced to $126.4\%\omega_0$ at $x = 15020\lambda$ due to the huge energy drain of the self-modulated pulse around 40%. In a brief conclusion, a 6.6ps flat pulse with amplitude $a_0 = 0.35$ and laser wavelength $\lambda = 1\mu m$ can be modulated to a broad bandwidth over $100\%\omega_0$ with a high transformation rate $\sim 90\%$.

According to Eq. (4) we know that the increase of plasma density can shorten the self-modulation time. The relation between modulation duration t_m and laser propagation length L is $L = (1-\omega'^2_{pe}/2\omega_0^2)ct_m \approx ct_m$ in tenuous plasma. Here we performed a series of simulations under different plasma densities with other parameters unchanged. The pulse duration is 660τ. Figure 2(a) describes the bandwidth and energy conversion efficiency of the self-modulated light though different plasma length under $n_e = 0.006n_c$ and $a_0 = 0.35$. The bandwidth is enlarged with the propagation distance, and finally saturates at $\Delta\omega_0 = 112\%\omega_0$. On the contrary, energy transformation rate almost linearly decreases with the propagation distance. Therefore, a tradeoff should be made for the optimal modulation length via considering both bandwidth and energy conversion efficiency. When the plasma density is enhanced to $n_e = 0.01n_c$, the overall tendency of the black and red lines are similar to the $n_e = 0.006n_c$ case with comparison between Figs. 2(a) and 2(b). However, the modulation length under $n_e = 0.01n_c$ is almost halved when the bandwidth is saturated. Note that the bandwidth saturation level of $n_e = 0.01n_c$ is slightly larger than that of $n_e = 0.006n_c$. In summary, plasma density shortens the modulation length via increasing the SRFS growth rate, whereas it has little effect on the bandwidth saturation level.

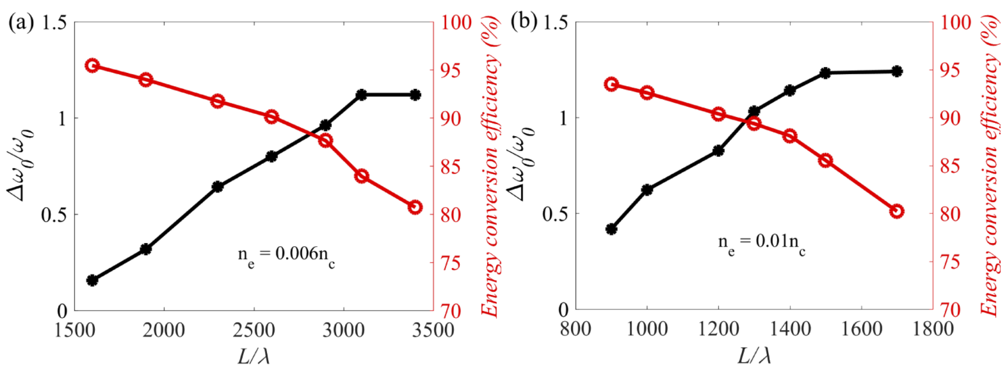

Fig. 2. Bandwidth and energy conversion efficiency of the self-modulated light though different plasma length. The plasma densities are (a) $n_e = 0.006n_c$ and (b) $n_e = 0.01n_c$. The pump laser amplitude is $a_0 = 0.35$.

Self-modulation of high-power laser is determined by the laser intensity under a given density. Figure 3(a) presents the case in the weak quasi-linear regime $a_0 = 0.2$. We find that the pump laser is broadened to a bandwidth $42.6\%\omega_0$ with over 26% energy loss. Laser with a small amplitude $a_0 \sim 0.2$ takes a long time $\sim 5000\tau$ to develop intense SRFS, meanwhile the energy loss of SRBS should be taken into account in this weak quasi-linear regime. This result validates the theoretical prediction that the minimum laser amplitude is around $a_0 = 0.2$ in case of massive energy loss. The electron plasma wave is driven into quasi-linear regime at $a_0 = 0.5$. The output carrier at $L = 3100\lambda$ possesses a broad bandwidth $\Delta\omega_0 = 76\%\omega_0$ with a high transformation rate 92.68% as shown in Fig. 3(b). When the laser amplitude is increased to $a_0 = 1$, the transmissivity

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is enhanced to 96.3% with bandwidth decreasing to 46.87%ω_0. However, when the laser intensity enters into the strongly relativistic regime, the laser self-modulation is suppressed by electron plasma wavebreaking. For an example, only a few weak sidebands can be found under $a_0 = 1.5$ as displayed in Fig. 3(d). The simulation results indicate that self-modulation of high-power laser efficiently works in the sub-relativistic regime, and the self-modulation process can be controlled by changing plasma density or laser intensity.

