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Nonequilibrium plasma channel in gaseous media formed by powerful UV laser as a waveguide for transportation and amplification of short microwave pulses

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Abstract
The evolution of strongly nonequilibrium plasma in a channel created in gaseous media by powerful UV femtosecond laser pulse is studied. It is demonstrated that such a plasma channel can be used as a waveguide for both transportation and amplification of the microwave radiation. The specific features of such a plasma waveguide are studied on the basis of the self-consistent solution of the kinetic Boltzmann equation for the electron energy distribution function in different spatial points of the gas media and the wave equation in paraxial approximation for the microwave radiation guided and amplified in the channel. The results of modeling for rare gases (xenon) and air are compared. The amplification factor in xenon plasma in dependence on channel radius, intensity and frequency of the input RF radiation is analyzed.

Keywords: laser and microwave radiation, plasma waveguide, amplification of the electromagnetic radiation, electron energy distribution function, Boltzmann equation, wave equation in paraxial approximation

(Some figures may appear in colour only in the online journal)

1. Introduction

Recent technological progress in photonics and materials science makes it possible to obtain different types of sources of radiation in the terahertz (THz) or subterahertz frequency range. Such sources of radiation are of significant interest in a number of research fields such as chemistry [1], molecular biology [2], medicine [3] and materials science [4]. The continuously increasing interest in terahertz and subterahertz radiation and its possible applications is due to its ability to penetrate a lot of materials [5] which are usually opaque in the infrared and visible ranges. Also, a number of physical and chemical processes (vibrational dynamics of macromolecules and crystalline lattices, reconstruction of hydrogen bounds, etc) can be controlled and governed by this low-frequency radiation.

The goal of our letter is to study the process of transportation of focused microwave pulses in the subterahertz frequency band with low divergence and the possibility of their amplification in a plasma channel in atomic (xenon) and molecular (air) gases at distances of the order of 100 cm.

It is known that if the electron energy distribution function (EEDF) in a plasma is characterized by the energy intervals with the inverse population, such a situation can be used for amplification of the electromagnetic radiation [6, 7]. Such an EEDF can be easily obtained in the process of multiphoton ionization of a gas by a high-intensity laser pulse under the conditions when the pulse duration is comparable or even less than the average time of EEDF relaxation governed by electron-atomic collisions. To realize the regime of amplification, one needs the gas of atoms or molecules characterized by the transport cross section increment with the energy where the peak of photoelectrons is found to exist. In [8] it was demonstrated that such a regime of amplification of electromagnetic radiation can be realized in a xenon plasma created by powerful (10^{10}–10^{12} W cm^{-2}) excimer KrF laser pulse ($\hbar\Omega = 5$eV) of femtosecond duration in the subterahertz frequency band ($\omega < \nu_{tr}$, ν_{tr} is the transport frequency) on time duration up to 100 ns. In [9] the possibility to amplify the subterahertz radiation in different gases was analyzed. The amplification regime in the air plasma was studied in [10]. It was found that amplification in air plasma created by the third harmonic of the Ti:Sa laser is also possible, but positive value of a gain factor is found to exist only for rather short durations ~20 ps. Hence, there is a possibility to amplify only extremely short radio-frequency pulses with a duration of 2–3 cycles.

The anomalous refractive properties of the strongly nonequilibrium plasma produced by the short UV laser pulse were studied in [11]. In the case of low-frequency radiation ($\omega < \nu_{tr}$), such a plasma appears to be optically more dense in comparison with unionized gas, in contrast to the typical situation where plasma is an optically less dense medium. Just such a situation is of interest in respect to the creation of a sliding-mode plasma waveguide [12]. In the present paper, we develop the self-consistent approach to the problem of transportation of the radio-frequency (RF) pulse in the nonequilibrium plasma channel. This approach is based on the joint solution of the Boltzmann equation for the EEDF evolution in the strongly nonequilibrium plasma and the wave equation in the paraxial approximation for the RF pulse transported through the channel and is applied for the case of xenon and air plasma. The process of guiding and simultaneous amplification of the RF radiation in the plasma channel formed by a powerful KrF laser femtosecond pulse in xenon is studied in relation to plasma channel radius and different parameters of the input RF pulse.

2. Electrodynamic features of a nonequilibrium plasma channel

For the radiation with frequency ω electrodynamic features of a plasma channel are determined by complex permittivity $\xi_\omega = \xi_{\omega'} + i\xi_{\omega''}$ or complex conductivity $\sigma_\omega = \sigma_{\omega'} + i\sigma_{\omega''}$ that are related to each other by the expression

$$\xi_\omega = 1 + i\frac{4\pi\sigma_\omega}{\omega}. \tag{1}$$

The general expression for the complex conductivity in a relatively weak electromagnetic field when the two-term expansion for the EEDF $n(\varepsilon, t)$ is valid can be written in a form [13, 14]:

$$\sigma_\omega = \frac{\omega_p^2}{6\pi}\int_0^\infty \frac{\varepsilon^{3/2}(\nu_{tr}(\varepsilon) + i\omega)}{\omega^2 + \nu_{tr}^2(\varepsilon)}\left(-\frac{\partial n(\varepsilon, t)}{\partial\varepsilon}\right)d\varepsilon. \tag{2}$$

Here $\omega_p^2 = 4\pi e^2 n_e / m$ is the plasma frequency squared, n_e is the electron density and $\nu_{tr}(\varepsilon) = N\sigma_{tr}(\varepsilon)\sqrt{2\varepsilon / m}$ is the transport frequency of electron-atomic collisions, $\sigma_{tr}(\varepsilon)$ is the transport cross section and N is the gas density. We should also mention that the evolution of the EEDF is rather slow in time and external electromagnetic field of frequency ω can be considered as quasimonochromatic. The EEDF in equation (2) is normalized according to the condition $\int n(\varepsilon, t)\sqrt{\varepsilon}\, d\varepsilon = 1$.

