Generation of High-Energy Few-Cycle Laser Pulses by Using the Ionization-Induced Self-Compression Effect

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A mechanism behind the ionization-induced self-compression effect for ultrashort laser pulses propagating in gas-filled capillaries is proposed. It is shown that as a result of excitation of the nonlinear-plasma waveguide laser pulses producing gas ionization can be self-compressed to few-cycle duration. This effect is used for high-energy laser pulses and its scalability to J-level energies is demonstrated.

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The generation of high-energy few-cycle pulses, which play an important role in the studies of extreme nonlinear optics, is a challenge in contemporary laser physics. This is especially true for high-field science where most of the experiments are sensitive to the electric field of the laser pulse rather than to the intensity profile, so that the use of few-cycle pulses leads to reliable generation of attosecond pulses [1]. Actually, there are two ways for producing high-energy laser pulses with ultrashort duration. The first one is based on the impressive progress of conventional solid-state laser systems. In particular, based on Ti:sapphire technology laser pulses up to the PW level with 25–30-fs duration can be now produced [2]. The second way aiming at few-cycle duration, e.g., especially below 10 fs for the Ti:sapphire wavelength of about 800 nm, relies on the optical parametric chirp pulse amplification (OPCPA) technology [3], which has slower progress in obtaining high-energy pulses but it has a high potential, including ultrabroad amplification along with high gain. It should also be mentioned that there is a technique based on the self-filamentation effect that has been developed successfully, showing compression of the driving pulse down to few-cycle duration [4,5]. However, the main limitation comes from the fact that the laser power should not greatly exceed the self-focusing one and also the energetic efficiency of this compression is low, less than 10% [6,7]. These limitations can be overcome by using low density gases and ionization nonlinearity itself for pulse compression [8,9]. The idea of ionization self-compression was first introduced in Ref. [10] where it was shown that ionization-induced frequency chirping can be compensated in a plasma, thus leading to pulse compression. Wagner *et al.* was the first to demonstrate experimentally ionization-induced self-compressing from 26 to 13 fs [11] for a laser pulse propagating in a capillary. However, this propagation is essentially non-one-dimensional and the mechanism of self-compressing is still unclear.

In this Letter, we first look into the physics behind the ionization-induced self-compression effect for laser pulses propagating inside gas-filled capillaries, and then demonstrate a possibility of compressing them to few-cycle duration. Finally, we show that the concept of the ionization-induced self-compression is scalable to higher pulse energies covering the range from sub-mJ to multi-J, aiming at producing an output laser power up to the PW level. These results open the prospect of high-energy few-cycle laser sources, particularly by using a conventional high power Ti:sapphire laser system.

For assessing the ultimate potential of the proposed scheme of ionization self-compression in an oversized waveguide (capillary), as well as for detailed analysis we employ the well-proven slowly evolving wave approach (SEWA) [12]. As the density of the forming plasma, N, is much less than the critical value $N_{\rm cr} = m\omega^2/(4\pi e^2)$ ($N \ll N_{\rm cr}$) (ω is the pulse carrier frequency), assuming that the field changes only slightly on the wavelength scale and the transverse size of the beam is large compared to the characteristic longitudinal scale of the field (quasioptical beam), the Maxwell equations can be reduced to the form which for a linearly polarized field in the corresponding reference frame $\tau = t - z/c$ together with the corresponding boundary condition [13] may be written as

$$\frac{\partial^2 E}{\partial z \partial \tau} - \Delta_\perp E + \beta N E = 0, \qquad \frac{\partial E}{\partial r}\bigg|_{r=1} = -\alpha \frac{\partial E}{\partial \tau}, \quad (1)$$

where $\beta = \omega_{pm}^2 a^2/c^2$, $\alpha = 4\pi \frac{a}{\lambda_0} \frac{\sqrt{\varepsilon_w - 1}}{\varepsilon_w + 1}$; a and ε_w are the radius and dielectric permittivity of the capillary walls, respectively; and $\omega_{pm}^2 = 4\pi e^2 N_m/m$, N_m is the gas density. Here, we introduced the following dimensionless variables: $z \to z/2ka^2 = z/4z_R$, $r \to r/a$, $N \to N/N_m$, $E \to E/E_a$, where $z_R = ka^2/2$ is the Rayleigh length, $k = \omega/c$ is the wave number in vacuum, E_a is the characteristic atomic field. Equations (1) are closed by the ionization balance equation with the tunnel ionization rate [14]. The advantage of using linear polarization (as compared, e.g., with the circular one) is that the ionization losses in the tunneling regime are negligibly small [15,16].

