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Strong terahertz radiation generation by beating of extra-ordinary mode lasers in a rippled density magnetized plasma

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Abstract

A scheme of terahertz radiation generation is proposed by beating of two extra-ordinary lasers having frequencies and wave numbers (ω_1, $\vec{k_1}$) and (ω_2, $\vec{k_2}$), respectively in a magnetized plasma. Terahertz wave is resonantly excited at frequency ($\omega_1 - \omega_2$) and wave number ($k_1 - k_2 + q$) with a wave number mismatch factor q which is introduced by the periodicity of plasma density ripples. In this process, the lasers exert a beat ponderomotive force on plasma electrons and impart them an oscillatory velocity with both transverse and longitudinal components in the presence of transverse static magnetic field. The oscillatory velocity couples with density ripples and produces a nonlinear current that resonantly excites the terahertz radiation. Effects of periodicity of density ripples and applied magnetic field are analyzed for strong THz radiation generation. The terahertz radiation generation efficiency is found to be directly proportional to the square of density ripple amplitude and rises with the magnetic field strength. With the optimization of these parameters, the efficiency $\sim 10^{-3}$ is achieved in the present scheme. The frequency and power of generated THz radiation can be better tuned with the help of parameters like density ripple amplitude, periodicity and applied magnetic field strength in the present scheme.

Keywords: Extraordinary Laser; Magnetized Plasma; Rippled Plasma; Terahertz Generation

1. INTRODUCTION

The terahertz (THz) radiation generation has attracted a wide-spread interest in the scientific community due to potential applications of these waves in medical and biological imaging, remote sensing, material characterization, explosive detection, and outer space communication (Pickwell *et al.*, 2006; Zhong *et al.*, 2006; Beard *et al.*, 2002; Shen *et al.*, 2005). Conventional methods using semiconductors and electro-optic crystals were not efficient enough to achieve high energy pulses of terahertz radiation. Since then, various routes are proposed to generate strong electromagnetic wave in terahertz range by employing high power laser plasma interaction. Plasma as a nonlinear media for terahertz generation has an added advantage of not having damage limit. Hamster *et al.* (1993) observed a high power terahertz radiation from a plasma short pulse produced by laser, employing 1 TW, 100 fs laser beam focused on gas and solid targets. They also observed terahertz radiation in a laser induced plasma channel where ponderomotive force drives radiations (Hamster *et al.*, 1994). Antonsen *et al.* (2007) examined the ponderomotive force driven THz radiation generation in a plasma with space periodic axial density variation.

Gildenberg *et al.* (2007) proposed a novel scheme of employing a femtosecond laser pulse on a low density gas jet target. In this model, the laser quickly tunnel ionizes the gas in the axial region. Electrons born inside the pulse retain finite transverse momentum after the passage of the pulse and set in oscillations of the electron plasma cylinder with respect to the ion cylinder, producing THz radiation at the frequency of oscillation $\omega_p/\sqrt{2}$, where ω_p is the plasma frequency of the cylinder. Liu *et al.* (2009) derived a scheme for producing tunable teraheartz radiation using a short pulse laser to tunnel ionize a gas jet immersed in a magnetic field. Tripathi *et al.* (2010) proposed that a two-dimensional amplitude modulated laser propagating in a ripple-density plasma can resonantly excite THz radiation at the modulation frequency $\Omega = \omega_p/\sqrt{2}$. Du *et al.* (2011) investigated the THz radiation generation from two color laser pulse interaction with gas targets using Ammosov-Delone-Krainov ionization model. Hu *et al.*

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(2010) proposed a scheme to improve the intensity of THz radiation, which is emitted from a single laser filament through transition-Cherenkov radiation mechanism.

Pathak *et al.* (2009) employed the free electron laser concept in a rippled density plasma and looked for the possibility of radiation generation in the THz range. A weakly relativistic electron beam propagating through a rippled underdense plasma couples with a seed terahertz signal to produce a space charge beam mode. This beam mode beats with density ripple and generates a coherent electromagnetic wave in the THz frequency range in forward direction. For an electron beam with 5 MW power, they proposed ~40 kW at 1 THz frequency. Tripathi *et al.* (1990) proposed a mechanism for short wavelength electromagnetic wave generation in a periodic dielectric material. When a moderately energetic electron beam passes through a periodic dielectric along with a copropagating electromagnetic wave, the latter gets amplified. Kumar *et al.* (2010) have studied the excitation of THz plasmons Eigen mode by a relativistic sheet electron beam propagating through a parallel plane guiding semiconductor system. They achieved a growth rate of 5.93×10^8 rad/s at a frequency of 0.51 THz of surface plasmons for a beam current of 168 A.