If the transport frequency does not depend on energy, the complex refractive index is the same for any EEDF and for the case of weakly ionized plasma ($\omega_p << \nu_{tr}, \omega$) can be written in the well-known form

$$n_\omega = n_{\omega'} + i\, n_{\omega''} = 1 - \frac{\omega_p^2}{2(\omega^2 + \nu_{tr}^2)} + i\frac{\omega_p^2\nu_{tr}}{2(\omega^2 + \nu_{tr}^2)\omega}. \tag{3}$$

In particular, one derives from (3) that plasma is an optically less dense medium in comparison with the unionized gas. Imaginary part of (3) determines the absorption coefficient of the electromagnetic radiation with frequency ω in plasma [14]:

$$\mu_\omega = 2\frac{\omega}{c} \times n_{\omega''} = \frac{\omega}{c} \times \xi_{\omega''} = \frac{\omega_p^2\nu_{tr}}{c(\omega^2 + \nu_{tr}^2)} \tag{4}$$

For an arbitrary dependence $\nu_{tr}(\varepsilon)$ more general expressions for the refractive index should be used:

$$\begin{aligned} n_{\omega'} &= 1 - \frac{2\pi\sigma_{\omega''}}{\omega} = 1 - \frac{\omega_p^2}{3}\int_0^\infty \frac{\varepsilon^{3/2}}{\omega^2 + \nu_{tr}^2}\left(-\frac{\partial n}{\partial\varepsilon}\right)d\varepsilon, \\ n_{\omega''} &= \frac{2\pi\sigma_{\omega'}}{\omega} = \frac{\omega_p^2}{3\omega}\int_0^\infty \frac{\varepsilon^{3/2}\nu_{tr}}{\omega^2 + \nu_{tr}^2}\left(-\frac{\partial n}{\partial\varepsilon}\right)d\varepsilon. \end{aligned} \tag{5}$$

Typically, the EEDF decreases with the increase of energy, i.e. $\partial n / \partial\varepsilon$ is negative and both of the integrals in (5) are positive. Hence, for such a more general case, the plasma channel also appears to be optically less dense in comparison with unionized media and the absorption coefficient is positive, $\mu_\omega > 0$. However, as the energy intervals with positive derivative $\partial n / \partial\varepsilon$ contribute negatively to the integrals (5), both of them may become negative. Hence, plasma turns out to be an amplifying medium. Also, it can be optically denser than the neutral gas. The conditions when the integrals in (5) can become negative are discussed in detail in [11]. In particular, in the energy range of inverse population in continuum for low frequencies ($\omega << \nu_{tr}$), the condition

$$\frac{d}{d\varepsilon}\varepsilon / \sigma_{tr}(\varepsilon) < 0 \tag{6}$$

should be satisfied to obtain the positive gain factor in a plasma, i.e. transport cross section should increase more rapidly than the linear dependence. If the condition

$$\frac{d}{d\varepsilon}\varepsilon^{1/4} / \sigma_{tr} < 0 \tag{7}$$

is fulfilled, plasma will be an optically denser medium compared with the neutral gas. The latter condition is much softer than the previous one and is fulfilled for a lot of atoms and molecules. If both inequalities (6) and (7) are satisfied, a plasma channel can be used as the waveguide for both transportation and amplification of the microwave radiation.

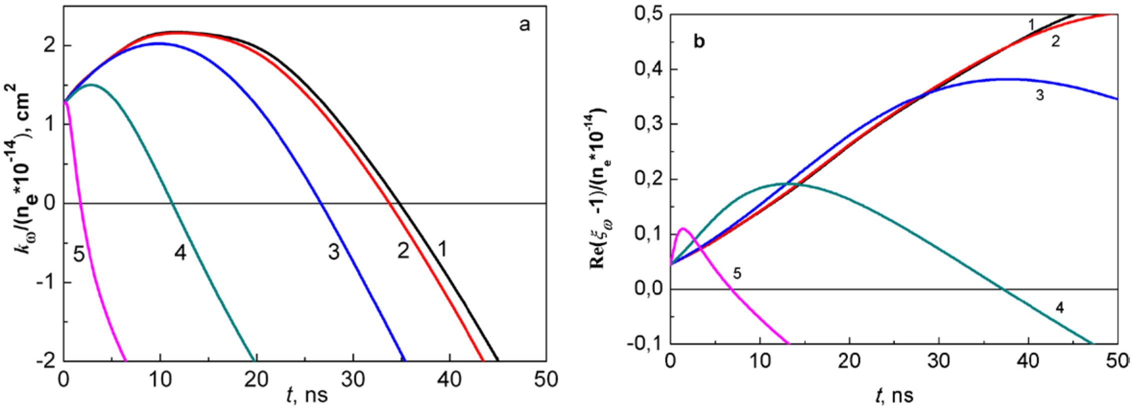

Figure 1. The gain factor (a) and the real part of plasma permittivity (b) per one electron in xenon plasma for different electronic concentrations (cm^{-3}): 1—10^{10}, 2—10^{11}, 3—10^{12}, 4—10^{13}, 5—10^{14}. Negative values correspond to absorption of a RF radiation in plasma.

To study temporal evolution of real and imaginary parts of plasma conductivity or permittivity in a plasma channel, the Boltzmann kinetic equation for the EEDF in two-term expansion was solved numerically taking the influence of the transported RF field and electron–electron collisions into account. The details of the numerical procedure as well as the information on the set of cross sections used can be found in [9].

