*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-4.022 (2004)*

Density modulation produced by laser pulses at modest intensities and induced phase reflection in underdense plasmas

Q. -J. Zhang, Z.-M. Sheng, Y. Cang, and J Zhang

Laboratory of Optical Physics, Institute of Physics, CAS, Beijing 100080, China

1. Introduction

The interaction of light with periodic layered media is very different to continuous media [1-3]. In this paper, we study the plasma density modulations formed in pre-plasma in front of a solid target and the induced phase reflection, where the average plasma density is lower than the critical density. Dependence of the phase reflection on laser and plasmas parameters are discussed. The phase reflection may significantly reduce laser absorption in ICF targets.

2. Density modulations

We consider the interaction of a plane laser pulse with a pre-plasma in front of target as shown in Fig. 1(a). The total interfering field caused by the input and reflected laser pulses in pre-plasma can be given by $\vec{a}(x,t) = [a_1 \cos(k_f x - \omega t)\hat{e}_z + a_2 \cos(k_f x + \omega t)\hat{e}_z]$, where $k_f = k_0(1 - n_0/n_c)^{1/2}$, k_0 is the wave-vector of the laser in unperturbed plasma and vacuum, respectively. The electron density modulation at the earlier time stage $\delta n_e = -(2k_f{}^2 c^2/\omega_p^2) a_1 a_2 \cos(2k_f x)[1 - \cos(\omega_p t)]$ [3] has the same period in space with that of the ion density, so that they can form a bulk grating-like structure with a wavelength of π / k_f.

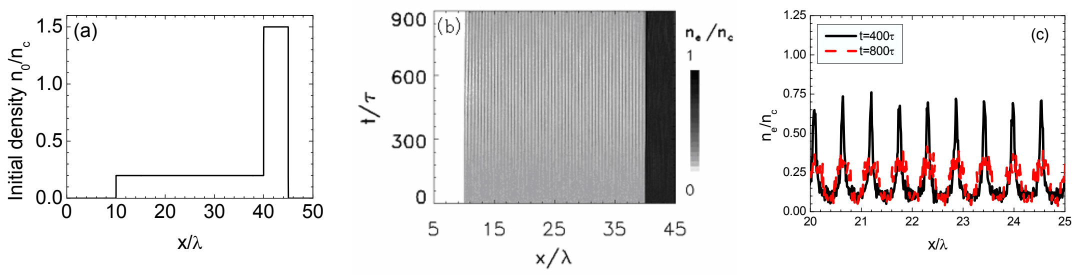

Fig. 1 (a) The initial density profile of plasma used in the simulation; (b) Spatial-temporal evolution of the plasma density gratings; (c) Snapshots of the plasma density distributions at t=400 τ and 800 τ .

We have also conducted particle-in-cell simulations with the initial plasma profile shown in Fig. 1(a). A semi-infinite laser pulse with $a(t) = a_0 \tanh(t/10\tau)$ is launched from the left boundary, where τ is the period of laser. We take $a_0 = eE_0/m\omega_0 c = 0.03$. A density-modulation grating with period $\Lambda = \lambda_f / 2$ (λ_f is the laser wavelength in plasma) grows up, as shown in Fig. 1(b). The maximal density modulated can reach up to about 4 times of the unperturbed plasma density, as shown in Fig. 1(c).

3. Phase reflection

Figure 2 shows the spatial-temporal evolvement of the laser field. At $t \approx 50\tau$, the input and reflected laser pulses interfere to form a standing wave. At $t \approx 200\tau$, the standing-wave pattern is distorted in plasma.

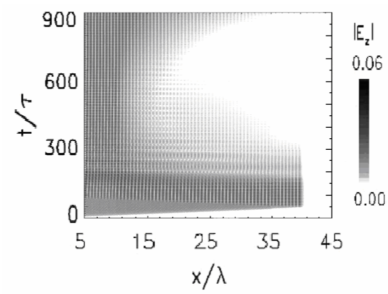

Fig. 2 The spatio-temporal evolution of the laser field for $a_0 = 0.03$

This is obviously due to the formulation of the plasma density grating, which changes the phases of both the incident and reflected waves. Afterwards the laser field in plasma almost disappears entirely around $t = 600\tau \sim 650\tau$, Later on, the laser pulse can propagate again because the density modulation relaxes for lack of the support of the ponderomotive force. The plasma density at $t \approx 800\tau$ is lower than that at $t \approx 400\tau$, shown in Fig. 1(c). The reflection occurring at low-density areas of plasma is called the phase reflection. This is the period of the induced density grating satisfies the Bragg reflection condition $\Lambda = \lambda_f / 2$, so the light can be totally reflected.