The presence of magnetic field may strongly influence the nonlinear interaction of short pulse high intensity lasers with plasma, because magnetized plasma may support various new modes depending upon the orientation of magnetic field with respect to the incident laser. Verma *et al.* (2011) obtained the mode structure of right circularly polarized nonlinear laser Eigen mode in a self created plasma channel in the presence of an axial magnetic field, and observed that the presence of magnetic field modifies the Eigen frequency of the fundamental laser Eigen modes in stimulated Raman scattering. Paknezhad *et al.* (2011) studied the nonlinear effects in the interaction of high power short laser pulse with plasma up to third-order nonlinearity in the presence of external magnetic field. They show an increase in the growth rate of Raman backward instability due to cyclotronic motion of plasma electrons in the external magnetic field. Ghorbanalilu *et al.* (2012) studied the conversion of a fraction of a laser beam to its second and third harmonics into a transversely magnetized plasma. The harmonic radiation cut-off when magnetic field increases to saturation strength. Verma *et al.* (2009) shown the effect of the azimuthal magnetic field to generate laser second harmonic in a rippled density plasma and found that, as magnetic field increases, generation of second harmonic becomes faster. In a similar fashion, the amplitude and energy conversion efficiency of terahertz radiation generation may also be enhanced by utilizing cyclotron resonance condition for maximum energy transfer in magnetized plasma.

In the present paper, we study terahertz generation by beating of two extra-ordinary lasers in rippled density magnetized plasma. The static magnetic field $\vec{B}_s$ is perpendicular to the direction of laser propagation, while the ripple wave vector is parallel to the laser wave vector (Fig. 1). Due to

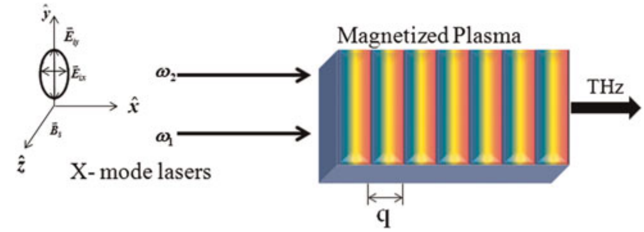

Fig. 1. (Color online) Schematic of beat excitation of terahertz radiation in the presence of transverse static magnetic field $\vec{B}_s$.

the presence of a static magnetic field in the direction of the laser propagation, there are components of nonlinear ponderomotive force in the direction of the lasers and perpendicular to it. In the presence of corrugation in the plasma density (space-periodic plasma density structure), the ponderomotive force gives rise to an oscillatory current that oscillates at beating frequency of lasers, which produces terahertz radiation. The density ripple of suitable wave number turns the process to be a resonant one.

The organization of this paper is as follows: the model equations for THz radiation generation by beating of two extra-ordinary lasers are derived in Section 2. In the same section, amplitude and efficiency of THz radiation generation are also calculated. Section 3 is devoted for discussion.

2. TERAHERTZ RADIATION GENERATION DUE TO LASER BEATING

Consider a laser produced rippled plasma of density $n_0 = n_0^0 + n_q$, $n_q = n_{q_0} e^{iqx}$ with static magnetic field $B_s\hat{z}$, where n_{q_0} is the amplitude of ripple, and q is the periodicity of the density ripple, structure. These plasma density ripples can be produced using various techniques involving transmission ring grating and patterned mask, where the control of ripple parameters might be possible by changing groove period, groove structure and duty cycle in such a grating, and by adjusting the period and the size of mask (Kuo *et al.*, 2007; Malik & Nishida, 2011; Malik & Stroth, 2011; Bhasin *et al.*, 2009; Layer *et al.*, 2007; Malik *et al.*, 2012). Two x-mode lasers co-propagate through it along the $\hat{x}$-direction with electric field:

$$\vec{E}_j = \left(\hat{y} - \frac{\epsilon_{jxy}}{\epsilon_{jxx}}\hat{x}\right) A_{0j} e^{-i(\omega_j t - k_j x)}, \tag{1}$$

where

$$k_j = \frac{\omega_j}{c}\left(1 - \frac{\omega_p^2}{\omega_j^2}\frac{\omega_j^2 - \omega_p^2}{\omega_j^2 - \omega_p^2 - \omega_c^2}\right)^{1/2}, \quad j = 1, 2.$$

Here, $\omega_p = \sqrt{n_0 e^2/\epsilon_0 m}$ and $\omega_c = eB_s/m$ are the electron plasma frequency and electron cyclotron frequency, respectively; $-e$ and m are electronic charge and mass, respectively; and $\varepsilon_{jxx} = [1 - (\omega_p^2/\omega_j^2 - \omega_c^2)]$ and $\epsilon_{jxy} = -i$

$[\omega_c\omega_p^2/\omega_j(\omega_j^2-\omega_c^2)]$ are components of the dielectric tensor ε_j. Lasers impart oscillatory velocities to plasma electrons, given by

$$\begin{aligned} v_{jx} &= +\frac{eE_{jy}}{m(\omega_j^2-\omega_c^2)}\left(\omega_c + i\omega_j\frac{\epsilon_{jxy}}{\epsilon_{jxx}}\right),\\ v_{jy} &= -\frac{eE_{jy}}{m(\omega_j^2-\omega_c^2)}\left(i\omega_0 + \omega_c\frac{\epsilon_{jxy}}{\epsilon_{jxx}}\right). \end{aligned} \tag{2}$$

Lasers beat together and exert a ponderomotive force F_p on plasma electrons at frequency $\omega=\omega_1-\omega_2$ and wave vector $\vec{k}=\vec{k}_1-\vec{k}_2$.