For the case of multiphoton ionization of xenon by KrF laser radiation, inelastic processes do not contribute to the evolution of the EEDF as the excitation potentials exceed the value of 8.31 eV while the position of the lowest photoionization peak is approximately 2.87 eV. In figure 1 we present the calculations of temporal evolution of the gain factor per one electron and the real part of plasma permittivity for the RF frequency $\omega = 5 \times 10^{11}\,s^{-1}$ and for different electronic densities. First, we note that for rather low electronic densities both values are found to increase in time, while the photoelectron peak gradually shifts in time towards lower energies due to elastic collisions, but still locates in the range where inequalities (6) and (7) are satisfied. Also, it can be seen that for rather small time intervals the gain factor is proportional to the electronic density. As for the real part of plasma permittivity $\mathrm{Re}\,\xi_\omega - 1$, for small time intervals this value increases even faster than electronic density (see figure1(b)). On the other hand, the increment of the electron density leads to faster Maxwellization of the EEDF which results in the rapid decrement of the time interval during which the gain factor is still positive and the real part of plasma permittivity is greater than unity.

Results of calculations of the gain factor for different values of radiation intensity with a frequency $\omega = 5 \times 10^{11}\,s^{-1}$ are presented in figure 2 and demonstrate that the time interval during which the gain factor is positive reduces from 20 to 2 ns with increase of RF intensity from zero to $10^3\,W\,cm^{-2}$. For the RF field intensity of $10\,kW\,cm^{-2}$, amplification in a plasma channel is possible for very short times (about ~0.1 ns). From a practical point of view, it means that microwave pulses of 2 ns duration can be amplified to the intensity of ~1 kW cm^{-2}. We also note that the amplification of RF pulse in the plasma channel results in a decrement of electron energy, i.e. an external electric field of an RF pulse leads to the cooling of the plasma electron component.

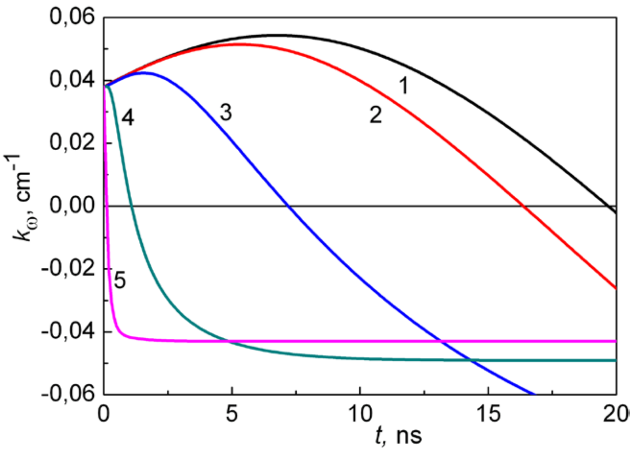

Figure 2. Time dependence of the gain factor of electromagnetic radiation for different intensities of the RF radiation ($W\,cm^{-2}$): $I = 0$ (1), 10 (2), 10^2 (3), 10^3 (4), 10^4 (5). The data obtained for electronic density $n_e = 3 \times 10^{12}\,cm^{-3}$ and $\omega = 5 \times 10^{11}\,s^{-1}$.

Similar simulations of electrodynamic features of the plasma channel produced in air by third harmonic of the Ti:Sa laser were also performed. The data obtained are presented in figures 3 and 4. The main difference between the cases of air and xenon plasma is that relaxation of the EEDF in air due to vibrational excitation collisions is found to be much faster. As a result, the positive value of the gain factor is found to exist for approximately 20 ps only. The refractive index of the air plasma is greater than unity for the time intervals of ~100 ps. On the other hand, the air plasma permittivity is not sensitive to electron–electron collisions up to $n_e \sim 10^{14}\,cm^{-3}$ and to the intensity of the transported RF field in the range below $10^3\,W\,cm^{-2}$.

3. Propagation and amplification of the RF pulses in a plasma waveguide

In this chapter we will discuss propagation of a short RF pulse in a plasma channel created in xenon by a femtosecond KrF laser pulse. Our analysis is based on the self-consistent solution of the wave equation for the RF pulse and the Boltzmann equation for the EEDF in a plasma channel at different spatial

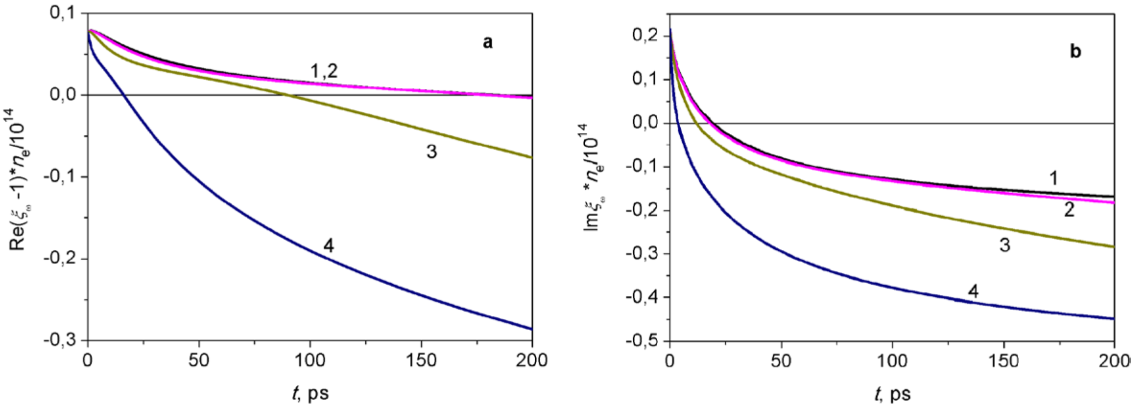

Figure 3. Real (*a*) and imaginary (*b*) parts of plasma permittivity per one electron in air plasma for different electronic concentrations (cm^{-3}): 1—10^{12}, 2—10^{14}, 3—10^{15}, 4—10^{16}. Negative values correspond to absorption of a RF radiation in plasma.

