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On the Possibility of the Amplification of Subterahertz Electromagnetic Radiation in a Plasma Channel Created by a High-Intensity Ultrashort Laser Pulse

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The evolution of the electron energy distribution function in a plasma channel in a xenon plasma at atmospheric pressure created by radiation of a KrF femtosecond laser has been considered. It has been shown that, owing to the existence of the Ramsauer minimum in the transport scattering cross section, such a channel can be used to amplify electromagnetic waves up to the terahertz frequency range at relaxation times of the energy spectrum of $\sim 10^{-7}$ s. The gain factor has been calculated as a function of the time and radiation frequency.

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The nonlinear ionization of atoms of a gas medium in the field of high-intensity femtosecond laser pulse leads to the formation of a plasma structure, which can be interesting for a number of applications. In particular, the appearing plasma can be a source of multicharged ions [1, 2] and excited (Rydberg) atoms [3, 4]. An extended plasma channel appearing in a gas in the case of focusing of high-intensity laser radiation in the visible or infrared frequency range is an efficient source of high harmonics currently used to form attosecond pulses [5, 6].

An important feature of the plasma structure appearing in the field of an ultrashort laser pulse is its strong nonequilibrium. In particular, the energy spectrum of photoelectrons appearing in multiphoton ionization of the gas under the conditions where the pulse duration is smaller than or about the frequency of atomic collisions consists of peaks corresponding to the absorption of a certain number of photons. Such an electron energy distribution function exhibits energy ranges characterized by inverse population. As is known, this can be used to amplify electromagnetic radiation in a plasma [7–9].

The possibility of using the plasma channel created by a high-intensity ultrashort pulse of a KrF excimer laser ($\hbar\Omega = 5$ eV) in xenon for the amplification of radio-frequency radiation is analyzed in this work. The evolution of the electron energy spectrum in the relaxing plasma created by the laser pulse is examined using the Boltzmann kinetic equation and the gain factor of electromagnetic radiation in the plasma channel is calculated as a function of the time and radiation frequency. It is shown that such a relaxing plasma can be used as an effective amplifying medium for radio-frequency radiation pulses, including those in the subterahertz frequency range.

It is noteworthy that the amplification of electromagnetic radiation in the plasma channel created by an ultrashort laser pulse ionizing the gas is close in physical meaning to the effect of the negative absolute conductivity in the gas-discharge plasma predicted in [10, 11], experimentally detected in [12], and discussed in detail in review [13].

For the analysis of the properties and evolution of the plasma channel created by radiation of a high-intensity femtosecond laser, it is significant that the channel appears only owing to the multiphoton or tunneling ionization of atoms. In this case, avalanche ionization can be neglected. Moreover, for pulses with the duration $\tau_p \sim 100$ fs, elastic collisions of electrons with the atoms of the medium during the pulse can also be neglected. Indeed, the characteristic time of collisions of electrons with atoms (or molecules) in a gas can be estimated as $T_c \approx 1/N\sigma v$, where $N \approx 2.5 \times 10^{19}$ cm^{-3} is the density of particles at atmospheric pressure, $\sigma \cong 10^{-15}$ cm^2 is the collision cross section, and $v \sim 10^8$ cm/s is the velocity of electrons appearing in photoionization. Under these conditions, $T_c \sim 4 \times 10^{-13}$ s, which exceeds the duration of the laser pulse. This means that the energy spectrum of photoelectrons by the end of the laser pulse is determined only by the photoionization of atoms (molecules) of the gas and can be obtained by solving the problem of the ionization of a single atom (molecule) in a strong laser field. The evolution of the spectrum caused by elastic and inelastic collisions, which is described by the Boltzmann kinetic equation, occurs in the postpulse regime. For this reason, under the conditions of interest, the problem of the ionization of the gas by laser radiation can be considered independently of the problem of the evolution of the spectrum of photoelectrons and the solution of the former problem is used as the initial condition for the latter problem.

