

Terahertz radiation by self-focused amplitude-modulated Gaussian laser beam in magnetized ripple density plasma

RAM KISHOR SINGH AND R. P. SHARMA

Centre for Energy Studies, Indian Institute of Technology Delhi, New Delhi-110016, India

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Abstract

This paper presents a theoretical model for efficient terahertz (THz) radiation by self-focused amplitude-modulated laser beam in preformed ripple density plasma. The density of plasma is modified due to ponderomotive nonlinearity which arises because of the nonuniform spatial profile of the laser beam in magnetized plasma and leads to the self-focusing of the laser beam. The rate of self-focusing depends on the intensity of the amplitude-modulated beam as well as on the externally applied magnetic field strength. The electron also experiences time-dependent ponderomotive force by the laser beam at modulated frequency. A nonlinear current at THz frequency arises on account of the coupling between the ripple density plasma and nonlinear oscillatory velocity of the electrons. The yield of the generated THz radiation enhances with enhancement in self-focusing of the laser beam and applied magnetic field.

Keywords: Amplitude-modulated Gaussian laser beam; Magnetized plasma; Ponderomotive nonlinearity; Self-focusing; Terahertz radiation

1. INTRODUCTION

Terahertz (THz) spectrum (0.1–10 THz), lying between microwave (MW) and infrared regions, has potential applications in the field of communication (Federici & Moeller, 2010), explosives detection (Tonouchi, 2007), nondestructive testing (Federici *et al.*, 2005), cellular-level imaging (Ferguson & Zhang, 2002), biological and chemical sensing, and tomographic imaging (Siegel, 2004). Various nonplasma-based techniques using nonlinear electro-optic crystals (Lee *et al.*, 2000), photoconductive antennas and semiconductors (Jepsen *et al.*, 1996; Hashimshony *et al.*, 1999; Shen *et al.*, 2004), gyrotron-based sources (Glyavin *et al.*, 2008), and so on have been used for the generation of THz radiation which leads to low-power conversion efficiency as well as emitter breakdown at high-power irradiance. To avoid the damage of THz emitter, one can use either laser filamentation in air or laser interaction with preformed plasma as a THz emitter (Yugami *et al.*, 2002; Doranian *et al.*, 2005; Xie *et al.*, 2006; D'Amico *et al.*, 2007, 2008; Kim *et al.*, 2007, 2008; Kostin & Vvedenskii, 2010; Tripathi *et al.*, 2010; Singh *et al.*, 2013; Sharma & Singh, 2014; Singh & Sharma, 2014).

Xie *et al.* (2006) have studied the THz generation in the femtosecond pulsed laser-induced air plasma with the employment of the third-order nonlinear optical process, mixing the fundamental and second-harmonic beams in the ionized plasma, while emitted THz field polarity and strength can be controlled by the relative phase between fundamental and second-harmonic beams. Hu *et al.* (2010) have experimentally demonstrated the THz radiation from a femtosecond laser filament in air by the transition-Cherenkov radiation mechanism. D'Amico *et al.* (2007) have experimentally investigated the generation of linearly polarized and coherent THz radiation by a femtosecond laser beam filament created in air, and they have further investigated the role of external electric field along the filament axis and observed the emission of enhanced incoherent and nonpolarized THz yield. Yugami *et al.* (2002) have experimentally demonstrated the radiations from MWs to THz frequency range from the Cherenkov wake, excited by the ultrahigh power pulse laser in magnetized plasma.

THz radiation can also be generated by the beating of two lasers in preformed ripple density plasma, by considering collisional, ponderomotive, and relativistic nonlinearity. Self-focused amplitude-modulated beam can also generate the THz radiation in the ripple density plasma (Kumar *et al.* 2015). Cho *et al.* (2015) have investigated the THz radiation by two counter propagating laser beams in preformed

Address correspondence and reprint requests to: Ram Kishor Singh, Centre for Energy Studies, Indian Institute of Technology Delhi, New Delhi-110016, India. E-mail: ram007kishor@gmail.com

weakly magnetized plasma. The effect of cross-focusing of the two co-propagating laser beams on the generation of THz yield has been studied in the presence of an external applied electric or magnetic fields and it is observed that generated THz yield enhances several times due to cross-focusing of the laser beams as compared with that without the cross-focusing mechanism (Sharma & Singh, 2014; Singh & Sharma, 2014).

The self-focusing of femtosecond laser beam takes place in air due to optical Kerr nonlinearity, while the high-power laser beam gets self-focused in the preformed plasma via any nonlinearity: collisional, ponderomotive, or relativistic. These nonlinearities depend on the time scale of the pulse viz. (1) $t_\varepsilon (= m_i/2m_e v) < t_p$, for collisional; (2) $t_\varepsilon \gg t_p$, for the ponderomotive; and (3) $t_{pe} \approx t_p$, for the relativistic nonlinearity to be dominant. Here, t_ε , t_p , and t_{pe} are the energy relaxation, duration of pump beam, and electron plasma period, respectively, while v is the collisional frequency, m_i and m_e are the ion and electron mass, respectively (Sodha *et al.*, 1974a, b, 1976).