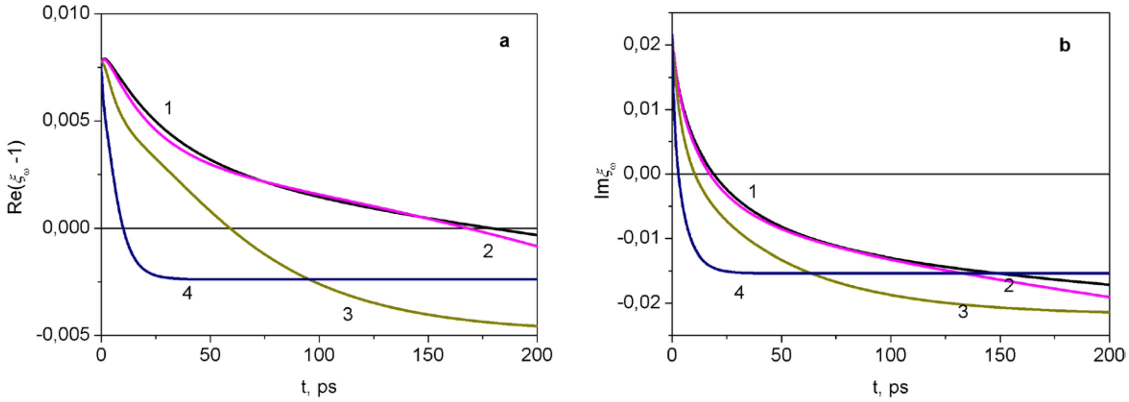

Figure 4. Real (*a*) and imaginary (*b*) parts of plasma permittivity per one electron in the air plasma for different intensities of the RF radiation ($W\,cm^{-2}$): $I = 0$ (1), 10^3 (2), 10^4 (3), 10^5 (4). The data obtained for electronic density $n_e = 10^{13}\,cm^{-3}$ and $\omega = 5 \times 10^{11}\,s^{-1}$.

points. If the RF field is weak enough and does not influence plasma parameters, the set of Boltzmann equations can be solved independently from the wave equation. In this case, the RF pulse propagates in a channel with given plasma properties slow varying in time. Much more complicated is the situation when the RF pulse is strong enough and produces a significant effect on the evolution of the EEDF. In this case, the self-consistent analysis of the equations is mandatory.

As is known, propagation of the electromagnetic radiation in the medium is described by the wave equation:

$$\nabla^2 \vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial \vec{j}}{\partial t}. \tag{8}$$

Here $\vec{E}$ is an electric field strength and $\vec{j}$ is a density of electric current in a plasma. Further, we will suppose the field to be linearly polarized. To analyze the process of microwave pulse propagation qualitatively, we use paraxial approximation for the solution of equation (8) (for details see the monograph [15]). According to this approximation, for the pulse propagation along z-direction electric field E should be represented as

$$E(\vec{r}, t) = E_0(\rho, z, t) \cdot \exp(\mathrm{i}(\mathrm{kz} - \omega t)). \tag{9}$$

Here E_0 is the envelope of the RF pulse, $k = \omega/c$ is the wave number and ρ is the perpendicular spatial coordinate. If we neglect a temporal dispersion, the expression for the current density can be written in a simple form $j(\vec{r}, t) = \sigma_\omega E(\vec{r}, t)$. Assuming that $|\partial\sigma_\omega / \partial t| << \omega|\sigma_\omega|$, $|\nabla \sigma_\omega| << k|\sigma_\omega|$, i.e. plasma conductivity is a slow-varying function in time and space, one derives from (8) the following equation for the RF pulse envelope in the paraxial approximation

$$\mathrm{i}k\left(\frac{\partial E_0}{\partial z} + \frac{n_\omega}{c}\frac{\partial E_0}{\partial t}\right) = -\frac{1}{2}\nabla_\perp^2 E_0 + \frac{2\pi\sigma''_\omega}{\omega}k^2 E_0 + \mathrm{i}\frac{1}{2}kk_\omega E_0 + \frac{2\pi}{c^2}\left(E_0\frac{\partial\sigma_\omega}{\partial t}\right) \tag{10}$$

where $k_\omega = -\mu_\omega = 4\pi\sigma'_\omega / c$ is the plasma gain factor (if $k_\omega < 0$ plasma absorbs the radiation) and $n_\omega = 1 + \mathrm{i}2\pi\sigma_\omega / \omega$ is the complex refractive index. The first term in the right part in equation (10) stands for the diffraction divergence of the electromagnetic field, the second one describes plasma focusing (defocusing) features and the third term represents the absorption (amplification) process. The last term in the right part of (10) is small in comparison with previous ones and gives some corrections to the focusing/defocusing and amplification/absorption of the wave field.