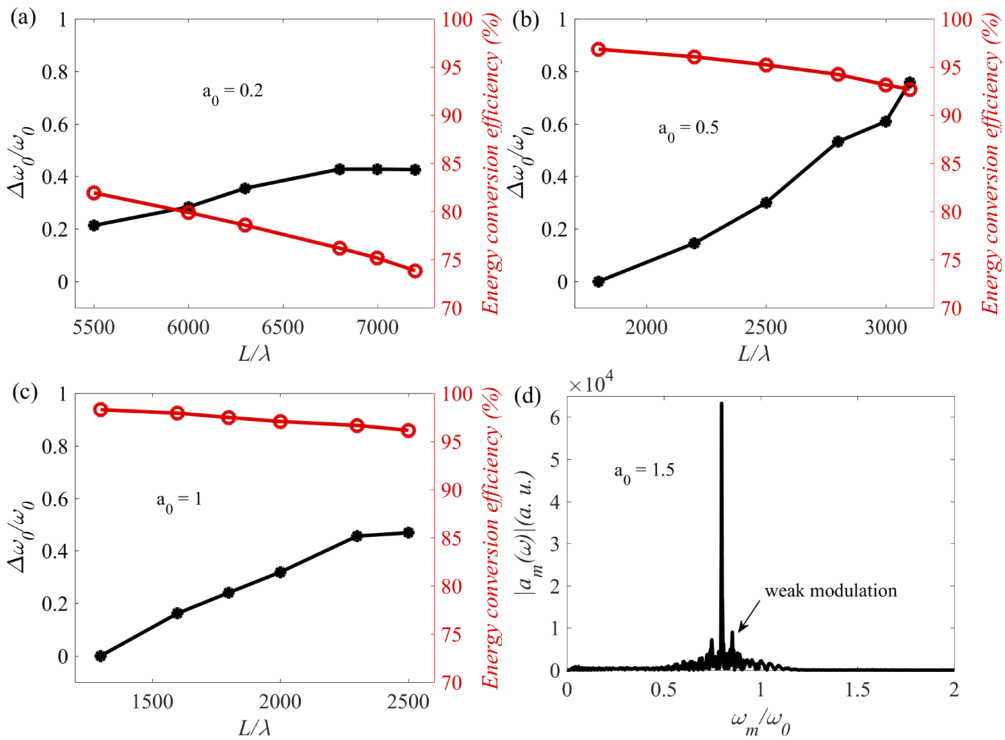

Fig. 3. (a)-(c) Bandwidth and energy conversion efficiency of the self-modulated light though different plasma length under $n_e = 0.005n_c$. The pump laser amplitudes are (a) $a_0 = 0.2$, (b) $a_0 = 0.5$ and (c) $a_0 = 1$. (d) Spectrum of the self-modulated pulse diagnosed at $x = 2500\lambda$ under $a_0 = 1.5$.

To further validate the self-modulation of high-power intense laser in tenuous plasma in high dimension, we performed a two-dimensional (2D) PIC simulation. Moving window is used to save the computing resource. The length of the window is 230λ, where the pump laser occupies a region from -192λ to -2λ with two 20λ gaussian-envelope edges on both ends of the laser. The laser holds its peak amplitude $a_0 = 0.8$ from -172λ to -22λ. The spot size of the pulse is 6λ at focal plane $x = 50\lambda$. Plasma locates from 0 to 1250λ in the longitudinal direction with 20λ width. Ion mass is $m_i = 4080m_e$ with an effective charge $Z = 1$. Plasma density is homogeneous $n_e = 0.01n_c$. We have taken 80 cells per wavelength in both transverse and longitudinal directions.

Note that the pulse defocuses after passing though the focal plane $x = 50\lambda$, and therefore the peak intensity is lower than $a_0 = 0.7$ at $t = 600\tau$ as shown in Fig. 4(a). We find envelop fluctuations of the self-modulated pulse in both longitudinal and transverse directions. As discussed in the theoretical section, self-modulation is closely related to the laser intensity, and therefore the inhomogeneous intensity distribution in transverse direction of the Gaussian beam leads to the envelop fluctuations. The phase modulation has already been found at $t = 600\tau$ as seen from the Fourier spectrum of the light exhibited in Fig. 4(b). 600τ later, the wavenumber

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spectrum is broadened to a large bandwidth as displayed in Fig. 4(c). The spectrum of the whole self-modulated pulse summarized along the transverse direction is displayed in Fig. 4(d). We obtain the bandwidth $\Delta\omega_0 = 87\%\omega_0$ and $\Delta\omega_{\mathrm{FWHM}} = 28.72\%\omega_0$ from the spectrum.

