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Modulation of ionization on laser frequency in ultra-short pulse intense laser–gas-target*

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Based on the dispersion relation of intense laser pulse propagating in gradually ionized plasma, this paper discusses the frequency modulation induced by ionization of an ultra-short intense laser pulse interacting with a gas target. The relationship between the frequency modulation and the ionization rate, the plasmas frequency variation, and the polarization of atoms (ions) is analysed. The numerical results indicate that, at high frequency, the polarization of atoms (ions) plays a more important role than plasma frequency variation in modulating the laser frequency, and the laser frequency variation is different at different positions of the laser pulse.

Keywords: intense laser pulse, tunnelling ionization, partially stripped plasma
PACC: 5240D, 4225B

1. Introduction

In view of the fact that the atoms cannot be fully stripped in many experiments of intense laser target (especially high Z target) interaction, the study of intense laser pulse interacting with partially stripped plasmas has attracted considerable attention over the past few years.[1−6] In the laser electric field, the trajectory of the bound electrons are distorted, and the partially stripped atoms are polarized, which induces the polarized current; therefore, many characteristics of laser pulse propagating in partially stripped plasma experience obvious change. Researches have shown that in the process of intense laser pulse interacting with partially stripped plasma, the stimulated Raman scattering and stimulated Brillouin scattering,[4] the self-generated magnetic field,[5] and the modulation instability[6] of the laser pulse are very different from the corresponding processes of intense laser pulse interacting with fully stripped plasmas.

The modulation of the laser frequency is one of the most important phenomena in the interaction of intense laser pulse and plasmas, and it directly relates with the generation of the supercontinua spectrum. Furthermore, the modulation instability can distort the shape of the laser pulse and affect the propagation of laser energy in the plasma.[6] The upshifting of the laser frequency is mainly caused by the variation of the dielectric function of the medium.[7−10] If the dielectric function only varies with the spacial variation, then the laser frequency conserves but the wavenumber varies; if the dielectric function only varies with the temporal variation, then the laser frequency varies and the wavenumber is conserved. In previous researches, only the electronic plasmas are taken into account, so the dielectric function is written as $\varepsilon = 1 - \omega_{\rm p}^2/\omega^2$. (The corresponding dispersion relation is $\omega^2 = \omega_{\rm p}^2 + k^2c^2$, where ω is laser frequency, k is the wavenumber, $\omega_{\rm p}$ is the plasma frequency, c is the light velocity in vacuum.) Suppose that the plasma frequency varies from 0 to $\omega_{\rm p}$ in a time interval $\Delta\tau$, then the laser frequency would change to $\omega_{\rm s} = \left(\omega^2 + \omega_{\rm p}^2\right)^{1/2}$ from ω in this time interval,[7−10] i.e. the laser frequency is up-shifted. In the partially stripped plasma, namely with the polarization of the atoms (ions) taken into account, the dielectric function is $\varepsilon = 1 - \omega_{\rm p}^2/\omega^2 + 4\pi\chi^{(1)} + 4\pi\chi^{(3)}\,(\boldsymbol{E}\cdot\boldsymbol{E})$, where $\chi^{(1)}$ and $\chi^{(3)}$ are the first and the third susceptibilities associated with the bound electrons; therefore, besides the variation of plasma frequency $\omega_{\rm p}$, the variation of susceptibilities and laser intensity can induce the modulation of the dielectric function, the laser frequency and wavenumber.

In this paper, the modulation of laser frequency is

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discussed based on the dispersion relation of a ultrashort intense laser propagating in a gas target, and the effect of the variation of plasma frequency and atoms (ions) polarization is discussed based on the analysis of the ionization of gas atoms (ions) in the laser field.

