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Terahertz generation by the high intense laser beam

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Abstract. The terahertz (THz) frequency radiation produced as a result of nonlinear interaction of high intense laser beam with low-density ripple in collisionless magnetoplasma has been studied under the paraxial ray approximation. The relativistic change of electron mass leads to self-focusing of laser beam when the initial power of laser beam is greater than its critical power. The self-focused laser beam couples with the pre-existing density ripple to produce a nonlinear current driving the THz radiation at different frequency. The applied magnetic field enhances the nonlinear coupling efficiency. Appropriate expressions for the beam width parameter of the laser beam and the electric vector of the THz wave have been evaluated. Theory and numerical simulations show that this THz source is capable of providing power of Giga watt level.

1. Introduction

Recently, the production of monochromatic and sufficiently powerful electromagnetic radiation covering all necessary spectrums is considered as one of the important challenges [1–4]. At present the terahertz (THz) physics is the area of special research interest and has very wide applications such as medical imaging [5, 6], security identification [7, 8], and time domain spectroscopy [9–11]. The key issue with plasma is to find appropriate ways of producing THz emission with high conversion efficiencies. The earlier attempts to generate THz radiation depended upon accelerating electron beams via synchrotron accelerators [12], or the impacting of short laser pulses with solid targets (semiconductors or nonlinear crystals) [13, 14]. The energy produced by these conventional techniques did not exceed a few μJ per pulse. Leemans et. al. [15] used ultra short pulse laser to generate accelerated electron beams, thereby achieving THz radiation in the range of 10–100 μJ per pulse by using plasma as a medium. The first direct observation of a laser-induced wakefield has been reported by Hamster et al. [16]. Laser pulses with a power of 10^{12} W were focused on both gas and solids targets. The radiative processes at THz frequencies, which were observed from the resulting plasmas, are driven by ponderomotively induced space charge fields. Antonson et al. [17] suggested a scheme of corrugated plasma channels, which can be achieved using a primary laser pulse (500 mJ, 100 ps) to create an ionized region and then using a second pulse (100 mJ, 50 ps) after 2 ns to drive nonlinear currents, which generate THz radiation.

Sharma et al. [18] have studied the generation of THz radiation by the interaction of high-power laser beam with density ripple of plasma wave. But the lasers are being used at ultrarelativistic power for the generation of THz sources. At such high power flux, the theory of THz generation, as proposed by Sharma et al. [18], is not applicable because at such high power laser flux the relativistic nonlinearity is more important than ponderomotive nonlinearity.

In this paper we study the relativistic effects of electron mass increasing to generate THz radiation when a high intense laser beam is propagating in magnetized plasma with a propagation vector parallel to static magnetic field. By difference in pump wave frequency (ω_0) and density ripple frequency (ω_1), we get frequency (ω_2) in the range of THz frequency. Thus, the THz radiation is resonantly excited if the matching conditions are satisfied. Since the THz radiation production is related to power flux of laser beam, we study the effect of relativistic self-focusing of laser beam propagation when the paraxial ray approximation is considered (Sec. 2). In Sec. 3 we introduce a theory and numerical simulation to calculate the normalized THz radiation amplitude by the beating of pump wave and density ripple when relativistic nonlinearity is considered. In Sec. 4 typical parameters of laser beam and ambient plasma are introduced and the results are discussed. Finally, the conclusion of the present paper is summarized in Sec. 5.

2. Relativistic self-focusing of the laser beam

Consider a uniform magnetoplasma of equilibrium electron density n_0 submerged in static magnetic field $\vec{B}_0$ aligned along z-direction. The electric field vector $\vec{E}_{0+}$ of right circular polarized electromagnetic wave propagating along z-direction via magnetoplasma can be written

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as follows [19]:

$$\vec{E}_{0+} = \vec{A}_{0+} \exp i(\omega_0 t - k_{0+} z), \tag{1}$$

where, $\vec{A}_{0+} = \vec{E}_x + i\vec{E}_y$ is the electric field amplitude, ω_0 and k_{0+} are the angular frequency and wave vector, respectively, k_{0+} is related to dielectric constant as $k_{0+}^2 = \frac{\varepsilon_{0+}\omega_0^2}{c^2}$, and c is the velocity of light in vacuum. The electron relativistic motion equation in the presence of high intense laser is

$$m_0\gamma \frac{\partial}{\partial t}\vec{v}_j = -e\vec{E}_j - \frac{e}{c}\left(\vec{v}_j \times \vec{B}_0\right), \tag{2}$$

where γ, $\vec{v}$, and $\vec{B}_0$ are the relativistic factor, the oscillation velocity imparted by laser beam, and the external magnetic field, respectively .