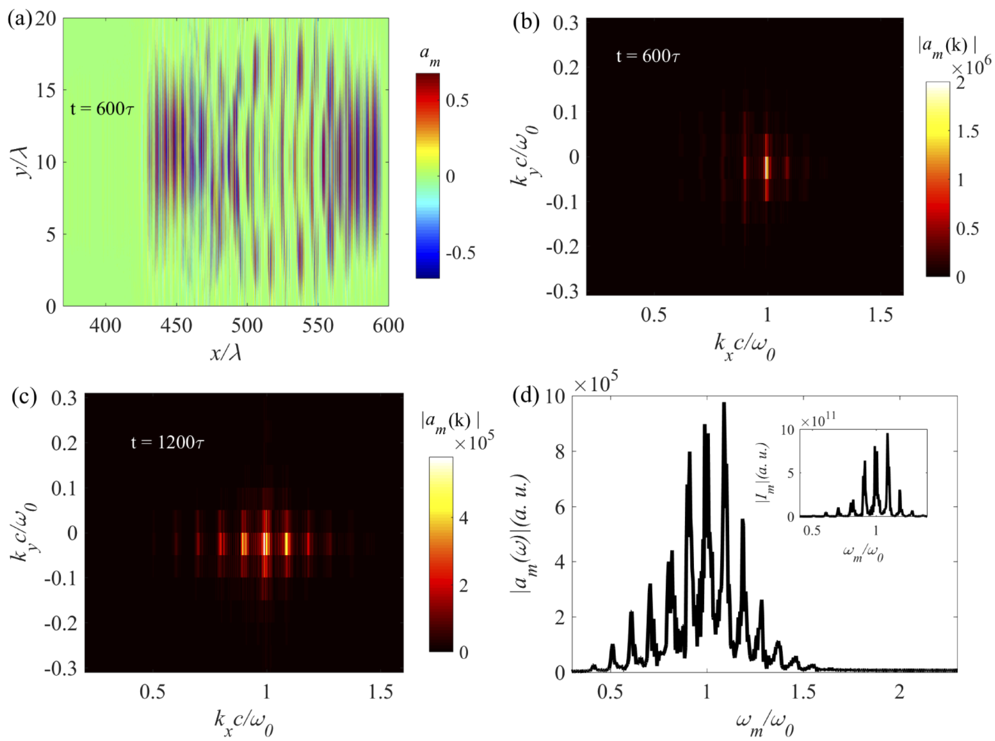

Fig. 4. (a) Spatial distribution of self-modulated light at $t = 600\tau$. Wavenumber distributions of self-modulated light at (b) $t = 600\tau$ and (c) $t = 1400\tau$. (d) Spectrum of the whole self-modulated pulse summarized along the transverse direction. The inset of (d) is the intensity spectrum.

The above 1D and 2D PIC simulations validate the theoretical predictions that high-power laser with amplitude within $0.2 \lesssim a_0 \lesssim 1.2$ can be efficiently modulated to a broad bandwidth around $100\%\omega_0$ in the interactions with tenuous plasma $0.001n_c<n_e \lesssim 0.01n_c$.

4. Discussion

As shown above, the high-power laser can be efficiently self-modulated in the quasi-linear regime. A reasonable configuration of optical system is required in different applications. For an example, the high-power laser with peak intensity $I \sim 10^{16}\mathrm{W/cm^2}$ is usually used in the shock ignition, which brings huge laser-energy loss and target preheat via intense parametric instabilities. Therefore, the suppression of parametric instability is one of the primary issues in ICF [3]. Multi-frequency laser with broad bandwidth is thought to be a candidate for the effective suppression of parametric instabilities [11,12].

Broad bandwidth can reduce the saturation level of the electrostatic field in inhomogeneous plasma, and the beamlet modes develop parametric instabilities independently when their frequency intervals satisfy a certain threshold [12]. According to the above simulation results, the frequency interval of the self-modulated pulse is $\delta\omega = \omega_{pe}' \sim 10^{-1}\omega_0$, and the FWHM of the amplitude spectrum is $\Delta\omega_{\mathrm{FWHM}} \sim 30\%\omega_0$, which are sufficient to detune the coherence of beamlet modes and reduce the instability intensity with comparing to the pump laser.