2. Basic equations

The wave equation of an intense laser pulse propagating in partially stripped plasmas is

$$\frac{\partial^2 \boldsymbol{E}}{\partial t^2} + c^2 \left[\nabla \times (\nabla \times \boldsymbol{E})\right] = -4\pi \frac{\partial \boldsymbol{J}}{\partial t} - 4\pi \frac{\partial^2 \boldsymbol{P}}{\partial t^2}, \quad (1)$$

where $\boldsymbol{J} = -en_{\rm e}\boldsymbol{v}$, $n_{\rm e}$ is the density of free electrons, $\boldsymbol{v}$ is the velocity of free electrons, and $\boldsymbol{P} = \left[\chi^{(1)} + \chi^{(3)}(\boldsymbol{E}\cdot\boldsymbol{E})\right]\boldsymbol{E}$ is the polarization of the atoms (ions). Considering the gas possesses the centrosymmetry, the second susceptibility $\chi^{(2)} = 0$.

For the expansion of the polarization field in powers of the field to be valid we require $\chi^{(1)} >> \chi^{(3)}(\boldsymbol{E}\cdot\boldsymbol{E})$, which in terms of laser intensity I is $I << \frac{c}{4\pi}\eta_0 \frac{\chi^{(1)}}{\chi^{(3)}}$, where $\eta_0 = (1+4\pi\chi^{(1)})^{1/2}$ is the linear refractive index. As an example, for typical neutral Ar gas at standard temperature and pressure (STP), $n_{\rm a0} = 2.7\times10^{19}{\rm cm}^{-3}$, the susceptibilities are $\chi^{(1)} \cong 10^{-3}$ and $\chi^{(3)} \cong 3.4\times10^{-18}$esu,[2] and the laser intensity is limited to $I << 7\times10^{16}{\rm Wcm}^{-2}$.

In the present paper, we consider a linear polarized laser pulse $\boldsymbol{E} = \frac{1}{2}\boldsymbol{A}{\rm e}^{{\rm i}\varphi} + {\rm c.c.}$, where $\boldsymbol{A}$ is a slowly varying function both in time on the laser radiation period $(2\pi/\omega)$ and in space on its wavelength $(2\pi/k)$, φ is the phase of the wave. Therefore, the frequency and wavenumber are $\omega(z,t) = \frac{\partial\varphi}{\partial t}$ and $k(z,t) = -\frac{\partial\varphi}{\partial z}$ respectively. Considering that $\frac{1}{\chi^{(1)}}\frac{\partial\chi^{(1)}}{\partial t}$, $\frac{1}{\chi^{(3)}}\frac{\partial\chi^{(3)}}{\partial t}$, $\frac{1}{I}\frac{\partial I}{\partial t} << \omega^2$ and neglecting the harmonic, we can derive the dispersion relation for the pump wave from Eq.(1) as

$$\omega^2 - k^2c^2 \cong \omega_{\rm p}^2 - 4\pi\left[\chi^{(1)} + 3\chi^{(3)}\langle\boldsymbol{E}\cdot\boldsymbol{E}\rangle\right]\omega^2, \quad (2)$$

where $\omega_{\rm p} = \left(\frac{4\pi e^2 n_{\rm e}}{m_{\rm e}}\right)^{1/2}$. Using $\frac{\partial k}{\partial t} = -\frac{\partial\omega}{\partial z}$ and $I = \frac{c}{4\pi}\eta_0\langle\boldsymbol{E}\cdot\boldsymbol{E}\rangle$, and differentiating Eq.(2) with respect to time, we get

$$\left(\eta_0^2 + 12\pi\chi^{(3)}\frac{4\pi}{c\eta_0}I\right)\frac{\partial\omega^2}{\partial t} + v_g\frac{\partial\omega^2}{\partial z} = \frac{\partial\omega_{\rm p}^2}{\partial t} - 4\pi\left(\frac{\partial\chi^{(1)}}{\partial t} + \frac{\partial\chi^{(3)}}{\partial t}\frac{12\pi}{c\eta_0}I + \chi^{(3)}\frac{12\pi}{c\eta_0}\frac{\partial I}{\partial t}\right)\omega^2, \quad (3)$$

where $v_{\rm g}$ is the group velocity of the laser pulse. Eq.(3) shows that the modulation of laser frequency not only relies on the variation of plasma frequency but also relies on the variation of susceptibilities and laser intensity.