In the moderate fields with the intensity of radiation of the KrF laser $\sim 10^{12}$–10^{13} W/cm^2, the Stark shift of the continuum boundary can be neglected. Correspondingly, ionization of xenon atoms is three-photon. The position of the first peak in the spectrum of photoelectrons corresponds to the energy $\varepsilon_0 = 3\hbar\Omega - I_i \approx 2.87$ eV (where $I_i = 12.13$ eV is the ionization potential). Higher above-threshold ionization peaks are almost absent. The analysis of the experimental and theoretical data (see [14]) shows that the ionization probability in the indicated intensity range is a cubic function of the radiation intensity I: $w_i \sim I^3$. For the density of xenon atoms of 2.5×10^{19} cm^{-3}, the degree of ionization by the end of the laser pulse with the duration $\tau_p \sim 100$ fs is $\alpha = N_e/N \approx 10^{-6}$–$10^{-4}$ (where N_e is the electron density). The width of the peak is determined by the pulse duration and is $\Delta\varepsilon \approx 0.2$ eV.

Analyzing the evolution of the energy spectrum, we assume that the plasma channel with a given degree of ionization and strongly nonequilibrium electron energy distribution function is formed at the initial (zero) time. The distribution function is approximated by the Gaussian

$$n(\varepsilon, t=0) = \frac{1}{\Delta\varepsilon\sqrt{\pi\varepsilon}}\exp\left[-\frac{(\varepsilon-\varepsilon_0)^2}{(\Delta\varepsilon)^2}\right]. \qquad (1)$$

This electron energy distribution function is normalized as

$$\int_0^{+\infty} n(\varepsilon, t=0)\sqrt{\varepsilon}\,d\varepsilon = 1. \qquad (2)$$

The quantity $n(\varepsilon, t)\sqrt{\varepsilon}$ is the probability density of the existence of the electron with the energy ε.

The time evolution of spectrum (1) was analyzed using the Boltzmann kinetic equation for the electron energy distribution function in the two-term approximation. Since the lower threshold for the excitation of electronic states of the xenon atom exceeds 8 eV, the time dependence of the electron energy distribution function can be calculated taking into account only elastic collisions of electrons with xenon atoms. In this case, the Boltzmann equation can be represented in the form

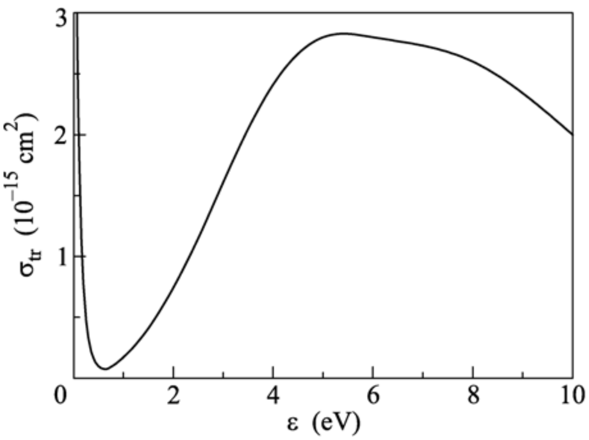

Fig. 1. Transport scattering cross section on xenon atoms.

$$\frac{\partial n(\varepsilon, t)}{\partial t}\sqrt{\varepsilon} = \frac{2m}{M}\frac{\partial}{\partial\varepsilon}\left\{\nu_{tr}(\varepsilon)\varepsilon^{3/2}\left[n(\varepsilon, t) + T\frac{\partial n(\varepsilon, t)}{\partial\varepsilon}\right]\right\}. \qquad (3)$$