Given by,

$$\vec{F}_p = -e(\vec{v}\times\vec{B}) - m(\vec{v}\cdot\nabla\vec{v}) \tag{3}$$

Substituting values of $\vec{v}_1$ and $\vec{v}_2$ in Eq. (3), we obtain the x and y components of the ponderomotive force, as follows:

$$\begin{aligned} F_{px} &= \frac{e^2}{2mi(\omega_2^2-\omega_h^2)}\left[\frac{\omega_c^2}{(\omega_1^2-\omega_h^2)}(k_2+k_1)\right.\\ &\left.+\frac{(\omega_2^2-\omega_p^2)}{\omega_1\omega_2}k_1 - \frac{(\omega_1^2-\omega_p^2)(\omega_2^2-\omega_h^2)}{\omega_1\omega_2(\omega_1^2-\omega_h^2)}k_2\right]A_{1y}A_{2y}^*, \end{aligned}$$

and

$$\begin{aligned} F_{py} &= \frac{e^2}{2mi(\omega_2^2-\omega_h^2)}\left[-\frac{\omega_c(\omega_2^2-\omega_p^2)}{\omega_2(\omega_2^2-\omega_h^2)}k_2 + \frac{\omega_c(\omega_1^2-\omega_p^2)}{\omega_1(\omega_1^2-\omega_h^2)}k_1\right.\\ &\left.+\frac{\omega_c}{\omega_1}k_1 - \frac{\omega_c(\omega_2^2-\omega_h^2)}{\omega_1(\omega_1^2-\omega_h^2)}k_2\right]A_{1y}A_{2y}^*, \end{aligned} \tag{4}$$

where, $\omega_h^2=\omega_p^2+\omega_c^2$. The ponderomotive force drives space charge oscillation at $\omega=\omega_1-\omega_2$ and wave number $(\vec{k}=\vec{k}_1-\vec{k}_2)$. Let the space charge potential of this mode be ϕ. The oscillatory velocity of electrons in the presence of static magnetic field due to space charge oscillations along with ponderomotive force is given by

$$\begin{aligned} v_x &= \frac{\omega}{m(\omega^2-\omega_c^2)}\left[-ek\phi + \frac{\omega_c}{\omega}F_{py} + iF_{px}\right],\\ &\text{and}\\ v_y &= \frac{\omega}{m(\omega^2-\omega_c^2)}\left[-iek\frac{\omega_c}{\omega}\phi + iF_{py} - \frac{\omega_c}{\omega}F_{px}\right]. \end{aligned} \tag{5}$$

The nonlinear velocity given by Eq. (5) along with continuity equations produce density perturbation given by $n=n^L+n^{NL}$, where

$$n^L = \frac{1}{4\pi e}k^2\chi\phi, \tag{6}$$

and

$$n^{NL} = \frac{in_0 k}{m(\omega^2-\omega_c^2)}F_{px}, \tag{7}$$

where $\chi=-\omega_p^2/(\omega^2-\omega_c^2)$. Linear density perturbation (n^L) is induced self consistently by space charge field and nonlinear density perturbation (n^{NL}) is the consequence of ponderomotive force. Here, density perturbation is assumed to be small as compared to the density ripple. Using the density perturbation $n=n^L+n^{NL}$ in the Poisson's equation $\nabla^2\phi=4\pi ne$, we obtain

$$\varepsilon\phi = -\frac{4\pi e}{k^2}n^{NL}, \tag{8}$$

where, $\epsilon=1+\chi$. One can rearrange Eq. (8) as follows:

$$\phi = -\frac{4\pi n_0 e}{mk(\omega^2-\omega_h^2)}\left[iF_{px} + \frac{\omega_c}{\omega}F_{py}\right]. \tag{9}$$

Substituting this value of ϕ in Eq. (5), we obtain

$$\begin{aligned} v_x &= \frac{\omega}{m(\omega^2-\omega_h^2)}\left[iF_{px} + \frac{\omega_c}{\omega}F_{py}\right],\\ &\text{and}\\ v_y &= -\frac{\omega F_{px}}{m(\omega^2-\omega_h^2)} + i\frac{(\omega^2-\omega_p^2)F_{py}}{m\omega(\omega^2-\omega_h^2)}. \end{aligned} \tag{10}$$