In Eq. (3), the variation of plasma frequency on time is caused by the ionization of bound electrons in the laser field. Considering the atoms may be ionized more than one time, we have[10]

$$\frac{\partial\omega_{\rm p}^2}{\partial t} = \frac{\partial\omega_{\rm p1}^2}{\partial t} + \frac{\partial\omega_{\rm p2}^2}{\partial t} + \cdots = \gamma_1(\omega_{\rm a0}^2 - \omega_{\rm p1}^2) + \gamma_2(\omega_{\rm p1}^2 - \omega_{\rm p2}^2) + \cdots, \quad (4)$$

where γ_1, γ_2, ... are the first, second, ... steps of ionization rate respectively, $\omega_{\rm a0}^2 = 4\pi e^2 n_{\rm a0}/m_{\rm e}$, $\omega_{\rm p1}^2 = 4\pi e^2 n_{\rm e1}/m_{\rm e}$, $\omega_{\rm p2}^2 = 4\pi e^2 n_{\rm e2}/m_{\rm e}$, ..., $n_{\rm a0}$ is the initial density of gas atoms, $n_{\rm e1}$, $n_{\rm e2}$, ... are the free electron density generated by the first, second, ... steps of ionization of the gas atoms respectively.

If the optical frequency is far below any atomic resonance, the susceptibilities can be approximately given by[2,11]

$$\chi_{\rm a}^{(1)} \cong \frac{2n_{\rm a}\mu^2}{\hbar\Omega_{\rm R}}, \quad (5)$$

$$\chi_{\rm a}^{(3)} \cong \frac{8n_{\rm a}\mu^4}{\hbar^3\Omega_{\rm R}^3}, \quad (6)$$

where $n_{\rm a}$ is the density of neutral atoms, $\mu \cong er_{\rm B}$, $r_{\rm B} = \hbar^2/e^2m_{\rm e}$ is the Bohr radius, $\Omega_{\rm R}$ is the atomic resonant frequency. Since $\Omega_{\rm R}$ is roughly proportional to the ionization potential $U_{\rm I}$, the rates of the susceptibilities of ionized atom to the neutral atom are[2]

$$\chi_+^{(1)}/\chi_{\rm a}^{(1)} \approx U_{\rm I}/U_{\rm I}^+, \quad (7)$$

$$\chi_+^{(3)}/\chi_{\rm a}^{(3)} \approx (U_{\rm I}/U_{\rm I}^+)^3. \quad (8)$$

Similarly, we have $\chi_{++}^{(1)}/\chi_+^{(1)} \approx U_{\rm I}^+/U_{\rm I}^{++}$, $\chi_{++}^{(3)}/\chi_+^{(3)} \approx (U_{\rm I}^+/U_{\rm I}^{++})^3$, ..., where $U_{\rm I}^+$, $U_{\rm I}^{++}$, ... are the ionization potential of different species of ions, $\chi_+^{(1)}$, $\chi_{++}^{(1)}$, ... and $\chi_+^{(3)}$, $\chi_{++}^{(3)}$, ... are the linear and nonlinear susceptibilities of different species of ions. Eqs.(5) and (6) imply that the susceptibilities are proportional to the density of atoms, i.e. $\chi_j^{(i)} = \sigma_j^{(i)} n_j$ (i=1, 3; $j = a, +, ++, \cdots$), where $\sigma_j^{(i)}$ is the proportional coefficient, and n_j is the density of different species of ions. Therefore, the total linear and nonlinear susceptibilities are

$$\chi^{(1)} \cong \sigma_{\rm a}^{(1)} n_{\rm a} + \sigma_+^{(1)} n_+ + \sigma_{++}^{(1)} n_{++} + \cdots, \quad (9)$$

$$\chi^{(3)} \cong \sigma_{\rm a}^{(3)} n_{\rm a} + \sigma_+^{(3)} n_+ + \sigma_{++}^{(3)} n_{++} + \cdots. \quad (10)$$