When the pulse width τ_L is very short, viz. $\tau_L \ll (\omega_{pe})^{-1}$, only relativistic nonlinearity will be established. Using (2), we calculate electron-oscillating velocity (v_{0+}) for right circular polarized mode of laser beam as

$$\vec{v}_{0+} = \vec{v}_x + i\vec{v}_y = \frac{ie\vec{E}_{0+}}{m_0\gamma\omega_0\left(1 - \dfrac{\omega_{ce}}{\gamma\omega_0}\right)}, \tag{3}$$

where e, m_0, and $\omega_{ce} = \frac{eB_0}{m_0 c}$ are the electronic charge, rest mass of electron, and the electron–cyclotron frequency, respectively, and $\gamma = (1 - \frac{v_{0+}^2}{c^2})^{-\frac{1}{2}}$.

Proposing $(\gamma - 1 < 1)$ [20], the relativistic factor γ will be

$$\gamma \cong 1 + \frac{1}{2}\cdot\left(\frac{e}{m_0 c\omega_0}\right)^2 \cdot \frac{A_{0+}\cdot A_{0+}^*}{\left(1 - \dfrac{\omega_{ce}}{\omega_0}\right)^2} = 1 + \alpha_+ A_{0+}\cdot A_{0+}^*. \tag{4}$$

The relativistic nonlinearity factor, $\alpha_+ = \frac{e^2}{2m_0^2c^2\omega_0^2}\cdot\frac{1}{(1-\frac{\omega_{ce}}{\omega_0})^2}$, will become zero at nonrelativistic regime (i.e. $\gamma = 1$).

The general wave equation of electromagnetic wave propagating through magnetized plasma can be given as

$$\nabla^2\vec{E} - \nabla(\vec{\nabla}\cdot\vec{E}) + \frac{\omega_0^2}{c^2}\underline{\underline{\varepsilon}}\cdot\vec{E} = 0. \tag{5}$$

In relativistic regime, the components of the dielectric constant tensor $\underline{\underline{\varepsilon}}$ will be as follows:

$$\varepsilon_{xx} = \varepsilon_{yy} = 1 - \frac{\omega_{pe}^2}{\omega_0^2\gamma\left(1 - \dfrac{\omega_{ce}^2}{\omega_0^2\gamma^2}\right)},$$

$$\varepsilon_{xy} = -\varepsilon_{yx} = \frac{-i\left(\dfrac{\omega_{pe}^2}{\omega_0^2\gamma}\right)\left(\dfrac{\omega_{ce}}{\omega_0\gamma}\right)}{\left(1 - \dfrac{\omega_{ce}^2}{\omega_0^2\gamma^2}\right)},$$

$$\varepsilon_{xz} = \varepsilon_{yz} = \varepsilon_{zx} = \varepsilon_{zy} = 0,$$

$$\varepsilon_{zz} = 1 - \frac{\omega_{pe}^2}{\omega_0^2\gamma},$$

where the effective dielectric constant corresponding to right circular polarized electromagnetic wave (pump) ε_+ will take the following formula:

$$\varepsilon_+ = \varepsilon_{xx} - i\varepsilon_{xy} = 1 - \frac{\dfrac{\omega_{pe}^2}{\omega_0^2\gamma}}{\left(1 - \dfrac{\omega_{ce}}{\omega_0\gamma}\right)},$$

where $\omega_{pe} = (\frac{4\pi n_0 e^2}{m_0})^{\frac{1}{2}}$ is the electron plasma frequency.

