Excitation of high-intensity terahertz surface modes of plasma slab under action of *p*-polarized two-frequency laser radiation

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(Received 11 November 2021; accepted 24 March 2022; published 8 April 2022)

The excitation of the terahertz (THz) high-intensity surface modes when the two-frequency *p*-polarized laser radiation interacts with a plasma slab is studied. It was found that the significant amplification of the laser field in the plasma slab occurs when *p*-polarized laser radiation is incident at the angle of total reflection. It is shown that, under the action of laser radiation ponderomotive forces, the resonant excitation of the THz mode of the plasma slab occurs if the frequency difference of the laser fields coincides with the eigenfrequency of the surface mode. It is established that the giant increase in the energy flux density of the THz mode occurs when *p*-polarized laser radiation is incident at the angle of total reflection on the near-critical plasma slab with rare electron collisions if the conditions of resonant excitation are satisfied. It is shown that in this case the energy flux density of THz mode can significantly exceed the laser intensity.

DOI: 10.1103/PhysRevE.105.045203

I. INTRODUCTION

Interest in the generation of terahertz (THz) radiation is associated with the possibilities of its use in scientific research and practical applications [1]. At present, the most intense THz radiation has been experimentally recorded upon laser irradiation of lithium niobate crystals [2,3] and various organic crystals [4,5]. The important parameter that characterizes the generation of THz radiation under laser-matter interaction is the conversion rate of the laser pulse energy into THz signal. Under the action of laser pulses on gas jets in a vacuum chamber, this coefficient has the small value of the order of 10^{-6}–10^{-7} [6–11]. As the pressure in the gas jet increases, the conversion efficiency can increase by two orders of magnitude due to the formation of clusters [12,13]. The conversion rate in the interaction of laser radiation with gases can be significantly increased if two-color (multicolor) pumping is used. When a two-color (multicolor) laser pulse is focused in the ambient air and a plasma filament is formed that emits THz waves, this coefficient is of the order of 10^{-3} [14–17]. It was experimentally and theoretically established that an increase in the wavelength of two-color pumping to the midinfrared range leads to an increase in the conversion coefficient up to several percent [18]. Under laser action on metal targets, the conversion rate changes from small values of the order of 10^{-6}–10^{-7} in experiments [19–23] to the value of 10^{-3} in [24], where THz radiation was emitted from the rear surface of a thin metal foil. It should be noted that the high efficiency of THz radiation generation (up to 0.1%) takes place under laser action on photoconductive media, when surfaces and flat layers of photoconductors are irradiated [25,26], due to the excitation of eigenmodes in these media. The efficiency of the laser-to-THz energy conversion is significantly high and is equal approximately 3% at laser irradiation of nonlinear organic crystals [4,5] and lithium niobate crystals [2]. Theoretically, the sufficiently large value of the conversion coefficient about 13% is predicted in [27], where the interaction of laser radiation with lithium niobate crystals cooled to the temperature 10K is considered. The efficiency of THz radiation generation can be significantly increased due to the excitation of low-frequency eigenmodes in a material medium under laser action. It was shown in [28] that the energy flux density of THz modes of the plasma slab can be comparable to the intensity of two-frequency *s*-polarized laser radiation if the resonance condition is satisfied and the frequency difference of the laser fields coincides with the frequency of the eigenmode. In this article, the excitation of the THz mode under the action of two-frequency *p*-polarized laser radiation on the slab of near-critical plasma is considered and it is shown that the energy flux density of the THz mode can significantly exceed the laser radiation intensity. This effect occurs due to (a) the significant amplification of the *p*-polarized laser field in the near-critical plasma slab when it is incident at the angle of total reflection and (b) the resonant excitation of the THz eigenmode of plasma slab when its frequency coincides with the frequency difference of the laser fields. In the article, we assume that the incident laser radiation has sufficiently large spatial sizes and temporal duration, which allows us to use the plane waves approximation.

The article has the following structure: in the second section, the boundary problem for *p*-polarized two-frequency laser radiation incident on a plasma slab with a subcritical electron concentration is solved, and the spatial distribution of the laser field inside the plasma slab is found. The ponderomotive potential in the plasma at the difference frequency is calculated and it is shown that it has the maximum value when the laser radiation is incident at the angle of total reflection on the plasma slab with the near-critical electron density. In the third section, the excitation of the THz mode of the plasma

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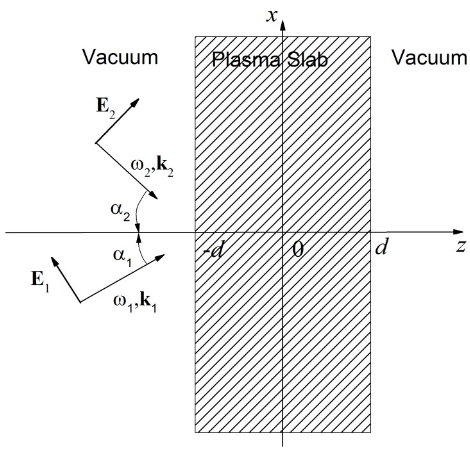

FIG. 1. The incidence of two-frequency p-polarized laser radiation on the plasma slab.

slab under the action of the ponderomotive force of laser radiation at the difference frequency is considered. It is shown that when laser radiation is incident at the angle of total reflection, only the symmetric mode of the plasma slab is excited, for which the space-time distribution of the electromagnetic field in the plasma and in vacuum is found. It is established that the significant increase in the THz mode field occurs under resonance conditions, when its eigenfrequency coincides with the frequency difference between the laser fields. In the fourth section, the Poynting vector of the THz mode of the plasma slab is calculated and the dependence of its absolute value on the incidence angle of laser radiation and the slab thickness is investigated. It is shown that the energy flux density of the THz mode is maximum when the two-frequency laser radiation is incident at the angle of total reflection on the near-critical plasma slab with the thickness comparable to the laser wavelength under resonance conditions, when the difference between the laser frequencies coincides with the eigenfrequency of the plasma slab mode. In the Conclusion section, the main results of the article are presented and the estimates for the energy characteristics of the THz mode are given. It is shown that, under the conditions of modern experiments, the energy flux density of the THz mode can significantly exceed the laser radiation intensity.