To get an insight into the physics behind the ionization-induced self-compression in a gas-filled hollow capillary, we first consider the basic ideas underlying the proposed scheme.

Our key idea is to use a gas having density such that it would allow violating the condition of single-mode propagation due to the forming tunnel-ionized plasma and thus exciting the nonlinear-plasma waveguide in which leaking eigenmodes may propagate [17]. Such an ionization-induced plasma waveguide can provide anomalous dispersion needed for self-compression of the driving pulse. Violation of the condition of single-capillary-mode propagation may be readily assessed using the Brillouin concept for description of the formation of field spatial structure in the waveguide. According to this concept, the transverse structure may be regarded to be a result of interference of the rays incident on and reflected from the walls at an angle determined by the transverse wave number [18]: $\theta_{nm} \simeq \varkappa_{nm}/k$, where $\varkappa_{nm} \simeq k[1 - \frac{u_{nm}^2}{2(ka)^2}]$ and u_{nm} is the mth root of the equation $J_n(u_{nm}) = 0$. Assuming that the gas is fully single ionized, the condition of violation of the single-mode propagation in the capillary may be written as

$$N_m[\mathrm{cm}^{-3}] > N_m^\star[\mathrm{cm}^{-3}] = \frac{mc^2}{4\pi e^2}\frac{u_{12}^2 - u_{11}^2}{a^2} \simeq \frac{7\times 10^{12}}{(a[\mu m])^2}, \quad (2)$$

where $u_{11} = 2.405$ and $u_{12} = 5.52$ are the first and the second zeros of the zero-order Bessel function. Therefore, for the gas density $N_m > N_m^\star$ in a hollow capillary, a narrow (compared to the transverse size of the capillary) plasma waveguide may be formed, where leaking eigenmodes may propagate with the transverse structure of the field differing appreciably from the modes of the capillary. The existence of such a waveguide is attributed to a sharp dependence of the ionization rate on the laser field, which leads to the formation of an abrupt (on the wavelength scale) jump of the refraction index. Actually, this plasma waveguide is analogous to a capillary but it has a much smaller relative index of refraction and, hence, a worse Q factor. It is worth noting that the use of an external capillary, where differential gas pumping can be applied, strongly helps us to produce a plasma waveguide (a gas jet where such guiding can also occur usually has small propagation lengths [17]) and also radiation can propagate inside this waveguide over distances greatly exceeding the channeling length of a freely localized plasma waveguide because of the presence of external boundaries (walls of the capillary).

Figure 1 shows the evolution of the pulse intensity and plasma density in the capillary filled with hydrogen at a gas pressure of 7.5 Torr and capillary diameter $2a = 185\lambda \simeq 125$ μm ($\lambda = 800$ nm for Ti:sapphire laser). The field distribution at the input was specified to be

