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Ionization-induced leaking-mode channeling of intense short laser pulses in gases

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We demonstrate that short laser pulse self-guiding over distances of many Rayleigh lengths can be achieved in the absence of any focusing nonlinearity as a result of trapping of a leaking wave in a plasma channel produced by field-induced ionization in the saturation regime. A detailed computational study of the new self-guiding effect in both cases of comparatively long laser pulses, when the traditional approximation of the slowly varying complex amplitude is valid, and of high intense ultrashort laser pulses comprising only few field cycles have been performed.

1. Introduction

In the last decade, the development of compact sources of ultrashort (10–100 fs) and highly intense (10^{15}–10^{20} W/cm^2) laser pulses has opened new fields in investigation of the laser-matter interactions (Mourou & Umstadter 1992). Some important applications of super-strong fields require formation of rather long laser-produced plasma structures for interaction with optical radiation over distances of many Rayleigh lengths. That is why the search of regimes when high-power laser pulses themselves produce elongated interaction channels in plasmas (i.e., self-channeling regimes) is of particular interest.

Self-channeling regimes recently observed in experiments (Sullivan *et al.* 1994; Borisov *et al.* 1994; Braun *et al.* 1995; Nibbering *et al.* 1996) have been attributed to the focusing nature of relativistic and Kerr nonlinearities that cause an increase of the refractive index and deviation of light rays toward stronger field regions. In the case of gas ionization at the axis of a Kerr-effect induced wave-guide (Braun *et al.* 1995; Nibbering *et al.* 1996; Anderson *et al.* 1995), the influence of focusing nonlinearity should be especially strong since it is not only to prevent the divergence of rays due to linear diffraction but also to balance refraction of radiation from the axis, that is caused by emerging plasma. Experimentally observed extra-long waveguides produced by a few millijoules, 100-fs laser pulses at ionization of atmospheric air (Braun *et al.* 1995; Nibbering *et al.* 1996) have been interpreted as plasma structures having a core where the ionization nonlinearity prevails and an outer cladding where the dominating Kerr nonlinearity generates opposite-in-sign positive variations of the refractive index and hence keeps the radiation from divergence.

In this paper, we demonstrate that the saturable ionization nonlinearity alone, without any focusing nonlinearity, is a sufficient mechanism for self-channeling of an ultrashort laser pulse. At first sight, this statement looks absurd since in accord with a common concept a nonlinearity with a growing dependence of the refractive index with the field intensity is needed for the

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self-guiding effect. The idea of self-guiding at defocusing ionization nonlinearity consists in the following. Owing to a strong dependence of the field ionization rate on the field intensity, a laser pulse can produce a plasma distribution that is smooth near the axis and sharply bounded at the periphery of the cross section (a plasma filament with sharp boundaries). In spite of a negative variation of the refractive index at the axis, this distribution can guide an electromagnetic wave in the form of a leaking mode with exponentially small losses over the distances of many free-space Rayleigh lengths. As distinct from the common self-guiding effect where the field localization is achieved due to the total internal reflection at the periphery of a waveguide, in this case the quasilocalization is obtained due to the strong reflection of the trapped wave from the plasma boundary that is sharp as compared to the transverse scale (transverse wavelength) of this wave. Hence, the leakage losses are an inherent feature of the plasma waveguide though this factor may have only a minor contribution to the overall wave dissipation as compared for example to the ionization losses. Note that the leaking-wave radiation has been measured in the recent experiment on laser-plasma interaction (Nibbering *et al.* 1996); however, the authors have interpreted the observed channeling as a self-effect due to the Kerr nonlinearity.

2. Quasi-stationary stepwise model

Formation of a channel with a sharply bounded radial plasma profile can be facilitated in the case of the strong saturation of ionization, which is typical for this nonlinearity and corresponds to the complete depletion of one or several electronic states in atoms. The result of saturation is a flattening of the plasma profile near the axis and a corresponding decrease of refraction in the center of the channel where the main part of the laser energy is propagated. This regime seems easier to be implemented in single-species gases at not so high pressures when the saturation can be reached before the free electron concentration becomes too large and leaves no chance to balance the strong refraction.