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Figure 5 displays the schematic diagram for the self-modulation of high-power laser in tenuous plasma. The high-power laser is focused on the tenuous plasma to reach the optimal intensity $I \sim 10^{17}\mathrm{W/cm^2}$ and then gradually defocuses in the modulation process, which is validated by the above 2D simulation. Under shock ignition, the target is expected be placed in the region where the modulated laser intensity is around $I \sim 10^{16}\mathrm{W/cm^2}$. This scheme is a potential way for the suppression of parametric instability in ICF.

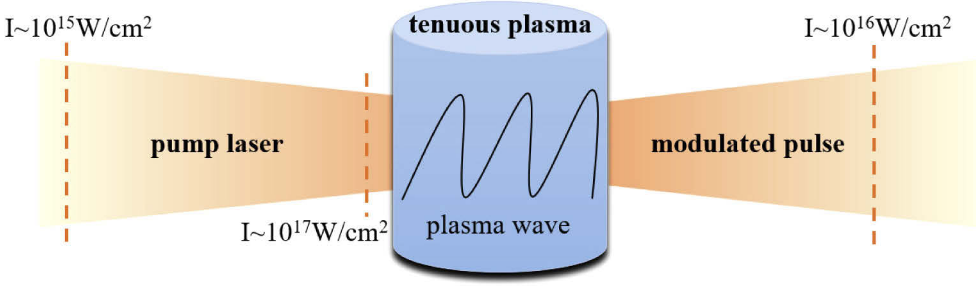

Fig. 5. Schematic diagram for the self-modulation of high-power laser in tenuous plasma. A high-power laser focuses on the tenuous plasma, and gradually defocuses in the modulating process.

Here we consider the effect of pulse duration on the laser self-modulation. The plasma parameters are same to the above first simulation case. For a short pulse with duration 160τ, we find an obvious down-shift of the spectrum after a long time propagation $\sim 4800\tau$ according to Fig. 6(a). In this case, the laser pulse length is much shorter than the plasma length, and this process is similar to the Self-Modulated Wake Field Acceleration (SMWFA) [24,36,37]. Different from this, convection should be considered for a picoseconds pulse. When the pulse duration is increased to 2560τ, one finds from Fig. 6(b) that the self-modulation is reduced at $n_e = 0.005n_c$ with comparing to 2060τ case in Fig. 1(f). The central frequency is much higher than the others with $\Delta\omega_{\mathrm{FWHM}} = 0$. The electron plasma wave has been detuned in the latter part of the long pulse, therefore, the self-modulation is weakened. One way to reduce the mismatch is to decrease the plasma density. The $\Delta\omega_{\mathrm{FWHM}}$ is increased to $21\%\omega_0$ under the case $n_e = 0.004n_c$.

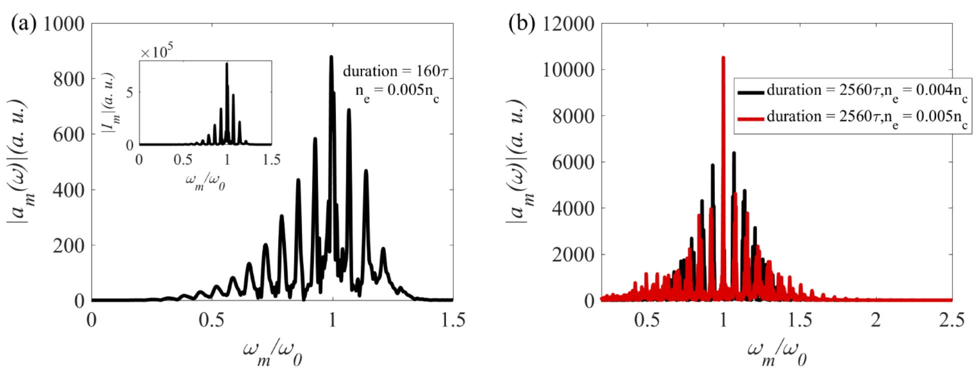

Fig. 6. (a) Spectrum of the self-modulated pulse with duration 160τ under $n_e = 0.005n_c$. (b) Spectra of the self-modulated pulse with duration 2560τ under different densities. The spectra are diagnosed at $x = 4800\lambda$. The inset of (a) is the intensity spectrum.

Now we discuss about the effect of plasma parameters on the laser self-modulation process. The modulation target can be produced by the gas jet or capillary discharge. The pump laser ionizes the tenuous gas, and meanwhile excites a quasi-linear electron plasma wave.