The situation in our study is when $k_\omega > 0$ and $\sigma''_\omega < 0$. Such a situation is of interest with respect to the creation of the plasma waveguide being capable of amplifying the transported radiation. Actually, the amplification duration τ_{ampl} corresponds to the amplification distance of about $c \times \tau_{\mathrm{ampl}}$ (τ_{ampl}

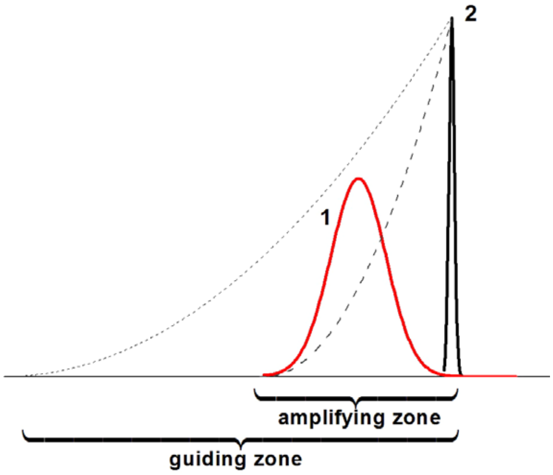

Figure 5. Spatial structure of radio (1) and laser (2) pulses for a given instant of time. Dash curves are spatial profiles of the gain factor and the refractive index.

is the time interval of the positive gain factor existence) which equals to tens of centimetres. The same applies to the focusing properties of the plasma, but the guiding length is typically several times longer. So, a laser pulse creates the plasma channel characterized by amplifying and guiding «trails» (see figure 5). If we launch a laser pulse and a RF pulse just one after another, the latter will continually be located in the amplifying and guiding zones of a laser pulse.

It can be seen from equation (10) that in the case $\mathrm{Re}n_\omega = 1 - 2\pi\sigma''_\omega / \omega > 1$ the plasma channel can partly suppress the diffraction divergence of the RF radiation. If the condition

$$(\mathrm{Re}n_\omega - 1)\, k^2R^2 > 1 \tag{11}$$

(here R is the plasma channel radius) is satisfied, the channel will look like a waveguide and can transport the radiation without divergence. For $\omega = 5 \cdot 10^{11}\,\mathrm{s}^{-1}$ and $k = \omega / c \approx 16.7\,\mathrm{cm}^{-1}$ and $\Delta n_\omega = \mathrm{Re}\, n_\omega - 1 \sim 0.001$ (see figure 1(*b*)), the guiding regime of propagation will be realized for R > 2 cm. It means that in order to create such a plasma channel with electron density $n_e \sim 10^{12}\,\mathrm{cm}^{-3}$, a laser pulse should have the power at least at sub-terawatt level.

First, we discuss the results of numerical integration of the wave equation (10) for the case of weak field when the contribution of an amplified RF pulse to the EEDF evolution in a plasma channel can be neglected. We assume that the RF pulse is characterized by the sine-squared temporal envelope $E_0(t) \sim \sin^2(\pi t / \tau_p)$, where $\tau_p = 50T$ $(T = 2\pi / \omega)$ is the pulse duration. Typical distributions of the electric field envelope $|E_0(\rho, t - z / c, \tau)|$ for the initial RF field and electron density distribution in plasma channel with Gaussian profiles, characterized by the radius $\rho_0 = 2$ cm versus the variable $\tau = t - z / c$ (for $\rho_0 = 0$) and the radial variable ρ (for $\tau = \tau_p / 2$ that corresponds to the maximum of the envelope of the initial pulse) are presented in figure 6. The first of these distributions can be considered as the temporal envelope of the pulse at different fixed values of z or as a distribution over z—coordinate at a fixed instant of time. For the RF pulse duration $\tau_p = 50T$ the spatial length of the pulse is equal to $c\tau_p \approx 1.9$ cm. For such a pulse $k_\omega \approx 0.04\,\mathrm{cm}^{-1}$ and can be considered to be nearly constant for all the propagation time (see figure 2). The electric field E_0 increases with propagation length approximately exponentially $E_0 \sim \exp(hz)$ with $h \approx 0.024\,\mathrm{cm}^{-1}$. This value is even a little larger than $k_\omega / 2 \approx 0.019\,\mathrm{cm}^{-1}$. This difference arises from the partial focusing effect during the propagation of the RF pulse in the plasma waveguide. As for the radial distribution (see figure 6(*b*)), it is nearly the Gaussian one for all instants of time.

The case of the initial RF pulse with relatively high intensity when the guiding RF field contributes significantly to the evolution of the EEDF in the plasma channel is more interesting. The results of such calculations for the initial RF intensity $I_0 = 10^3\,\mathrm{W\,cm}^{-2}$ are presented in figure 7. It can be seen for the same propagation length of 120 cm that there is an increase of the peak intensity of the RF pulse only approximately six times. The pulse shape is found to be distorted significantly, mainly because of the dominant enhancement at the leading edge of the pulse. As for the trailing edge of the pulse, it can be seen in figure 6(*a*) that for the propagation distances of 60 cm and more the significant absorption of the RF intensity is observed due to dramatic reconstruction of the EEDF by the RF pulse. As a result, the shorter RF pulse with leading peak and broader spectrum is formed in such a propagation regime.