Using (4) the effective dielectric constant ε_+ can be written as follows:

$$\varepsilon_+ = 1 - \frac{\left(\dfrac{\omega_{pe}}{\omega_0}\right)^2}{\left(1 - \dfrac{\omega_{ce}}{\omega_0}\right)} + \frac{\left(\dfrac{\omega_{pe}}{\omega_0}\right)^2}{\left(1 - \dfrac{\omega_{ce}}{\omega_0}\right)^2}\alpha_+ A_{0+}A_{0+}^*. \tag{6}$$

It is obvious that the effective dielectric constant ε_+ consists of a linear part ε_{0+} and a nonlinear part $\phi_+(A_{0+}A_{0+}^*)$, where the latter is appearing as a result of relativistic electron mass increase. Both parts of the effective dielectric constant ε_+ may written as follows:

$$\varepsilon_{0+} = 1 - \frac{\left(\dfrac{\omega_{pe}}{\omega_0}\right)^2}{\left(1 - \dfrac{\omega_{ce}}{\omega_0}\right)}, \tag{7}$$

$$\phi_+ = \varepsilon_{2+}A_{0+}A_{0+}^*, \tag{8}$$

where

$$\varepsilon_{2+} = \frac{1}{2}\left(\frac{e}{m_0 c\omega_0}\right)^2 \frac{\left(\dfrac{\omega_{pe}}{\omega_0}\right)^2}{\left(1 - \dfrac{\omega_{ce}}{\omega_0}\right)^4}. \tag{9}$$

One can consider that the electromagnetic wave inside magnetoplasma is a transverse wave, since its field varies along external magnetic field (i.e. z-direction) larger than its variation via wave front plane (i.e. x–y plane) [21], so no space charge occurs, and thus

$$\vec{\nabla}\cdot\vec{D} = \vec{\nabla}\cdot(\underline{\underline{\varepsilon}}\vec{E}) = 0. \tag{10}$$

Using (10) with components of dielectric tensor, one obtains

$$\frac{\partial E_z}{\partial z} \cong -\frac{1}{\varepsilon_{zz}}\left[\varepsilon_{xx}\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y}\right) + \varepsilon_{xy}\left(\frac{\partial E_y}{\partial x} - \frac{\partial E_x}{\partial y}\right)\right]. \tag{11}$$

Putting (11) in (5) and using zero-order approximation, we can obtain differential equation for circular polarized electric field amplitude A_{0+} as

$$\frac{\partial^2 A_{0+}}{\partial z^2} + \frac{1}{2}\left(1 + \frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)A_{0+}$$

$$+\frac{\omega_0^2}{c^2}\left(\varepsilon_{0+} + \varepsilon_{2+}A_{0+}A_{0+}^*\right)A_{0+} = 0, \tag{12}$$

where the product of nonlinear part with $\frac{\partial^2 A_{0+}}{\partial x^2}$ or $\frac{\partial^2 A_{0+}}{\partial y^2}$ has been neglected [22]. We assume $A_{0+} = A'_{0+}$

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$\exp i(\omega_0 t - k_{0+} z)$ and substituting its value in (12), one gets

$$-2ik_{0+}\frac{\partial A'_{0+}}{\partial z} + \frac{1}{2}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)A'_{0+}$$

$$+\frac{\omega_0^2}{c^2}(\varepsilon_{2+}A'_{0+}A'^{*}_{0+})A'_{0+} = 0, \tag{13}$$

where A'_{0+} is the complex amplitude.

Proposing a two-dimensional Gaussian beam (i.e. $\frac{\partial}{\partial y} = 0$), and introducing an eikonal $A'_{0+} = A^0_{0+}\exp(ik_{0+}S_+)$, where A^0_{0+} and S_+ are real function and phase of laser beam inside magnetoplasma, respectively, (13) after separating real and imaginary parts can be written as follows [21]:

$$2\frac{\partial S_+}{\partial z} + \frac{1}{2}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)\left(\frac{\partial S_+}{\partial x}\right)^2 - \frac{1}{2k_{0+}^2 A^0_{0+}}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)$$

$$\times\frac{\partial^2 A^0_{0+}}{\partial x^2} = \frac{\varepsilon_{2+}}{\varepsilon_{0+}}\left(A^0_{0+}\right)^2, \tag{14}$$

$$\frac{\partial\left(A^0_{0+}\right)^2}{\partial z} + \frac{1}{2}\left(A^0_{0+}\right)^2\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)\frac{\partial^2 S_+}{\partial x^2}$$

$$+\frac{1}{2}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)\frac{\partial S_+}{\partial x}\frac{\partial\left(A^0_{0+}\right)^2}{\partial x} = 0. \tag{15}$$

In the paraxial ray approximation, S_+ can be expanded to $S_+ = \frac{1}{2}x^2\beta_+(z)+\varphi_+(z)$, where β_+^{-1} may be explained as the curvature radius of laser beam and φ_+ is a constant independent of x.