Furthermore, we have $\sigma_+^{(1)}/\sigma_{\rm a}^{(1)} \approx U_{\rm I}/U_{\rm I}^+$, $\sigma_+^{(3)}/\sigma_{\rm a}^{(3)} \approx (U_{\rm I}/U_{\rm I}^+)^3$, $\sigma_{++}^{(1)}/\sigma_+^{(1)} \approx U_{\rm I}^+/U_{\rm I}^{++}$, $\sigma_{++}^{(3)}/\sigma_+^{(3)} \approx (U_{\rm I}^+/U_{\rm I}^{++})^3$, ... Therefore,

$$\begin{aligned}\frac{\partial\chi^{(1)}}{\partial t} \cong&\sigma_{\rm a}^{(1)}\frac{\partial n_{\rm a}}{\partial t}+\sigma_+^{(1)}\frac{\partial n_+}{\partial t}+\sigma_{++}^{(1)}\frac{\partial n_{++}}{\partial t}+\cdots\\ =&(\sigma_+^{(1)}-\sigma_{\rm a}^{(1)})\gamma_1(n_{\rm a0}-n_{\rm e1})\\ &+(\sigma_{++}^{(1)}-\sigma_+^{(1)})\gamma_2(n_{\rm e1}-n_{\rm e2})+\cdots,\end{aligned} \tag{11}$$

$$\begin{aligned}\frac{\partial\chi^{(3)}}{\partial t} \cong&\sigma_{\rm a}^{(3)}\frac{\partial n_{\rm a}}{\partial t}+\sigma_+^{(3)}\frac{\partial n_+}{\partial t}+\sigma_{++}^{(3)}\frac{\partial n_{++}}{\partial t}+\cdots\\ =&(\sigma_+^{(3)}-\sigma_{\rm a}^{(3)})\gamma_1(n_{\rm a0}-n_{\rm e1})\\ &+(\sigma_{++}^{(3)}-\sigma_+^{(3)})\gamma_2(n_{\rm e1}-n_{\rm e2})+\cdots.\end{aligned} \tag{12}$$

In the process of intense laser pulse interacting with target, the laser energy reduces via all kinds of absorbance mechanisms, but for simplicity, we only take the ionization into account, so

$$\frac{\partial I}{\partial t} \cong -c\left[U_{\rm I}\gamma_1(n_{\rm a0}-n_{\rm e1})+U_{\rm I}^+\gamma_2(n_{\rm e1}-n_{\rm e2})+\cdots\right]. \tag{13}$$

Substituting Eqs.(4), (11), (12), and (13) into Eq.(3), we get

$$\begin{aligned}&\left(\eta_0^2+4\pi\chi^{(3)}\frac{4\pi}{c\eta_0}I\right)\frac{\partial\omega^2}{\partial t}+v_{\rm g}\frac{\partial\omega^2}{\partial z}\\ =&\frac{4\pi e^2}{m_{\rm e}}\left[\gamma_1(n_{\rm a0}-n_{\rm e1})+\gamma_2(n_{\rm e1}-n_{\rm e2})+\cdots\right]\\ &-4\pi\{[(\sigma_+^{(1)}-\sigma_{\rm a}^{(1)})\gamma_1(n_{\rm a0}-n_{\rm e1})+(\sigma_{++}^{(1)}-\sigma_+^{(1)})\\ &\times\gamma_2(n_{\rm e1}-n_{\rm e2})+\cdots]+[(\sigma_+^{(3)}-\sigma_{\rm a}^{(3)})\gamma_1(n_{\rm a0}-n_{\rm e1})\\ &+(\sigma_{++}^{(3)}-\sigma_+^{(3)})\gamma_2(n_{\rm e1}-n_{\rm e2})+\cdots]\frac{12\pi}{c\eta_0}I-\chi^{(3)}\frac{12\pi}{\eta_0}\\ &\times[U_{\rm I}\gamma_1(n_{\rm a0}-n_{\rm e1})+U_{\rm I}^+\gamma_2(n_{\rm e1}-n_{\rm e2})+\cdots]\}\omega^2.\end{aligned} \tag{14}$$