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A relatively homogeneous density is required for stimulated Raman forward rescattering, due to the wavenumber mismatch of the scattering light and the electrostatic wave in inhomogeneous plasma [27]. To develop stimulated Raman forward rescattering in inhomogeneous plasma, the overall density scale length needs to satisfy $L_{inh} \gg t_{\mathrm{FRS}}c$, i.e., $L_{inh} \gtrsim 10^3\lambda$. For an example, we have performed several simulations with inhomogeneous plasma $n_e = 0.004(1 + x/L_{inh})n_c$ and 660τ duration lasers. The spectra are diagnosed at the same point where $n_e = 0.008n_c$. Based upon Fig. 7(a), the self-modulation of pulse with $a_0 = 0.35$ has been suppressed at $L_{inh} = 4000\lambda$. The SRFS growth rate is increased for $a_0 = 0.5$, and therefore the spectrum is found to be broadened obviously. When L_{inh} is enhanced to 6000λ for the pulse with $a_0 = 0.35$, the $\Delta\omega_{\mathrm{FWHM}}$ is enlarged to $18\%\omega_0$ as shown in Fig. 7(b).

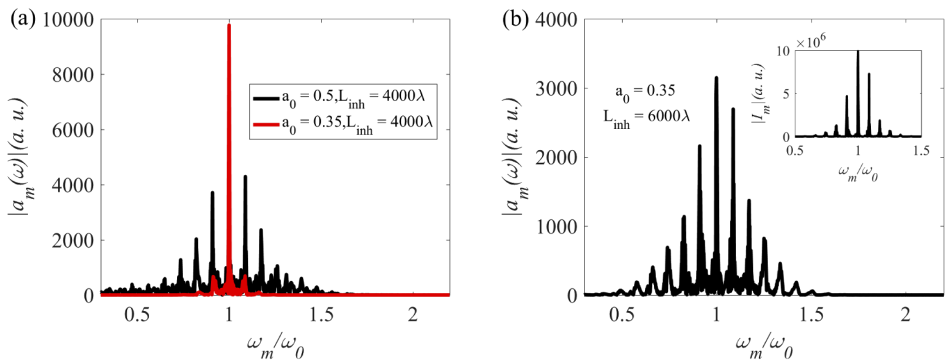

Fig. 7. (a) Spectra of the self-modulated pulse under the same density scale length $L_{inh} = 4000\lambda$ and different pump amplitude. (b) Spectrum of the self-modulated pulse under $a_0 = 0.35$ and density scale length $L_{inh} = 6000\lambda$. The spectra are diagnosed at $n_e = 0.008n_c$. The inset of (b) is the intensity spectrum.

Plasma may be weakly preheated by the pre-pulse. However, this initial temperature has little effect on the laser self-modulation due to the large phase velocity of electrostatic wave $v_F \sim c$ in the tenuous plasma.

As all known, electron-ion collision rate is proportional to the plasma density. Therefore, collisional damping is not the major energy loss in the interaction of picosecond pulse with tenuous plasma. The collision loss of the above first simulation case at $x = 3600\lambda$ is around 2.2%, which is obtained from the simulation including particle collisions.

Filamentation is a transverse instability which leads to the uneven intensity distribution. The filamentation growth rate in weak relativistic regime is [26]

$$\Gamma_{Fi} = \frac{\omega_{pe}^2 a_0^2}{8\omega_0}. \tag{5}$$

Considering the first simulation example presented in the above section with $\omega_{pe} = 0.07\omega_0$ and $a_0 = 0.35$, the characteristic time for the development of filamentation is $t_{Fi} = 2079\tau$. Therefore, filamentation has to be considered when the interaction length is larger than 3000λ.

5. Conclusion

In summary, we have shown theoretically and numerically that tenuous plasma can directly modulate high-power intense laser to a broad spectrum over $100\%\omega_0$ with high energy conversion efficiency. High-power intense laser can be efficiently self-modulated in plasma wave quasi-linear regime where the laser amplitude satisfies $0.2 \lesssim a_0 \lesssim 1.2$. Parametric instabilities except SRFS are saturated at a low level in this quasi-linear regime within tenuous plasma, and therefore the

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self-modulated laser possesses a high energy transformation rate. The characteristic time for the development of forward SRS is in the order of $10^2\tau$. When SRFS is fully developed, the high-power laser is deeply modulated via stimulated Raman forward rescattering. Therefore, millimeters-long plasma is required for laser self-modulation. The self-modulation process can be controlled by changing plasma density or laser intensity. Theoretical predictions are validated via both 1D and 2D PIC simulations. Such unique broadband high-power lasers are expected to have a wide range of potential applications.

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Disclosures

The authors declare no conflicts of interest.

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