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Terahertz wave generation by beating of two spatial-Gaussian lasers in collisional plasma

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This paper revisits the resonant excitation of terahertz (THz) radiation by beating of two spatial-Gaussian laser beams shaving different frequencies and wave numbers but the same electric fields, where the ponderomotive force in the transverse direction is resulted due to the beating and spatial variation of the field of lasers. Effect of the electron-neutral collision frequency on the THz wave generation in the collisional plasma has been discussed.

1. Introduction

Terahertz (THz) wave lies between microwaves and infrared in the frequency spectrum (Pearson et al. 2011). The wide variety of possible applications utilizing THz wave, such as spectroscopy, biological imaging, medicine, industry, material characterization, topography and remote sensing (Ferguson and Zhang 2002; Malik et al. 2011), chemical and security identification (Shen et al. 2005; Zhong et al. 2006), etc. make the development of THz sources critical.

Lately, there exist a variety of THz sources many of which are available commercially. Small-scale sources include far-infrared (Crocker 1964) and quantum cascade lasers (Scamarcio et al. 1997), laser-driven THz antennae (Auston et al. 1984; Exter et al. 1989) and crystals (Jiang and Zhang 1999), and backward wave oscillators (Staprans et al. 1973). In general, bright THz sources are based on free-electron devices, for example, gyrotrons (Gold and Nusinovich, 1997) and free-electron lasers (Ramian 1992; Berryman et al. 1996; Bolotin et al. 2005). These can be large and relatively expensive to operate, therefore research into new THz sources continues (Leemans et al. 2003).

Different groups around the world have taken different schemes for generating THz sources (Blanchard et al. 2007; Zhao et al. 2012). In order to develop efficient THz sources, several schemes have been proposed. For example, tunable THz wave generation can be achieved by super-luminous laser pulse interaction with large band-gap semiconductors and electro-optic crystals (Faure et al. 2004), e.g. $LiNbO_3$, ZnSe, ZnTe, and GaSe.

Since the plasma can handle very high power and shows strong nonlinear effects (Pukhov 2002), several experiments have employed plasma as a medium for THz wave generation using sub-picosecond laser pulses and energetic electron beams (Leemans

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et al. 2004). THz wave generation by laser pulses in plasmas was first demonstrated by Hamster et al. (1993). The source of this wave is the current driven by the ponderomotive force of a laser pulse or electron beam. In order for this current to couple one or more electromagnetic modes of the plasma, the plasma density must be inhomogeneous, or there must be a strong background magnetic field (Yoshii et al. 1997). The transfer of energy from a driver to THz wave is limited by the fact that electromagnetic modes in a uniform plasma have superluminal phase velocities and so will quickly fall out of phase with the generated current, which travels with the driver at its group velocity (Pearson et al. 2011).

Malik et al. (2010) have investigated the THz generation by tunnel ionization of a gas jet with the help of superposed femtosecond laser pulses. Yugami et al. (2002) experimentally and Yoshii et al. (1997) have theoretically demonstrated THz wave generation when Cerenkov wake is excited in perpendicularly magnetized plasma. In other mechanisms also, the THz wave emission has been produced from the plasma and electron-beam based THz emitters, such as coherent waves from plasma oscillations driven by ultra-short laser pulses (Hamster et al. 1993), synchrotron wave from accelerated electrons (Carr et al. 2002), and transition radiation of electron beams (Abo-Bakr et al. 2003). Loffler and Roskos (2002) have used a static electric field for achieving enhanced THz wave field. Cook and Hochstrasser (2000) considered THz wave generation when the fundamental and second harmonic lasers of peak intensities $\sim 5 \times 10^{14}\,\mathrm{W/cm^2}$ are simultaneously focused into air; peak THz fields at 2 kV/cm have been observed by them at 2 THz frequency. Sheng et al. (2005a, b) have proposed a scheme in which a short pulse laser excites a large amplitude plasma wake field, which in the presence of axial density gradient produces wave at plasma frequency (ω_p) via mode conversion. Wu et al. (2007) have studied the effect of transverse magnetic field on this process and have found remarkable enhancement in the efficiency of THz generation. Antonsen et al. (2007) have proposed corrugated plasma channel for the phase matched THz wave generation by the ponderomotive force of a laser pulse. Assuming Gaussian profiles for the pump amplitude, Fedele et al. (1986) have reported radial electric field components generated by the propagation of two electromagnetic waves resonantly beating in plasma. The generation of radial field in the plasma beat wave excitation has also been shown by de Angelis et al. (1987) and Di Massa et al. (1990). In addition, Fedele et al. (1990) have obtained very small wavelength electromagnetic waves by using low energy electron beams. Malik et al. (2011) have proposed a scheme of THz wave generation by beating of two lasers with Gaussian envelopes in space, co-propagating in plasma having space-periodically modulated/corrugated density. Also, Malik et al. (2012) have proposed another (Malik et al. 2011) scheme of THz wave generation, in the presence of a static magnetic field perpendicular to the direction of the propagation of the lasers. Most of the mentioned plasmas addressed in this area have been assumed collisionless which is not true in real operation.

