Harmonic filtering in an optically thin laser-generated plasma

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We investigate the harmonic spectrum of the field transmitted by a plasma layer irradiated by a strong laser beam. With the help of particle-in-cell simulations, we show how field ionization affects the harmonic low-frequency filtering properties of an overdense plasma. We also show the possibility of obtaining chirped pulses in the field transmitted by a solid layer undergoing ionization. [S1063-651X(98)15412-0]

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I. INTRODUCTION

In the past few years, we have witnessed important advances in the study of the interaction of intense ultrashort laser pulses with matter. The nonperturbative character of such interactions leads to strong nonlinear processes that are reflected in the high-frequency components of the scattered radiation. One of the main motivations of these investigations is therefore the search of sources of intense coherent high-frequency radiation. High-order harmonics have been observed in a broad range of situations. The earliest investigations focused on the study of intense laser fields interacting with single atoms or very dilute gases [1]. However, the efficiency of the harmonic emission in such cases is low and, in addition, is degraded when we increase the density of the gas due to phase mismatch effects. Other targets such as atomic clusters and especially solid targets seem to be more promising. In the latter case, the large number of particles involved results in intense scattered radiation and, from an experimental point of view, they are much easier to handle. For these reasons, intense experimental and theoretical activity has recently been devoted to this subject [2].

The theoretical investigations on solid targets have traditionally been based on the pre-plasma approximation, which considers the solid layer to be completely ionized from the beginning. In this situation, harmonics result from the relativistic motion of the accelerated electrons at the surface, which can be described by means of an *oscillating mirror* model [3]. However, the theoretical description of a solid layer undergoing ionization shows that harmonics can also be formed by inhomogeneities in the index of refraction caused by time-dependent ionization [4,5]. The relative importance of these effects depends on the intensity of the field and the particular properties of the medium [6].

However, harmonic generation is not the only result of the interaction of laser pulses with dense matter. It is well known that when the frequency of the incident field is smaller than the plasma frequency of the medium, i.e., in overdense plasmas, the pulse cannot propagate through it, vanishing completely in a short space length (skin depth). This is different in the case of an ionizing medium in which the plasma is created by the pulse, since initially the medium is transparent and the field penetrates it until the increasing ionized electron density becomes overdense and the field is consequently reflected.

In this paper we will focus our study on the transmitted radiation by an ionizing solid layer interacting with a strong laser beam. The form of the transmitted field can be regarded as a consequence of two different processes: the dynamics of the generation and the field propagation. For overdense plasmas, harmonics are mainly produced at the surface at which the incident field is aimed. Once generated, the harmonic field propagates inside the medium. Depending on its density, the plasma layer will be overcritical for the lower harmonic frequencies and undercritical for the higher ones. As a result, the lower-frequency harmonics will be reflected and the transmitted field will contain only the higher-frequency part of the harmonic spectrum. Thus the medium behaves as a low-frequency filter. This fact has been checked with numerical simulations [7,8] and also experimentally [9] only for the case of a preformed plasma. It can be used as a method to measure plasma densities in overdense media.

Here we extend the study to the case of a plasma generated by an intense pulse impinging on an ionizing medium. We check this idea with the aid of numerical simulations and study the effect of time-dependent ionization in this scheme. We also have to take into consideration the fact that ionization is not homogeneous along the target depth. This comes from the fact that the field-induced ionization at the front surface of the target, where the incident wave impinges, forms a rapidly growing charged sheet that attenuates the field transmitted to the bulk. The result is that the impinging pulse experiences an *effective plasma* thinner than the original target. The pulse is initially attenuated, but the evanescent part, once it has less intensity than the critical one needed to ionize the rest of the foil, propagates through a transparent medium and is not filtered. We will also show that we can use two effects, harmonic generation and time-dependent ionization, to obtain pulses of a frequency that varies stepwise along the pulse in the field transmitted by an initially transparent ionizing thin foil.