The process of phase reflection can also be illustrated by the evolution of the reflectivity at the left vacuum-plasma boundary. As shown in Fig. 3(a), the phase reflection starts around $t \approx 200\tau$. The part with reflectivity grater than 1 is caused by the sum of phase reflection and the reflection from the overcritical density surface. The absorption shown in Fig. 3(b) and the laser field inside the pre-plasma shown in Fig. 3(c) display a similar oscillatory feature. This has been caused by some interactive feedback of the reflection, transmission, and density modulation. After $t \approx 750\tau$, the reflectivity begins to reduce due to decay of the density grating.

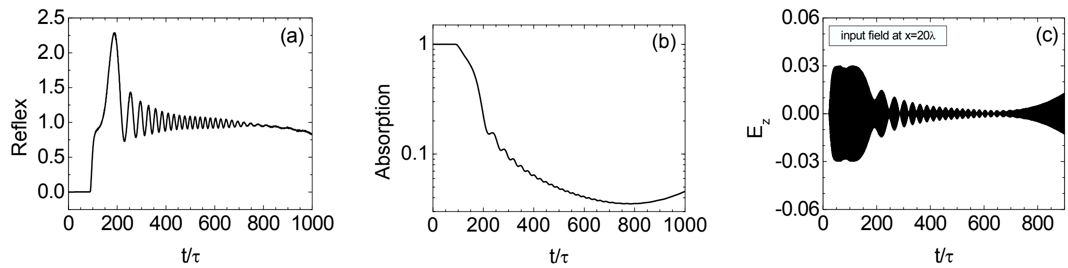

Fig. 3 The temporal evolution of the reflectivity (a), the absorption (b), and the laser field (c) at $x = 20\lambda$ in plasma. Here $a_0 = 0.03$.

As a simple model, we consider the propagation of an infinite plane wave in a preformed structure with a period Λ shown in Fig. 4(a). The laser field in whole space can be expressed with the following equations:

$$E(x) = \begin{cases} 1 \cdot e^{-ik_0 x} + \alpha e^{ik_0 x} & x < 0 \\ a_0 e^{-ik_1 x} + b_0 e^{ik_1 x} & 0 < x < \Lambda_1 \\ c_0 e^{-ik_2 (x-\Lambda_1)} + d_0 e^{ik_2 (x-\Lambda_1)} & \Lambda_1 < x < \Lambda \\ a_m e^{-ik_1 (x-m\Lambda)} + b_m e^{ik_1 (x-m\Lambda)} & m\Lambda < x < m\Lambda + \Lambda_1 \\ c_m e^{-ik_2 (x-m\Lambda-\Lambda_1)} + d_m e^{ik_2 (x-m\Lambda-\Lambda_1)} & m\Lambda + \Lambda_1 < x < (m+1)\Lambda \\ \beta e^{-ik_0 x} & (m+1)\Lambda < x \end{cases} \quad (6)$$

where $m = 1,2,3......$, $k_{1,2} = k_0 (1 - n_{1,2} / n_c)^{1/2}$ is the wave vector and $n_{1,2}$ is the density in layered plasmas, and the unperturbed plasma density $n_0 = (n_1 \Lambda_1 + n_2 \Lambda_2) / \Lambda$. Utilizing Eq. (6), one can deduce the reflectivity $|\alpha|^2$ and transmission $|\beta|^2 = 1 - |\alpha|^2$. Figs. 4(b) and 4(c) show the reflectivity as a function of the maximum modulation density for initial plasma densities at $n_0 / n_c = 0.2$ and 0.1, respectively. It shows that, when the period $\Lambda = \lambda_f / 2$, the reflectivity reaches to 1 within a few periodic structures, even though the average plasma density is much less than the critical density. Because the reflected wave resonates with the periodic structure, the laser is totally reflected by this Bragg grating-like structure.