Oscillations at $(\omega, \vec{k}_1-\vec{k}_2)$ in the presence of density ripple $n_{q_0}e^{iqx}$ excite nonlinear current at $(\omega, \vec{k}_1-\vec{k}_2+q)$, which can be written as

$$\vec{J}^{NL} = -\frac{1}{2}n_{q_0}e\vec{v}_\omega e^{iqx}, \tag{11}$$

where, $\vec{v}_\omega$ is given by Eq. (10). It can be observed from Eq. (11) that J^{NL} varies as $\sim e^{-i(\omega t-kx)}$, where, $k=k_1-k_2+q$, and it is responsible for terahertz radiation generation. It is clear that, wave number q of density ripple is responsible for providing extra momentum in x-direction to achieve the resonance condition. The resonance condition can be tuned by varying plasma density and magnetic field (B_s). For strong THz radiation, plasma density ripples should be periodic, otherwise $k(=k_1-k_2+q)$ will exhibit non-periodic behavior; resonance condition can not be achieved and maximum energy transfer will not take place and consequently a weak field THz radiation will be generated. The wave equation governing the propagation of terahertz wave can be written as

$$-\nabla^2\vec{E} + \nabla.(\nabla.\vec{E}) = \frac{4\pi i\omega}{c^2}\vec{J} + \frac{\omega^2}{c^2}(\epsilon.\vec{E}), \tag{12}$$

where, ϵ is the plasma permittivity tensor at ω. Taking fast

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phase variations in the electric field profile of terahertz radiation as $\vec{E} = \vec{A}(x)e^{-i(\omega t - kx)}$, the wave equation governing the propagation of terahertz waves can be splitted into x and y components and rearranged as follows:

$$A_x = -\frac{4\pi i}{\omega \epsilon_{xx}} J_x^{NL} - \frac{\epsilon_{xy}}{\epsilon_{xx}} A_y, \quad (13)$$

and

$$\left[2ik\frac{\partial A_y(x)}{\partial x} + \frac{\omega^2}{c^2}\epsilon_{yy}A_y(x) - k^2 A_y(x)\right]e^{-i(\omega t - kx)} = -\frac{4\pi\omega}{c^2}J_y^{NL} - \frac{\omega^2}{c^2}\epsilon_{yx}A_x. \quad (14)$$

Substituting the value of A_x from Eq. (13) into Eq. (14), we obtain

$$2ik\frac{\partial A_y(x)}{\partial x}e^{-i(\omega t - kx)} + \left[\frac{\omega^2}{c^2}\left(\epsilon_{yy} + \frac{\epsilon_{xy}\epsilon_{yx}}{\epsilon_{xx}}\right) - k^2\right] A_y(x)e^{-i(\omega t - kx)} = -\frac{4\pi i\omega}{c^2}J_y^{NL} + \frac{4\pi i\omega}{c^2}\frac{\epsilon_{yx}}{\epsilon_{xx}}J_x^{NL}. \quad (15)$$

From Eq. (15), it can be observed that terahertz radiation generation demands to satisfy the following dispersion relation for exact phase matching condition in rippled magnetized plasma:

$$\frac{k^2c^2}{\omega^2} = \epsilon_{yy} + \frac{\epsilon_{xy}\epsilon_{yx}}{\epsilon_{xx}}. \quad (16)$$

This expression is the dispersion relation of x-mode terahertz radiation, which gives the following phase matching condition

$$q = \frac{\omega}{c}\left|\left(\epsilon_{yy} + \frac{\epsilon_{xy}\epsilon_{yx}}{\epsilon_{xx}}\right)^{1/2} - 1\right|. \quad (17)$$

This phase matching condition provides the estimate of periodicity of rippled structure and suggests that the maximum energy transfer from beating lasers to THz radiation will take place at resonance $\omega \simeq \omega_h$. In Figure 2a, we have plotted normalized periodicity of rippled structure (cq/ω_p) as a function of normalized THz wave frequency (ω/ω_p) and normalized cyclotron frequency, when $\omega_p/2\pi = 1$ THz and $\omega_1 = 2\times10^{14}$ rad/s (CO_2 laser). Periodicity of ripples q decreases with THz wave frequency, but increases with betatron frequency. The periodicity q attains maximum value as ω tends to ω_h. So, we can conclude that for the efficient energy transfer at resonance $\omega \simeq \omega_h$, the wavelength of density ripples $(\lambda_r = 2\pi/q)$ should be small corresponding to larger value of q i.e., sharp ripples at closer distances should be constructed for strong THz radiation. The excited THz radiation can propagate through the plasma as extra-ordinary electromagnetic wave only if its frquency lies in the two propagating regimes of extra ordinary wave in a plasma given by (1) $\omega_L < \omega < \omega_h$ and (2) $\omega > \omega_R$ where $\omega_L = \frac{1}{2}\left[-\omega_c + \sqrt{\omega_c^2 + 4\omega_p^2}\right]$ and $\omega_R = \frac{1}{2}\left[\omega_c + \sqrt{\omega_c^2 + 4\omega_p^2}\right]$. In the present scheme $\omega_c/\omega_p = 0.0 - 0.6$ and correspoding to this, variation of ω_L/ω_p, ω_R/ω_p, and ω_h/ω_p is shown in Figure 2b. Regions I and III are non-propagating regions and regions II and IV are propagating regions for the present scheme. It is clear from Figure 2b that, the frequency of THz radiation in the present sceme $\omega/\omega_p = 1.6 - 3.0$ lies in propagating regime IV. Thus excited THz radiation can easily move out of the plasma by propagating through it as extra-ordinary electromagnetic wave.