II. NUMERICAL CALCULATIONS

Let us consider a short laser pulse impinging perpendicularly on a foil of an ionizing solid medium. If the foil is thin enough and the laser is not tightly focused, the dynamics in the transverse direction may be neglected and the problem can be considered as one dimensional in space. By contrast, the nature of the collective interaction between charges and the magnetic field term in the Lorentz force requires considering the three dimensions for velocities and accelerations.

We therefore use a so-called one-dimensional in space–three-dimensional in velocity (1D3V) particle-in-cell (PIC) code [10,11], where the plasma dynamics is calculated by discretization of the charge density in quasiparticles, which are governed by the Lorentz force. Simultaneously, at each time step, the particle distribution is integrated in the form of a charge density, which is used to solve the Maxwell equations consistently. In our code, Maxwell equations are solved through the integration of the wave equations for the retarded potentials.

We will present two kinds of calculations, some of them with the above-mentioned pre-plasma approximations, while others are used with an extension of the PIC code that includes time-dependent ionization. In the preplasma code, the plasma is described by means of pseudoparticles initially uniformly distributed over the plasma length, which is chosen to be one laser wavelength. In addition, a constant ion background is introduced to preserve neutrality. For the interaction times and the field intensities used in this paper, it is reasonable to neglect the ion dynamics. When ionization is introduced in the PIC code, the initial electron and ion densities are null and a constant density of bound electron-ion pairs is distributed along the plasma length.

Ionization dynamics is included in our code by means of the ionization rate corresponding to the fundamental state of hydrogen in the tunneling limit (in a.u.) [12,13],

$$W(x,t)=\frac{4}{|\vec{E}(x,t)|}\exp\left(\frac{-2}{3|\vec{E}(x,t)|}\right). \tag{1}$$

The rates are different for other targets, but their field dependence is similar. Strictly speaking, these rates should be used in the range of parameters in which tunneling ionization is present. It is worth pointing out that, although we are using maximum field amplitudes that are above this range, the ionization is completed at the plasma surface before the pulse turn-on has reached its maximum value. After the ionization, the field inside the medium is screened by this surface charge layer and therefore is effectively less intense than the incident field. In addition, we would like to stress that the choice of the ionization dynamics is not critical for our purposes, as long as it is time dependent. In our PIC code, the ionization rate is computed at every time step and a negative charge quasiparticle is released, leaving a fixed positive charge in its location. The charge of the particle is calculated to be the fraction of population ionized times the electron charge. Similar schemes have been used in other PIC codes including field ionization [14,15].

Finally, the electric field is considered to be a plane wave aimed perpendicularly to the plasma surface. The field envelope has the form of a half period of a sinus square function. The basic interaction geometry is depicted in Fig. 1.

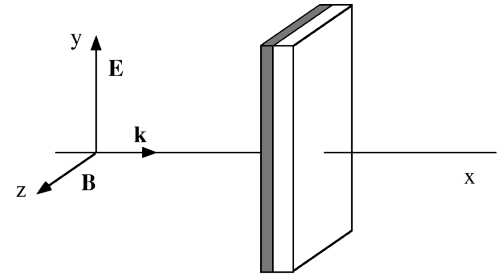

FIG. 1. Interaction geometry. The plasma layer (in gray) is created by the incident field.

III. RESULTS AND DISCUSSION

Let us first start with the well-known case of a preformed plasma [7–9]. Figure 2 shows the harmonic spectrum $|E(\omega)|^2$ of the transmitted field for an incident field frequency $\omega_0=0.05$ a.u. ($\lambda_0\simeq 0.9$ μm). The target is considered to be initially completely ionized, with a density N_e seven times above the critical value [Fig. 2(a)] and fifteen times above the critical value [Fig. 2(b)]. The slab width is $d=\lambda_0$ and hence the plasma thickness is greater than the collisionless skin depth $\delta=c/\omega_{p0}$, with the plasma frequency $\omega_{p0}=(4\pi e^2N_e/m)^{1/2}=\omega_0(N_e/N_c)^{1/2}$. Here the critical density stands for the density for which the medium refractive index vanishes at the frequency of the incident field $[N_c=(m/4\pi e^2)\omega_0^2]$. From this definition it is clear that a density above a critical value for some frequency may be undercritical for the high-frequency harmonics. The scaling of the critical density with the harmonic number follows the law $N_c^{(m)}=(m/4\pi e^2)\omega_m^2=m^2N_c$, where ω_m is the frequency of the mth harmonic and N_c the critical density for the fundamental frequency. This means that, in Fig. 2(a), the plasma density is undercritical for the third harmonic, whereas in the case of Fig. 2(b), it is overcritical for the third but undercritical above the fifth. In connection with these facts, the harmonic spectrum of Fig. 2(a) reflects the opacity of the plasma layer for the fundamental frequency and the transparency for the higher harmonics, therefore acting as a low-frequency filter. With the same approach, Fig. 2(b) depicts the filtering of the first and third harmonics.