Malik and Malik (2011) have proposed a mechanism for the generation of tunable THz radiation under the application of two femtosecond laser pulses and an external magnetic field, where quick tunnel ionization is achieved that leads to higher plasma density evolution and large residual current for the efficient THz radiation generation. They have also proposed a uniform asymptotic theory of the free-space paraxial propagation of coherent flattened Gaussian beams in the limit of non-small Fresnel numbers. The pivotal role played by the error function in the mathematical description of the related wavefield is stressed (Borghi 2013). In the other work, they have proposed two super-Gaussian laser beams with different frequencies for obtaining

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more collimated THz radiation at a desired position based on their order/index and for enhancing the efficiency of the scheme by realizing stronger transient transverse current due to the spatial variation of their fields. For the laser intensity of $\sim 10 \times 14$ W/cm^2 and along with the application of a periodic density structure, a resonant excitation of the THz radiation is achieved together with the efficiency of scheme as $\sim$0.006 (Malik and Malik 2012).

The role of an external direct current (DC) magnetic field in tuning of the frequency and power of THz radiation and obtaining focused radiation is clarified in a beating process using two spatial-triangular lasers, where nonlinear ponderomotive force acting on the electrons provides oscillating current in longitudinal and transverse directions. The transient transverse current oscillating at the beating frequency produces THz radiations in extraordinary mode, when the beating frequency of lasers matches the upper hybrid frequency for the resonant excitation (Malik and Malik 2013).

To the best of our knowledge, THz wave characteristics of the collisional plasma have never been addressed in the plasma literature. In the present study, we have investigated the effect of the electron-neutral collision frequency on the THz wave generation by beating of two lasers with a Gaussian envelope in space, co-propagating along the z direction in the presence of periodically modulated plasma density with wave number α (parallel to the laser wave vector) in the collisional plasma.

The work is organized as follows: first of all, we studied nonlinear current due to the ponderomotive force developed because of beating of two Gaussian lasers of different frequencies and wave numbers in the collisional plasma. Further, we discussed the effect of the electron-neutral collision on the intensity of the THz emitted wave and the exact phase matching condition (as an input parameter) which its optimization is very important in the generation of the THz field.

2. Basic equations

Two Gaussian linear polarized (in the y direction) lasers of frequencies ω_1 and ω_2, with wave numbers k_1 and k_2 respectively, have been considered, co-propagating in the z direction within a collisional plasma. Further, a rippled density plasma, $n = n_0 + n'$ with $n' = n_\alpha e^{i\alpha z}$ has been assumed (see Fig. 1). Such plasma density ripples may be produced using various techniques involving patterned mask and transmissive ring grating, where control of the ripple parameters could be possible by changing of the period or structure of the groove or masks etc. (Hazra et al. 2004; Pai et al. 2005; Kuo et al. 2007; Layer et al. 2007).