II. BOUNDARY VALUE PROBLEM FOR *p*-POLARIZED TWO-FREQUENCY LASER RADIATION

Let two waves of the p-polarized laser radiation with constant amplitudes and close frequencies $\omega_1,\ \omega_2$ fall from vacuum ($z < -d$) on the plasma slab occupying the space region $-d \leqslant z \leqslant d$ (see Fig. 1), where the frequency difference $\Delta\omega_0 = \omega_1 - \omega_2 > 0$ is assumed to be small in comparison with the frequencies themselves, $\Delta\omega_0 \ll \omega_0 = (\omega_1 + \omega_2)/2$. We will assume that the laser waves fall at the angles $\alpha_1,\ -\alpha_2$, which are measured from the normal to the plasma slab boundary and which are approximately equal, $\alpha_1 - \alpha_2 \ll \alpha = (\alpha_1 + \alpha_2)/2$. If XOZ is the incidence plane, then the wave vectors of the incident waves have the form $\mathbf{k}_1 = (\omega_1/c)[\mathbf{e}_z \cos\alpha_1 + \mathbf{e}_x \sin\alpha_1]$ and $\mathbf{k}_2 = (\omega_2/c)[\mathbf{e}_z \cos\alpha_2 - \mathbf{e}_x \sin\alpha_2]$, which corresponds to the counterpropagation of the waves in the direction of the x axis along the plasma slab boundary, where c is the speed of light, and $\mathbf{e}_x, \mathbf{e}_z$ are the basis vectors of the x and z axes, respectively. Then, in vacuum, the magnetic field of the incident p-polarized laser radiation can be represented in the following form:

$$\mathbf{B}_L^{\rm inc}(\mathbf{r},t) = \mathbf{e}_y E_{0L}\left\{\cos\left[\omega_1 t - \frac{\omega_1}{c}[(z+d)\cos\alpha_1 + x\sin\alpha_1]\right] + \cos\left[\omega_2 t - \frac{\omega_2}{c}[(z+d)\cos\alpha_2 - x\sin\alpha_2]\right]\right\}, \tag{1}$$

where $\mathbf{e}_y$ is the basis vector of the y axis, and E_{0L} is the amplitude electric field of the laser radiation, which we will assume to be the same for both waves. Let the plasma electron density N_{0e} be less than the critical value $N_{0e} < N_{cr}$, where $N_{cr} = m_e\omega_0^2/(4\pi e^2)$, $e,\ m_e$ are the charge and mass of the electron.

Let us consider the boundary value problem for the incidence of one wave with frequency ω_1 and wave vector $\mathbf{k}_1$ on the plasma slab. In this case, the distribution of the magnetic field $\mathbf{B}_L^{(1)}(\mathbf{r},t)$ of the laser radiation at the frequency ω_1 in the whole space has the form

$$\mathbf{B}_L^{(1)}(\mathbf{r},t) = \frac{1}{2}\mathbf{e}_y E_{0L}\exp\left(-i\omega_1 t + i\frac{\omega_1}{c}x\sin\alpha_1\right) \times\left\{\exp\left[i\frac{\omega_1}{c}(z+d)\cos\alpha_1\right] + R(\omega_1,\alpha_1)\exp\left[-i\frac{\omega_1}{c}(z+d)\cos\alpha_1\right]\right\} + \text{c.c.},\quad z \leqslant -d, \tag{2}$$

$$\mathbf{B}_L^{(1)}(\mathbf{r},t) = \frac{1}{2}\mathbf{e}_y E_{0L}\exp\left(-i\omega_1 t + i\frac{\omega_1}{c}x\sin\alpha_1\right) \times\frac{2\varepsilon_1\cos\alpha_1}{D(\omega_1,\alpha_1)}\{\exp[-ik_1(z-d)] \times\left(\varepsilon_1\cos\alpha_1 - \sqrt{\varepsilon_1 - \sin^2\alpha_1}\right) - \exp[ik_1(z-d)] \times\left(\varepsilon_1\cos\alpha_1 + \sqrt{\varepsilon_1 - \sin^2\alpha_1}\right)\} + \text{c.c.},\quad -d \leqslant z \leqslant d, \tag{3}$$

$$\mathbf{B}_L^{(1)}(\mathbf{r},t) = -\frac{1}{2}\mathbf{e}_y E_{0L}\exp\left(-i\omega_1 t + i\frac{\omega_1}{c}x\sin\alpha_1\right) \times\frac{4\varepsilon_1\cos\alpha_1\sqrt{\varepsilon_1 - \sin^2\alpha_1}}{D(\omega_1,\alpha_1)} \times\exp\left[i\frac{\omega_1}{c}(z-d)\cos\alpha_1\right] + \text{c.c.},\quad z \geqslant d, \tag{4}$$

where $k_1 = (\omega_1/c)\sqrt{\varepsilon_1 - \sin^2\alpha_1}$ is the z component of the wave number of laser radiation in the plasma layer, $\varepsilon_1 \equiv \varepsilon(\omega_1) = 1 - (\omega_p^2/\omega_1^2)(1 - i\nu_{ei}/\omega_1)$ is the plasma dielectric constant at the frequency ω_1, $\omega_p = \sqrt{4\pi e^2 N_{0e}/m_e}$ is the plasma frequency, ν_{ei} is the frequency of electron-ion collisions, and the expressions for the reflection coefficient $R(\omega_1,\alpha_1)$ and dispersion function $D(\omega_1,\alpha_1)$ have the form

$$R(\omega_1,\alpha_1)=\frac{\exp(2ik_1d)-\exp(-2ik_1d)}{D(\omega_1,\alpha_1)}\times\left(\varepsilon_1\cos\alpha_1-\sqrt{\varepsilon_1-\sin^2\alpha_1}\right)\times\left(\varepsilon_1\cos\alpha_1+\sqrt{\varepsilon_1-\sin^2\alpha_1}\right), \quad (5)$$

$$D(\omega_1,\alpha_1)=\left(\varepsilon_1\cos\alpha_1-\sqrt{\varepsilon_1-\sin^2\alpha_1}\right)^2\exp(2ik_1d)-\left(\varepsilon_1\cos\alpha_1+\sqrt{\varepsilon_1-\sin^2\alpha_1}\right)^2\exp(-2ik_1d). \quad (6)$$