3. Numerical results

In the ultra-short laser pulse, the collisional ionization rate is small, and the bound electrons are mainly ionized by photoionization.[12] The photoionization includes two regimes, i.e. tunnelling regime and multiphoton regime. These regimes are characterized by the Keldysh parameter $\gamma_{\rm K} = (U_{\rm I}/U_{\rm os})^{1/2}$,[2,13,14] where $U_{\rm os} = (1/2)m_{\rm e}(eE_0/m_{\rm e}\omega)^2$ is the electron oscillation energy, E_0 is the peak electric field of the laser pulse. The low field limit ($\gamma_{\rm K} > 1$) corresponds to the multiphoton ionization regime, whereas the high field limit ($\gamma_{\rm K} < 1$) corresponds to the tunnelling ionization regime. In the present paper, we consider a Gaussian intense laser pulse ($I(0) = I_0\exp(-\tau^2/\tau_{\rm L}^2){\rm Wcm}^{-2}$, where $\tau_{\rm L} =$ 15fs, $I_0 \sim 10^{15}{\rm Wcm}^{-2}$) interacting with Ar gas target ($U_{\rm I} = 15.8$eV, $U_{\rm I}^+ = 27.6$eV, $U_{\rm I}^{++} = 40.7$eV). The corresponding electron oscillation energy $U_{\rm os} > 90$eV (where the wavelength $\lambda = 1.06\mu$m is presumed), i.e. $\gamma_{\rm K} < 1$, therefore, we only take the tunnelling ionization into account. (In the wings of the laser pulse where $I < 10^{13}{\rm Wcm}^{-2}$, the bound electron is mainly ionized by multiphoton ionization regime. If the multiphoton ionization time is very short, e.g. several femto-second, the multiphoton ionization regime should be taken into account.) In the laser pulse body, the Ar atoms mainly occurs at the first, second and third step of tunnelling ionization, and the ionization rates respectively are[2,13]

$$\begin{aligned}\gamma_1 =&4\Omega_0\left(\frac{U_{\rm I}}{U_{\rm H}}\right)^{5/2}\left(\frac{I_{\rm H}}{I}\right)^{1/2}\\ &\times\exp\left[-\frac{2}{3}\left(\frac{U_{\rm I}}{U_{\rm H}}\right)^{3/2}\left(\frac{I_{\rm H}}{I}\right)^{1/2}\right],\end{aligned} \tag{15}$$

$$\begin{aligned}\gamma_2 =&4\Omega_0\left(\frac{U_{\rm I}^+}{U_{\rm H}}\right)^{5/2}\left(\frac{I_{\rm H}}{I}\right)^{1/2}\\ &\times\exp\left[-\frac{2}{3}\left(\frac{U_{\rm I}^+}{U_{\rm H}}\right)^{3/2}\left(\frac{I_{\rm H}}{I}\right)^{1/2}\right],\end{aligned} \tag{16}$$

$$\begin{aligned}\gamma_3 =&4\Omega_0\left(\frac{U_{\rm I}^{++}}{U_{\rm H}}\right)^{5/2}\left(\frac{I_{\rm H}}{I}\right)^{1/2}\\ &\times\exp\left[-\frac{2}{3}\left(\frac{U_{\rm I}^{++}}{U_{\rm H}}\right)^{3/2}\left(\frac{I_{\rm H}}{I}\right)^{1/2}\right],\end{aligned} \tag{17}$$

where $\Omega_0 = 4.1\times10^{16}{\rm s}^{-1}$, $I_{\rm H} = 3.6\times10^{16}{\rm Wcm}^{-2}$, $U_{\rm H} = 13.6$eV. The variation of electrons density in the laser pulse can be obtained by substituting Eqs.(15)–(17) into Eq.(4) and using $n_{\rm e} = \dfrac{m_{\rm e}}{4\pi e^2}\omega_{\rm p}^2$, the variation of laser intensity in the propagating process can be obtained by Eq.(13). The numerical results are shown in Fig.1.