Due to the variation of the lasers field amplitudes along the y axis, a transverse component of the nonlinear ponderomotive force might be created in the y direction, and the z component of the ponderomotive force could be provided by beating of two laser fields assumed as

$$\vec{E}_j = \hat{y} E_{\mathrm{L}} e^{\frac{-y^2}{a_0^2}} e^{i(k_j z - \omega_j t)} (j = 1, 2), \tag{1}$$

where a_0 is the beam width where the amplitude of the field becomes $1/e$ times of its maximum value. The oscillatory velocities $\vec{v}_j e\vec{E}_j/m(i\omega_j - \nu_{\mathrm{en}})$, which attained by the collisional plasma electrons due to the laser fields, can impart a ponderomotive force on the plasma electrons at the beat frequency (resonance frequency) $\omega = \omega_1 - \omega_2$ and

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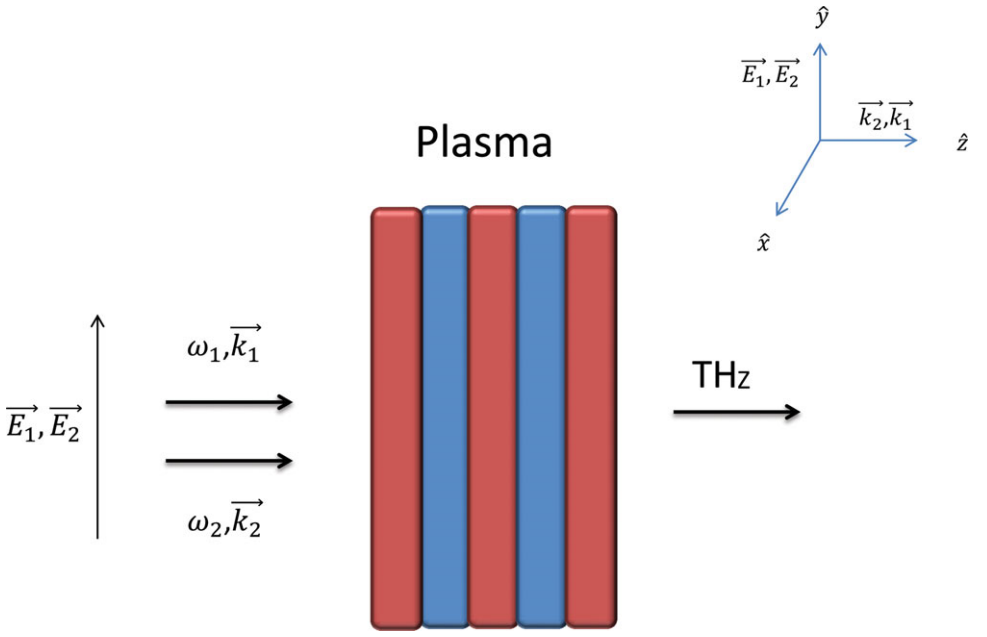


FIGURE 1. (Colour online) Two Gaussian lasers with different frequencies, co-propagating in the z direction in collisional plasma with rippled density.

wave number $k = k_1 - k_2$. The ponderomotive potential in collisional plasma could be given by

$$\varphi_p = -\frac{m}{2e}\vec{v}_1 \cdot \vec{v}_2^{*} = \frac{eE_{\mathrm{L}}^2}{2m(i\omega_1 - \nu_{\mathrm{en}})(i\omega_2 + \nu_{\mathrm{en}})} e^{-\frac{2y^2}{a_0^2}} e^{i(kz-\omega t)}. \tag{2}$$