This magnetic field distribution of the laser radiation at the frequency ω_1, Eqs. (2)–(6), is obtained by solving the Maxwell equations in vacuum and in the plasma slab and using the continuity conditions of the tangential components of the electromagnetic field at both plasma-vacuum interfaces, taking into account the form of the incident p-polarized wave (1). From Eqs. (2)–(6) it follows that in a collisionless plasma ($\mathrm{Im}\varepsilon_1=0$), when the condition $\mathrm{Re}\varepsilon_1=\sin^2\alpha_1$ is fulfilled, the reflection coefficient is equal to $R_1(\omega_1,\alpha_1)=1$ and the magnetic field of the laser radiation at $z\geqslant d$ is equal to zero [see Eq. (4)]. This means that, under the condition $\mathrm{Re}\varepsilon_1=\sin^2\alpha_1$, the total reflection effect of the incident laser radiation with frequency ω_1 from the plasma slab takes place in the absence of collisions of electrons. For laser radiation at the frequency ω_2, the distribution of the magnetic field $\mathbf{B}_L^{(2)}(\mathbf{r},t)$ can be easily obtained from Eqs. (2)–(6) by replacing $\omega_1\to\omega_2$ and $\alpha_1\to-\alpha_2$.

Using the expression for the magnetic field (3), we find the distribution of the electric field of the laser radiation at the frequency ω_1 in the plasma slab,

$$\mathbf{E}_L^{(1)}(\mathbf{r},t)=-\frac{1}{2}\exp\left(-i\omega_1t+i\frac{\omega_1}{c}x\sin\alpha_1\right)\frac{2E_{0L}\cos\alpha_1}{D(\omega_1,\alpha_1)}\{[\varepsilon_1\cos\alpha_1+\sqrt{\varepsilon_1-\sin^2\alpha_1}]\times[\mathbf{e}_x\sqrt{\varepsilon_1-\sin^2\alpha_1}-\mathbf{e}_z\sin\alpha_1]\exp[ik_1(z-d)]+[\varepsilon_1\cos\alpha_1-\sqrt{\varepsilon_1-\sin^2\alpha_1}]\times[\mathbf{e}_x\sqrt{\varepsilon_1-\sin^2\alpha_1}+\mathbf{e}_z\sin\alpha_1]\exp[-ik_1(z-d)]\}+\text{c.c.},\quad -d\leqslant z\leqslant d. \quad (7)$$

If the inequality $|k_1|d\ll1$ is satisfied, expression (7) is noticeably simplified and takes the form

$$\mathbf{E}_L^{(1)}(\mathbf{r},t)=\frac{1}{2}\exp\left(-i\omega_1t+i\frac{\omega_1}{c}x\sin\alpha_1\right)E_{0L}\cos\alpha_1\times\frac{\mathbf{e}_x\left[\varepsilon_1\cos\alpha_1+i\frac{\omega_1}{c}(z-d)\left(\varepsilon_1-\sin^2\alpha_1\right)\right]-\mathbf{e}_z\sin\alpha_1\left[1+i\frac{\omega_1}{c}(z-d)\varepsilon_1\cos\alpha_1\right]}{\left[\varepsilon_1\cos\alpha_1-i\frac{\omega_1}{c}d\left(\varepsilon_1-\sin^2\alpha_1\right)\right]\left[1-i\frac{\omega_1}{c}d\varepsilon_1\cos\alpha_1\right]}. \quad (8)$$

From formula (8) it follows that when the laser radiation is incident at the angle of total reflection $\mathrm{Re}\varepsilon_1=\sin^2\alpha_1$, the noticeable amplification of the laser field occurs in the plasma slab with the near-critical electron concentration, when $\mathrm{Re}\varepsilon_1\to0$. Note that the similar effect of the amplification of a p-polarized laser pulse field under the condition of its total reflection from the boundary of a semi-infinite plasma was considered earlier in [29].

Using a similar expression for the electric field of laser radiation in the plasma slab at the frequency ω_2, we can calculate the ponderomotive potential at the difference frequency $\Delta\omega_0$ if we use the formula

$$\Phi(\mathbf{r},t)=\frac{m_e}{e}\left\langle\mathbf{V}_L^{(1)}(\mathbf{r},t)\mathbf{V}_L^{(2)}(\mathbf{r},t)\right\rangle, \quad (9)$$

where the velocity of electrons $\mathbf{V}_L^{(i)}$ in the field of laser radiation with frequency ω_i and electric field $\mathbf{E}_L^{(i)}(\mathbf{r},t)$, here $i=1,2$, is determined from the equation

$$\frac{\partial}{\partial t}\mathbf{V}_L^{(i)}(\mathbf{r},t)=\frac{e}{m_e}\mathbf{E}_L^{(i)}(\mathbf{r},t), \quad (10)$$

and the angle brackets $\langle\ldots\rangle$ in (9) denote averaging over the oscillation period of the laser field. Let both waves of laser radiation fall at the angle of total reflection, which, taking into account the approximate coincidence of frequencies $\omega_1\approx\omega_2\approx\omega_0$ and angles of incidence $\alpha_1\approx\alpha_2\approx\alpha$, is determined by the formula

$$\sin^2\alpha=\varepsilon'(\omega_0) \quad (11)$$

or $\cos^2\alpha=\omega_p^2/\omega_0^2$, where $\varepsilon'(\omega_0)=\mathrm{Re}\varepsilon(\omega_0)$ is the real part of the plasma dielectric constant. Then, taking into account Eqs. (8)–(11), the ponderomotive potential at the difference frequency can be written as

$$\Phi(\mathbf{r},t)=\tfrac{1}{2}\Phi_1\exp(-i\Delta\omega_0t+2\,ik_0x\sin\alpha)+\text{c.c.}, \quad (12)$$

where its amplitude has the form

$$\Phi_1=\frac{V_E}{2\omega_0}E_{0L}\frac{\sin^2\alpha\cos^2\alpha}{\left[\sin^2\alpha\cos\alpha+k_0d\varepsilon''(\omega_0)\right]^2+\varepsilon''^2(\omega_0)\cos^2\alpha}, \quad (13)$$

where $k_0=(\omega_1+\omega_2)/2c=\omega_0/c$, $V_E=eE_{0L}/(m_e\omega_0)$ is the velocity of the electron oscillations in the field of laser radiation; $\varepsilon''(\omega_0)=\mathrm{Im}\varepsilon(\omega_0)$ is the imaginary part of the plasma dielectric constant, which is small due to inequality $\nu_{ei}\ll\omega_0$. It should be noted that formula (13) was obtained under the condition

$$k_0d\sqrt{\varepsilon''(\omega_0)}\ll1, \quad (14)$$

which follows from the inequality $|k_1|d\ll1$ [see Eq. (8)] taking into account relation (11). The ponderomotive potential