Substituting the phase matching condition in Eq. (15), we obtain the amplitude of THz radiation

$$|A_y| = \frac{n_{q_0}}{4n_0kc^2e}\frac{\omega\omega_p^2}{(\omega^2 - \omega_h^2)}\left[\left(\omega + \omega_c|\epsilon_{yx}/\epsilon_{xx}|\right)^2 f_{px}^2 + \left(\omega_c + \frac{\omega^2 - \omega_p^2}{\omega}|\epsilon_{yx}/\epsilon_{xx}|\right)^2 f_{py}^2\right]^{1/2} x, \quad (18)$$

where, $f_{px} = iF_{px}$ and $f_{py} = iF_{py}$. The normalized amplitude of terahertz radiation can be written as follows:

$$\left|\frac{A_y}{A_1}\right| = \frac{(n_{q_0}/n_0)}{4(kc/\omega)}\frac{(\omega x/c)\omega_p^2}{(\omega^2 - \omega_h^2)}\left[\left(\omega + \omega_c|\epsilon_{yx}/\epsilon_{xx}|\right)^2 G_x + \left(\omega_c + \frac{\omega^2 - \omega_p^2}{\omega}|\epsilon_{yx}/\epsilon_{xx}|\right)^2 G_y\right]^{1/2}, \quad (19)$$

where

$$G_{px} = \frac{\omega_2^2|v_2|^2}{4(\omega_2^2 - \omega_h^2)}\left[\frac{\omega_c^2}{(\omega_1^2 - \omega_h^2)}(k_2 + k_1) + \frac{(\omega_2^2 - \omega_p^2)}{\omega_1\omega_2}k_1 - \frac{(\omega_1^2 - \omega_p^2)(\omega_2^2 - \omega_h^2)}{\omega_1\omega_2(\omega_1^2 - \omega_h^2)}k_2\right]^2,$$

and

$$G_{py} = \frac{\omega_2^2|v_2|^2}{2(\omega_2^2 - \omega_h^2)}\left[-\frac{\omega_c(\omega_2^2 - \omega_p^2)}{\omega_2(\omega_2^2 - \omega_h^2)}k_2 + \frac{\omega_c(\omega_1^2 - \omega_p^2)}{\omega_1(\omega_1^2 - \omega_h^2)}k_1 + \frac{\omega_c}{\omega_1}k_1 - \frac{\omega_c(\omega_2^2 - \omega_h^2)}{\omega_1(\omega_1^2 - \omega_h^2)}k_2\right]^2.$$

This equation reveals that the normalized terahertz amplitude is directly proportional to the normalized amplitude of density ripples n_{q_0}/n_0, thus THz field increases on increasing ripple amplitude. Its explanation lies in Eq. (11); higher the ripple amplitude, greater the number of electrons involving in the generation of oscillatory nonlinear current. Higher number of charge carriers result into higher nonlinear current $(\vec{J}^{NL})$, which leads to more efficient THz radiation. Similar type of observations are made by Antonsen *et al.* (2007) who proposed that the phase matching requirements for efficient energy transfer from laser pulse to THz can be matched in a parabolic plasma channel (in radius) by z sequence of