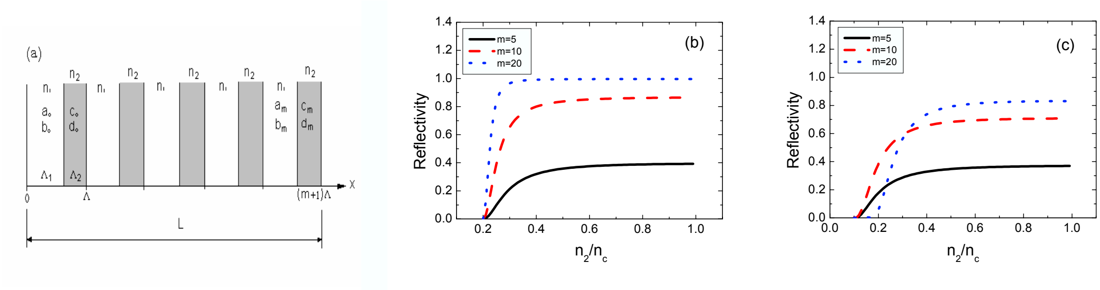

Fig. 4 (a) The sketch of the layered periodic structure with a period Λ. (b) and (c) show the reflectivity as a function of the maximum modulation density for initial plasma density at n_0/n_c=0.2 (with fixed n_1/n_c=0.1) and 0.1 (with fixed n_1/n_c=0), respectively.

4. Effects of the laser and plasmas parameters

We keep $a_0 = 0.03$ and the thickness of pre-plasma $L = 20\lambda$. Figure 5(a) and 5(b) shows the spatio-temporal evolution of laser field distributions for $n_0 = 0.1n_c$ and $n_0 = 0.4n_c$, respectively. In the former case, the phase reflection appears at a reduced spatio-temporal space as compared with $n_0 = 0.2n_c$, consistent with our model calculations given in Figs. 4(b) and 4(c). While for $n_0 = 0.4n_c$, the phase reflection appears earlier and sustains longer than the other two cases for relatively lower densities. This is because the plasma density peak is higher than the other two cases. The thickness of the pre-plasma has little influence on the phase reflection. As shown in Figs. 4(b) and 4(c), significant phase reflection occurs even for 5 layers.

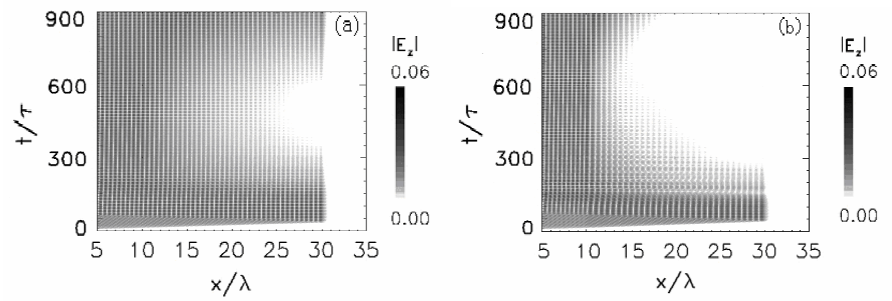

Fig. 5. The spatial-temporal evolution of the laser field for $a_0 = 0.03$ and (a) $n_0 = 0.1n_c$, (b) $n_0 = 0.4n_c$.

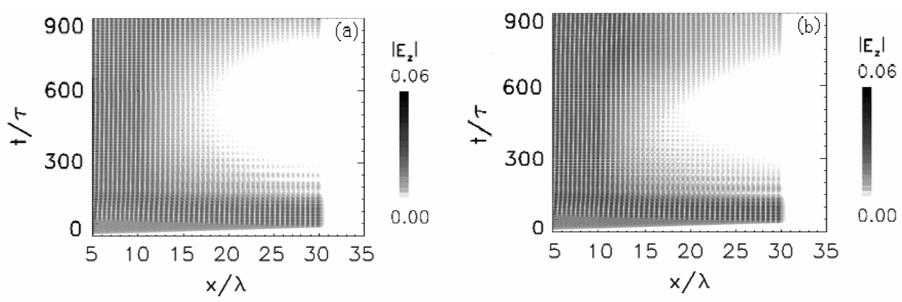

Fig. 6 The spatial-temporal evolution of the laser field for $n_0 = 0.2n_c$ and (a) $a_0 = 0.03$, (b) $a_0 = 0.04$.