(13) is maximum

$$\Phi_{1,\max} = \frac{V_E}{4\omega_0}\frac{E_{0L}}{\varepsilon''(\omega_0)}\frac{1}{k_0 d + \sqrt{1+k_0^2d^2}}, \tag{15}$$

when laser radiation is incident on the slab of near-critical plasma at the angle of total reflection

$$\sin^2\alpha = \varepsilon'(\omega_0) = \sqrt{1+k_0^2d^2}\,\varepsilon''(\omega_0), \tag{16}$$

which, due to the inequality (14), is sufficiently small. Under the action of the ponderomotive potential of laser radiation (12), (13), electromagnetic fields are excited in the plasma slab at the difference frequency. In this case, in accordance with Eqs. (15) and (16), the strongest effect can be expected for the almost normal incidence of p-polarized two-frequency laser radiation on the plasma slab with the near-critical electron concentration (16), when the ponderomotive potential has the maximum value (15).

Equations (12)–(16) were obtained in the linear approximation without taking relativistic effects into account, when Eq. (10) was used. Therefore, the formulas for the ponderomotive potential (12)–(16) are applicable when the following condition is fulfilled:

$$\frac{V_E^2}{4c^2} \ll \frac{\nu_{ei}}{\omega_0}\left(k_0 d + \sqrt{1+k_0^2d^2}\right). \tag{17}$$

This inequality follows from the condition that the velocity of motion of electrons in plasma in the field of laser radiation (8) is small compared to the speed of light.

III. EXCITATION OF THz MODES OF THE PLASMA SLAB UNDER PONDEROMOTIVE ACTION OF p-POLARIZED TWO-FREQUENCY LASER RADIATION

To describe the excitation of THz eigenmodes of the plasma slab under the action of ponderomotive forces of the p-polarized two-frequency laser radiation, we will use Maxwell's equations for the electric $\mathbf{E}(\mathbf{r},t)$ and magnetic $\mathbf{B}(\mathbf{r},t)$ fields, as well as the equation for the electron velocity $\mathbf{V}(\mathbf{r},t)$ (see, for example, [28,29]),

$$\begin{aligned} \mathrm{rot}\mathbf{B}(\mathbf{r},t) &= \frac{1}{c}\frac{\partial}{\partial t}\mathbf{E}(\mathbf{r},t) + \frac{4\pi}{c}eN_e(z)\mathbf{V}(\mathbf{r},t),\\ \mathrm{rot}\mathbf{E}(\mathbf{r},t) &= -\frac{1}{c}\frac{\partial}{\partial t}\mathbf{B}(\mathbf{r},t),\\ \left(\frac{\partial}{\partial t}+\nu_{ei}\right)\mathbf{V}(\mathbf{r},t) &= \frac{e}{m_e}[\mathbf{E}(\mathbf{r},t) - \nabla\Phi(\mathbf{r},t)], \end{aligned} \tag{18}$$

where $N_e(z) = N_{0e}[\theta(z+d) - \theta(z-d)]$ is the coordinate-dependent electron density, which is zero in vacuum ($z < -d,\ z > d$) and is equal to N_{0e} in the plasma slab ($-d \leqslant z \leqslant d$), and $\theta(z)$ is the unit Heaviside step function. In accordance with the form of the ponderomotive potential (12), all physical quantities at the difference frequency can be represented in the following form:

$$\begin{aligned} &\{\mathbf{E}(\mathbf{r},t), \mathbf{B}(\mathbf{r},t), \mathbf{V}(\mathbf{r},t)\}\\ &= \tfrac{1}{2}\{\mathbf{E}_1(z), \mathbf{B}_1(z), \mathbf{V}_1(z)\}\\ &\quad\times \exp(-i\Delta\omega_0 t + 2\,ik_0 x\sin\alpha) + \text{c.c.} \end{aligned} \tag{19}$$

Taking into account the space-time dependence (19), from the set of Eqs. (18) follows the equation for the amplitude of the y component of the magnetic field $\mathbf{B}_1(z) = \mathbf{e}_y B_1(z)$,

$$\begin{aligned} &\frac{d}{dz}\left\{\frac{1}{\varepsilon(\Delta\omega_0,z)}\frac{d}{dz}B_1(z)\right\} - \left\{\frac{4k_0^2\sin^2\alpha}{\varepsilon(\Delta\omega_0,z)} - \frac{\Delta\omega_0^2}{c^2}\right\}B_1(z)\\ &= -\frac{2k_0\sin\alpha}{c\,\Delta\omega_0}\Phi_1(z)\frac{d}{dz}\left\{\frac{\omega_p^2(z)}{\varepsilon(\Delta\omega_0,z)}\right\}, \end{aligned} \tag{20}$$

where $\omega_p(z) = \sqrt{4\pi e^2N_e(z)/m_e}$, $\varepsilon(\Delta\omega_0,z) = 1 - [\omega_p^2(z)/\Delta\omega_0^2](1 - i\nu_{ei}/\Delta\omega_0)$ are the Langmuir frequency and dielectric constant of the plasma, depending on the z coordinate, respectively, it is also assumed that the inequality $\Delta\omega_0 \gg \nu_{ei}$ is satisfied. In this case, the components of the electric field are expressed in terms of the magnetic field by the following relations:

$$\begin{aligned} E_{1,x}(z) &= -\frac{ic}{\Delta\omega_0\varepsilon(\Delta\omega_0,z)}\\ &\quad\times\left\{\frac{d}{dz}B_1(z) + 2\frac{k_0\omega_p^2(z)}{c\,\Delta\omega_0}\sin\alpha\,\Phi_1(z)\right\},\\ E_{1,z}(z) &= -\frac{c}{\Delta\omega_0\varepsilon(\Delta\omega_0,z)}\\ &\quad\times\left\{2k_0\sin\alpha\,B_1(z) + \frac{\omega_p^2(z)}{c\,\Delta\omega_0}\frac{d}{dz}\Phi_1(z)\right\}. \end{aligned} \tag{21}$$