This is the diffusion equation in the energy space. Here, T is the gas temperature (below, we take $T \approx 0.03$ eV), m is the mass of the electron, M is the mass of the atom, and $\nu_{tr} = N\sigma_{tr}(\varepsilon)\sqrt{2\varepsilon/m}$ is the transport frequency, where $\sigma_{tr}(\varepsilon)$ is the transport scattering cross section. Equation (3) with initial condition (1) was solved numerically using an explicit scheme in the energy range $\varepsilon = 0$–5 eV. The energy and time integration step were $\delta\varepsilon = 0.01$ eV and $\tau = 2 \times 10^{-12}$ s. As a result, the Curant condition, $\tau \le \frac{M}{4m}\left[\frac{\delta\varepsilon}{\varepsilon}\frac{\delta\varepsilon}{T}(\nu_{tr})^{-1}\right]$, was satisfied for any energy in the indicated range. The transport scattering cross section was taken from [15, 16] and is shown in Fig. 1. The characteristic feature of this cross section (as well as the transport cross section in other heavy noble gases) is the presence of the Ramsauer minimum and a section with the positive derivative $d\sigma_{tr}/d\varepsilon$ in the energy range of 0.64–5.0 eV. As is known [8], this feature of the transport cross section can be responsible for the appearance of the amplification of electromagnetic radiation in the plasma. Indeed, the expression for the complex conductivity $\sigma(\omega) = \sigma'(\omega) + i\sigma''(\omega)$ at the frequency ω can be written in the form (see, e.g., [7, 8])

$$\sigma(\omega) = \frac{2}{3}\frac{e^2N_e}{m}\int_0^{+\infty}\frac{\varepsilon^{3/2}(\nu_{tr} + i\omega)}{\omega^2 + \nu_{tr}^2}\left(-\frac{\partial n}{\partial\varepsilon}\right)d\varepsilon. \qquad (4)$$

The real part of this expression describes the dissipation of the energy of the electromagnetic wave in the

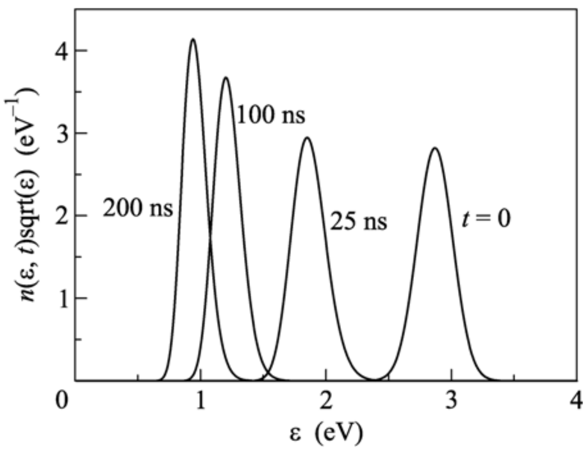

Fig. 2. Electron energy distribution functions in xenon at various times after the creation of the plasma channel by the pulse of the KrF laser.

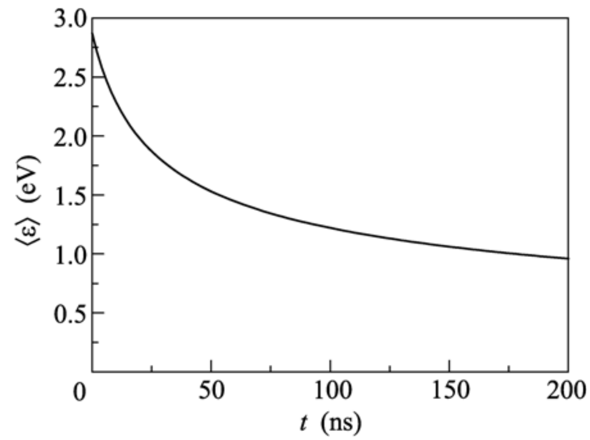

Fig. 3. Time dependence of the spectrum-average energy of photoelectrons.

plasma. The absorption coefficient at the frequency ω can be easily represented in the form

$$\mu_\omega = \frac{4\pi\sigma'}{c} = \frac{8\pi}{3}\frac{e^2 N_e}{m}\int_0^{+\infty}\frac{\varepsilon^{3/2}\nu_{\rm tr}}{\omega^2+\nu_{\rm tr}^2}\left(-\frac{\partial n}{\partial\varepsilon}\right)d\varepsilon. \quad (5)$$