Therefore, by $\vec{f}_p^{NL} = -\mathrm{e}\nabla\varphi_p$, the z and y components of the ponderomotive forces have been obtained as the following expressions:

$$\vec{f}_p^{\mathrm{NL}} \rightarrow \begin{cases} f_{p,z}^{\mathrm{NL}} = -\frac{ike^2E_{\mathrm{L}}^2}{2m(i\omega_1-\nu_{\mathrm{en}})(i\omega_2+\nu_{\mathrm{en}})} e^{-\frac{2y^2}{a_0^2}} e^{i(kz-\omega t)} \\ f_{p,y}^{\mathrm{NL}} = \frac{e^2E_{\mathrm{L}}^2}{2m(i\omega_1-\nu_{\mathrm{en}})(i\omega_2+\nu_{\mathrm{en}})a_0} \left(\frac{4y}{a_0}\right) e^{-\frac{2y^2}{a_0^2}} e^{i(kz-\omega t)} \end{cases}. \tag{3}$$

In the presence of a nonlinear ponderomotive force in this collisional plasma, the equations of motion and continuity of electrons, $\frac{\partial \vec{v}_1^{\mathrm{NL}}}{\partial t} = \frac{e\vec{\nabla}\varphi_p}{m} - \nu_{\mathrm{en}}\vec{v}_1$ and $\frac{\partial n_1^{\mathrm{NL}}}{\partial t} = -n_0\vec{\nabla}\cdot\vec{v}_1^{\mathrm{NL}}$, will be controlled nonlinear density perturbation, n_1^{NL}, and velocity perturbation, v_1^{NL}. Hence, the nonlinear density perturbation could be obtained as $n_1^{\mathrm{NL}} = -\chi_c n_0\vec{\nabla}\cdot\vec{f}_p^{\mathrm{NL}}/m\omega_p^2$, where $\chi_c = -\frac{\omega_p^2}{\omega(\omega - i\nu_{\mathrm{en}})}$ is the electric susceptibility of the collisional plasma at the lasers beat frequency ω in which $\omega_p = \sqrt{\frac{4\pi n_0 e^2}{m}}$ is the electron plasma frequency and ν_{en} is the electron-neutral collision frequency. This nonlinear density perturbation might result to a self-consistent space-charge potential φ at the lasers beat frequency ω and wave number k, inducing another linear self-consistent type of density perturbation, $n_1^L = -\chi_c\vec{\nabla}\cdot\vec{\nabla}\varphi/4\pi e$.

By inserting values of n_1^{L} and n_1^{NL} in Poisson's equation $\nabla^2\varphi = 4\pi e(n_1^{\mathrm{L}} + n_1^{\mathrm{NL}})$ and calculating the value of $\vec{\nabla}\varphi(\frac{4\pi n_0 e}{m\omega^2\varepsilon_c}\vec{f}\,p^{\mathrm{NL}})$, where $\varepsilon_c = 1 - \chi_c$, we could obtain the

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electrostatic potential φ in terms of the ponderomotive force $\vec{f}_p^{NL}$ as the main source of plasma perturbation (Bhasin and Tripathi 2009).

In order to calculate the electron velocity, equation of motion, by taking into account the contribution of self-consistent electric force, $e\vec{\nabla}\phi$, the nonlinear ponderomotive force $\vec{f}_p^{NL}$ and electron-neutral collision force $m\nu_{en}\vec{v}$ must be used. With the help of the equation of motion,

$$\frac{\partial \vec{v}^{\mathrm{NL}}}{\partial t} = \frac{e\vec{\nabla}\varphi}{m} + \frac{\vec{f}_p^{\mathrm{NL}}}{m} - \nu_{\mathrm{en}}\vec{v}, \tag{4}$$

the nonlinear velocity perturbation will be achieved as the below expression:

$$\vec{v}^{\mathrm{NL}} = \frac{-\omega^3 + i\nu_{\mathrm{en}}\left(\omega^2 - \omega_p^2\right)}{m\omega\left(\omega^2 - \omega_p^2 - i\nu_{\mathrm{en}}\omega\right)(i\omega - \nu_{\mathrm{en}})}\vec{f}_p^{\mathrm{NL}}. \tag{5}$$