Solving Eq. (20) in plasma slab and vacuum and taking into account the continuity boundary conditions of the tangential components of the low-frequency electromagnetic field at the plasma-vacuum interface, after simple calculations, we obtain the following distribution of the magnetic field in the whole space:

$$\mathbf{B}(\mathbf{r},t) = \tfrac{1}{2}\mathbf{e}_y B_1(z)\exp(-i\Delta\omega_0 t + 2\,ik_0x\sin\alpha) + \text{c.c.}, \tag{22}$$

where

$$\begin{aligned} B_1(z) &= \frac{2\omega_0}{\Delta\omega_0}k_p^2\sin\alpha\exp[\kappa_0(z+d)]\\ &\quad\times\left\{\frac{\Phi_-}{T_a(\Delta\omega_0)} + \frac{\Phi_+}{T_s(\Delta\omega_0)}\right\},\quad z\leqslant -d, \end{aligned} \tag{23}$$

$$\begin{aligned} B_1(z) &= \frac{2\omega_0}{\Delta\omega_0}k_p^2\sin\alpha\left\{\frac{\Phi_-}{T_a(\Delta\omega_0)}\frac{\cosh(\kappa z)}{\cosh(\kappa d)}\right.\\ &\quad\left.-\frac{\Phi_+}{T_s(\Delta\omega_0)}\frac{\sinh(\kappa z)}{\sinh(\kappa d)}\right\},\quad -d\leqslant z\leqslant d, \end{aligned} \tag{24}$$

$$\begin{aligned} B_1(z) &= \frac{2\omega_0}{\Delta\omega_0}k_p^2\sin\alpha\exp[-\kappa_0(z-d)]\\ &\quad\times\left\{\frac{\Phi_-}{T_a(\Delta\omega_0)} - \frac{\Phi_+}{T_s(\Delta\omega_0)}\right\},\quad z\geqslant d, \end{aligned} \tag{25}$$

where the dispersion functions of the symmetric $T_s(\Delta\omega_0)$ and antisymmetric modes $T_a(\Delta\omega_0)$ have the form [30]

$$\begin{aligned} T_s(\Delta\omega_0) &= \kappa\coth(\kappa d) + \kappa_0\varepsilon(\Delta\omega_0),\\ T_a(\Delta\omega_0) &= \kappa\tanh(\kappa d) + \kappa_0\varepsilon(\Delta\omega_0), \end{aligned} \tag{26}$$

where $\kappa_0 = \sqrt{4\omega_0^2\sin^2\alpha - \Delta\omega_0^2}/c$, $\kappa = \sqrt{4\omega_0^2\sin^2\alpha - \Delta\omega_0^2\varepsilon(\Delta\omega_0)}/c$, $\Phi_\pm = [\Phi_1(-d) \pm \Phi_1(d)]/2$, $k_p = \omega_p/c$, $\varepsilon(\Delta\omega_0) = 1 - (\omega_p^2/\Delta\omega_0^2)(1 - i\nu_{ei}/\Delta\omega_0)$. Note that the name of the mode (symmetric or antisymmetric) is associated with the form of the spatial distribution of the electric field component $E_{1,x}(z)$ in the plasma slab, which is directed along the boundary (see [30]). For the symmetric mode, this component of the electric field is proportional to the hyperbolic cosine $E_{1,x}(z) \propto \cosh(\kappa z)$, and for the antisymmetric mode, to the hyperbolic sine $E_{1,x}(z) \propto \sinh(\kappa z)$.

It follows from the Eqs. (23)–(26) that the low-frequency magnetic field is determined by the values of the ponderomotive potential $\Phi_1(-d)$, $\Phi_1(d)$ only at the boundaries of the plasma slab. In the general case, when the dispersion functions $T_s(\Delta\omega_0)$ and $T_a(\Delta\omega_0)$ vanish the symmetric and antisymmetric modes of the plasma slab are excited. However, in our case of the incidence of laser radiation at the angle of total reflection (11) when the amplitude of the ponderomotive potential has the form (13), only the symmetric mode of the plasma layer is excited. This is due to the equality to zero $\Phi_- = 0$, since the ponderomotive potential does not depend on the spatial z coordinate [see Eq. (13)] and its values coincide at the boundaries of plasma slab. It follows from Eqs. (23)–(26) that the significant amplification of the low-frequency field in vacuum and in the plasma slab occurs under resonance conditions, when the frequency difference of the laser fields coincides with the eigenfrequency of the symmetric surface mode,

$$\Delta\omega_0 = \Omega_s, \tag{27}$$

when the real part of the dispersion function $T_s(\Delta\omega_0)$ vanishes. In the plasma with the near-critical electron concentration $\omega_0 \approx \omega_p$ at small angles of incidence of laser radiation $\sin^2\alpha \ll 1$, the surface mode frequency Ω_s is determined by the formula

$$\Omega_s = 2\omega_0 \sin\alpha(1 - 2\sin^2\alpha\coth^2 k_0 d), \tag{28}$$

which is obtained under the condition $\sin^2\alpha \ll \tanh^2 k_0 d$. This condition imposes the condition on the minimum thickness of the plasma slab. Under resonance conditions (27), (28), there is the significant increase in the electromagnetic fields of the symmetric eigenmode of the plasma slab, since the denominator of the Eqs. (23)–(25) contains only a small imaginary part of the dispersion function, which is proportional to the frequency of electron collisions. In this case, the low-frequency magnetic field (23)–(25) has the form

$$\mathbf{B}_s(\mathbf{r},t) = \mathbf{e}_y \frac{4\omega_0^2}{c\nu_{ei}} \sin\alpha \frac{2\sinh^2(k_0 d)}{2k_0 d + \sinh(2k_0 d)} \times \Phi_1 H_s(z) \sin(\Omega_s t - 2k_0 x \sin\alpha), \tag{29}$$

where its spatial distribution is determined by the function

$$H_s(z) = \begin{cases} -\exp[4k_0(z+d)\sin^2\alpha \coth k_0 d], & z \leqslant -d, \\ \sinh(k_0 z)/\sinh(k_0 d), & -d \leqslant z \leqslant d, \\ \exp[-4k_0(z-d)\sin^2\alpha \coth k_0 d], & z \geqslant d, \end{cases} \tag{30}$$

and the amplitude of the ponderomotive potential Φ_1 at the incidence of laser radiation at the angle of total reflection (11) is determined by formula (13). The expressions for the magnetic field (29), (30) together with the formulas for the components of the electric field (21) make it possible to analyze the energy characteristics of the THz mode of the plasma slab.