This paper, deals with the effect of transverse magnetic field on the propagation of amplitude-modulated laser beam and the role of self-focusing on the generation of THz radiation. We present a theoretical model for self-focusing of the amplitude-modulated Gaussian laser beam, in magnetized ripple density plasma and generation of THz radiation at modulation frequency, when ponderomotive nonlinearity is operative. The use of ripple density is very similar to the periodic index change in the periodically polled lithium niobate crystals for the THz phase matching (Lee *et al.*, 2000). This paper is organized as follows: In Section 2, we have discussed the self-focusing of an amplitude-modulated Gaussian laser beam in magnetized plasma. In Section 3, we have evaluated an expression for the nonlinear current density at modulated frequency and radiated THz wave amplitude. Section 4 presents the discussion of numerical results. Section 5 summarizes the conclusion remarks.

2. SELF-FOCUSING OF AMPLITUDE-MODULATED LASER BEAM

Consider, a high-power amplitude-modulated Gaussian laser beam propagating along the x -direction with frequency ω_0 and wave vector k_0 in the magnetoplasma, having static magnetic field (B_0), perpendicular to the direction of propagation (z -direction) of the beam. The electric field of the laser beam for the extraordinary mode (x -mode) is given by

$$\vec{E} (= \hat{x}E_x + \hat{y}E_y) = \{\hat{x}A_x(x, y, z, t) + \hat{y}A_y(x, y, z, t)\} \times \exp\{-i(\mathbf{k}_0 x - \omega_0 t)\} \quad (1)$$

where $E_x = -\left(\frac{\varepsilon_{xy}}{\varepsilon_{xx}}\right)E_y$, $\varepsilon_{xx} = 1 - \omega_p^2/(\omega_0^2 - \omega_c^2)$, and $\varepsilon_{xy} = \omega_c \omega_p^2 / i\omega_0(\omega_0^2 - \omega_p^2)$. Due to the nonuniform spatial profile of the amplitude-modulated Gaussian beam, the maximum irradiance occur at the center and decreases in the

radial direction. When the laser beam is propagating in magnetized plasma, then density redistribution occurs along the magnetic field due to the ponderomotive force (Sharma, 1978). The ponderomotive force along the external applied magnetic field can be written as (Sharma, 1978; Sodha *et al.*, 1979),

$$F_{pz} = \frac{-e^2}{4m_e(\omega_0^2 - \omega_c^2)} \frac{\partial}{\partial z} \times \left\{ (E_x \cdot E_x^* + E_y \cdot E_y^*) + \frac{i\omega_c}{\omega_0} (E_y \cdot E_x^* - E_x \cdot E_y^*) \right\} \quad (2)$$

where $\omega_c = eB_0/m_e c$ is the electron cyclotron frequency. The modified density of electrons can be written as follows (Sodha *et al.*, 1974a, b, 1979, 1980):

$$n = n_0 \exp(-\alpha E_y \cdot E_y^*) \quad (3)$$

where

$$\alpha = \frac{e^2}{8k_B T_0 m_e (\omega_0^2 - \omega_c^2)} \left[1 + \frac{\omega_c^2 \omega_p^4}{\omega_0^2 (\omega_0^2 - \omega_h^2)^2} + \frac{2\omega_c^2 \omega_p^2}{\omega_0^2 (\omega_0^2 - \omega_h^2)} \right],$$

$\omega_h = (\omega_p^2 + \omega_c^2)^{1/2}$, k_B is the Boltzmann constant and T_0 is the electron temperature. The wave equation can be written as,

$$\nabla^2 \vec{E} - \nabla(\nabla \cdot \vec{E}) = \frac{4\pi \partial \vec{J}}{c^2 \partial t} + \frac{1}{c^2} \frac{\partial^2 \vec{E}}{\partial t^2} \quad (4)$$

where $\vec{J} = -ne(v_x \hat{x} + v_y \hat{y})$. Now using Eq. (1) in Eq. (4) and separating the x and y components of the wave equation, we obtain as follows:

$$A_x = \frac{i\omega_c}{\omega_0} \frac{\omega_p^2}{(\omega_0^2 - \omega_h^2)} A_y \quad (5a)$$

$$\begin{aligned} & -2i\mathbf{k}_0 \frac{\partial A_y}{\partial x} + \delta_+ \frac{\partial^2 A_y}{\partial y^2} + \frac{\partial^2 A_y}{\partial z^2} \\ & = \left(\frac{n - n_0}{n_0} \right) \times \frac{\omega_p^2 (\omega_0^2 - \omega_p^2)}{c^2 (\omega_0^2 - \omega_h^2)} A_y + \frac{2i\omega_0}{c^2} \frac{\partial A_y}{\partial t} \end{aligned} \quad (5b)$$

where $\delta_+ = 1 - \omega_c^2 \omega_p^4 / \omega_0^2 (\omega_0^2 - \omega_h^2)^2$ and $\mathbf{k}_0 = (\omega_0/c) \{1 - (\omega_p^2 (\omega_0^2 - \omega_p^2) / \omega_0^2 (\omega_0^2 - \omega_h^2))\}^{1/2}$. For the slowly converging and diverging nature of the laser beam, we assume the solution of Eq. (5b) as follows:

$$A_y(x, y, z, t) = A_0(x, y, z, t) \exp\{-i\mathbf{k}_0 S(x, y, z, t)\} \quad (6)$$

On transforming the coordinates (x, t) to $x(=x)$, $\xi = t - x/v_g$ (where $1/v_g = \omega_0/k_0 c^2$) and by substituting Eq. (6) into (5b), we obtain the real and imaginary parts as follows