Figure 1 shows the distribution of plasma density and laser intensity after a laser pulse propagated 80μm in the Ar gas target. The laser pulse propagated from left to right. In Fig.1(a), the initial laser intensity $I_0 = 5\times10^{14}{\rm Wcm}^{-2}$, and in the laser pulse body, the Ar atoms mainly occur at the first step of ionization. In Fig.1.(b), the initial laser intensity $I_0 = 5\times10^{15}{\rm Wcm}^{-2}$. The figure shows that the third step ionization of Ar atoms occurred, and the I, II and III sections are the free electrons generated by the first, second and third ionization respectively. The distinctive parts of the laser pulse that the first, second and third step of ionization occurs result from the large ionization potential gaps.[12]

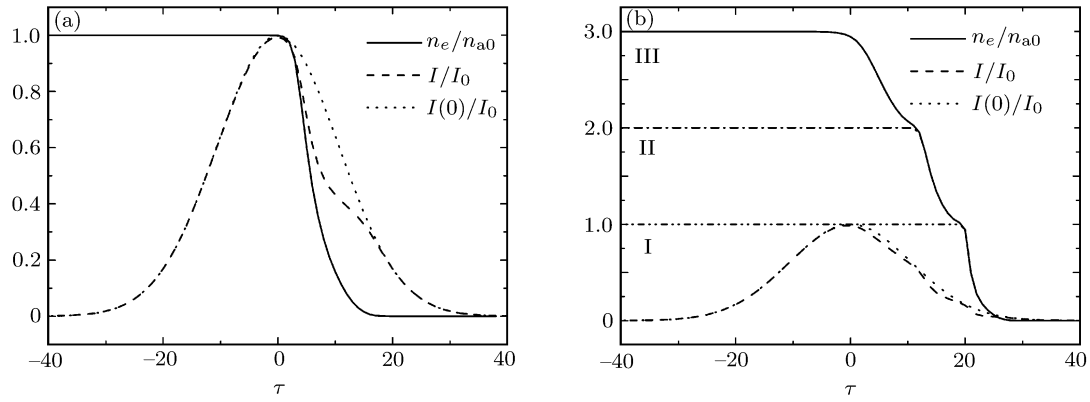


Fig.1. The distribution of plasma density and laser intensity after the Gaussian laser pulse ($\tau_{\rm L}$ = 15fs, λ = 1.06μm) with different intensity (a) $I_0 = 5\times10^{14}{\rm Wcm}^{-2}$, (b) $I_0 = 5\times10^{15}{\rm Wcm}^{-2}$ propagated 80μm in the Ar gas target ($n_{a0} = 2.7\times10^{19}{\rm cm}^{-3}$). I denotes the varying laser intensity. The solid line denotes the relative plasma density, the dashed line denotes the relative laser intensity, and the dotted line denotes the normalized initial laser intensity.

For typical neutral Ar gas at standard temperature and pressure (STP), we have $4\pi\chi^{(1)} + 4\pi\chi^{(3)}\dfrac{4\pi}{c\eta_0}I \sim 10^{-2} << 1$, and simultaneous, $\sigma_{\rm a}^{(1)} \approx 3.7\times10^{-23}$, $\sigma_{+}^{(1)} \approx 2.1\times10^{-23}$, $\sigma_{++}^{(1)} \approx 1.4\times10^{-23}$, $\sigma_{+++}^{(1)} \approx 0.95\times10^{-23}$, $\sigma_{\rm a}^{(3)} \approx 1.3\times10^{-37}$, $\sigma_{+}^{(3)} \approx 2.4\times10^{-38}$, $\sigma_{++}^{(3)} \approx 7.6\times10^{-39}$, and $\sigma_{+++}^{(3)} \approx 2.4\times10^{-39}$ can be obtained. Assume that $\eta_0 \approx 1$ and only take the first, second and third step of ionization into account, Eq. (4) can be approximated to