In next examples, we keep $n_0 = 0.2n_c$. Figure 6(a) and 6(b) show the cases for $a_0 = 0.03$ and $a_0 = 0.04$, respectively. Because the velocity of electrons and ions inside the density grating are larger when it is induced by laser pulses at higher intensities, the density grating can decay more quickly. As a result, the phase reflection also disappears fast.

Figure 7 illustrates a more convincing example. We launch two same laser pulses with amplitude $a_1 = a_2 = 0.04$ from the two sides of a plasma slab with $n_0 = 0.2n_c$. The spatio-temporal evolutions of the plasma density and the laser field are shown in Figs. 7(a) and 7(b), respectively. The white region in the middle of the Fig. 7(b) suggests that the laser pulses are reflected by the induced density grating.

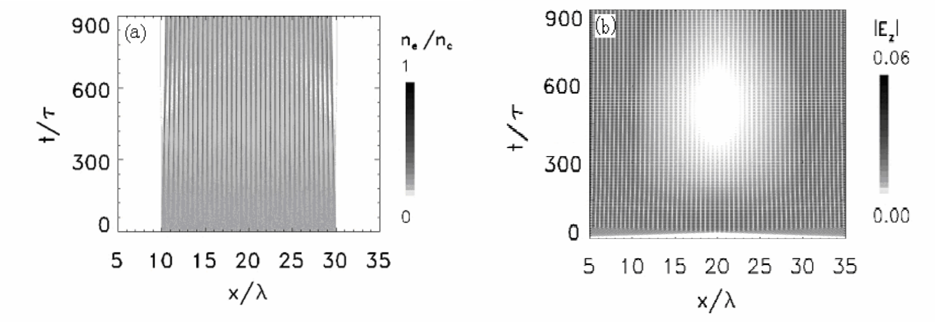

Fig. 7. Two counter-propagating laser pulse with amplitudes $a_1 = a_2 = 0.04$ overlap in a plasma slab with density $n_0 = 0.2n_c$. (a) The spatio-temporal evolution of the plasma density; (b) The spatio-temporal evolution of the laser field.

For an inhomogeneous density profile in Fig. 8(a), though the density grating in Fig. 8(b) is not uniform, the Bragg reflection condition is also locally tenable, so that the phase reflection still occurs in Fig. 8(c).

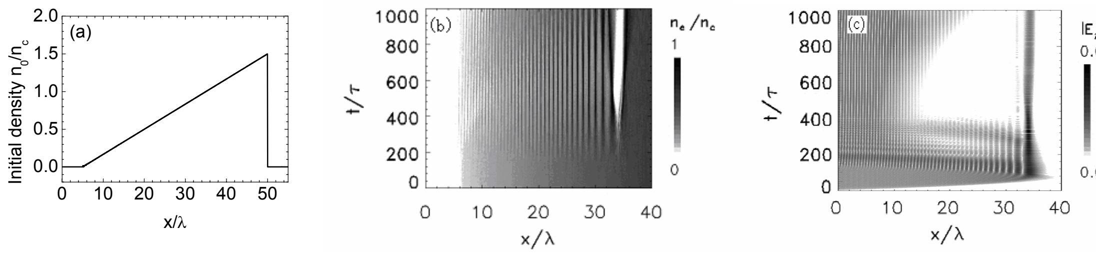

Fig. 8. The interaction of a laser pulse with $a_0 = 0.04$ with plasma in a linear density profile. (a) The initial density profile of plasma; (b) The spatio-temporal evolution of the plasma density; (c) The spatio-temporal evolution of the laser field.

Acknowledgements

This work has been supported in part by the NNSFC (Grant Nos. 10105014, 10335020), the National High-Tech ICF Committee in China, and the NKBRSF under Grant No. G1999075200.

References

[1] P. Yeh, *Optical Waves in Layered Media,* (John Wiley & Sons, Inc., New York, America, 1988) p. 123, 129

[2] I. Nebenzahl *et al.*, Phys. Rev. Lett. **60**, 1030 (1988); J. X. Ma *et al*, J. Opt. Soc. Am. B **8**, 1442 (1991); G. P. Gupta and B. K. Sinha, Phys. Plasmas **5**, 2252 (1998); A. A. Andreev *et al.*, Phys. Plasmas **9**, 581 (2002).

[3] Z. -M. Sheng et al., Appl. Phys. B **77**, 673(2003); P. Zhang et al., Phys. Plasmas **10**, 2093 (2003).