The electron energy distribution function usually decreases with the energy, i.e., $\partial n/\partial\varepsilon < 0$ and, correspondingly, the integral in Eq. (5) is positive and $\mu_\omega > 0$. However, in the process of the photoionization of atoms by short pulses, inevitably appearing spectral ranges with the positive derivative, $\partial n/\partial\varepsilon > 0$, make a negative contribution to the integral in Eq. (5) and reduce the absorption coefficient. The authors of [8] showed that the integral in Eq. (5) can be negative in the low-frequency range $\omega < \nu_{\rm tr}$ (in our case, this condition is satisfied even in the subterahertz frequency range $\omega \le 10^{12}$ s^{-1}) in gases with the pronounced Ramsauer effect for distribution function (1). In this situation, the medium can amplify radio-frequency radiation.

Under the accepted assumptions, the gain factor $k_\omega = -\mu_\omega$ (see Eq. (5)) is proportional to the degree of plasma ionization. For this reason, to increase it, the intensity of ionizing radiation of the KrF laser should seemingly be increased. However, electron–electron collisions, which promote faster Maxwellization of the spectrum of photoelectrons and, correspondingly, the disappearance of the amplification effect, are disregarded in the calculation of the electron energy distribution function within our model. As is known [7], electron–electron collisions in the presence of only elastic collisions significantly affect the evolution of the energy spectrum in the plasma under the condition

$$\alpha = N_e/N \ge \frac{2m}{M}\frac{\sigma_{\rm tr}}{\sigma_{ee}}, \quad (6)$$

where $\sigma_{ee} = \frac{\pi e^4}{\varepsilon^2}L(\varepsilon)$ is the cross section for electron–electron (Coulomb) collisions and $L(\varepsilon)$ is the Coulomb logarithm, which is a smooth function of the energy. Taking $L \approx 1$, we conclude that condition (6) in the energy range $\varepsilon \approx 2.5$ eV corresponding to the position of the peak in the spectrum of photoelectrons is satisfied for $\alpha \ge 10^{-6}$ or $N_e > 3 \times 10^{13}$ cm^{-3}.

When the energy spectrum is rearranged owing only to the elastic collisions of electrons with neutral atoms, the characteristic relaxation time of the electron energy distribution function can be estimated as

$$\tau_\varepsilon \approx \frac{M}{2m}(\nu_{\rm tr})^{-1}. \quad (7)$$

Under our conditions, estimate (7) gives $\tau_\varepsilon \approx 10^{-7}$ s. This means that the amplification of electromagnetic radiation in the plasma can be expected at these times. Thus, the plasma channel created in xenon by the radiation of the KrF femtosecond laser allows the amplification of radio-frequency pulses (up to the terahertz frequency range) with a duration of several tens of nanoseconds.

Numerical calculations confirm our estimates. Figure 2 shows the electron energy distribution function calculated from Eq. (3) in xenon for various times. As can be seen, during the entire calculation time (200 ns), the electron energy distribution function is characterized by a pronounced maximum, which is gradually shifted toward lower energies. In this case, the diffusion spreading of the spectrum in energy can be neglected. Furthermore, a decrease in the frequency of elastic collisions $\nu_{\rm tr}$ with the deceleration of electrons leads to the inverse effect, narrowing of the peak in the spectrum of photoelectrons. Figure 3 shows the time dependence of the spectrum-average energy of photoelectrons:

$$\langle \varepsilon(t) \rangle = \int_0^{+\infty} n(\varepsilon, t = 0)\varepsilon^{3/2} d\varepsilon. \quad (8)$$

This dependence also indicates a significant decrease in the electron cooling rate in time.