To describe the excitation of THz fields in the plasma slab under the ponderomotive action of two-frequency laser radiation, we used the equation for the electron velocity from (18) in the linear approximation without taking relativistic effects into account. This approximation is applicable if the following condition is satisfied:

$$\frac{V_E^2}{4c^2} \ll \left(\frac{\nu_{ei}}{\omega_0}\right)^{3/2} \frac{k_0 d + \sqrt{1 + k_0^2 d^2}}{\left(1 + k_0^2 d^2\right)^{1/4}} \frac{2k_0 d + \sinh(2k_0 d)}{\sinh(2k_0 d)}, \tag{31}$$

which is obtained taking into account formulas (21), (27)–(30). This condition imposes the limitation on the intensity of laser radiation, which cannot exceed the value indicated on the right-hand side of the inequality.

IV. PHYSICAL CHARACTERISTICS OF LOW-FREQUENCY MODES OF THE PLASMA LAYER

Equations (27), (28), (13), (21) allow us to find the energy flux density of THz radiation by the formula

$$\mathbf{S}(\mathbf{r},t) = \frac{c}{4\pi}[\mathbf{E}(\mathbf{r},t) \times \mathbf{B}(\mathbf{r},t)]. \tag{32}$$

After simple calculations for the Poynting vector (32) of the symmetric mode of the plasma layer under resonance conditions (27), we have the following expression:

$$\mathbf{S}_s(z) = \mathbf{e}_x \frac{4\omega_0^2}{\nu_{ei}^2} \frac{V_E^2}{c^2} I_L \left[\frac{2\sinh^2(k_0 d)}{2k_0 d + \sinh(2k_0 d)}\right]^2 \times G^2(\alpha) H_s^2(z) \frac{\mathrm{Re}\,\varepsilon(\Omega_s, z)}{|\varepsilon(\Omega_s, z)|^2}, \tag{33}$$

where $I_L = cE_{0L}/(8\pi)$ is the intensity of laser radiation, and the dependence of the energy flux density on the incidence angle of the laser radiation is determined by the function

$$G(\alpha) = \frac{\sin^3\alpha\cos^2\alpha}{[\sin^2\alpha\cos\alpha + k_0 d\varepsilon''(\omega_0)]^2 + \varepsilon''^2(\omega_0)\cos^2\alpha}. \tag{34}$$

Since the real part of dielectric constant in the plasma is negative, it follows from formulas (29), (33) that the energy of the low-frequency mode in vacuum is carried in the direction of the wave vector, and in a plasma slab, the energy is carried in the opposite direction. In this case, the energy flux density

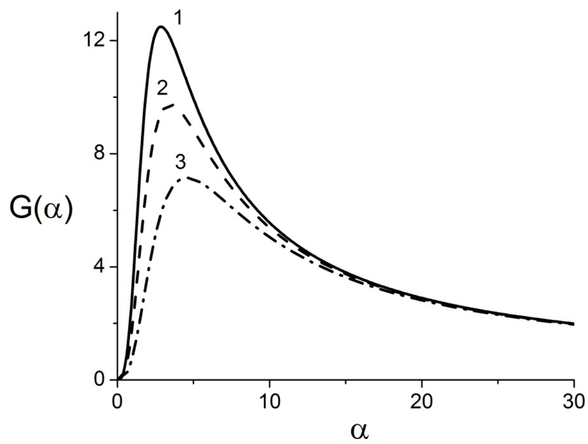

FIG. 2. Angular dependence of the energy flux density of the surface mode (34) for $\varepsilon''(\omega_0) = 10^{-3}$. Curves 1–3 correspond to the values of the plasma slab thickness $k_0d = 0.5;\ 1;\ 2$.

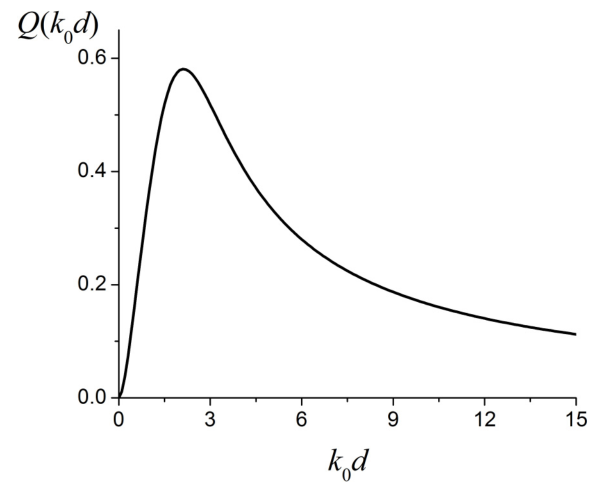

FIG. 3. The dependence of the energy flux density of the THz mode (39) on the thickness of the plasma slab.

in vacuum significantly exceeds the analogous value in the plasma slab due to the inequality $|\varepsilon(\Omega_s)| \gg 1$ which occurs at small angles of incidence of two-frequency laser radiation $\sin^2\alpha \ll 1$. Therefore, we will consider the Poynting vector of the symmetric eigenmode in vacuum near the boundary of the plasma slab at $z \to \pm d$,

$$\mathbf{S}_s(z \to \pm d) = \mathbf{e}_x S_0 = \mathbf{e}_x \frac{4\omega_0^2}{\nu_{ei}^2}\frac{V_E^2}{c^2} I_L \left[\frac{2\sinh^2(k_0d)}{2k_0d + \sinh(2k_0d)}\right]^2 G^2(\alpha). \tag{35}$$