$$\begin{aligned}\frac{\partial\omega^2}{\partial t} + v_{\rm g}\frac{\partial\omega^2}{\partial z} \cong & \frac{4\pi e^2}{m_{\rm e}}\left[\gamma_1(n_{\rm a0}-n_{\rm e1}) + \gamma_2(n_{\rm e1}-n_{\rm e2}) + \gamma_3(n_{\rm e2}-n_{\rm e3})\right] \\ & + 4\pi\{\left[1.6\gamma_1(n_{\rm a0}-n_{\rm e1}) + 0.7\gamma_2(n_{\rm e1}-n_{\rm e2}) + 0.45\gamma_3(n_{\rm e2}-n_{\rm e3})\right]\times10^{-23} \\ & + \left[10.6\gamma_1(n_{\rm a0}-n_{\rm e1}) + 1.64\gamma_2(n_{\rm e1}-n_{\rm e2}) + 0.52\gamma_3(n_{\rm e2}-n_{\rm e3})\right]\frac{12\pi}{c}I\times10^{-38} \\ & + 12\pi\times3.4[U_{\rm I}\gamma_1(n_{\rm a0}-n_{\rm e1}) + U_{\rm I}^{+}\gamma_2(n_{\rm e1}-n_{\rm e2}) + U_{\rm I}^{++}\gamma_3(n_{\rm e2}-n_{\rm e3})]\times10^{-18}\}\omega^2. \end{aligned} \tag{18}$$

Using Eqs.(4), (15)–(17), we achieve the numerical calculation of Eq.(18), and the results are shown in Fig.2.

Figure 2 shows the modulation of laser frequency after the Gaussian laser pulse with different initial intensity and wavelength propagated 80μm in the Ar gas target. The laser pulse propagated from left to right. In Figs.2(d)–(f), the three peaks from right to left denote the frequency modulation results from the first, second and third step of ionization respectively. Figure 2 shows that, i) if the ionization rate of the gas not only varies in time but also varies in space, the laser frequency variation is different at different positions of the laser pulse. At the position where the ionization rate is higher, the frequency increases faster. As in Fig.2(d), where $I_0 = 5\times10^{15}{\rm Wcm}^{-2}$ and $\lambda = 1.06\mu$m, in the front edge of the laser pulse, the maximal frequency can get to 3.4 times of the initial laser frequency, but in the back edge of the laser pulse, the laser frequency varies little. The reason is that the ionization of Ar atoms mainly occurs in the front edge of the laser pulse; ii) with the laser pulse at higher frequency, the polarization of atoms (ions) has greater contribution to the increase of laser frequency. For example, in Figs.2(a) and (d), due to the initial laser frequency being low, the polarization of atoms (ions) contributes little to the increase of laser frequency, but in Figs.2(c) and (f), due to the initial laser pulse frequency being higher, the increased frequency is 1.11 and 1.22 times the initial frequency excluding the contribution of polarization, and 1.32 and 1.62 times of initial frequency for including the

contribution of polarization. The maximal variation of $\Delta\omega^2$ included the contribution of polarization approximately is 3 times greater than the maximal variation quantity excluded the contribution of polarization, i.e. at high initial frequency, the polarization of atoms (ions) plays a more important role than plasma frequency variation in modulating the laser frequency.