Introducing initially Gaussian beam with initial beam radius x_0 as

$$\left(A^0_{0+}\right)^2 = \frac{E_{00}^2}{f_+}\exp\left(-\frac{x^2}{x_0^2 f_+^2}\right), \tag{16}$$

and substituting S_+ in (15), $\beta(z)$ will take the following form [23]:

$$\beta_+(z) = 2\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)^{-1}\frac{1}{f_+}\frac{df_+}{dz},$$

where f_+ represents the beam width parameter.

Using A^0_{0+} and $\beta_+(z)$ values in (15) and assuming initially plane wave front condition as ($f_+ = 1$ and $\frac{df_+}{dz} = 0$ at $z = 0$), we obtain

$$\frac{d^2 f_+}{dz^2} = \frac{1}{4}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)^2\frac{1}{k_{0+}^2 x_0^4 f_+^3} - \frac{1}{2}\left(1+\frac{\varepsilon_{0+}}{\varepsilon_{0zz}}\right)$$

$$\times\left(\frac{\varepsilon_{2+}E_{00}^2}{\varepsilon_{0+}}\right)\frac{1}{x_0^2 f_+^2}. \tag{17}$$

Since (17) represents the spot size variation of laser beam profile as a result of competition between diffraction and self-focusing terms (first and second terms on the right-hand side of (17), it has been solved numerically for external magnetic fields.

3. Terahertz (THz) generation mechanism

The generation mechanism of THz radiation $(\vec{E}_{t+}, \omega_t, \vec{k}_{t+})$ depends upon nonlinear coupling between high intense laser beam $(\vec{E}_{0+}, \omega_0, \vec{k}_{0+})$ and rippled density plasma $(\vec{E}_1, \omega_1, \vec{k}_1)$. The phase-matching conditions are $\omega_0 = \omega_1 + \omega_t$ and $\vec{k}_{0+} = \vec{k}_1 + \vec{k}_{t+}$, where $\vec{E}_1$, $\vec{k}_1$ and $\vec{E}_{t+}$, $\vec{k}_{t+}$ are the electric fields and wave vectors of plasma wave and THz wave, respectively. The electric fields of these waves can be written as

$$\vec{E}_1 = \hat{z}E_1\exp i(\omega_1 t - k_1 z), \tag{18}$$

$$\vec{E}_{t+} = \vec{A}_{t+}\exp i(\omega_t t - k_{t+} z), \tag{19}$$

where $\vec{A}_{t+} = \vec{E}_{tx} + i\vec{E}_{ty}$ is amplitude of the right circular polarized THz field.

The relativistic oscillating velocity, $\vec{v}_1 = -\frac{ie\vec{E}_1}{m_e\gamma\omega_1}$, obtained by plasma wave field in z-direction is related to density ripple plasma as $v_1 = \frac{\omega_1}{k_1}\mu$, where $\mu = \frac{\tilde{n}_p}{n_0}$ is the normalized ripple density amplitude representing ratio between perturbed density $\tilde{n}_p$ and background plasma density n_0, and $n_p = n_0 + \tilde{n}_p\exp i(\omega_1 t - k_1 z)$.

The nonlinear interaction between electromagnetic field and plasma wave field can be governed by the following equations:

The continuity equation, $\frac{\partial n_j}{\partial t} = -\vec{\nabla}\cdot(n_j\vec{v}_j)$,

and the momentum equation, $m_j\gamma\frac{\partial\vec{v}_j}{\partial t} + m_j(\vec{v}_j\cdot\nabla)\vec{v}_j = -e\vec{E} - \frac{e}{c}(\vec{v}_j\times(\vec{B}+\vec{B}_0))$,

where n_j, m_j, and v_j are the particle density, the mass, and the velocity of species $j = i, e$, respectively; $\vec{E}$ and $\vec{B}$ are the self-consistent electric fields associated with the wave.