(Sodha *et al.*, 1980):

$$\frac{\partial A_0^2}{\partial x^2} + \delta_+ A_0^2 \frac{\partial^2 S}{\partial y^2} + A_0^2 \frac{\partial^2 S}{\partial z^2} + \delta_+ \frac{\partial S}{\partial y} \frac{\partial A_0}{\partial y} + \frac{\partial S}{\partial z} \frac{\partial A_0}{\partial z} = 0 \quad (7a)$$

$$2 \frac{\partial S}{\partial x} + \delta_+ \left(\frac{\partial S}{\partial y} \right)^2 + \left(\frac{\partial S}{\partial z} \right)^2 = \frac{1}{k_0^2 A_0} \left(\delta_+ \frac{\partial^2 A_0}{\partial y^2} + \frac{\partial^2 A_0}{\partial z^2} \right) - \frac{\omega_p^2 (\omega_0^2 - \omega_p^2)}{k_0^2 c^2 (\omega_0^2 - \omega_p^2)} \left(\frac{n - n_0}{n_0} \right) \quad (7b)$$

The solution of Eqs (7a) and (7b) can be written as,

$$A_0^2 = \frac{E_{00}^2 (1 + \mu \cos \Omega \xi)^2}{f_1 f_2} \exp \left(-\frac{y^2}{r_0^2 f_1^2} - \frac{z^2}{r_0^2 f_2^2} \right) \quad (8a)$$

and

$$S = \frac{y^2}{2} \beta_1(x) + \frac{z^2}{2} \beta_2(x) \quad (8b)$$

The intensity variation of the laser beam is described by Eq. (8a), which depends on the dimensionless beam width parameters f_1 and f_2 along the propagation direction, in the paraxial regime. Now, putting Eqs (8a) and (8b) in Eq (7a) and comparing the coefficients of y^2 and z^2 , we can get the value of $\beta_1(x) = (1/\delta_+)(df_1/dx)$ and $\beta_2(x) = df_2/dx$. The governing equations for dimensionless beam width parameters f_1 and f_2 can be obtained from Eq. (7b) as follows (Akhmanov *et al.*, 1968):

$$\frac{d^2 f_1}{dx^2} = \frac{\delta_+^2}{k_0^2 r_0^4 f_1^3} - \frac{\delta_+ \omega_p^2 (\omega_0^2 - \omega_p^2)}{k_0^2 c^2 (\omega_0^2 - \omega_p^2)} \frac{\alpha E_{00}^2 (1 + \mu \cos \Omega \xi)^2}{r_0^2 f_1 f_2} \times \exp \left(-\frac{\alpha E_{00}^2 (1 + \mu \cos \Omega \xi)^2}{f_1 f_2} \right) \quad (9a)$$

$$\frac{d^2 f_2}{dx^2} = \frac{1}{k_0^2 r_0^4 f_2^3} - \frac{\omega_p^2 (\omega_0^2 - \omega_p^2)}{k_0^2 c^2 (\omega_0^2 - \omega_p^2)} \frac{\alpha E_{00}^2 (1 + \mu \cos \Omega \xi)^2}{r_0^2 f_1 f_2} \times \exp \left(-\frac{\alpha E_{00}^2 (1 + \mu \cos \Omega \xi)^2}{f_1 f_2} \right) \quad (9b)$$

Equations (9a) and (9b) show the variation of dimensionless beam width parameter in the magnetoplasma.

3. THZ RADIATION

For the generation of THz radiation, we consider the propagation of amplitude-modulated Gaussian laser beam, with electric field as given by Eq. (1), through the ripple density plasma with density variations given as: $n = n_0 + n_q e^{-iqx}$, where n_q and q are amplitude and wave number of the density ripple, respectively. The electrons also respond at the modulated frequency of pump laser on account of ponderomotive force. This oscillatory velocity couples with the density ripple and leads to the generation of nonlinear current

density, which is the source of THz radiation. The density ripple in the plasma is playing the key role for the propagation of generated THz wave. The ponderomotive force at modulated frequency ($\Omega \ll \omega_0$) can be written as,

$$\vec{F}_P^\Omega = \left(-\frac{e^2}{2m_e \omega_0^2} \vec{\nabla} (\vec{E} \cdot \vec{E}^*) \Big|_\Omega \right) = (\hat{x} F_{px0} + \hat{y} F_{py0} + \hat{z} F_{pz0}) \times \exp \left\{ i \Omega \left(t - \frac{x}{v_g} \right) \right\} \quad (10)$$

The nonlinear oscillatory velocity of the electrons at modulated frequency $\Omega (= \omega_T)$ can be obtained from the equation of motion as follows:

$$\frac{\partial \vec{v}_{nl}}{\partial t} = -(\vec{v}_{nl} \times \hat{z}) \omega_c + \frac{\vec{F}_P^\Omega}{m_e} \quad (11)$$

The nonlinear oscillatory velocity components can be evaluated from Eq. (11) as (Ginzburg, 1970), $v_x^{nl} = (\omega_T F_{px}^\Omega + i \omega_c F_{py}^\Omega) / im_e (\omega_T^2 - \omega_c^2)$ and $v_y^{nl} = (\omega_T F_{py}^\Omega - i \omega_c F_{px}^\Omega) / im_e (\omega_T^2 - \omega_c^2)$. The wave equation for THz generation in magnetized plasma can be written as,

$$\nabla^2 \vec{E}_T - \nabla (\nabla \cdot \vec{E}_T) = \frac{4\pi}{c^2} \frac{\partial (\vec{J}_T^1 + \vec{J}_T^{nl})}{\partial t} + \frac{1}{c^2} \frac{\partial^2 \vec{E}_T}{\partial t^2} \quad (12)$$