Similar simulations for propagation of the ultrashort RF pulse of two periods of field oscillations were performed for the air plasma channel formed by the third harmonic of the Ti:Sa laser. We will restrict ourselves to the case of rather weak field only when transported RF field does not contribute to the EEDF evolution. Similar to the case of xenon, we assume that the RF pulse is characterized by the sine-squared temporal envelope $E_0(t) \sim \sin^2(\pi t / \tau_p)$, where $\tau_p = 2T$ is the two-cycle pulse duration. The distributions of the electric field envelope $|E_0(\rho, t - z / c, \tau)|$ for the initial RF field and electron density distribution in plasma channel characterized by the radius $\rho_0 = 2$ cm versus the retarded time $\tau = t - z / c$ (for $\rho = 0$) and the radial variable ρ are presented in figure 8 for input peak RF intensity $10\,\mathrm{W\,cm}^{-2}$. In comparison with the pulse propagation in xenon plasma, the temporal dependences of the gain factor and the refractive index are essential even for two-cycled RF pulse. As a result, the leading edge of the pulse is amplified dominantly while the trailing edge locates in the zone of very low amplification or even absorption. Therefore, the temporal profile of the pulse is distorted significantly and pulse duration becomes shorter (see figure 8(*a*)). We would like to stress here that our consideration is only qualitative as the paraxial approximation is not valid for such short pulses and numerical solution of the second-order wave equation (8) is strongly desirable.

To conclude the study of RF pulse propagation in a plasma channel formed by powerful UV laser pulse, let us now discuss the results of simulation in xenon obtained for different initial parameters of an input RF pulse (its peak intensity and frequency) and the radius of the plasma channel. The field amplification factor $g = E_0(z) / E_0(z = 0)$ for different input RF intensities in relation to the propagation length is presented

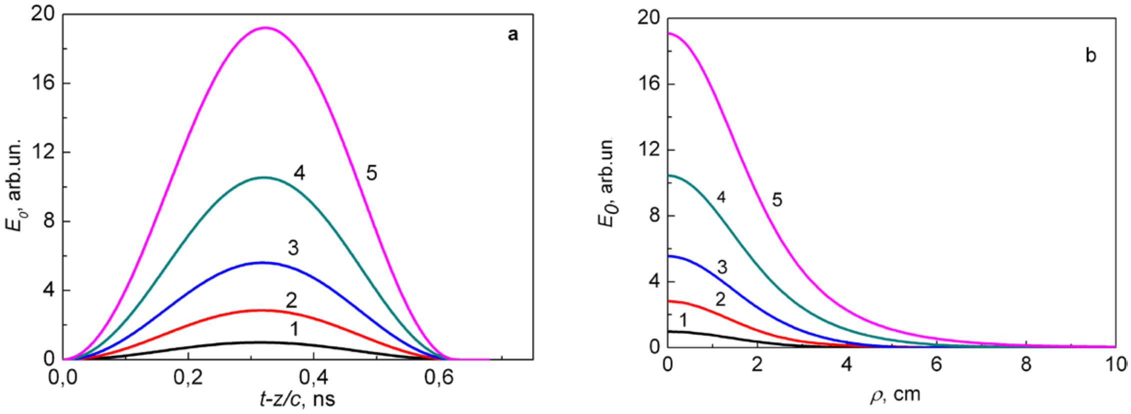

Figure 6. Temporal (a) and radial (b) profiles of the electric field envelope of the amplifying pulse in xenon plasma channel at different propagation distances z: 1—0 cm, 2—30 cm, 3—60 cm, 4—90 cm, 5—120 cm. Initial peak intensity is 0.1 W cm^{-2}.

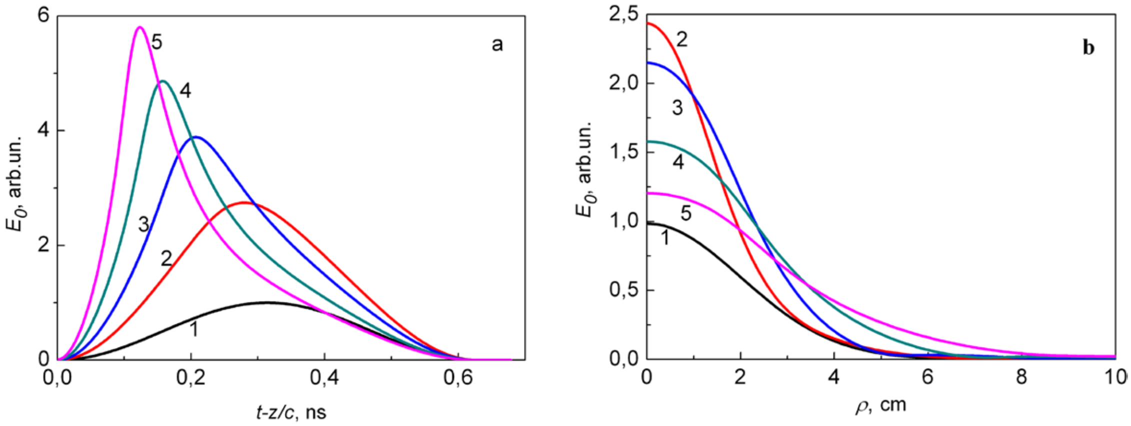

Figure 7. Temporal (a) and radial (b) profiles of the electric field envelope of the amplifying pulse in xenon plasma channel at different propagation distances z: 1—0 cm, 2—30 cm, 3—60 cm, 4—90 cm, 5—120 cm. Initial peak intensity is 10^3 W cm^{-2}.