A combination of two factors, a sharp dependence of the ionization rate and a strong saturation, allows us to compose a simple analytical model for the self-guiding (Babine *et al.* 1996; Sergeev *et al.* 1997). Assuming the electron concentration to be saturated at a level N_0 everywhere inside the induced plasma waveguide with the radius a, so that $(k_0 a)^{-2} \ll N_0/N_{cr} \ll 1$, we obtain for the spatial decrement h of the self-trapped leaking mode the following expression:

$$h \approx \frac{6}{k_0^2 a^3 \sqrt{N_0/N_{cr}}}, \tag{1}$$

where $k_0 = \omega_0/c$ and $N_{cr} = m\omega_0^2/4\pi e^2$. For a quite powerful laser pulse focused on the gas in a spot with the size a_0, we expect that the ionized region is wider than the radiation beam, $a > a_0$. The ratio of the leakage distance $z^* = 1/h$ to the free-space Rayleigh length z_F can be presented in the form

$$\frac{z^*}{z_F} = \frac{k_0 a^3}{a_0^2} \sqrt{\frac{N_0}{N_{cr}}}. \tag{2}$$

This expression demonstrates the physical requirements for the long-distance channeling ($z^*/z_F \gg 1$).

3. Self-channeling of comparatively long pulses

For a detailed study of the leaking-mode self-guiding effect, we have used two different models of a long laser pulse and a few optical cycle pulse. In the case of comparatively long laser pulses, when the traditional approach of the slowly varying complex amplitude is valid, for the optical field with the scalar amplitude E in the paraxial approximation we have used the equation

$$2ik_0 \frac{\partial E}{\partial z} + \frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} - \frac{4\pi e^2 N}{mc^2} E = 0 \tag{3}$$

that includes the factors of diffraction in the transverse (x, y) directions and ionization nonlinearity. The electron density N is governed by a simple dynamical equation:

$$\frac{\partial N}{\partial \tau} = (N_0 - N) f(|E|) \tag{4}$$

that describes the ionization with the field-dependent rate $f(|E|)$, saturated at the level N_0. Here N_0 is the gas density. The time $\tau = t - z/V_{gr}$ has been counted from the pulse arrival at a given point along the propagation path z. The ionization rate, $f(|E|)$, is taken as the cycle-averaged tunneling rate (Delone *et al.* 1994).

$$f(|E|) = 4\gamma \left| \frac{E_a}{E} \right|^{1/2} \exp\left(-\frac{E_a}{|E|} \right). \tag{5}$$

The values of the atomic field E_a, and the frequency may range in wide intervals depending on the concrete kind of the ionized species.

Here we present the results obtained for $\gamma = 10^5/\tau_0$, $N_0 = 25 \cdot (k_0 a_F)^2 N_{cr}$, and the collimated incident laser pulse with the Gaussian temporal and transverse distributions of intensity:

$$|E|^2 (z = 0, x, y, \tau) = E_0^2 \cdot E_a^2 \exp[-(x^2 + y^2) - \tau^2], \qquad E_0 = 1.5.$$

For numerical study, we used the following dimensionless variables: $z/z_F \to z$, $\bar{r}_\perp / a_F \to \bar{r}_\perp$, $\tau/\tau_0 \to \tau$, $N/(k_0 a_F)^2 N_{cr} \to N$, where $z_F = k_0 a_F^2$ is the vacuum Rayleigh length, and τ_0 is the laser pulse duration.

Figure 1 presents the maximum intensity of the pulse and the field intensity in the middle point of the pulse along the propagation distance z. In this picture, the self-trapping of the ionizing laser pulse in the induced long plasma channel over six Rayleigh length is distinctly seen. Our simulation points to the fact that the maximum of the laser intensity is shifted to the back part of the laser pulse due to the stronger beam spreading the leading part. So, here the laser pulse is shortening and, therefore, energy that belongs to the back part is guided over a longer distance. As it is seen in figure 2, the laser intensity is well localized in the transverse directions. This is due to a sharp profile of the plasma channel density.

The spatial distribution of plasma in the channel after the laser pulse passage is shown in figure 3. An almost homogeneous long plasma channel with sharp boundaries was created, which is interesting, for example, for wake-field experiments with ultrashort laser pulses.

The self-guiding effect under the investigation is characterized by several remarkable features. First of all, it concerns the form of the plasma filament. Due to the decrease of the intensity caused by the wave leakage, the area of the cross section, occupied by the field capable of strong ionization, is gradually narrowing. As a result with receding from the boundary the plasma filament becomes thinner (see figure 3) and takes ultimately the form of a sharpened needle. Hence, the decrease of the energy transmitted through the nonlinear guide is accompanied by a narrowing of the channel itself, which is rather unusual for self-guiding waves.