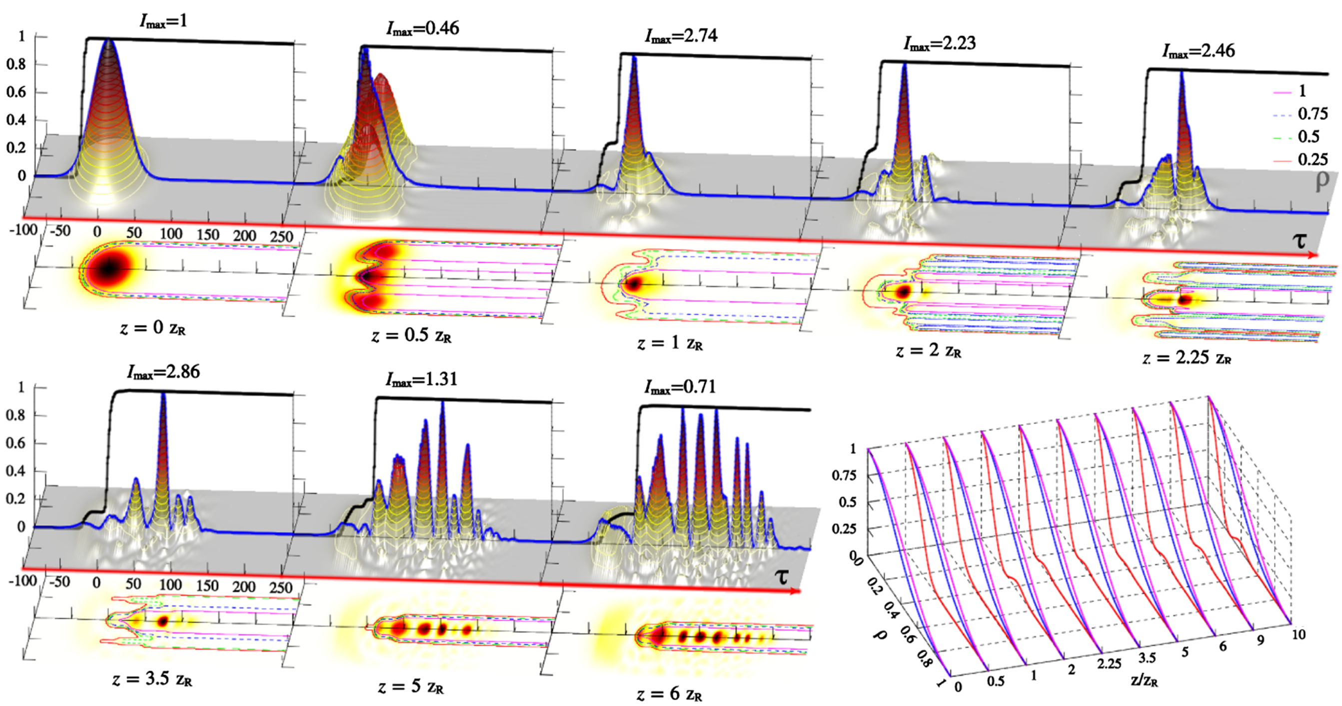

FIG. 1 (color online). Snapshots of the intensity distribution $|\hat{E}(z, r, \tau)|^2$ $[E(z, r, \tau) = \hat{E}(z, r, \tau)\exp(i\tau) + \mathrm{c.c.}]$ along the capillary having length $10z_R$ and diameter 185λ at gas pressure $p = 7.5$ ($\beta \simeq 53$) and the corresponding plasma density as well (at the second level, together with the pulse intensity projection density contour lines correspond to 0.25, 0.5, 0.75, 1 deg of gas ionization). Initial laser pulse parameters: $\tau_p = 50.26$, $E_0 = 0.2$. In the inset: transverse intensity distribution normalized to its maximum value along z (the unchanging lines are initial distribution and distribution of the fundamental mode $\overrightarrow{EH}_{11}$), narrow and wide profiles, respectively.

$E = E_0 \exp[-2\ln 2(\tau/\tau_p)^2 - (r/0.645)^2]\cos\tau$, where $E_0 = 0.2$ and $\tau_p = 50.26$. It is clear that, in spite of the sophisticated behavior of the field, a nonlinear mode is excited in the waveguide, which is apparently seen at the second level of this figure in the form of plasma density contour lines corresponding to different degrees of gas ionization. Changes in the transverse field distribution along the capillary are depicted in the inset of Fig. 1, clearly demonstrating the self-channeling effect, when the transverse size of the effective nonlinear-plasma mode is much smaller than the size of the capillary. So, the essential trailing part of the input pulse is now captured into the nonlinear narrow plasma waveguide giving rise to the focusing effect, i.e., enhanced intensities in the axial region as is clearly shown for $z \geq 1z_R$. At the same time, strong compression of this part of the driving pulse also occurs, i.e., at the distance $3.5z_R$ the compression factor, i.e., the ratio of initial pulse duration to its minimal duration, is about 6, obviously demonstrating compression to few-cycle duration. Thus, this simulation, indeed, shows the creation of a narrow (compared to the capillary diameter) plasma channel capable of ensuring anomalous character of group dispersion and that the hydrogen-filled hollow capillaries are suitable for the compression of mJ-level femtosecond pulses to few-cycle durations.