Now considering the THz radiation in the extra ordinary mode ($E_{Tz} = 0$, $E_{Tx} \neq 0$, $E_{Ty} \neq 0$). The linear oscillatory velocity of the electrons at THz frequency (ω_T) and wave number (k_T) can be written as (Ginzburg, 1970) $v_{Tx}^l = ie (\omega_T E_{Tx} + i \omega_c E_{Ty}) / m_e (\omega_T^2 - \omega_c^2)$ and $v_{Ty}^l = ie (\omega_T E_{Ty} - i \omega_c E_{Tx}) / m_e (\omega_T^2 - \omega_c^2)$. The linear and nonlinear current density at THz wave number and frequency can be written as

$$\vec{J}_T^1 = -en_0 (v_{Tx}^l \hat{x} + v_{Ty}^l \hat{y})$$

and

$$\vec{J}_T^{nl} = \frac{-en_q e^{-iqx}}{2} (v_x^{nl} \hat{x} + v_y^{nl} \hat{y}) \quad (13)$$

Now taking the fast phase variation $\vec{E}_T = \vec{E}_{T0}(x, y) \exp \{-i(k_T x - \omega_T t)\}$, we evaluate the x and y component of Eq. (12) as follows:

$$E_{Tx} = \frac{4\pi i}{\omega_T} (J_{Tx}^1 + J_y^{nl}) \quad (14a)$$

and

$$2ik_T \frac{\partial E_{Ty0}}{\partial x} + \left\{ k_T^2 - \frac{\omega_T^2}{c^2} \left(1 - \frac{\omega_p^2 \omega_T^2 - \omega_p^2}{\omega_T^2 \omega_T^2 - \omega_H^2} \right) \right\} E_{Ty0} = \left(\frac{n_q}{2n_0} \right) \left(\frac{\omega_p^2}{c^2} \right) \frac{[i \omega_c \omega_T F_{px0}^\Omega - (\omega_T^2 - \omega_p^2) F_{py0}^\Omega]}{(\omega_T^2 - \omega_H^2)} \quad (14b)$$

where

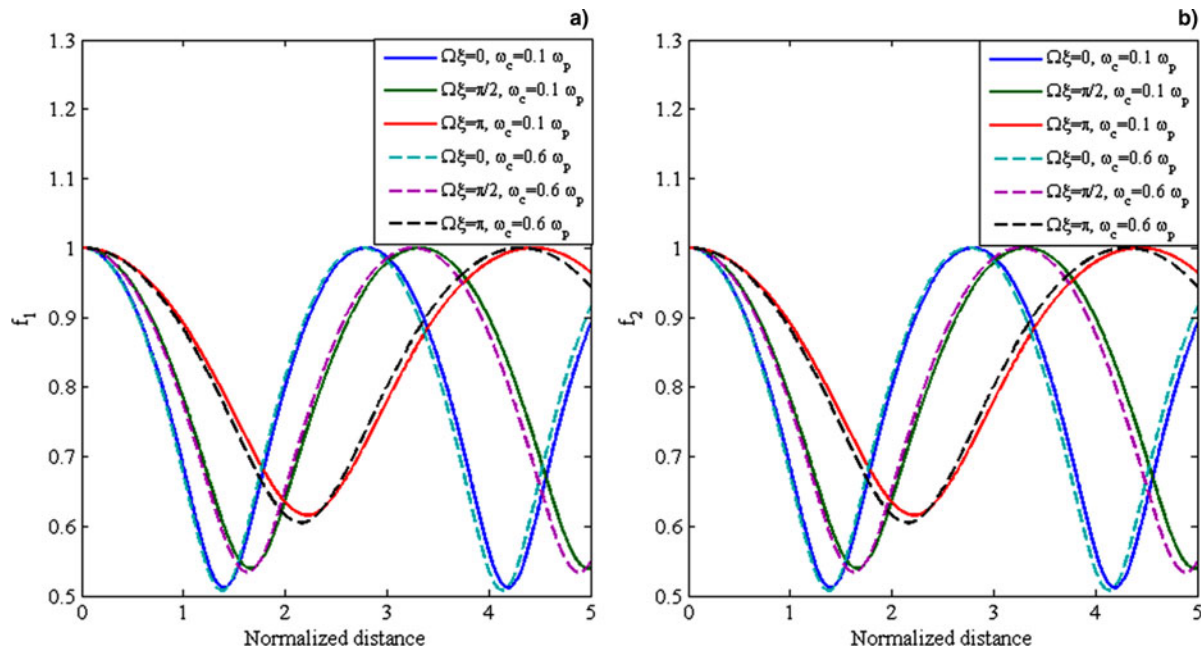


Fig. 1. Variation of beam dimensionless width parameters with normalized distance.

$$F_{px0}^{\Omega} = -\frac{e^2}{2m_e\omega_0^2} \left\{ 1 + \frac{\omega_c^2}{\omega_0^2(\omega_0^2 - \omega_h^2)} \frac{\omega_p^4}{\omega_0^2} \right\} \frac{\mu E_{00}^2}{f_1 f_2} \left\{ \frac{1}{f_1} \frac{\partial f_1}{\partial x} \left(\frac{2y^2}{r_0^2 f_1^2} - 1 \right) + \frac{1}{f_2} \frac{\partial f_2}{\partial x} \left(\frac{2z^2}{r_0^2 f_2^2} - 1 \right) - \frac{i\Omega}{v_g} \right\} \exp \left\{ -\frac{y^2}{r_0^2 f_1^2} - \frac{z^2}{r_0^2 f_2^2} \right\}$$

$$\text{and } F_{px0}^{\Omega} = \frac{e^2}{2m_e\omega_0^2} \left\{ 1 + \frac{\omega_c^2}{\omega_0^2(\omega_0^2 - \omega_h^2)} \frac{\omega_p^4}{\omega_0^2} \right\} \frac{\mu E_{00}^2}{f_1 f_2} \left(\frac{2y}{r_0^2 f_1^2} \right) \exp \left\{ -\frac{y^2}{r_0^2 f_1^2} - \frac{z^2}{r_0^2 f_2^2} \right\}.$$