Nonlinear current density could be obtained according to the following equation:

$$\vec{j}^{\mathrm{NL}} = -\frac{1}{2}n'e\vec{v}^{\mathrm{NL}}. \tag{6}$$

Assuming density perturbation to be small enough, n_1^{L} and $n_1^{\mathrm{NL}} \ll n'$ so that (6) shows that the current density $\vec{j}^{\mathrm{NL}}$ varies in accordance to $\vec{f}_p^{\mathrm{NL}}$, i.e. $\sim e^{i(kz-\omega t)}$. Since $\vec{j}^{\mathrm{NL}}$ is responsible for the generation of THz wave, the THz field will vary as $\sim e^{i(kz-\omega t)}$. Applying Maxwell's equations for evaluating the THz emitted wave,

$$\vec{\nabla}(\vec{\nabla}\cdot\vec{E}_{\mathrm{THz}}) - \nabla^2\vec{E}_{\mathrm{THz}} = \frac{\omega^2}{c^2}\varepsilon_c\vec{E}_{\mathrm{THz}} + \frac{4\pi i\omega}{c^2}\vec{j}^{\mathrm{NL}}, \tag{7}$$

taking divergence of (7) will result to the following expression for the THz field $\vec{E}_{\mathrm{THz}} = -\frac{4\pi i}{\omega\varepsilon_c}\vec{j}^{\mathrm{NL}}$, and making use of $\vec{j}^{\mathrm{NL}}$ could give the following normalized THz field:

$$\left|\frac{E_{\mathrm{THz}_y}}{E_{\mathrm{L}}}\right| = \frac{n_\alpha e E_0 y\omega_p^2}{n_0 m a_0^2\omega}\sqrt{\frac{\left[-\omega^6 + \left(\nu_{\mathrm{en}}\left(\omega^2 - \omega_p^2\right)\right)^2\right]}{\left(\omega_1^2 - \nu_{\mathrm{en}}^2\right)\left(\omega_2^2 + \nu_{\mathrm{en}}^2\right)\left(\left(\omega^2 - \omega_p^2\right)^2 + \nu_{\mathrm{en}}^2\omega^2\right)^2}}\, e^{-\frac{2y^2}{a_0^2}}. \tag{8}$$

In the rippled density plasma, the exact phase matching condition demands that $k' = k + \alpha = k_1 - k_2 + \alpha$ where $k'^2 - \frac{\omega^2}{c^2}\varepsilon_c = 0$. This condition also reads as

$$\frac{\alpha c}{\omega_p} = \frac{\omega}{\omega_p}\left[\sqrt{1 - \frac{\omega_p^2}{\omega\left(\omega - i\nu_{\mathrm{en}}\right)}} - 1\right]. \tag{9}$$

This equation specifies that $Re(\frac{\alpha c}{\omega_p})$ is the normalized period of the rippled density structure or the periodicity which plays an important role in THz wave generation.

3. Results and discussions

Here, we have studied the effect of the electron-neutral collision in a scheme of THz radiation generation by beating of two lasers with a Gaussian envelope in space, co-propagating along the z direction in the presence of periodically modulated or corrugated plasma density with wave number α (parallel to the laser wave vector), when $\omega_1 = 2.4 \times 10^{14}$ rad/s, $\omega_p = 2 \times 10^{13}$ rad/s, $a_0 = 0.1$ mm, $v_2 = 0.3c$,