For understanding the limiting possibilities of such compression we consider a simplified 1D case as in Ref. [10] but with a wave equation for the real electric field, which is beyond the slowly evolving envelope approximation. In this case, the laser field may be represented in the following form: $E(z, r, \tau) \simeq \mathcal{E}(z, \tau)\Phi^{\rm nl}(r)$, where $\Phi^{\rm nl}(r)$ is the transverse distribution of the nonlinear mode in the plasma capillary [e.g., the established transverse profile as in Fig. 1 (the solid line in the inset)]. Then, the ionization dynamics of the field in the capillary is governed by the following equation:

$$\frac{\partial^2 \mathcal{E}}{\partial z \partial \tau} + \beta N \mathcal{E} + \tilde{\alpha}\mathcal{E} = 0, \qquad (3)$$

where $\tilde{\alpha}$ is the medium dispersion defined here by the characteristic transverse scale of the nonlinear mode in the plasma waveguide $\tilde{a}$, i.e., $\tilde{\alpha} \sim 1/\tilde{a}^2$. It is known that the combined action of anomalous dispersion of group velocity and ionization nonlinearity is the necessary condition for achieving the effect of ionization-induced self-compression for femtosecond laser pulses [10]. Because of the self-phase-modulation caused by the gas field ionization, the frequencies at the leading edge are lower than at the trailing edge of the pulse. Such a pulse may be compressed in a medium with anomalous dispersion, where the blue spectral components may catch up with the red ones as they have a higher group velocity. Suitable conditions may be realized in a partially ionized plasma where the group velocity $v_{\rm gr} = c\sqrt{1 - \omega_{pm}^2/\omega^2}$ grows with increasing frequency and therefore the trailing edge of the pulse catches up with the leading edge. However, although the dielectric capillary itself and the plasma produced during gas ionization possess anomalous dispersion, their magnitudes are insufficient to group the spectral components. In Fig. 2 we show the evolution of the triangular pulse for the dispersion coefficient of an effective nonlinear plasma waveguide [10]

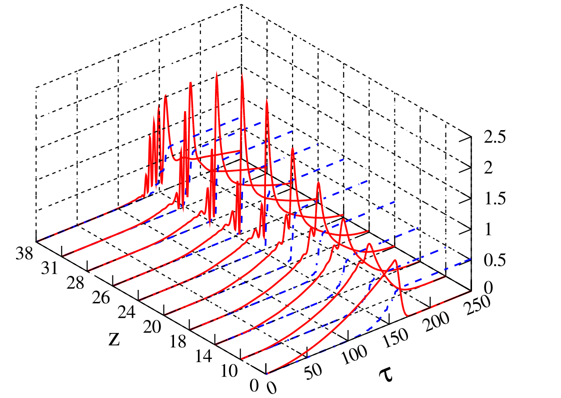

FIG. 2 (color online). 1D self-compression within the framework of the reduced wave equation (3) at $\beta = 1$, $\alpha = 5$. Initial pulse parameters: $\tau_p^{\rm in} = 9T_0$, $\mathcal{E}_{\rm in} = 0.075$. The shortest pulse duration is about $\tau_p^{\rm out} \simeq 1.2T_0$ and the corresponding peak intensity was amplified 2.5-fold as a result of compression ($\mathcal{E}_{\rm out} = \sqrt{2.5}\mathcal{E}_{\rm in}$). Solid line, intensity distribution; dotted line, plasma density distribution. The intensity is normalized to the input maximum value.

$$\mathcal{E}(z=0,\tau) = \mathcal{E}_{\rm in}\cos(\tau) \times \begin{cases} \tau/\tau_0, & 0 \leq \tau < \tau_0 \\ \exp\left(-\frac{2\ln 2}{16\pi^2}(\tau-\tau_0)^2\right), & \tau \geq \tau_0 \end{cases} \qquad (4)$$

at $\mathcal{E}_{\rm in} = 0.075$, $\tau_0 = 55\pi$, $\tilde{\alpha} = 5$, $\beta = 1$. Note that the input pulse duration at FWHM (full width at half-maximum) is nine laser cycles, $\tau_p^{\rm in} = 9T_0$. One can see in this figure that the pulse is self-compressed up to one and a half cycles ($\tau_p^{\rm out} \simeq 1.6T_0$), i.e., this method can provide even single-cycle pulses. However, when applying the 1D model to the real situation we have to be aware of the fact that the leading part of the pulse, which propagates in nonionized gas and therefore has the highest group velocity, does not participate in the compression effect. This actually lowers the energetic compression efficiency but not essentially since this part of the pulse energy can be small.