Another important feature that can be proved directly in an experimental observation is a specific transverse distribution of the frequency shift acquired by the guided wave. It is well known that any group element of the wave producing ionization experiences a blue shift of the frequency (Wood *et al.* 1988; Gildenburg *et al.* 1990). In the central part of the channel (near

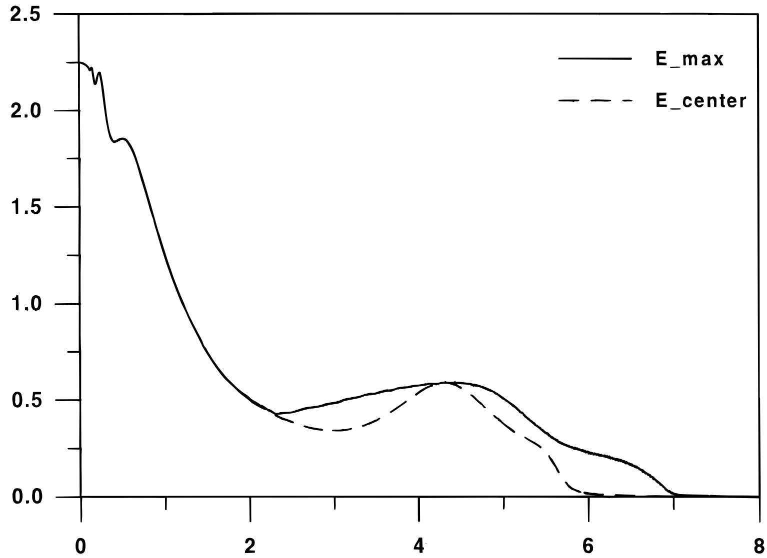

FIGURE 1. Field intensity at the axis of the channel in the middle of the temporal profile of the pulse as a function of propagation distance z measured in Rayleigh lengths.

the axis), a strong blue shift is acquired only at the leading front of the pulse due to gas ionization to the saturation level whereas the rest major part of the pulse propagates at a fixed frequency in the preformed plasma. On the contrary, at the periphery of the channel the frequency increases due to a gradual ionization over the time of the full pulse duration. If one evaluates the frequency shift averaged over the pulse at different positions from the axis, a frequency gradient directed toward the channel periphery will be readily seen. This effect is even more pronounced if we take into account that short-scale (i.e., high frequency) compo-

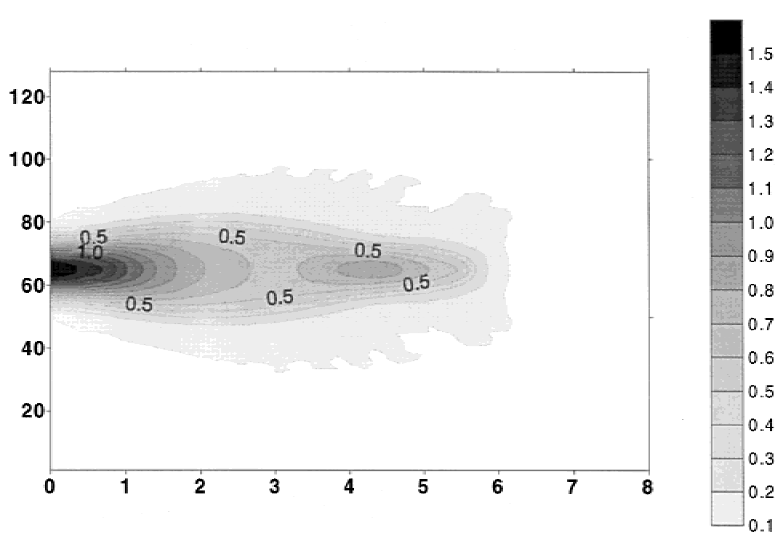

FIGURE 2. Contours of the field intensity in the center of the pulse in the plasma channel (longitudinal distance z measured in Rayleigh lengths).