Assuming a preionized plasma is an approximation that breaks down when considering the interaction with pulses with durations in the range of 100 s. In this case, the characteristic time for the target ionization might be of the order

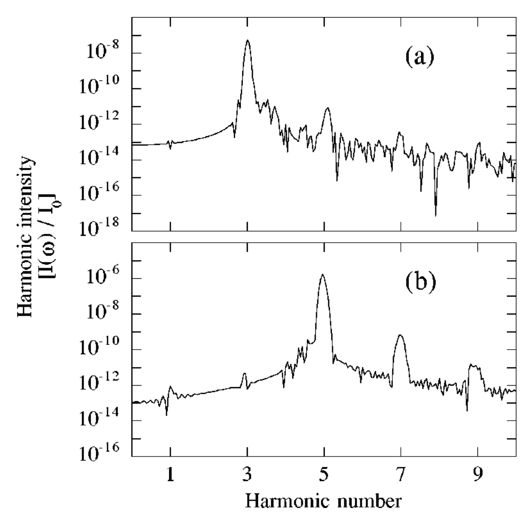

FIG. 2. Spectra of the transmitted fields for an incident pulse of frequency $\omega_0=0.05$ a.u. ($\lambda_0\simeq 0.8$ μm), 20 cycles long, and with a maximum amplitude (a) $E_0=0.5$ a.u. ($I\simeq 7.5\times 10^{15}$ W/cm^2) and (b) $E_0=4$ a.u. ($I\simeq 5\times 10^{17}$ W/cm^2) impinging on a preionized plasma foil of length $L=\lambda_0$ and free electron density (a) $N_0=7N_c$ and (b) $N_0=15N_c$.

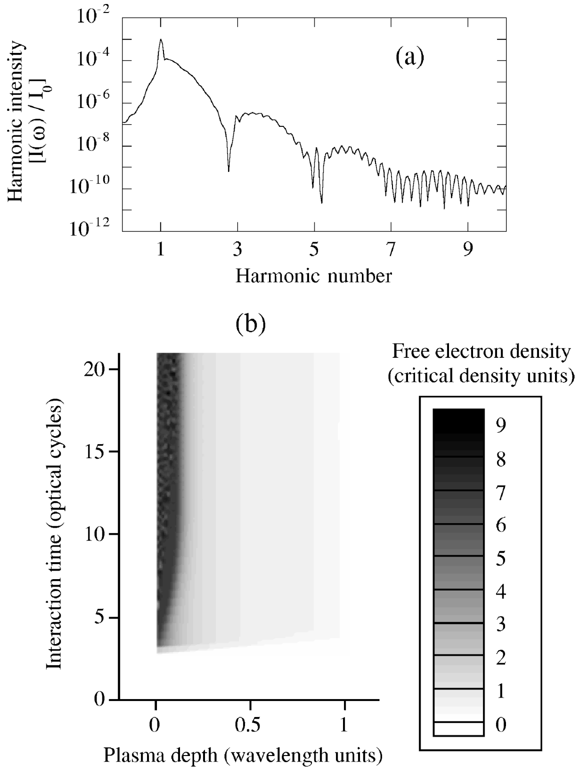

FIG. 3. (a) Spectrum of the transmitted field for the same parameters as in Fig. 2(a), but considering a not preionized target. (b) Evolution in time and space of the free electron density inside the foil.