A very attractive idea is to apply the ionization-induced self-compression effect, which has no limitation on the laser power, to high-energy pulses, especially for compressing down to few-cycle duration. The main limitation comes from the fact that the laser power should not exceed the critical one for self-focusing, i.e., ionization nonlinearity should be the dominant one. By choosing

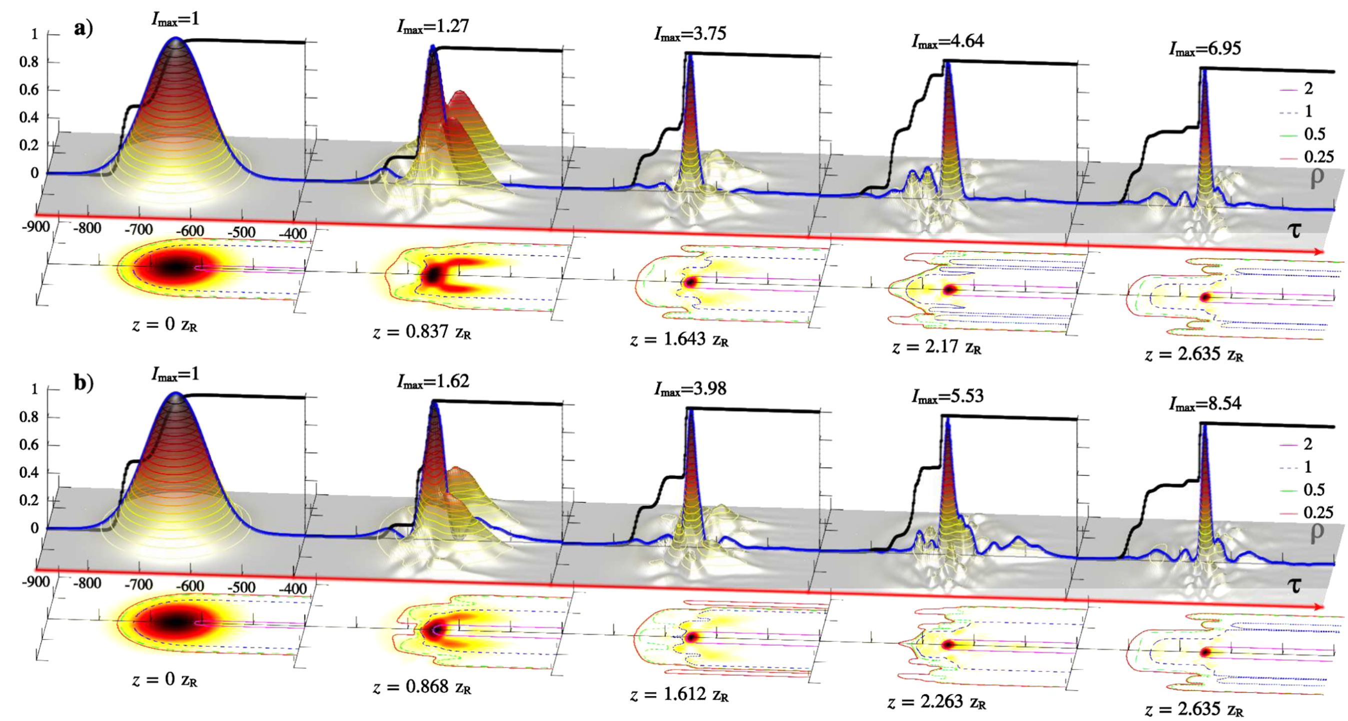

FIG. 3 (color online). Snapshots of the intensity distribution $|\hat{E}(z, r, \tau)|^2$ $[E(z, r, \tau) = \hat{E}(z, r, \tau)\exp(i\tau) + \mathrm{c.c.}]$ of the 60-fs laser pulse with an input amplitude of $E_0 = 0.55$ and corresponding plasma density (as in Fig. 1 but with additional line corresponding to 2 times He ionization) along the propagation distance in a helium-filled capillary with a diameter of (a) $d = 300\ \mu$m at a pressure of $p = 2$ Torr and (b) $d = 1200\ \mu$m at $p = 0.125$ Torr. The intensity is normalized to its maximum value.

appropriate gas pressure this requirement can be easily fulfilled.