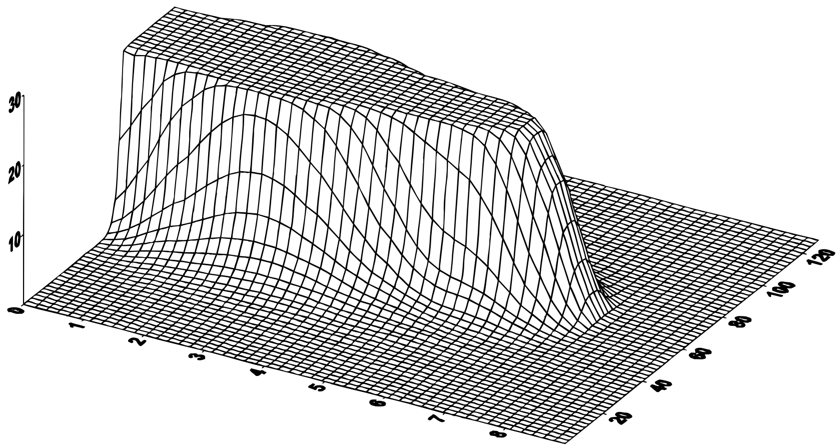

FIGURE 3. Transverse distribution of plasma density in the channel for different distances z measured in Rayleigh lengths. Here Rayleigh length equals 10.

nents trapped in the channel have a greater leakage coefficient at reflection from the sharp plasma boundary as compared to large-scale transverse components. These two factors results in a remarkable effect: the radiation frequency averaged over the pulse at the axis of the channel is decreasing in spite of the strong ionization, whereas the radiation propagating at the channel periphery is essentially blue-shifted, as seen in figure 4, where the radiation frequency shift averaged over the whole profile at each point in the cross section is shown for different distances from the gas boundary.

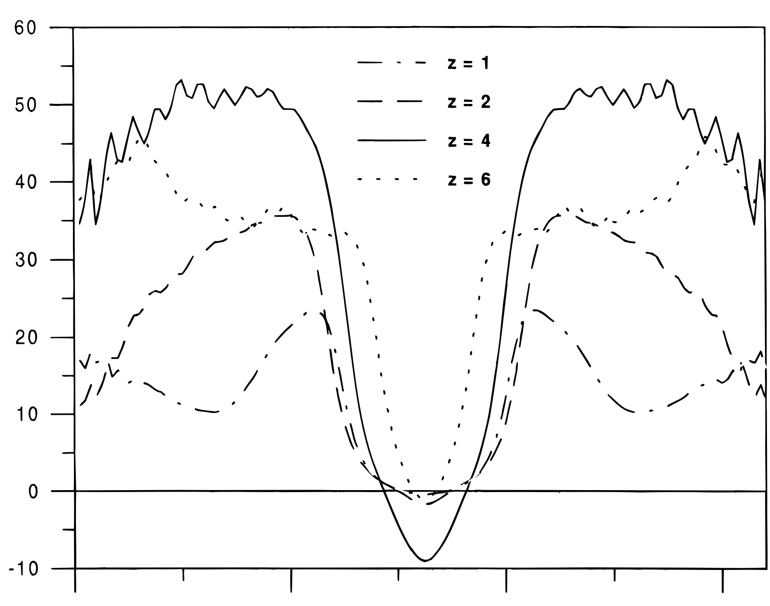

FIGURE 4. Radiation frequency shift averaged over the temporal pulse profile at different z measured in Rayleigh lengths. Here parameters for calculation are taken as $\gamma = 1.2 \cdot 10^4/\tau_0, N_0 = 9.5 \cdot (k_0 a_F)^2 N_{cr}, E_0 = 0.4$, and others are the same as in figures 1–3.

4. Self-channeling of few-optical-cycle pulses

The paraxial approximation used above is applicable only for quasi-monochromatic waves and does not allow one to describe strong variations on the scale of the wavelength or temporal period. These strong changes in the field structure can be essential at the leading pulse edge and especially in the case of ultrashort (few-optical-cycle) pulse. We have analyzed the self-channeling effect of such a pulse by the computer simulation on the basis of the equation set consisting of the 2D wave equation for the linear-polarized electric field $E_y \equiv E(x,z,t)$:

$$\frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial z^2} - \frac{1}{c}\frac{\partial^2 E}{\partial t^2} = \frac{4\pi e^2}{mc^2} NE, \tag{6}$$

and the equation for the electron density

$$\frac{\partial N}{\partial t} = W(E) = 4\Omega(N_0 - N)\frac{E_a}{|E|}\exp\left(-\frac{2}{3}\frac{E_a}{|E|}\right). \tag{7}$$