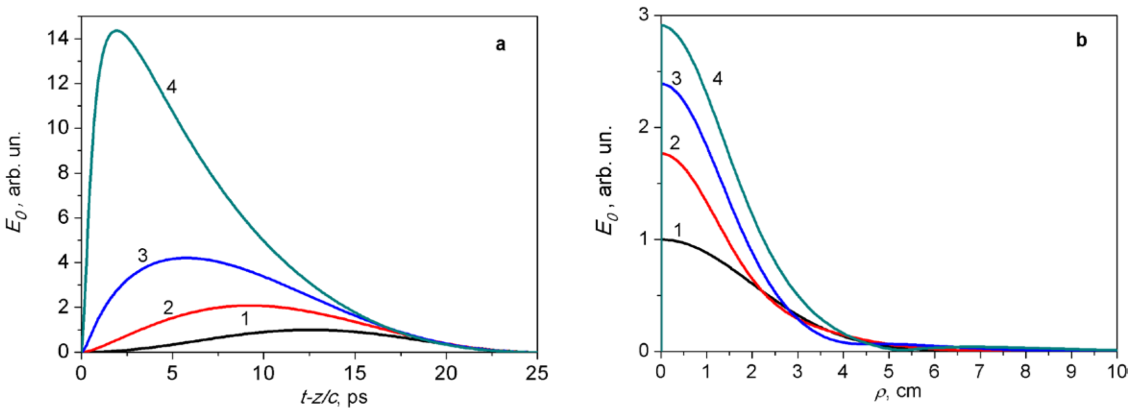

Figure 8. Temporal (a) and radial (b) profiles of the two-cycled pulse envelope propagated in air plasma channel at different propagation distances z: 1—0 cm, 2—30 cm, 3—60 cm, 4—90 cm. Initial peak intensity is 10 W cm^{-2}.

in figure 9. For small propagation lengths ≤20 cm and input RF intensities below 10^3 W cm^{-2} the RF pulse amplifies exponentially according to Bouguer law:

$$E_0(z) = E_0(z=0) \times \exp(k_\omega z/2).$$

At propagation lengths greater $L \geq 20$ cm the diffraction divergence also contributes and effective field amplification $g = E_0(z)/E_0(z=0)$ is found to grow up slowly with increase of L. We can also see that in the low-intensity limit the amplification factor does not depend on the input intensity and reaches the value $g \approx 20$ for the propagation length $L = 120$ cm. It means that output intensity increases ~400 times in comparison with input intensity. In the range of input intensities above 100 W cm^{-2} the g-factor drops dramatically for large propagation lengths. This occurs due to the rapid relaxation of the EEDF in the presence of RF field and decrement of the gain factor in a plasma channel. We also note the existence of the g-factor local maximum in relation to input

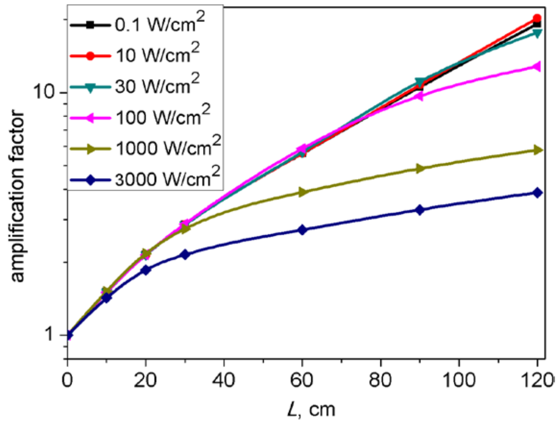

Figure 9. Field amplification factor in dependence of the propagation length for different input RF intensities (0.1, 10, 30, 10^2, 10^3 and $3 \times 10^3\,\text{W cm}^{-2}$). Electron density is $n_e = 3 \times 10^{12}\,\text{cm}^{-3}$ and $\omega = 0.5\,\text{THz}$, channel radius is 2 cm.

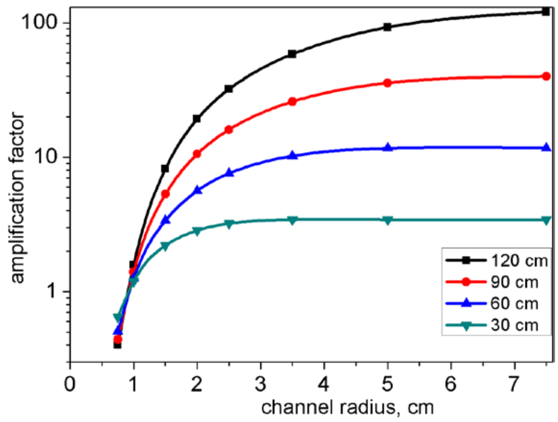

Figure 10. Field amplification factor in dependence of the plasma channel radius for different propagation lengths (30, 60, 90 and 120 cm). Electron density is $n_e = 3 \times 10^{12}\,\text{cm}^{-3}$, $\omega = 0.5\,\text{THz}$ and input RF intensity is $0.01\,\text{W cm}^{-2}$.

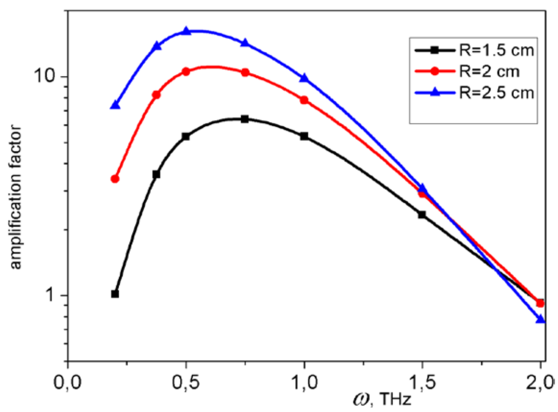

Figure 11. Field amplification factor in dependence of RF pulse frequency for different channel radius R. Electron density is $n_e = 3 \times 10^{12}\,\text{cm}^{-3}$, input RF intensity is $0.01\,\text{W cm}^{-2}$ and propagation length is $L = 90\,\text{cm}$.