Obviously, for high-energy pulses we have to use, first, gases with larger ionization potential and, second, capillaries with larger diameters as well. We choose helium as an atom with the highest ionization potential and also, which is more important, it allows implementing a two stage ionization regime during pulse propagation. Since we need to use a large-diameter capillary in which the anomalous dispersion coefficient is very small, it is necessary to generate a narrow plasma waveguide, as discussed above, which can be produced at the first stage of ionization when helium is single-ionized by the front part of the pulse. Then, at the second stage, the remaining part of the pulse, when double-ionized helium is generated can suffer the self-compression effect. In Fig. 3(a) we present the result of simulation of Eq. (1) for a linearly polarized laser pulse of 60 fs duration and 130 mJ energy propagating in a 300 μm diameter dielectric capillary at a pressure of $p =$ 2 Torr. As is clearly seen, the spatial structure of the laser field is trapped into a plasma waveguide and propagates with a slightly changed transverse structure, i.e., in the form of a nonlinear mode of the self-consistently produced waveguide. Moreover, during the propagation the laser pulse is compressed to a minimum duration of 6 fs at a capillary length of $L = 2.635 z_R = 18$ cm with the energy efficiency of about 18% (assessed by the level of pulse intensity decay by e^2 times). The intensity profiles of the laser pulse on the axis ($r = 0$) at the input and output of the capillary are plotted in Fig. 4. Besides the narrow compressed part of the pulse (dotted curve), the intensity distribution in Fig. 4 has wings containing a small fraction of the output signal energy. For comparison we also plotted the transform-limited pulse of 3.6 fs (solid line) corresponding to the spectrum of the compressed pulse. The modeling performed shows that quite a high efficiency of the proposed compression technique may be achieved, both in terms of its energy efficiency (up to 20 percent) and relative simplicity of its realization, where a correct choice of the dielectric capillary length is of primary importance.

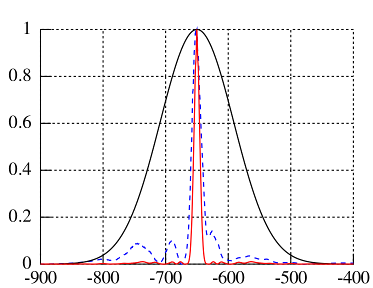

FIG. 4 (color online). Time profiles of the laser pulse: black solid curve, input pulse; dotted curve, compressed pulse at a length of $L = 2.635 z_R$; continuous curve, transform-limited pulse.

The most important issue of this technique is the energy scalability. Although the basic set of equations (1) does not allow self-similarity with respect to the capillary diameters as radiative damping γ depends on the diameter $\gamma \sim (\alpha a^2)^{-1}$, for larger diameters this damping becomes smaller. Thus, when the radiative damping is negligibly small, the solutions of Eqs. (1) should be scalable for fixed β. In fact, the result shown in Fig. 3(a) is scaled to larger diameters. To prove this statement we present in Fig. 3(b) results of simulation for the same input parameters as in Fig. 3(a) but for a diameter of 1.2 mm and also 0.125 Torr gas pressure, corresponding to the same β. As is clearly seen, the propagation dynamics is almost the same in both cases and even the lengths of compression are the same, $L = 2.635 z_R$. In this particular case, the incident 60 fs, 2 J pulse is compressed to 6 fs duration at a distance of about $L \simeq 3$ m, thus being capable of delivering 50 TW pulse at the output.

In conclusion, we have proposed a mechanism of the ionization-induced self-compression effect when a powerful femtosecond laser pulse is propagating in a dielectric gas-filled capillary. This mechanism is due to the formation of a nonlinear-plasma waveguide whose anomalous dispersion permits grouping short-wave spectral components arising in the course of gas ionization and capable of compressing laser pulses even down to a few-cycle duration. The compression effect is applied to the high-energy laser pulses where scalability to the J-level energies is shown.

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