A similar simulation model of the focused ultrashort pulse dynamics was used previously (Gildenburg *et al.* 1995) for the description of the strong self-blueshifting and ionizing "leader" formation effects. Equation (6) is valid at any ionization rate W. It is easily derived under a realistic assumption that free electrons are born with almost zero velocities as compared to those acquired further in the laser field. Equation (7) defines the tunneling ionization rate as a function of $E(x,z,t)$ at each instant of time by the known static expression. It is applicable for the optic field of frequency ω and amplitude E, when the following conditions are fulfilled: $\omega \ll \Omega, I \ll e^2E^2/2m\omega^2$, $E \ll E_a$, where I is the ionization energy.

At the time $t = 0$, the following initial conditions were set:

$$N = 0, \qquad E = F(x,z), \qquad \frac{\partial E}{\partial t} = G(x,z). \tag{8}$$

The functions $F(x,z)$, $G(x,z)$ were chosen so that the wave packet, in the absence of ionization ($\Omega = 0$), moves in the $+z$ direction, forming at some time $t = t_0$ the focused Gaussian pulse with the center at the point $x = z = 0$:

$$E(x,z,t_0) = A(x,z) = E_0 \sin(kz)\exp\left(-\frac{x^2}{2a^2} - \frac{z^2}{l^2}\right). \tag{9}$$

Here E_0 is the maximum field amplitude, a and l are the effective transverse and longitudinal focused pulse dimensions, respectively, $k = 2\pi/\lambda_0 = \omega_0/c$, and ω_0 is the fundamental laser

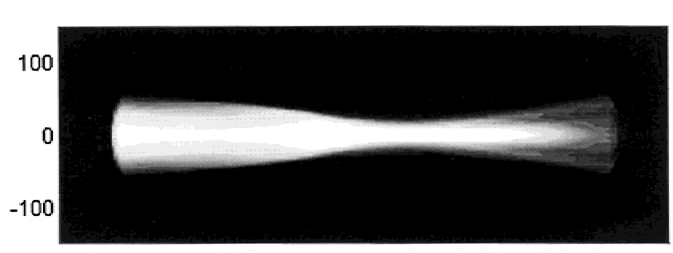

FIGURE 5. Plasma density distribution $N(x,z)$ after pulse passing.