The phase matching demands that $k_T = (\omega_T/c)\{1 - (\omega_p^2/(\omega_T^2 - \omega_p^2)/\omega_T^2(\omega_T^2 - \omega_h^2))\}^{1/2}$, while the wave vector satisfies the phase-matching condition $k_T = \Omega/v_g + q$.

4. RESULTS AND DISCUSSION

Equations (9a) and (9b) show the converging/diverging behavior of the laser beam in magnetized plasma. On the right-hand side of both the equations [Eqs (9a) and (9b)], the first term shows divergence (diffraction), while the second term is responsible for the convergence (nonlinear term) of the beam. We have solved the coupled Eqs (9a) and (9b) numerically by Runge–Kutta methods and using the following boundary conditions (Akhmanov *et al.*, 1968): $f_1|_{x=0} = f_2|_{x=0} = 1$ and $df_1/dx|_{x=0} = df_2/dx|_{x=0} = 0$. For the numerical illustration, we have chosen the following set of laser (CO₂)–plasma parameters: intensity of the laser beam, 10^{14} W/cm², initial radius of the laser beam, $r_0 = 30$ μm, $\omega_0 = 1.78 \times 10^{14}$ rad/s, $\omega_p = 2.5 \times 10^{13}$ rad/s, modulated frequency of laser beam, $\Omega = 1.5\omega_p$, $\mu = 0.1$, $\omega_c = 0.1\omega_p$, and $0.6\omega_p$. Figures 1(a) and 1(b) show the variation of dimensionless beam width parameters f_1 and f_2 with the normalized distance η , where $\eta = x/R_d$ and $R_d(= \omega_0 r_0^2/c)$ is

the diffraction length. The focusing rate of laser beam decreases with increasing the value of $\Omega\xi = 0, \pi/2$, and π . The applied external magnetic field also significantly affects the self-focusing rate.

Figure 2 shows the schematic diagram for the THz radiation in the presence of external applied static magnetic field in the ripple density plasma. The nonlinear current density at THz frequency arises due to the coupling of nonlinear oscillatory velocity of electron at modulation frequency with the density ripple. The propagation of THz radiation is governed by Eq. (14b) and the results are presented in Figures 3 and 4 for the exact phase-matching condition that is, $k_T = \Omega/v_g + q$. The energy transfer from the amplitude-modulated laser to the generated THz waves will be maxima when the exact phase matching is achieved. Here, the value of ripple

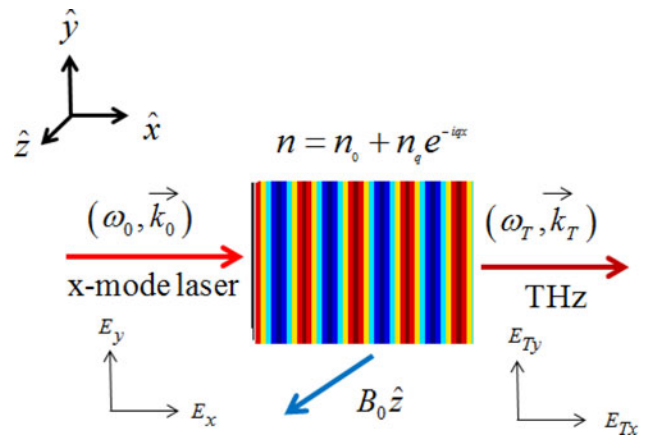


Fig. 2. Schematic diagram for the THz radiation in magnetized ripple density plasma.