In the ambient of magnetoplasma, the wave equation for electric vector $\vec{E}_{t+}$ with magnetoplasma can be written as [24],

$$\nabla^2\vec{E}_{t+}^2 - \frac{1}{c^2}\frac{\partial^2\vec{E}_{t+}}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial\vec{J}_{t+}}{\partial t}, \tag{20}$$

where, $\vec{J}_{t+}$ is the total current density vector in the presence of low-frequency electric field, $\vec{E}_{t+}$, and it is given by

$$\vec{J}_{t+} = \vec{J}_{1+} + \vec{J}_{2+}. \tag{21}$$

Here the linear current density $\vec{J}_{1+}$ is given by

$$\vec{J}_{1+} = -en_0\vec{v}^e_{1+} + en_0\vec{v}^i_{1+}, \tag{22}$$

and the nonlinear current density $\vec{J}_{2+}$ is given by

$$\vec{J}_{2+} = -e\tilde{n}^*_p\vec{v}_{0+} - en_0\vec{v}^e_{2+}, \tag{23}$$

where $\vec{v}^e_{1+}$ and $\vec{v}^i_{1+}$ represent the electron and the ion linear velocities, respectively, which can be obtained by solving the momentum equation with respect to the right circular polarized wave of low frequency as follows:

$$\vec{v}^e_{1+} = \frac{ie\vec{E}_{t+}}{m_0\gamma\omega_t\left(1-\frac{\omega_{ce}}{\omega_t\gamma}\right)}, \tag{24}$$

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$$\vec{v}_{1+}^{\,i} = \frac{ie\vec{E}_{t+}}{m_0\gamma\omega_t\left(1+\frac{\omega_{ci}}{\omega_t\gamma}\right)}, \tag{25}$$

where $\omega_{ci} = \frac{eB_0}{m_i c}$ is the ion–cyclotron frequency.

Introducing $\vec{B} = (\frac{\vec{ck}_{0+}}{\omega_0}) \times \vec{E}_{0+}$ in the momentum equation, the nonlinear velocity $\vec{v}_{2+}$ corresponding to the interaction of density ripple with electric field of the laser beam in magnetoplasma is

$$\vec{v}_{2+} = \frac{-ie\vec{E}_{0+}\left(\frac{\omega_{ce}}{\gamma}\right)k_{0+}v_1^*}{2m_0\gamma\omega_0^2\omega_t\left(1-\frac{\omega_{ce}}{\omega_0\gamma}\right)\left(1-\frac{\omega_{ce}}{\omega_t\gamma}\right)}. \tag{26}$$

Finally, the quiver electron velocity $\vec{v}_{0+}$ in laser field (see (3)) is

$$\vec{v}_{0+} = \frac{ie\vec{E}_{0+}}{m_0\gamma\omega_0\left(1-\frac{\omega_{ce}}{\omega_0\gamma}\right)}. \tag{27}$$

Substituting (24) and (25) in (22) and (26), and (27) in (23), the expressions of linear and nonlinear current densities will be

$$\vec{J}_{1+} = \frac{-i\omega_{pe}^2\vec{E}_{t+}}{4\pi\gamma\omega_t\left(1-\frac{\omega_{ce}}{\omega_t\gamma}\right)\left(1+\frac{\omega_{ci}}{\omega_t\gamma}\right)}, \tag{28}$$

$$\vec{J}_{2+} = \frac{-i\omega_{pe}^2\mu^*}{8\pi\gamma\omega_0\left(1-\frac{\omega_{ce}}{\omega_0\gamma}\right)}\left(1-\frac{\omega_1k_{0+}\omega_{ce}}{\omega_0k_1\gamma\omega_t\left(1-\frac{\omega_{ce}}{\omega_t\gamma}\right)}\right)\vec{E}_{0+}. \tag{29}$$

Considering ion to be immobile, its contribution in nonlinear interaction can be ignored. Putting (28) and (29) in (30), one gets the following equation:

$$\frac{d^2\vec{E}_{t+}}{dz^2} + \frac{\omega_t^2}{c^2}\left[1-\frac{\omega_{pe}^2}{\omega_t^2\gamma\left(1+\frac{\omega_{ci}}{\omega_t\gamma}\right)\left(1-\frac{\omega_{ce}}{\omega_t\gamma}\right)}\right]\vec{E}_{t+}$$

$$= \frac{\omega_{pe}^2\omega_t\mu^*}{2c^2\omega_0\gamma\left(1-\frac{\omega_{ce}}{\omega_0\gamma}\right)}\left[1-\frac{\omega_1k_{0+}\omega_{ce}}{\omega_0k_1\omega_t\gamma\left(\frac{\omega_{ce}}{\omega_t\gamma}-1\right)}\right]\vec{E}_{0+}. \tag{30}$$