Let us investigate the dependence of the energy flux density of the low-frequency mode on the incidence angle of laser radiation (35), which is determined by function (34). From formula (34) it follows that the maximum value of function $G(\alpha)$ is equal to

$$G_{\max} = \frac{1}{4\sqrt{\varepsilon''(\omega_0)}} \frac{\left[k_0d + \sqrt{4k_0^2d^2 + 3}\right]^{3/2}}{1 + 2k_0^2d^2 + k_0d\sqrt{4k_0^2d^2 + 3}}, \tag{36}$$

when laser radiation is incident on the boundary of the plasma slab with the near-critical electron density at small angles,

$$\sin^2\alpha = \varepsilon'(\omega_0) = \left[k_0d + \sqrt{4k_0^2d^2 + 3}\right]\varepsilon''(\omega_0), \tag{37}$$

as follows from inequality (14). The dependence of function (34) on the angle of incidence of laser radiation for various values the plasma slab thickness is shown in Fig. 2. From Fig. 2 and formulas (36), (37) it follows that the optimal angle of incidence increases, and the maximum of function (34) decreases with increasing slab thickness. Taking into account the results (36), (37), we find the maximum value of the energy flux density as the function of the plasma slab thickness,

$$S_{0,\max} = \frac{\omega_0^3}{\nu_{ei}^3}\frac{V_E^2}{4c^2} I_L Q(k_0d), \tag{38}$$

where

$$Q(k_0d) = \left[\frac{2\sinh^2(k_0d)}{2k_0d + \sinh(2k_0d)}\right]^2 \times \frac{\left[k_0d + \sqrt{4k_0^2d^2 + 3}\right]^3}{\left[1 + 2k_0^2d^2 + k_0d\sqrt{4k_0^2d^2 + 3}\right]^2}. \tag{39}$$

The function $Q(k_0d)$ is shown in Fig. 3, from which it follows that maximum value of the function (39) is $Q_{\max} \approx 0.581$ for the thickness of the plasma slab $k_0d \approx 2.12$. In accordance with this result, the maximum value of the energy flux density of the THz symmetric eigenmode is

$$S_{0,\max}^{(m)} \approx 0.145\frac{\omega_0^3}{\nu_{ei}^3}\frac{V_E^2}{c^2} I_L, \tag{40}$$

and the optimal angle of incidence of laser radiation (37) is determined by the formula

$$\sin^2\alpha = \varepsilon'(\omega_0) \approx 6.7\,\varepsilon''(\omega_0). \tag{41}$$

When the thickness of the plasma slab increases, the energy flux density of the THz mode, as follows from Fig. 3, decreases and, at large values of the parameter $k_0d \gg 1$, in accordance with formulas (38), (39), takes the form

$$S_{0,\max} = \frac{27}{64}\frac{\omega_0^3}{\nu_{ei}^3}\frac{V_E^2}{4c^2}\frac{I_L}{k_0d}. \tag{42}$$

It follows from formula (42) that the energy flux density of the THz mode at $k_0d \gg 1$ is inversely proportional to the thickness of the plasma slab $S_{0,\max} \propto 1/(k_0d)$.

Comparing the obtained result (40) with the energy flux density of the THz mode of the plasma slab at the incidence of s-polarized laser radiation [see formula (26) in [28]], we conclude that for p-polarization the THz energy flux density is $\omega_0/\nu_{ei} \gg 1$ times higher. It follows from formula (40) that, under the condition

$$\frac{V_E^2}{c^2} > 7\frac{\nu_{ei}^3}{\omega_0^3}, \qquad (43)$$

the energy flux density of the THz mode of the plasma slab can exceed the intensity of laser radiation. For example, at the frequency of collisions $\nu_{ei} = 10^{-3}\omega_0$ and the wavelength of laser radiation $\lambda_0 = 1\ \mu$m, inequality (43) is satisfied at the sufficiently low intensity $I_L > 10^{10}$ W/cm^2. It follows from formula (40) that even at moderate intensities of laser radiation $I_L = (10^{14}$–$10^{15})$ W/cm^2, the energy flux density of the THz mode can exceed the laser radiation intensity by several orders of magnitude. Such a significant value of the energy flux density of the THz mode of the plasma slab is associated with two effects. The first of them is the resonant excitation of the eigenmode of the plasma slab, when the difference in the frequencies of the laser fields coincides with the eigenfrequency of the symmetric mode of the slab. As the result of this resonance, the low-frequency electromagnetic field increases by ω_0/ν_{ei} times, and the energy flux density increases by a factor of $(\omega_0/\nu_{ei})^2$, respectively. The second effect is the significant increase in the field of p-polarized laser radiation in plasma at its almost normal incidence at the angle of total reflection on the plasma slab with the near-critical electron concentration. Due to the amplification of the p-polarized laser field in the plasma when it is incident at the angle of total reflection, the flux density of the THz mode of the plasma slab increases by the factor of ω_0/ν_{ei}, and this, as a result, leads to the appearance of the factor $(\omega_0/\nu_{ei})^3$ in formula (40) and to the giant increase in the energy flux density of the THz mode.

V. CONCLUSION

In this article, we considered the excitation of the high-intensity THz surface mode under the action of two waves of p-polarized laser radiation with different frequencies on the plasma slab with the subcritical electron density, when along its boundary the laser fields propagate towards each other. The boundary value problem for the two-frequency p-polarized laser radiation is solved, and the spatial distribution of the laser field in the plasma layer is found. It is shown that when laser radiation is incident at the angle of total reflection, the significant amplification of the p-polarized laser field occurs in the plasma slab with a near-critical electron concentration. The ponderomotive potential at the difference frequency is calculated and it is shown that the strongest ponderomotive effect on electrons occurs when laser radiation falls on the near-critical plasma slab at the angle of total reflection, the value of which is determined by the small imaginary part of the dielectric constant. The problem of the excitation of THz fields in plasma under the action of ponderomotive forces of laser radiation at the difference frequency is considered, and it is shown that their space-time distribution in the plasma slab is determined by the values of the ponderomotive potential at the slab boundaries. It was found that when the laser radiation is incident at the angle of total reflection, only the symmetric mode of the plasma slab is excited. It is shown that if the frequency difference of the laser fields coincides with the eigenfrequency of the symmetric mode of the plasma slab, its resonant excitation occurs and, as the result, the significant increase in the electromagnetic fields of the THz mode take place. The Poynting vector of the THz mode of the plasma slab is calculated and the dependence of its absolute value on the incidence angle of laser radiation and the slab thickness is investigated. It is shown that the THz energy flux density is maximum when two-frequency p-polarized laser radiation is incident on the near-critical plasma slab at the angle of total reflection and when the resonance condition is satisfied and the eigenfrequency of the THz mode coincides with the laser frequency difference. It is shown that the energy flux density of the THz mode of the plasma slab under the conditions of its resonant excitation can significantly exceed the intensity of laser radiation.