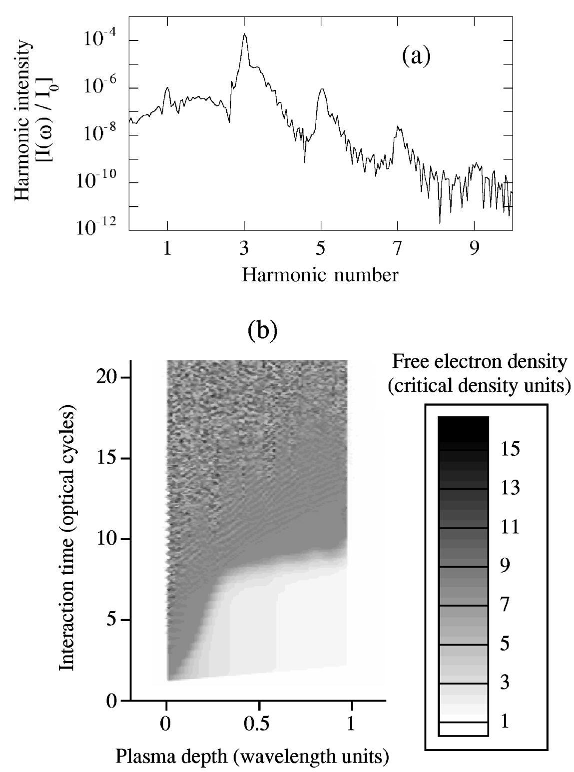

FIG. 4. Same as in Fig. 3, but for $E_0 = 4$ a.u.

of the pulse length and the dynamics should be consequently affected.

In Fig. 3(a) we can see the spectrum of the transmitted pulse for the same parameters as in Fig. 2(a), but taking into account the target ionization as mentioned in Sec. II. The most interesting thing to notice is that now no radiation filtering is achieved. A broadening of the harmonics, together with a blueshift, is also apparent. These latter facts are well explained by the dynamics of harmonic generation during ionization [4–6]. On the other hand, the degradation of the filtering properties of the solid target may be well understood by inspection of the electron density evolution in time, which is shown in Fig. 3(b). First, as the field penetrates the medium, electron charges are released by ionization. As discussed at the end of Sec. I, the ionization is more pronounced at the plasma surface and decreases with depth. When the stationary regime is reached, a plasma layer is already formed at the target surface. If the width of this plasma layer is smaller than the penetration depth, the incident field will not be completely reflected and an attenuated wave will propagate through the bulk. The damped field is not capable of ionizing enough the target bulk to create an overdense plasma. As a result, the bulk is transparent to the incident field and almost no filtering is attained.

The situation may change dramatically if we increase the incident field intensity. This is the case of Fig. 4, calculated with the same parameters as Fig. 3 but with a maximum field amplitude of 4 a.u. ($I \simeq 5\times 10^{17}$ W/cm^2). Now the third harmonic is two orders of magnitude higher than the fundamental one, which has been strongly filtered. The density plot represented in Fig. 4(b) reveals that complete ionization is not produced until the maximum of the pulse has reached the target, i.e., when the evanescent field is intense enough to excite the bulk neutral atoms. In this situation, the overdense region inside the plasma exceeds the penetration length of the incident field, but it does not affect the propagation of the higher harmonics, which are mainly generated at the plasma surface.

Finally, we would like to show one last example in which the dynamics of the ionization is a bit more complicated. In Fig. 5 we have represented the power spectrum of the transmitted pulse for the same parameters as in Fig. 2(b), but without a preionized target. We can observe three peaks of roughly the same height, the fifth harmonic a bit more intense than the fundamental and third harmonic. From this picture one could conclude that there is not a perfect filtering of the incident pulse regardless of the high plasma frequency when the medium is completely ionized. However, by inspection of the transmitted field as a function of time [Fig.