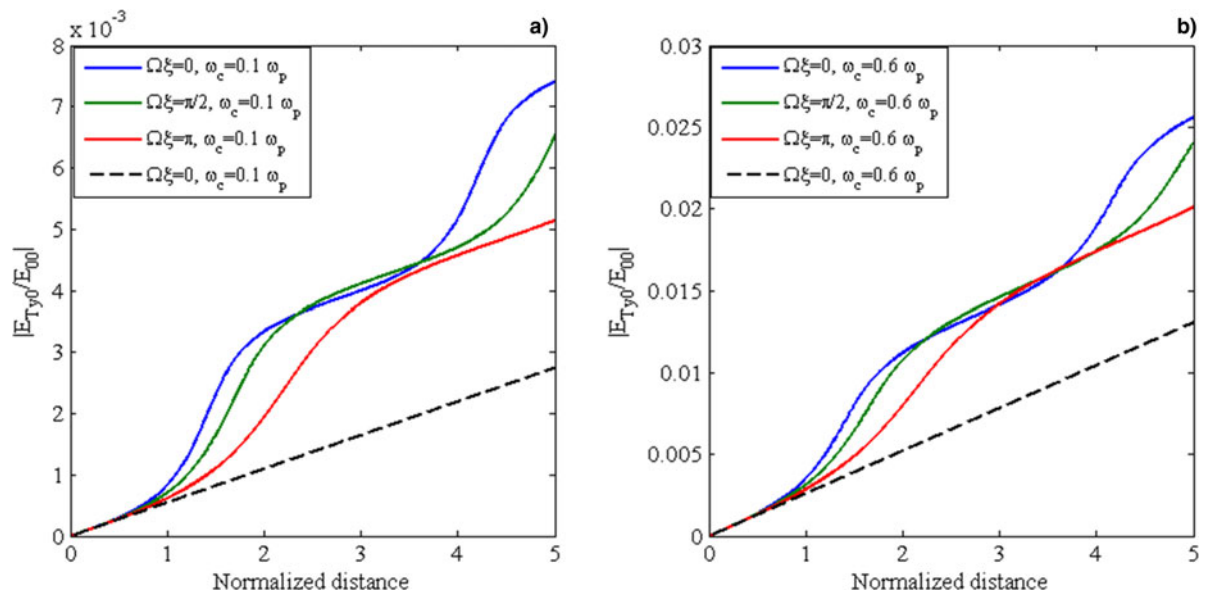


Fig. 3. Variation of THz radiation amplitude with normalized distance around the maximum irradiance ($y/r_0 = 0.4$, $z = 0$) for (a) $\omega_c = 0.1\omega_p$ and (b) $\omega_c = 0.6\omega_p$ for $n_q = 0.2n_0$.

wave number (q) is the key factor to achieve the exact phase-matching condition and for determining the interaction length. However, the generated THz wave can propagate in the magnetized plasma when the frequency of the generated wave lie either in between the left-hand cut-off frequency ($\omega_L = 1/2[-\omega_c + (\omega_c^2 + 4\omega_p^2)^{1/2}]$) and upper hybrid frequency (ω_h) or greater than the right-hand cut-off frequency ($\omega_R = 1/2[\omega_c + (\omega_c^2 + 4\omega_p^2)^{1/2}]$). In the present study, the right-hand cut-off frequency ω_R corresponding to $\omega_c = 0.1\omega_p$ and $0.6\omega_p$ come out to be 2.73×10^{13} and 3.49×10^{13} rad/s, respectively, which is smaller than the generated THz radiation frequency $\omega_T (= 3.77 \times 10^{13}$ rad/s). Thus it can be seen that the generated THz wave will propagate through the plasma. Since the maximum energy transfer

takes place near the resonance condition ($\omega_T \approx \omega_h$) for the THz radiation, hence the generation of THz radiation can be optimized by the strength of the externally applied magnetic field. The THz field radiation increases with increasing value of static magnetic field as ω_T approaches to the ω_h , and the wave is resonantly excited. The generated THz wave amplitude yield decreases with increasing value of $\Omega\xi$, because the focusing of laser beam decreases with increasing value of $\Omega\xi$. However, the laser power will decrease with the distance of propagation on account of the absorption (due to collisions) of the laser beam. Hence, the yield of the generated THz radiation will also fall with the distance of propagation due to absorption. This constraint has been taken care of by considering collisionless plasma (i.e., $\nu_0/\omega_0 \sim 10^{-4}$, where ν_0 is the collisional frequency) as well as the THz absorption length to be larger than interaction length in the numerical calculations. In Figures 3(a) and 3(b), dotted black lines show the generation of THz radiation in the case of laser beam propagation without divergence or convergence that is, $f_1(x) = f_2(x) = 1$ while solid lines show for the case of self-focused laser beam. The generated THz radiation field with the radial distance (y/r_0) has been plotted in Figure 4.

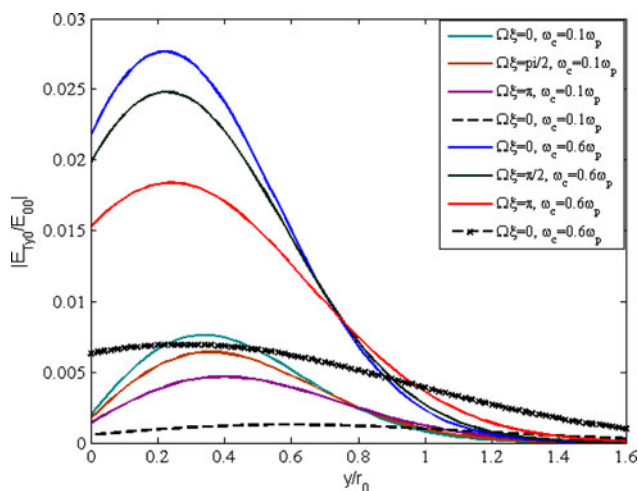


Fig. 4. Variation of THz radiation amplitude with radial distance y/r_0 of the laser beam for $n_q = 0.2n_0$.

The amplitude of the generated THz radiation increases with the distance of propagation. In the case of exact phase-matching condition, one can generate the strong THz radiation due to infinite interaction length. But the power of the laser beam can be reduced with the distance of propagation due to diffraction and collision (or any nonlinear mechanism) in the plasma and the less power are available for the generation of THz radiation, even when/when the exact phase-matching condition is satisfied. The self-focused laser beam is able to propagate longer distances in the plasma and as a result the energy conversion from laser to THz radiation is