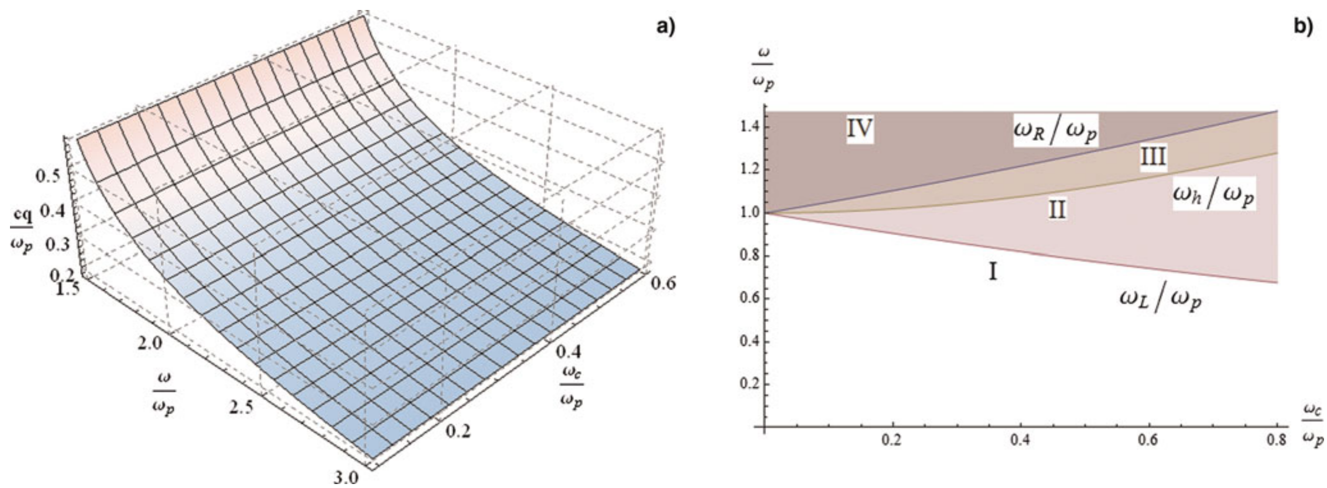

Fig. 2. (Color online) Plot of various parameters of THz radiation generation scheme by beat wave process. (**a**) Plot of the normalized ripple factor as a function of the nomalized frequency and normalized cyclotron frquency. (**b**) Sketch of the normalized frequency of THz radiation as a function of normalized cyclotron frquency. Lower, Middle and Upper lines are corresponding to ω_L/ω_p, ω_h/ω_p and ω_R/ω_p, respectively.

delta-function peaks with period d and strength Δ, in axial distance.

$$n_0(r, z) = n_{00}\left[1 + \frac{r^2}{2r_{ch}^2} + \Delta \sum_{l=-\infty}^{\infty} \delta(z - ld)\right].$$

Here, delta function type axial coagulated plasma density acts as ripples. This inhomogeneity couples with the density perturbation provided by ponderomotive force and gives rise to a nonlinear current responsible for THz generation.

It can be observed from Figure 3 that enhancement in THz wave amplitude is more pronounced, when THz frequency ω approaches the resonance condition $\omega \simeq 1.3\omega_p(\simeq \omega_h)$, and it can be attributed to the factor $(\omega^2 - \omega_h^2)$, present in denominator of Eq. (19). This factor is introduced in the potential ϕ of space charge mode of plasma due to the presence of perpendicular magnetic field. In the presence of magnetic field, the potential of space charge mode will achieve its peak value at $\omega \simeq \omega_h$ and energy transfer in beat wave process will be maximal. This maximally developed space charge mode along with density ripple give rise to strong nonlinear current