The electron energy distribution functions obtained in the numerical calculations were used to calculate the gain factor of electromagnetic radiation in the plasma. Figure 4 shows the calculation results for the electron density $N_e = 10^{12}$ cm^{-3} and various frequencies of the amplified radiation. They demonstrate that the assumptions made above are valid. The indicated N_e value is critical for the radiation frequency $\omega^* \approx 5 \times 10^{10}$ s^{-1}. Consequently, it is physically meaningful to calculate the gain factor only for $\omega > \omega^*$. Radiation with lower frequencies cannot propagate in the plasma. At the same time, a positive gain factor can be obtained only for $\omega < \nu_{tr}(\varepsilon)$. The calculations show that the gain factor is maximal for the lowest radiation frequency $\omega = 10^{11}$ s^{-1} used in them. In this case, the quantity k_ω in the process of relaxation of the energy spectrum increases at times $t \leq 100$ ns owing to a decreasing time dependence of the energy of the photoelectron peak and, thereby, the transport cross section in the energy range making the most significant contribution to the integral in Eq. (5). The increase in the radiation frequency ω is accompanied by a decrease in the maximum gain factor k_ω. The time interval during which the gain factor is positive decreases simultaneously. This circumstance is due to the fact that the condition $\nu_{tr}(\varepsilon) > \omega$ in the process of relaxation of the electron energy distribution function is violated at shorter times with an increase in the frequency of amplified radiation. However, under the conditions of interest, the gain factors $k_\omega \sim 0.01$–0.1 cm^{-1} existing for several tens of nanoseconds in the frequency range up to $\sim 10^{12}$ s^{-1} can be expected. An increase in k_ω is possible owing to an increase in the degree of ionization in the plasma channel. However, the electron density should not exceed the critical value for the frequency of the amplified field. In addition, the relaxation of the electron energy distribution function in this case is faster. This can lead to a decrease in the time during which the gain factor in the plasma is positive.

We also note that the effective population of high-energy (Rydberg) states of atoms that was observed in [3, 4, 17, 18] and occurs in the process of the ionization of the gas medium by a high-intensity ultrashort pulse can be an additional channel of the introduction of the energy in the electron component of the plasma owing to the presence of superelastic collisions. As a result, the slowing of the process of relaxation of the electron energy distribution function, as well as an increase in the time interval during which the gain factor is positive, can be expected.

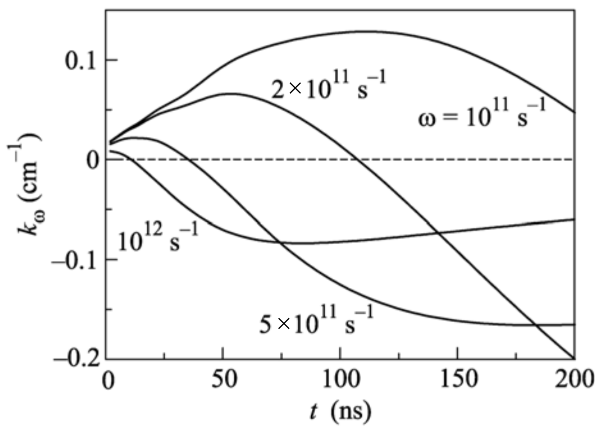

Fig. 4. Time dependence of the gain factor of the electromagnetic radiation with various frequencies ω in the plasma channel. Negative values correspond to the absorption of electromagnetic radiation in the plasma. The calculations were performed for densities of neutral atoms $N = 2.5 \times 10^{19}$ cm^{-3} and electrons $N_e = 10^{12}$ cm^{-3}.

To conclude, it has been shown that a plasma channel created in a dense gas by a high-intensity ultrashort laser pulse can be used to amplify radio-frequency pulses, including those in the terahertz frequency range with the duration of up to 100 ns. It is worth noting that xenon atoms used as an amplifying medium have a number of advantages as compared to other atoms of noble gases, which are also characterized by the existence of the Ramsauer minimum in the transport scattering cross section. This is due primarily to the fact that the transport cross section for xenon atoms in the range of 1–3 eV is maximal (which ensures the positive k_ω values for higher frequencies of the amplified field). Furthermore, xenon is characterized by the largest derivative $d\sigma_{tr}/d\varepsilon$ among noble gases.

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