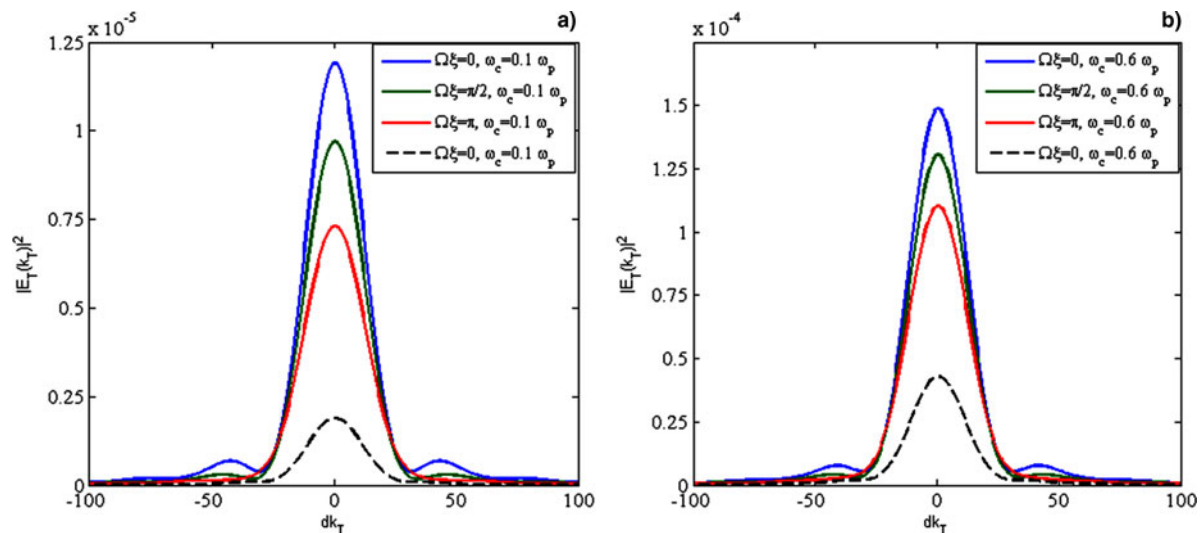


Fig. 5. Power spectra of THz radiation with cross-focusing (solid line) and without cross-focusing (dotted line) of laser beams at $y/r_1 = 0.4$ for (a) $\omega_c = 0.1\omega_p$ and (b) $\omega_c = 0.6\omega_p$ for $n_q = 0.2n_0$.

enhanced, as compared with that without self-focusing of the laser beam. Figures 5(a) and 5(b) show the power spectrum for the generation of THz radiation around the maximum irradiance ($y/r_0 = 0.4$, $z = 0$) with and without self-focusing (i.e., $f_1(x) = f_2(x) = 1$) for $n_q = 0.2n_0$, $\omega_c = 0.1\omega_p$, and $0.6\omega_p$, respectively.

5. CONCLUSION

In conclusion, the amplitude-modulated beam gets self-focused due to ponderomotive force. In magnetized plasma, the rate of self-focusing decreases with increasing $\Omega\xi$, while increases with increasing value of applied magnetic field and the intensity of laser beam enhances at the focused positions of the laser beam. The laser beam also exerts a ponderomotive force at modulation frequency on the electrons and the phase-matching condition is achieved by the density ripple. Self-focused laser beam can enhance the yield of THz radiation several times as compared with that without self-focusing of laser beam. The maximum THz yield can be achieved by resonant excitation which can be achieved with the help of applied external magnetic field. For the present study we have obtained the normalized power of the order of 10^{-4} times the initial power supplied by the laser beam. This work is also having the application in the field of guiding of the modulated laser beam due to externally applied transverse magnetic field in the plasma.

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REFERENCES

- AKHMANOV, S.A., SUKHORUKOV, A.P. & KHOKHLOV, R.V. (1968). Self-focusing and diffraction of light in a nonlinear medium. *Sov. Phys. Usp.* **10**, 609.
- CHO, M.-H., KIM, Y.-K., SUK, H., ERSFELD, B., JAROSZYNSKI, D.A. & HUR, M.S. (2015). Strong terahertz emission from electromagnetic diffusion near cutoff in plasma. *New J. Phys.* **17**, 043045.
- D'AMICO, C., HOUARD, A., AKTURK, S., LIU, Y., BLOAS, J.L., FRANCO, M., PRADE, B., COUAIRO, A., TIKHONCHUK, V.T. & MYSYROWICZ, A. (2008). Forward THz radiation emission by femtosecond filamentation in gases: theory and experiment. *New J. Phys.* **10**, 013015.
- D'AMICO, C., HOUARD, A., FRANCO, M., PRADE, B. & MYSYROWICZ, A. (2007). Coherent and incoherent radial THz radiation emission from femtosecond filaments in air. *Opt. Express* **15**, 15274.
- DORRANIAN, D., GHORANNEVISS, M., STARODUBTSEV, M., YUGAMI, N. & NISHIDA, Y. (2005). Microwave emission from TW-100 fs laser irradiation of gas jet. *Laser Part. Beams* **23**, 583.
- FEDERICI, J. & MOELLER, L. (2010). Review of terahertz and subterahertz wireless communications. *J. Appl. Phys.* **107**, 111101.
- FEDERICI, J.F., SCHULKIN, B., HUANG, F., GARY, D., BARAT, R., OLIVEIRA, F. & ZIMDARS, D. (2005). THz imaging and sensing for security applications-explosives, weapons and drugs. *Semicond. Sci. Technol.* **20**, S266.
- FERGUSON, B. & ZHANG, X.-C. (2002). Materials for terahertz science and technology. *Nat. Mater.* **1**, 26.
- GINZBURG, V.L. (1970). *The Propagation of Electromagnetic Waves in Plasmas*. New York: Pergamon.
- GLYAVIN, M.YU., LUCHININ, A.G. & GOLUBIATNIKOV, G.YU. (2008). Generation of 1.5-kW, 1-THz coherent radiation from a Gyrotron with a pulsed magnetic field. *Phys. Rev. Lett.* **100**, 015101.
- HASHIMSHONY, D., ZIGLER, A. & PAPADOPOULOS, K. (1999). Generation of tunable far-infrared radiation by the interaction of a superluminous ionizing front with an electrically biased photoconductor. *Appl. Phys. Lett.* **74**, 1669.
- HU, G.-Y., SHEN, B., LEI, A.-L., LI, R.-X. & XU, Z.-Z. (2010). Transition-Cherenkov radiation of terahertz generated by