By calculating relativistic factor γ by using similar technique as given in Sec. 2 [25], (30) takes the following form:

$$\frac{d^2\vec{E}_{t+}}{dz^2} + \left[\frac{\omega_t^2}{c^2}\left(1-\frac{\omega_{pe}^2}{\omega_t^2\left(1-\frac{\omega_{ce}}{\omega_t}\right)\left(1+\frac{\omega_{ci}}{\omega_t}\right)}\right)+\alpha_{t+}\right]\vec{E}_{t+}$$

$$= \left[\frac{\omega_{pe}^2\omega_t\mu^*}{2c^2\omega_0\left(1-\frac{\omega_{ce}}{\omega_0}\right)}\left(1-\frac{\omega_1k_{0+}\omega_{ce}}{\omega_0k_1\omega_t\left(\frac{\omega_{ce}}{\omega_t}-1\right)}\right)+\alpha_{tt+}\right]\vec{E}_{0+}, \tag{31}$$

where α_{t+} and α_{tt+} represent relativistic increasing mass contribution terms, which can be written as follows:

$$\alpha_{t+} = \frac{\omega_{pe}^2}{c^2\left(1-\frac{\omega_{ce}}{\omega_t}\right)^2}\alpha_+E_{0+}E_{0+}^*,$$

and

$$\alpha_{tt+} = \left(\frac{\omega_t\mu^*}{c^2}\right)\left(\frac{\omega_{pe}^2\left(\frac{2\omega_{ce}}{\omega_0}-1\right)}{\omega_0\left(1-\frac{\omega_{ce}}{\omega_0}\right)^2}\right.$$

$$-\frac{\omega_1k_{0+}\omega_{ce}\omega_{pe}^2}{\omega_0^2k_1\omega_t\left(\frac{\omega_{ce}}{\omega_t}-1\right)\times\left(1-\frac{\omega_{ce}}{\omega_0}\right)}$$

$$\left.\times\left(\frac{\omega_{ce}}{\omega_t\left(\frac{\omega_{ce}}{\omega_t}-1\right)}+\frac{\omega_{ce}}{\omega_0\left(1-\frac{\omega_{ce}}{\omega_0}\right)}-2\right)\right)\alpha_+E_{0+}E_{0+}^*.$$

It is obvious that the non-relativistic case will be satisfied when α_{t+} and α_{tt+} have vanished, and to obtain THz generation intensity, (31) has been solved numerically. Here f_+ is the function of z and is governed by (17).

The THz field generated by this mechanism can also be obtained numerically straight from (31) with appropriate boundary conditions where the laser beam width parameter is changing with distance propagation as given by (17).

4. Results and discussion

In this paper, the numerical calculations have been achieved using typical parameters, which are as follows: laser beam intensity $\sim 1.25\times10^{17}$ W.cm^{-2} (or $\alpha_0 = \frac{eE_{00}}{m_e\omega_0c} \sim 0.9$), frequency of pump laser, $\omega_0 = 10^{14}$ rad.s^{-1}, frequency of density ripple of the plasma wave, $\omega_1 = 0.99\times10^{14}$ rad.s^{-1}, laser beam radius, $x_0 = 40$ μm, applied magnetic fields, $B_0 = (85, 102,$ and $114)$ kG, plasma density, $n_0 = 2.55\times10^{18}$cm^{-3}, and normalized ripple density amplitude, $\mu = 0.4$.

The initial conditions for f_+ are $f_+ = 1$ and $\frac{df_+}{dz} = 0$ at $z = 0$. When laser beam propagates via plasma, the plasma density will be varying through the channel due to relativistic nonlinearity. But the relativistic nonlinearity introduced in the plasma depends upon the laser beam intensity. Equation (16) gives the intensity profile of laser beam, which depends on the beam width