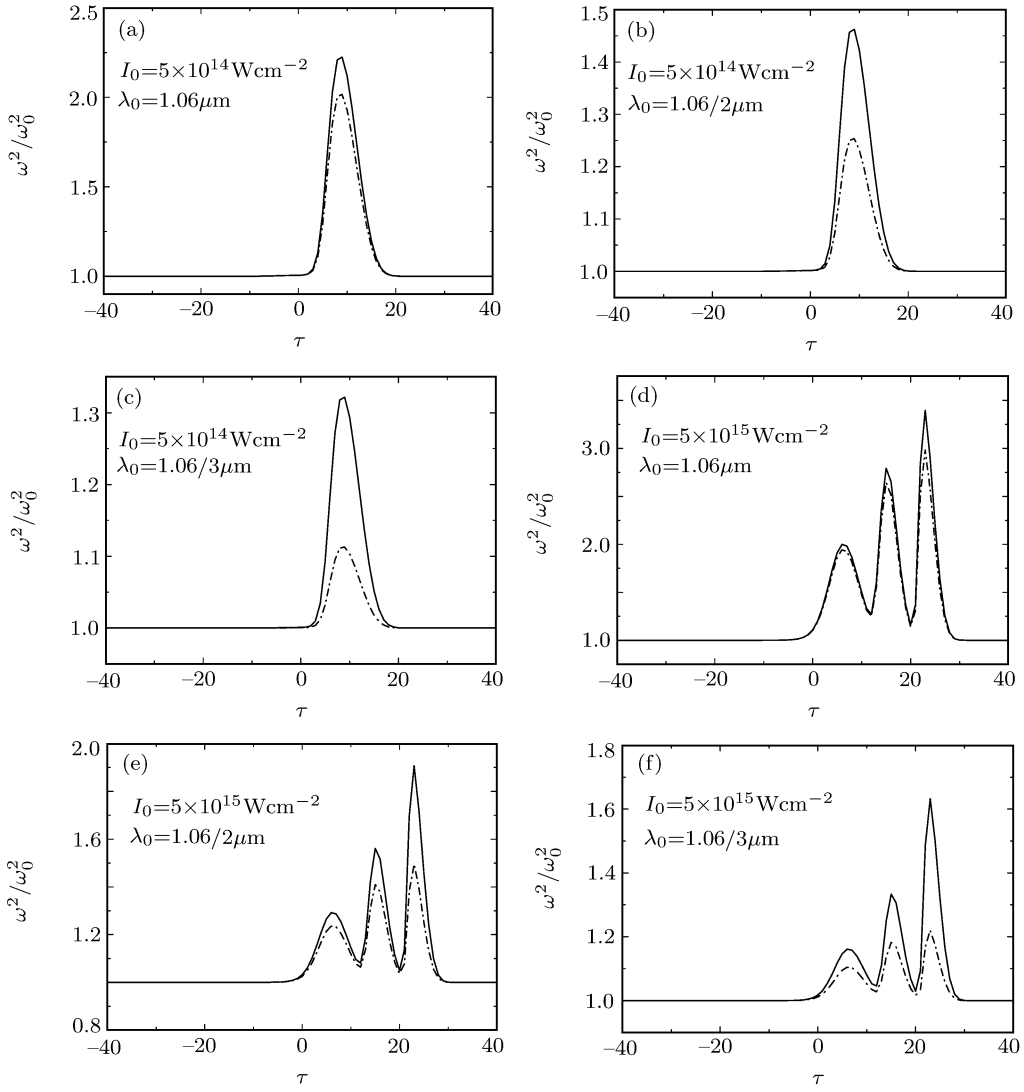


Fig.2. The modulation of laser frequency after the Gaussian laser pulse ($\tau_{\rm L}$ = 15fs) propagated 80μm in the Ar gas target ($n_{\rm a0} = 2.7 \times 10^{19}{\rm cm}^{-3}$) for different initial wavelength and intensity. (a) $\lambda = 1.06\mu$m, $I_0 = 5 \times 10^{14}{\rm Wcm}^{-2}$; (b)$\lambda = 1.06/2\mu$m, $I_0 = 5 \times 10^{14}{\rm Wcm}^{-2}$; (c) $\lambda = 1.06/3\mu$m, $I_0 = 5 \times 10^{14}{\rm Wcm}^{-2}$; (d) $\lambda = 1.06\mu$m, $I_0 = 5 \times 10^{15}{\rm Wcm}^{-2}$; (e) $\lambda = 1.06/2\mu$m, $I_0 = 5 \times 10^{15}{\rm Wcm}^{-2}$; (f) $\lambda = 1.06/3\mu$m, $I_0 = 5 \times 10^{15}{\rm Wcm}^{-2}$. The solid line denotes the total variation of laser frequency and the dash-dotted line denotes the laser frequency variation excluded the polarization effect.

4. Conclusion

In this paper, the frequency modulation of an intense laser pulse interacting with Ar gas target is discussed based on the dispersion relation of intense laser propagating in partially stripped plasma. The modulation of laser frequency directly relates to the variation of dielectric function, and the variation of dielectric function is caused by the ionization of gas atoms in the laser field. The ionization rate of gas atoms in the laser field determines the speed of ionization and the increasing speed of the laser frequency. In the partially stripped plasma, the higher initial laser frequency, the more important role the polarization of atoms (ions) plays in modulating the laser frequency than plasma frequency variation, and the laser frequency variation is different at different position of the laser pulse due to the different ionization rate.

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