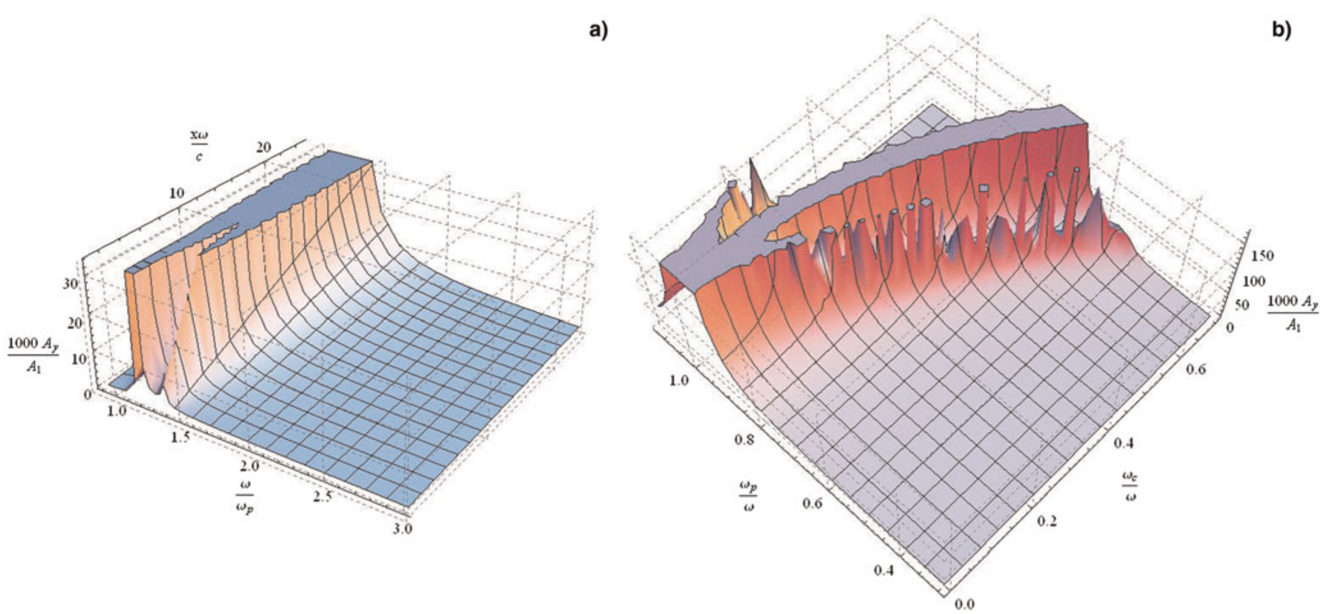

Fig. 3. (Color online) Diagram of THz amplitude radiation as a function of different parameters. (**a**) THz radiation field vs normalized frequency of beat and transverse distance when $n_{q_0}/n_0 = 0.2$ and $\omega_c/\omega_p = 0.6$. (**b**) Sketch of THz radiation field vs normalized frequency of beat and the cyclotron frequency when $n_{q_0}/n_0 = 0.2$.

responsible for maximum THz amplitude. The amplitude of THz wave decreases as one moves away from the resonance condition $\omega \simeq \omega_h$. For (approximately) $\omega < 1.3\omega_p$, $k^2 < 0$, so, the generation of THz does not take place. The amplitude A_y increases with the normalized distance (xc/ω) along propagation direction. THz wave attains maximum value for broader range of normalized frequency ω/ω_p with the increase of xc/ω values. In Figure 3b, we analyze simultaneous effects of electron plasma density and applied magnetic field on the amplitude of THz radiation. It can be observed that, a particular amplitude of THz radiation can be obtained in two ways: (1) either choosing higher value of magnetic field in a low density plasma or (2) choosing lower value of magnetic field at relatively higher density of plasma. This result is corresponding to resonant excitation of THz radiation. At resonance, $\omega^2 \sim \omega_h^2 \approx \omega_c^2 + \omega_p^2$, which gives us approximation condition for resonance as $\left(\omega_p^2/\omega^2\right) + \left(\omega_c^2/\omega^2\right) =$ constant. Thus, maximum amplitude is obtained when above condition is satisfied.

The efficiency of the THz radiation generation can be examined by calculating the ratio of the energies of THz radiation and the incident laser (pump). According to Rothwell *et al.* (2009), average electromagnetic energy per unit volume stored in electric and magnetic fields is given by

$$W_{Ei} = \frac{1}{2}\epsilon_0 \frac{\partial}{\partial \omega_i}\left[\omega_i\left(1 - \frac{\omega_p^2}{\omega_i^2}\right)\right]\langle |E_i|^2\rangle \tag{20}$$

and

$$W_{Bi} = \frac{\langle |B_i|^2\rangle}{2\mu_0} \text{ where } \langle B_i\rangle = \frac{k\langle E_i\rangle}{\omega_i}.$$

Using these expressions, we obtain the efficiency of the THz radiation as follows:

$$\begin{aligned}\eta &= \frac{W_{THz}}{W_{pump}} = \left|\frac{A_y}{A_1}\right|^2 \\ &= \left(\frac{(n_{q_0}/n_0)}{4(kc/\omega)}\frac{(\omega x/c)\omega_p^2}{(\omega^2 - \omega_h^2)}\right)^2 \Big[\left(\omega + \omega_c|\epsilon_{yx}/\epsilon_{xx}|\right)^2 G_x \\ &\quad + \left(\omega_c + \frac{\omega^2 - \omega_p^2}{\omega}|\epsilon_{yx}/\epsilon_{xx}|\right)^2 G_y\Big]\end{aligned} \tag{21}$$

In Figure 4, we have plotted the efficiency of THz radiation generation as a function of normalized beat frequency, normalized magnetic field, and normalized density ripple. Maximum efficiency is achieved at resonance condition and decreases sharply as one moves away from the resonance condition (Fig. 4a). The maximum efficiency at resonance increases with the ripple amplitude because number of electrons involved in the generation of oscillatory nonlinear current (leading to THz radiation generation) increases on increasing ripple amplitude (Fig. 4b).

All the dimensionless parameters are chosen for CO_2 laser ($\lambda = 1.06 \times 10^{-5}$ m), having frequency $\omega_1 = 2 \times 10^{14}$ rad/sec and intensity $I_L = 2 \times 10^{15}$ Wcm^{-2}. We have chosen the electron plasma frequency $\omega_p = 2\pi \times 10^{12}$ Hz, which is corresponding to the electron plasma density $n_0^0 = 1.78 \times 10^{19}\text{m}^{-3}$. Density ripple amplitude n_{q_0} is $3.53 \times 10^{18}\text{m}^{-3}$ for $n_{q_0}/n_0^0 = 0.2$. The value of applied magnetic field B_S lies in a range of $36 - 215$ kG corresponding to $\omega_c/\omega_p = 0.1 - 0.6$. Such magnetic fields can be generated by typical electric circuit having current carrying coil with magnetic core.