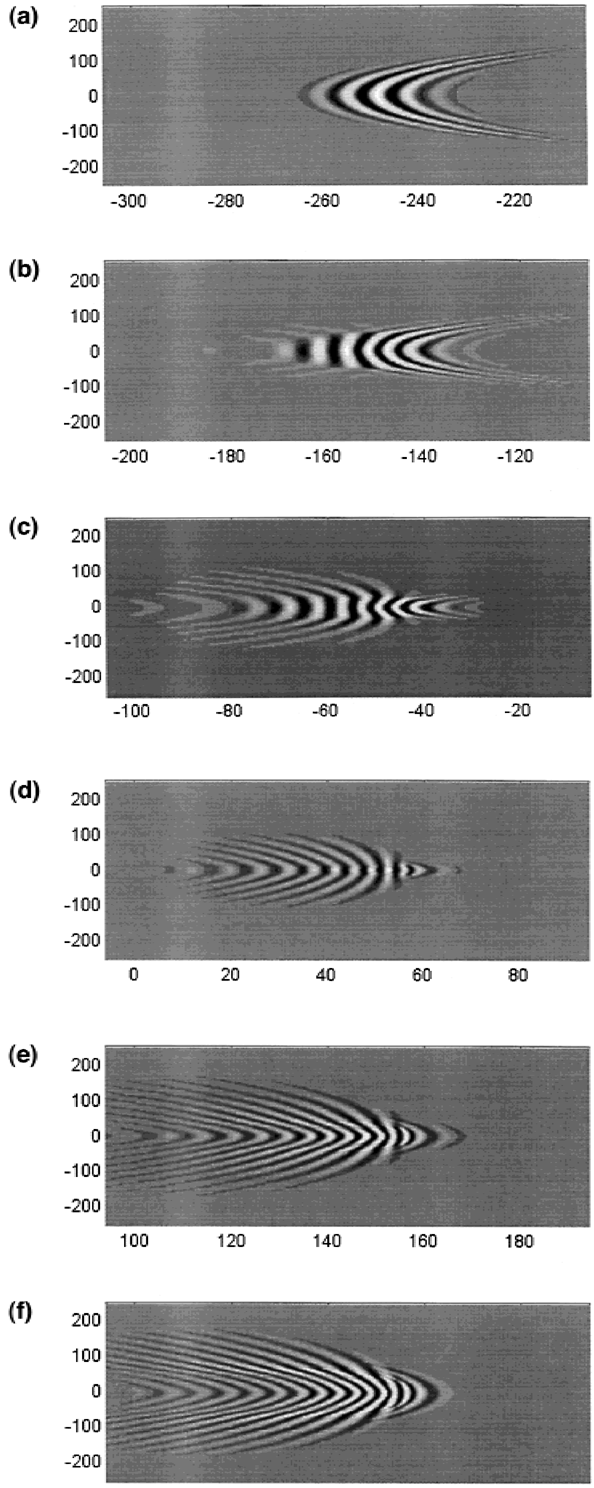

FIGURE 6. Spatio-temporal evolution of the electric field $E(x, z, t)$. (a)–(f) correspond to $t = 0$, 100, 200, 300, 400, and 500, respectively.

frequency. The functions $F(x,z)$, $G(x,z)$ were found on the basis of time reversibility of the field evolution in vacuum by the numerical integration of equation (6) with $N = 0$ at the initial conditions:

$$E(x,z,-t_0) = A(x,z), \qquad \frac{\partial E}{\partial t}(x,z,-t_0) = \frac{\partial A}{\partial z}, \tag{10}$$

followed by the change of sign in the time derivative $\partial E/\partial t$ at $t = 0$.

The equation system (10) was solved numerically for the parameter values: $kl = 3\pi$ (pulse length $2l = 3\lambda_0$); $ka = 4.3$ (vacuum Rayleigh length $z_F = ka^2 \approx 3\lambda_0$; $\Omega/\omega_0 = 22$; $N_0/N_{cr} = 0.135$; $E_0/E_a = 0.4$; and $\omega_0 t_0 = 250$. This case corresponds to a 10-fs laser pulse with the wavelength $\lambda_0 = 1$ μm and the maximum power of 40 MW, focused to the peak intensity of 5.8×10^{15} W/cm^2 into the 5-atm hydrogen gas. The space distributions of the wave electric field $E(x,z)$ and plasma density $N(x,z)$ at several times t, the time dependencies $E(t)$, and the time spectra of the field E_ω at some points of the z axis ($x = 0$) are shown on figures 5–8 in dimensionless variables: $x \to kx$, $z \to kz$, $t \to \omega_0 t$, $E \to 3E/2E_a$, and $N \to N/N_{cr}$ ($N_{cr} = m\omega_0^2/4\pi e^2$). One can see that a completely ionized plasma channel is created under the studied conditions (figure 5). The full channel length is 65 μm that is 22 times more than the Rayleigh length z_F ($12z_F$ before the free space focus point and $10z_F$ behind one). Figure 6 presents space distributions of the electric field $E(x,z)$ at six instants of time. Note that at the time $t = 200$, when the pulse passes the focal region, its transverse structure is well localized and trapped by the plasma channel with a quasirectangular density profile. The field amplitude on the axis ($x = 0$) is much higher than one out of the channel. This indicates that radiation losses of the leaking mode are quite small and, therefore, long self-guiding of the laser pulse takes place.

The plasma waveguide formation is accompanied by the large frequency upshifting effect, which is stronger here than in the case of the partial gas ionization (Gildenburg *et al.* 1995).