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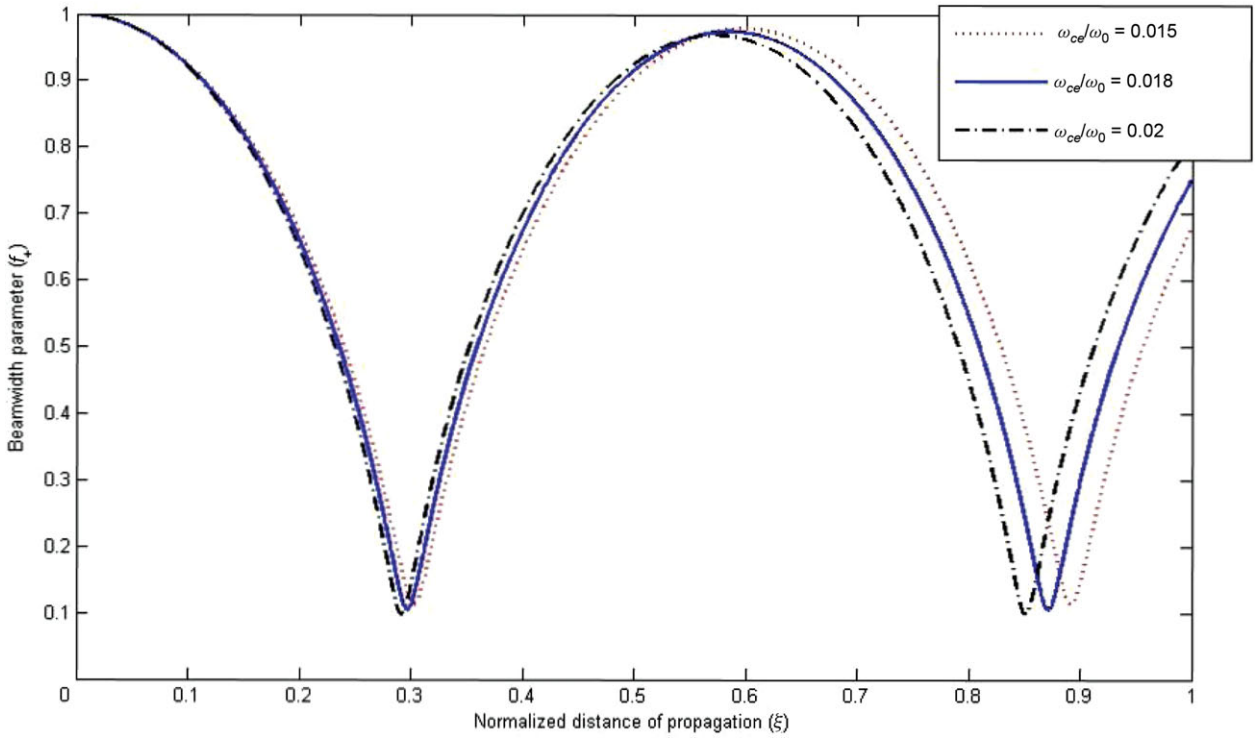


Figure 1. (Colour online) Variation of beam width parameter f_+ with normalized distance $\xi = \frac{z}{k_{0+}x_0^2}$. Dotted red line, blue solid line, and semi-dotted black line represent $\frac{\omega_{ce}}{\omega_0} = 0.015$, $\frac{\omega_{ce}}{\omega_0} = 0.018$, and $\frac{\omega_{ce}}{\omega_0} = 0.02$, respectively.