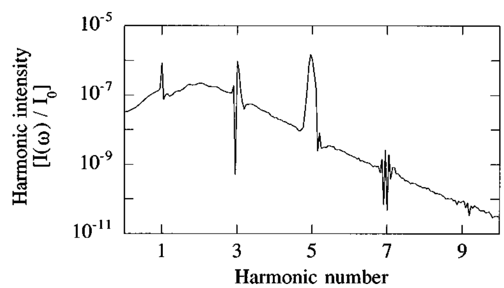

FIG. 5. Spectrum of the transmitted field for a pulse of maximum amplitude $E_0 = 4$ a.u. and an ionizing target with $N_0 = 15N_c$.

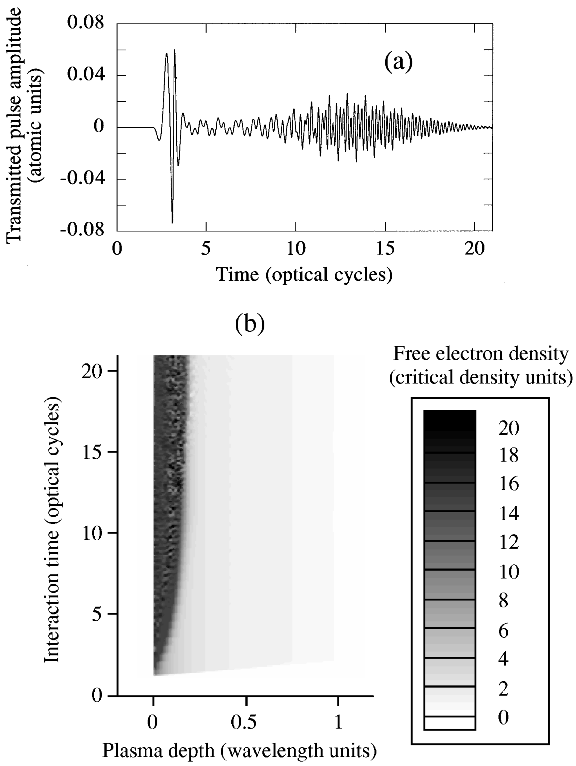

FIG. 6. (a) Transmitted pulse whose spectrum was shown in Fig. 5 and (b) the corresponding dynamics of the free electron density.

6(a)], we can see that it is chirped in time. Initially the transmitted field is governed by the fundamental frequency component ω_0; after several cycles the field shows a steplike transition to a frequency $3\omega_0$ and finally another step transition to $5\omega_0$. The mechanism underlying this step chirping is the time evolution of the filtering property of the target as ionization increases the charge density to overcritical, first for the fundamental frequency and afterward for the third harmonic.

This time-dependent filter can be easily understood with the help of Fig. 6(b). The first part of the pulse enters the medium ionizing a very thin slice. This part corresponds to the first intense burst in the transmitted pulse. In approximately two cycles the amplitude of the incident field has grown enough to ionize a length greater than the penetration depth for the first harmonic, which is then reflected. This point corresponds to the first shift in frequency at the fourth cycle of the transmitted field (the retardation of two optical periods reflects the fact that the transmitted field is calculated at a distance of two wavelengths from the front surface of the foil). The third harmonic, generated at the surface, propagates inside the target until the eighth cycle, when the surface layer becomes overcritical for this harmonic along a distance that exceeds the penetration depth. This point is observed at the tenth cycle of the transmitted field. After this, the plasma filters the fundamental and third harmonic, being transparent to the fifth and higher harmonics.

IV. CONCLUSIONS

We have investigated the possibility of using an ionizing overdense solid layer as an active low-frequency filter. By active we mean that the nonlinear dynamics of the target particles gives rise to a transmitted field composed of different harmonics of the incident field frequency. The filtering capabilities arise from the fact that high-order harmonics can propagate through a medium that is overdense for the fundamental and low-order harmonic frequencies. Our study shows that the inclusion of the time-dependent ionization may degrade the filtering properties in certain cases. We demonstrate, however, that in general, harmonic filtering may also been achieved for short pulses, in which time-dependent ionization plays a fundamental role. Finally, we analyze a case in which ionization leads to a steplike frequency chirping of the transmitted field.

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