In this article, to describe the generation of high-intensity THz modes in a plasma slab under laser action, we used the plane wave approximation for the two-frequency p-polarized laser field. This approximation makes it possible to clearly and simply describe the effect of amplification of THz fields under resonance conditions, when the frequency difference of the laser fields coincides with the frequency of the symmetric eigenmode of the plasma slab. However, under the conditions of real experiments, laser pulses with limited values of time duration τ, longitudinal $L = c\tau$ and transverse size R are used. Therefore, if the following inequalities for the longitudinal and transverse dimensions of the laser pulse and also for its duration,

$$L, R \gg 2d,\ 1/(k_0\sin^2\alpha);\ \tau \gg 1/\Delta\omega_0,\ 1/\nu_{ei}\ , \qquad (44)$$

are satisfied, then the plane wave approximation can be used. With regard to the consideration of the excitation of THz fields in the linear approximation, it is satisfied if inequality (31) is fulfilled, which is a stronger condition than (17).

In conclusion, we present estimates for the characteristics of the THz mode of the plasma slab under the conditions of modern laser-plasma experiments. Let two-frequency p-polarized laser radiation with intensity $I_L = 3\times10^{14}$ W/cm^2 and wavelengths 1300 and 1450 nm (see [31]) fall at the angle $\alpha \approx 3^\circ$ onto the plasma slab with thickness $2d = 30\ \mu$m ($2k_0d \approx 140$), the temperature $T_e = 500$ eV, and near-critical concentration $N_{0e} \approx 6.1\times10^{20}$ cm^{-3} of electrons. In accordance with formulas (27), (34), the THz mode is excited at the frequency $\Omega_s/2\pi \approx 24$ THz (wavelength $\lambda_s \approx 12.5\ \mu$m) with the energy flux density $S_0 \approx 8I_L = 2.4\times10^{15}$ W/cm^2 because the frequency of electron-ion collisions is equal to $\nu_{ei} \approx 8\times10^{-4}\omega_0 \approx 1.1\times10^{12}$ s^{-1} (the Debye radius in this case is $r_D \approx 7$ nm). The energy flux density of the THz mode in this example is almost an order of magnitude higher than the laser radiation intensity, and this is due to the resonant excitation of the surface eigenmode of the plasma slab and the significant increase in the laser field in the plasma slab. Note that for the value of the energy flux density $S_0 \approx 2.4\times10^{15}$ W/cm^2 obtained in this example, the velocity of the oscillatory motion of electrons in the THz field is determined by the relation $V^2/c^2 \approx 0.73\times10^{-18}S_0[\mathrm{W/cm^2}]\{\lambda[\mu\mathrm{m}]\}^2 \approx 0.26$, which allows using the linear approximation in Eqs. (18) due to the smallness of the relativistic effects. Experimentally, such the THz mode excitation scheme can be realized under the action of two-frequency p-polarized laser radiation on airgel targets, which have the low density of matter (0.001–0.15) g/cm^3 (see [32,33]). Airgel is a porous material that consists of the structural elements of solid-state density randomly distributed in matter (these can be thin membranes or wires) with the characteristic scale of the order of several tens of nanometers and micron-sized vacuum regions [33]. Under action of laser radiation with the intensity about 10^{14} W/cm^2, the ionization and heating of solid-state elements takes place and this leads to their expansion and filling of the pores. This process is called "homogenization" [33], as the result of which the almost homogeneous plasma with the near-critical electron density is formed within a few hundred picoseconds after the laser impact. Such a plasma slab with sharp boundaries and electron density close to the critical value, previously created using ionizing laser radiation, can later be used to excite THz surface modes under the action of a two-frequency laser field. Resonant excitation of the eigenmode of the plasma slab can be carried out using the laser system of the experiment [31], which makes it possible to generate radiation in the wavelength interval (1200–1450) nm with the increment of 50 nm. By changing the angle of incidence of the laser beams, the condition of resonant excitation of the eigenmode of the plasma slab in the THz frequency range can be satisfied. The methods of Otto [34] and Kretschmann [35] can be used to transform surface mode into bulk THz radiation. As a result, THz radiation with the intensity exceeding the intensity of the incident laser radiation can be obtained.

As shown above, the energy flux density of the THz mode can significantly exceed the intensity of laser radiation; however, due to condition (44), the total energy of the THz wave will be less than the total energy of the laser pulse. If we assume that the transverse size of the laser radiation incident on the target is $2R = 2$ mm, as in experiment [32], then for the above-mentioned plasma slab thickness $2d = 30\ \mu$m, the ratio of THz energy to laser energy is $\eta \approx (S_0/I_L)(2d/R) \approx 0.2$.

We note once again that the significant increase in the energy flux density of the THz mode of the plasma slab occurs under conditions of its resonant excitation by two-frequency laser radiation, when the frequency difference of the laser fields coincides with the eigenfrequency of the symmetric mode of the slab. It is well known that under resonance conditions, even the impact of a small driving force in a weakly dissipative medium leads to excitation of eigenoscillations with large amplitude. In this case, the contribution to the energy of eigenmodes can be made by both the work of the driving force and the internal energy of the medium. When the symmetric eigenmode of the plasma slab is excited by two-frequency laser radiation under resonance conditions, the increase in the energy of the THz mode can be associated with the energy transfer from both laser radiation and plasma particles.

The article considers the steady-state solution, which is established during the time interval, which exceeds the time between electron collisions $\Delta t \geqslant 1/\nu_{ei}$. The minimum laser pulse duration follows from inequality (44), $\tau \approx 1/\nu_{ei}$, and for the considered example is approximately equal to 0.9 ps. Note that the authors in Ref. [31] did not indicate the duration of the incident laser radiation. However, in their previous experiment [36], they used laser radiation with the duration of 9 ps to generate THz pulses. For such duration of 9 ps and the transverse size of 2 mm, the plane wave approximation for incident laser radiation, considered in this article, is quite justified.

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