3. DISCUSSION

A magnetized rippled density plasma can resonantly excite terahertz waves by the beating of two x-mode lasers of

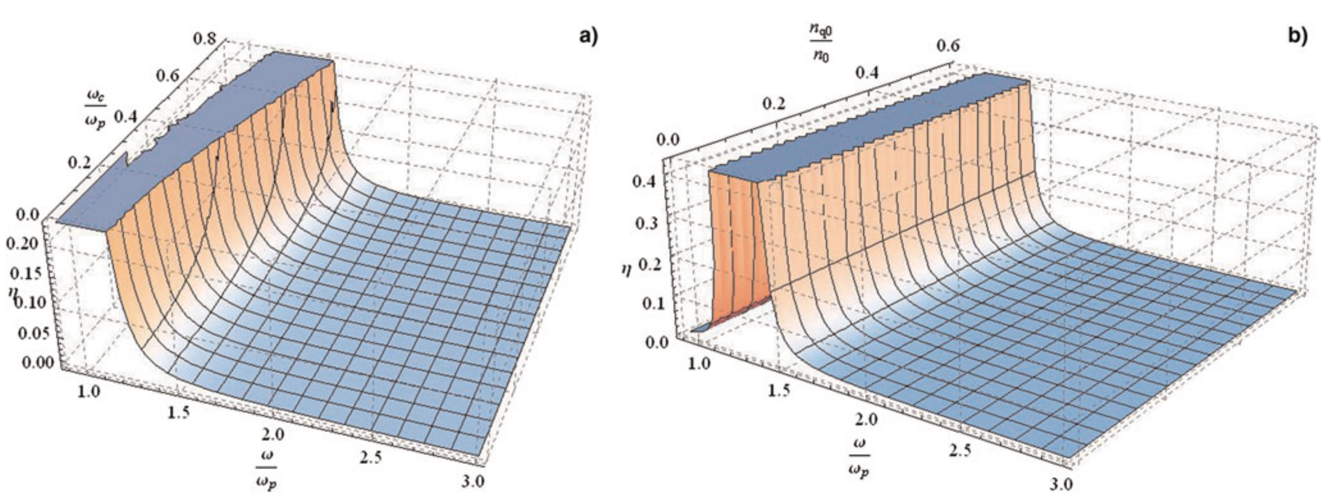

Fig. 4. (Color online) Diagram of the efficiency of THz as a function of different parameters. (**a**) Figure of efficiency of THz radiation vs normalized frequency and applied magnetic field when normalized distance $X = 10$. (**b**) Sketch of efficiency of THz radiation vs normalized frequency and normalized riple density amplitude when normalized distance $X = 10$ and applied magnetic field $\omega_c = 0.6$.

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frequencies in upper hybrid range when the periodicity of ripples satisfies the required phase matching conditions. The required ripple wave number for terahertz radiation generation increases as the magnetic field increases and decreases as the terahertz frequency increases. Thus, THz radiation frequency can be easily tuned by varying plasma density and applied magnetic field. The terahertz radiation amplitude scales directly to the density rippled amplitude and at the same time, THz efficiency is maximized as frequency (ω) approaches to resonance frequency ($\approx \omega_h$).

In this model, magnetic field plays two roles. It controls the phase velocity and group velocity of beating lasers on one side and the polarization of generated THz wave on the other. In case of Gaussian lasers, it will also affect the self focusing of laser beam as well as the geometry of THz wave (Sharma *et al.*, 2010). It may be mentioned that two long laser pluses are not necessary for THz generation. Instead, one could employ a single laser pulse of duration comparable to the inverse of the frequency of THz. Bhasin *et al.* (2009) have considered a scheme of resonant THz radiation generation by the optical rectification of a picosecond laser pulse in a rippled density magnetized plasma. The terahertz power scales as the square of density ripple amplitude and rises with magnetic field strength (similar to present scheme). But, the power conversion efficiency of this scheme is one order less as compared to present scheme.

The efficiency of the present scheme is much better than those of other investigators. For example, Sheng *et al.* (2008) reported theoretical as well as numerical simulation of powerful THz emission using inhomogeneous plasma density. In their model, the maximum energy conversion efficiency at peak intensity $5.48 \times 10^{12}\ \mathrm{W/cm^2}$ is 0.0005, which is much lower than present model. Malik *et al.* (2012) have reported the conversion efficiency $\sim$0.002 by beating of two spatial-Gaussian lasers; whereas in our case, the conversion efficiency is $\sim$0.015 where we use two x-mode lasers. Kim *et al.* (2008) proposed a model for the generation of THz radiation by irradiating different gases with a symmetry-broken laser field composed of the fundamental and second harmonic laser pulses. In that model, the energy conversion efficiency was $\sim 10^{-5}$, which is two order lesser as compared to present model. Hamester *et al.* (1993) also obtained the efficiency $\sim 10^{-5}$ with a single laser that is Gaussian in space and time which is two order lesser as compared to the conversion efficiency of present scheme.

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