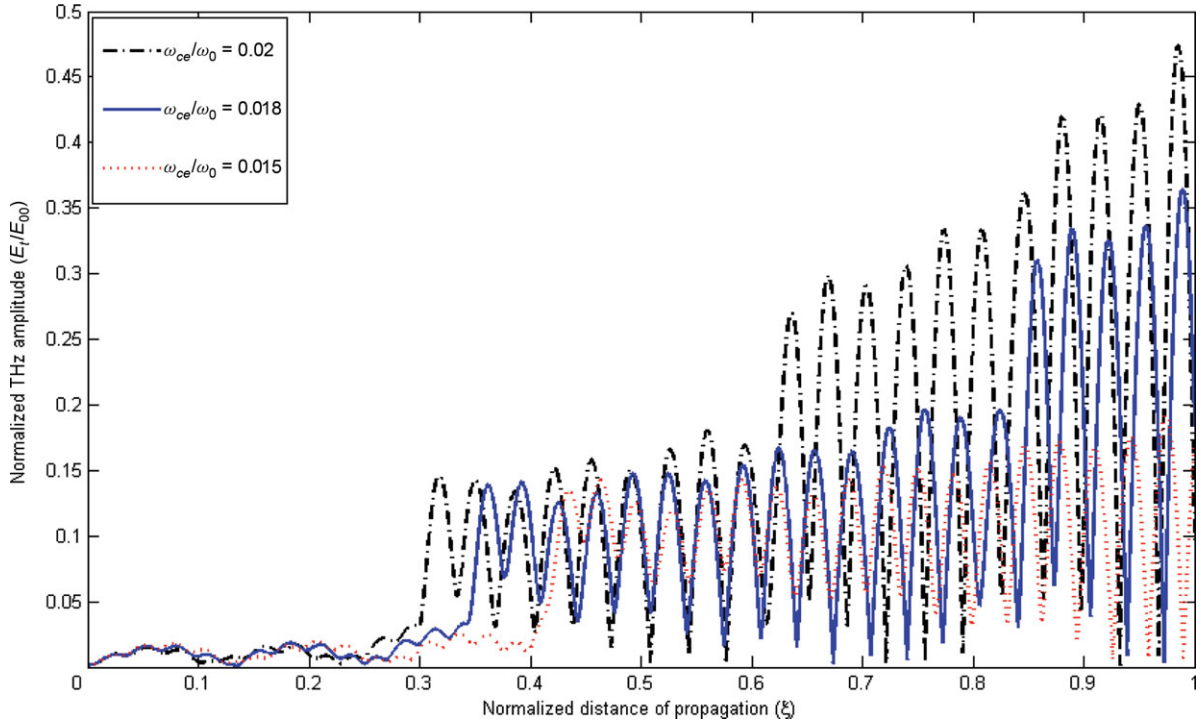


Figure 2. (Colour online) Variation of normalized THz field amplitude (the normalization with laser field amplitude) with normalized distance $\xi = \frac{z}{k_{0+}x_0^2}$. Dotted red line, blue solid line, and semi-dotted black line represent $\frac{\omega_{ce}}{\omega_0} = 0.015$, $\frac{\omega_{ce}}{\omega_0} = 0.018$, and $\frac{\omega_{ce}}{\omega_0} = 0.02$, respectively.

parameter f_+. In that case f_+ is obtained from the numerical simulation of (17).

Figure 1 shows that the beam width parameter f_+ of laser beam increases dramatically with increase in normalized distance of propagation, $\xi = \frac{z}{k_{0+}x_0^2}$, leading to increase in laser beam intensity extremely from (17). The value of f_+ decreases with increase in magnetic field, which is shown in the Fig. 1.

Figure 2 shows the normalized THz radiation amplitude variation with normalized distance of

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propagation. For the above set of parameters, the normalized THz radiation amplitude peak comes out at the frequency,$\omega_2 = 0.16$ THz. We find that the radiated electromagnetic wave has a power level in GW range by solving the (31) as shown in Fig. 2. We report the generation of THz radiation with maximum conversion efficiencies of 20%, 30%, and 40% for $(\omega_{ce}/\omega_0) = 0.015$, 0.018, and 0.02, respectively. It should be mentioned here that if the laser beam is not self-focused ($f_{0+} = 1$), the conversion efficiency is constant at the level of 0.6%. Therefore, self-focusing of the laser beam plays a very important role in this conversion mechanism. This is on account of the fact that self-focusing of the laser beam leads to enhanced intensity of laser, therefore the conversion process, which depends on the laser intensity, gets enhanced.

5. Conclusion

In this paper the THz radiation generation mechanism IS studied by the coupling of high intense laser beam and rippled density plasma via magnetoplasma where the relativistic nonlinearity has been operated. The nonlinear part of current density ($\vec{J}_{2+}$) will be responsible to generate THz radiation. The intensity of incident laser beam will increase more due to relativistic self-focusing and the THz amplitude also increases because of its dependence on laser amplitude (confirm from (31)). The increasing of applied magnetic field results in increase in self-focusing (see Fig. 1), and hence increase in laser beam intensity, which in turn leads to increase in THz radiation amplitude. It is obvious from (31) that the role of the applied magnetic field and self-focusing in the THz radiation generation is more complex. Numerical simulation shows that for the incident laser power flux $\approx 1.25 \times 10^{17}$W.cm^{-2}, laser beam radius, $x_0 = 40$ μm, laser frequency, $\omega_0 = 10^{14}$ rad.s^{-1}, density ripple frequency $(\omega_1) = 0.99 \times 10^{14}$ rad.s^{-1}, and plasma density $n_0 = 2.55 \times 10^{18}$ cm^{-3}, we can obtain GW power at the frequency, $\omega_2 = 0.16$ THz. One can consider this technique as a source of generating GW THz radiation power.

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