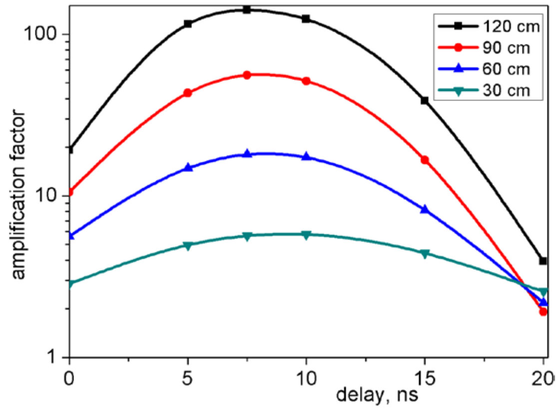

Figure 12. Field amplification factor in dependence of the time delay between laser and RF pulses for different propagation lengths (30, 60, 90 and 120 cm). Electron density is $n_e = 3 \times 10^{12}\,\text{cm}^{-3}$, input RF intensity is $0.01\,\text{W cm}^{-2}$ and $R = 2\,\text{cm}$.

intensity for any values of propagation length. For example, this maximum corresponds to $100\,\text{W cm}^{-2}$ for $L = 60\,\text{cm}$. This maximum appears to exist due to the additional focusing effect of a plasma arising in the process of EEDF relaxation at moderate intensities.

The dependence of the field amplification factor on plasma channel radius is presented in figure 10. The most important fact is that, in agreement with (11), effective amplification of the RF pulse takes place only for plasma channels of radius $R \geq 2\,\text{cm}$. For $R < 1\,\text{cm}$ both effects of amplification and plasma focusing cannot compensate the diffraction divergence of the pulse and its intensity decreases along the propagation length. The increment of the channel radius above 2–4 cm leads to the saturation of amplification factor at a level $g = \exp(k_\omega L/2)$.

It should be mentioned that there is an existence of the optimal value of frequency for effective RF pulse amplification for a given channel radius (see data in figure 11). For $R = 2\,\text{cm}$ this frequency is rather close to $\omega = 5 \times 10^{11}\,\text{s}^{-1}$. The decrement of the frequency and hence, the increment of the microwave radiation wavelength leads to the violation of the inequality (11) determining realization of the guiding regime. On the other hand, the amplification factor also falls down for high frequencies. When the condition $\omega \geq \nu_{\text{tr}}$ is fulfilled, the gain factor becomes negative and the amplification regime is impossible for any radius of the plasma channel. In the situation in the study, the regime of amplification can be realized for microwave frequencies $\omega \leq 1.8\,\text{THz}$.

All the data discussed above were obtained for the zero delay between optical and RF pulses. On the other hand, the data presented in figure 1 lead to the conclusion that in order to increase the amplification factor we should introduce the time delay between laser and microwave pulses. The value of this delay depends on the electronic density in the channel and for $n_e = 3 \times 10^{12}\,\text{cm}^{-3}$ this delay should be of order of 10 ns. The data presented in figure 12 confirm the above conclusion. The optimal delay in our situation is ~7.5 ns. Due to the increment of the gain factor and refractive index during the initial period of the EEDF evolution (see figure 1), such a delay value allows the amplification factor to be increased approximately five times.

4. Conclusions

Thus, in this letter it is shown that the nonequilibrium plasma channel created in xenon or in air by powerful femtosecond UV laser can be used to guide and amplify the RF pulses till the subterahertz frequency band. In xenon plasma, it is possible to amplify the RF pulses with a duration of tens of nanoseconds, while in the case of air plasma the rapid relaxation of the EEDF makes it possible to amplify extremely short RF pulses only. There is an opportunity to reach significant amplification by the launching of the laser and RF pulses, so that the RF pulse is continually located in the guiding and amplification zones of the laser pulse. In the case of plasma channel created in xenon, optimal parameters of RF pulse for guiding and amplification are discussed.

We would also note that the existence of the positive gain factor in the plasma channel in the subterahertz frequency range raises the question of the possibility to construct subterahertz maser, i.e. microwave generator. But, unfortunately, the level of spontaneous emission at the microwave frequency range is negligible and the problem which must additionally be solved is how to introduce a seed RF signal into the channel.

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References

[1] Skinner J L 2010 *Science* **328** 985
[2] Meister K *et al* 2013 *Proc. Natl. Acad. Sci.* **110** 1617
[3] Titova L V *et al* 2013 *Sci. Rep.* **3** 2363
[4] Grady N K *et al* 2013 *Science* **340** 1304
[5] Jepsen P U, Cooke D G and Koch M 2011 *Laser Photon. Rev.* **5** 124
[6] Bekefi G, Hirshfield Y L and Brown S C 1961 *Phys. Fluids* **4** 173
[7] Bunkin F V, Kazakov A E and Fedorov M V 1973 *Sov. Phys.—Usp.* **15** 416
[8] Bogatskaya A V and Popov A M 2013 *JETP Lett.* **97** 388
[9] Bogatskaya A V, Volkova E A and Popov A M 2013 *Quantum Electron.* **43** 1110
[10] Bogatskaya A V, Volkova E A and Popov A M 2014 *J. Phys. D: Appl. Phys.* **47** 185202
[11] Bogatskaya A V, Smetanin I V and Popov A M 2014 *J. Russ. Laser Res.* **35** 437
[12] Zvorykin V D, Levchenko A O, Smetanin I V and Ustinovski N N 2010 *JETP Lett.* **91** 226
[13] Ginzburg V L and Gurevich A V 1960 *Sov. Phys.—Usp.* **3** 115
[14] Raizer Y P 1977 *Laser - Induced Discharge Phenomena* (New York: Consultants Bureau)
[15] Akhmanov S A and Nikitin S Y 1997 *Physical Optics* (Oxford: Oxford University Press)