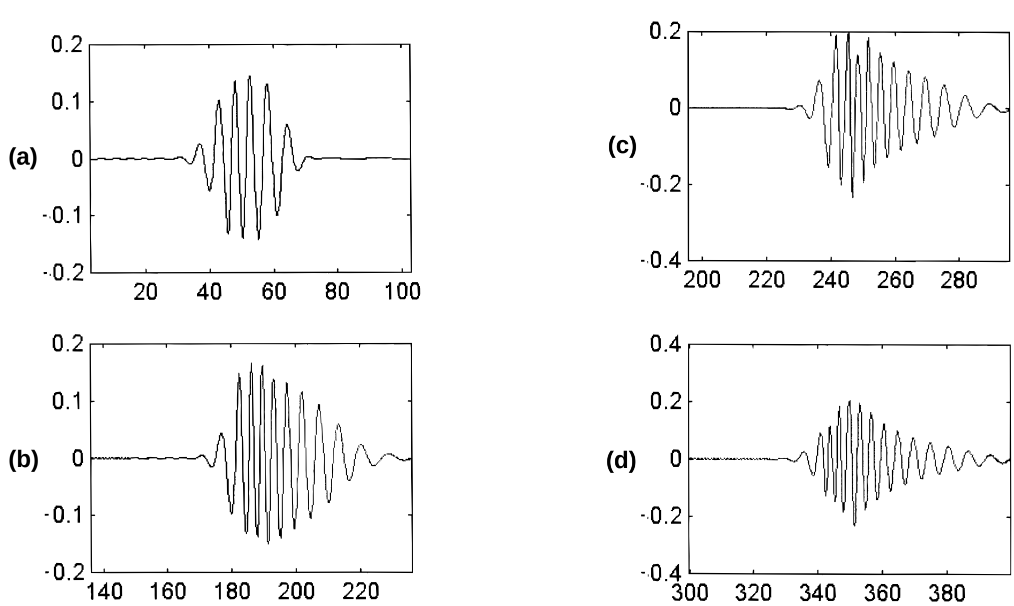

FIGURE 7. Plots of E versus time t at the points $x = 0$ and (a) $z = -200$, (b) $z = -60$, (c) $z = 0$, and (d) $z = 100$.

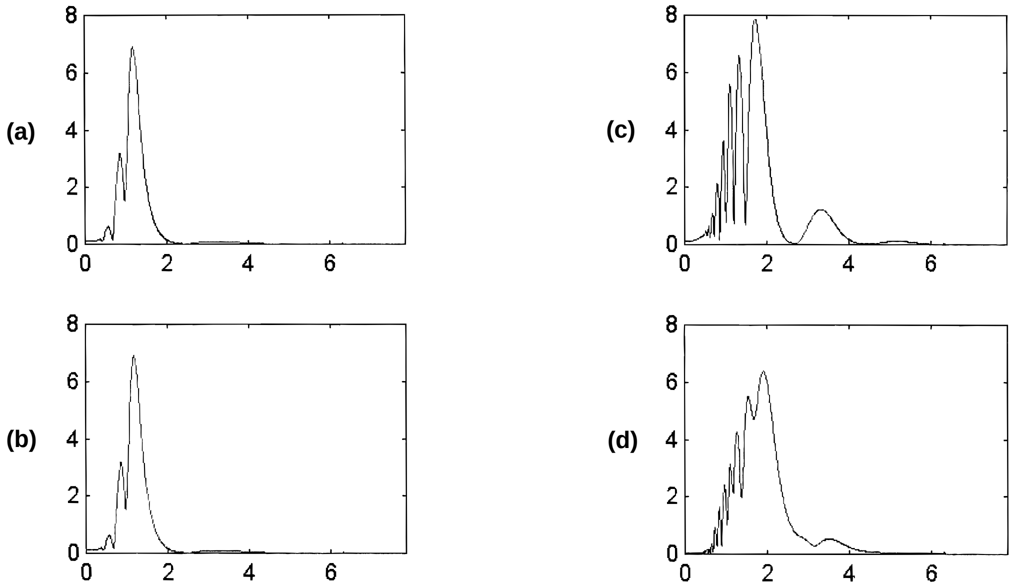

FIGURE 8. Time spectra of the electric field E_ω (in arbitrary units) versus ω/ω_0 at the points $x = 0$ and (a) $z = -200$, (b) $z = -60$, (c) $z = 0$, and (d) $z = 100$.

Time functions $E(t)$ and spectra of the field E_ω at different points of the z axis are shown at figures 7 and 8. The pulse form changes from the initial Gaussian one (figure 7a) to a "quasi-triangle" one with a sharp leading edge at the output of the waveguide (figure 7d). The corresponding upshift of the spectrum maximum is of the order of 100% and the spectrum as a whole experiences large extension in the blue side.

5. Summary

We have proposed and described an unusual opportunity for self-guiding of an ultrashort laser pulse in the leaking-mode regime over distances of many Rayleigh lengths without a focusing nonlinearity. This effect is attributed to the specific properties of ionization nonlinearity in the superstrong optical fields, namely, a sharp dependence on the electric field value and an easily attainable saturation. The effect is promising for various applications where creation of elongated plasma structures for enhanced super-strong field interactions is required.

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