- super-luminous ionization front in femtosecond laser filament. *Laser Part. Beams* **28**, 399.
- JEPSEN, P.U., JACOBSEN, R.H. & KEIDING, S.R. (1996). Generation and detection of terahertz pulses from biased semiconductor antennas. *J. Opt. Soc. Am. B* **13**, 2424.
- KIM, K.Y., GLOWNIA, J.H., TAYLOR, A.J. & RODRIGUEZ, G. (2007). Terahertz emission from ultrafast ionizing air in symmetry-broken laser fields. *Opt. Express* **15**, 4577.
- KIM, K.Y., TAYLOR, A.J., GLOWNIA, J.H. & RODRIGUEZ, G. (2008). Coherent control of terahertz supercontinuum generation in ultrafast laser–gas interactions. *Nat. Photonics* **2**, 605.
- KOSTIN, V.A. & VVEDENSKII, N.V. (2010). Ionization-induced conversion of ultrashort Bessel beam to terahertz pulse. *Opt. Lett.* **35**, 247.
- KUMAR, S., SINGH, R.K., SINGH, M. & SHARMA, R.P. (2015). THz radiation by amplitude-modulated self-focused Gaussian laser beam in ripple density plasma. *Laser Part. Beams* **33**, 257.
- LEE, Y.S., MEADE, T., PERLIN, V., WINFUL, H., NORRIS, T.B. & GALVANAUSKAS, A. (2000). Generation of narrow-band terahertz radiation via optical rectification of femtosecond pulses in periodically poled lithium niobate. *Appl. Phys. Lett.* **76**, 2505.
- SHARMA, A.K. (1978). Transverse self-focusing and filamentation of a laser beam in a magnetoplasma. *J. Appl. Phys.* **49**, 2396.
- SHARMA, R.P. & SINGH, R.K. (2014). Terahertz generation by two cross focused laser beams in collisional plasmas. *Phys. Plasmas* **21**, 073101.
- SHEN, Y.C., UPADHYA, P.C., BEERE, H.E., LINFIELD, E.H., DAVIES, A.G., GREGORY, I.S., BAKER, C., TRIBE, W.R. & EVANS, M.J. (2004). Generation and detection of ultrabroadband terahertz radiation using photoconductive emitters and receivers. *Appl. Phys. Lett.* **85**, 164.
- SIEGEL, P.H. (2004). Terahertz technology in biology and medicine. *IEEE Trans. Microw. Theory Tech.* **52**, 2438.
- SINGH, M., SINGH, R.K. & SHARMA, R.P. (2013). THz generation by cosh-Gaussian lasers in a rippled density plasma. *Euro. Phys. Lett.* **104**, 35002.
- SINGH, R.K. & SHARMA, R.P. (2014). Terahertz generation by two cross focused Gaussian laser beams in magnetized plasma. *Phys. Plasmas* **21**, 113109.
- SODHA, M.S., GHATAK, A.K. & TRIPATHI, V.K. (1974a). *Self-focusing of Laser Beams in Dielectrics, Plasmas and Semiconductor*. Delhi: Tata-McGraw-Hill.
- SODHA, M.S., GHATAK, A.K. & TRIPATHI, V.K. (1976). Self focusing of laser beams in plasmas and semiconductors. *Prog. Opt.* **13**, 169.
- SODHA, M.S., SALIMULLAH, M. & SHARMA, R.P. (1980). Generation of an ion-acoustic pulse by two electromagnetic pulses at difference frequencies in a collisionless plasma. *Phys. Rev. A* **21**, 1708.
- SODHA, M.S., SHARMA, R.P. & TRIPATHI, V.K. (1974b). Self distortion of an amplitude modulated electromagnetic beam in a plasma: Relaxation effects. *Appl. Phys.* **5**, 153.
- SODHA, M.S., SINGH, D.P. & SHARMA, R.P. (1979). Transient setting of ponderomotive nonlinearity, self-focusing, and plasma-wave excitation. *J. Appl. Phys.* **50**, 2678.
- TONOUCHI, M. (2007). Cutting-edge terahertz technology. *Nat. Photonics* **1**, 97.
- TRIPATHI, D., BHASIN, L., UMA, R. & TRIPATHI, V.K. (2010). Terahertz generation by an amplitude-modulated Gaussian laser beam in a rippled density plasma column. *Phys. Scr.* **82**, 035504.
- XIE, X., DAI, J. & ZHANG, X.C. (2006). Coherent control of THz wave generation in ambient air. *Phys. Rev. Lett.* **96**, 075005.
- YUGAMI, N., HIGASHIGUCHI, T., GAO, H., SAKAI, S., TAKAHASHI, K., ITO, H., NISHIDA, Y. & KATSULEAS, T. (2002). Experimental observation of radiation from Cherenkov wakes in a magnetized plasma. *Phys. Rev. Lett.* **89**, 065003.