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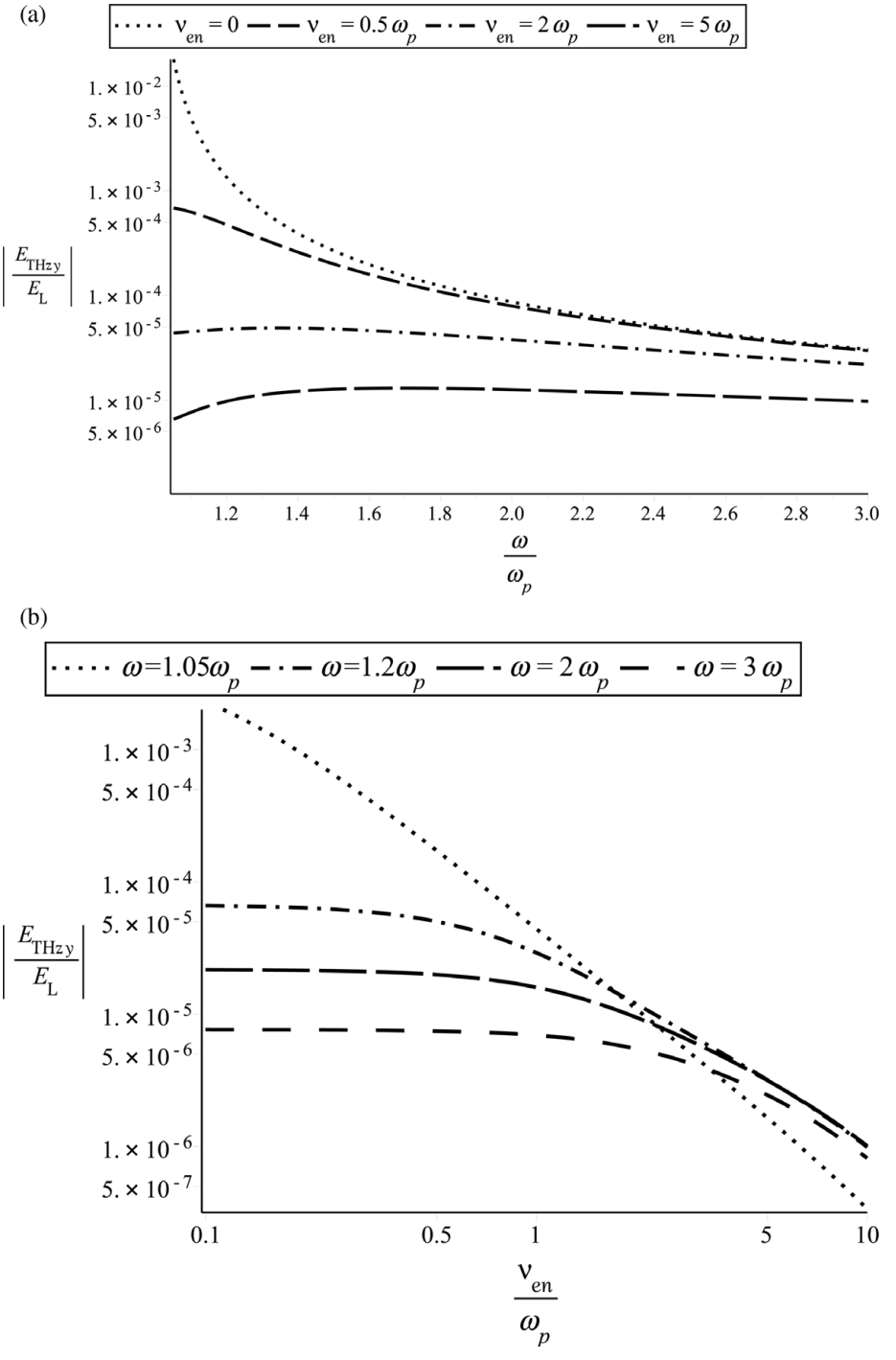


FIGURE 2. Normalized field of the emitted THz radiation *vs.* normalized beat wave frequency ($\frac{\omega}{\omega_p}$) for different values of the normalized collision frequency ($\frac{\nu_{en}}{\omega_p}$) ($\nu_{en} = 0$, refer to non-collisional plasmas (Malik et al. 2011)); (a) normalized field of the emitted THz radiation *vs.* normalized collision frequency ($\frac{\nu_{en}}{\omega_p}$) for different values of the normalized beat wave frequency ($\frac{\omega}{\omega_p}$); (b) when $\omega_1 = 2.4 \times 10^{14}$ rad/s, $\omega_p = 2 \times 10^{13}$ rad/s, $a_0 = 0.4$ mm, $v_2 = 0.3c$, $\frac{n_\alpha}{n_0} = 0.3$, and $y/a_0 = 0.9$.

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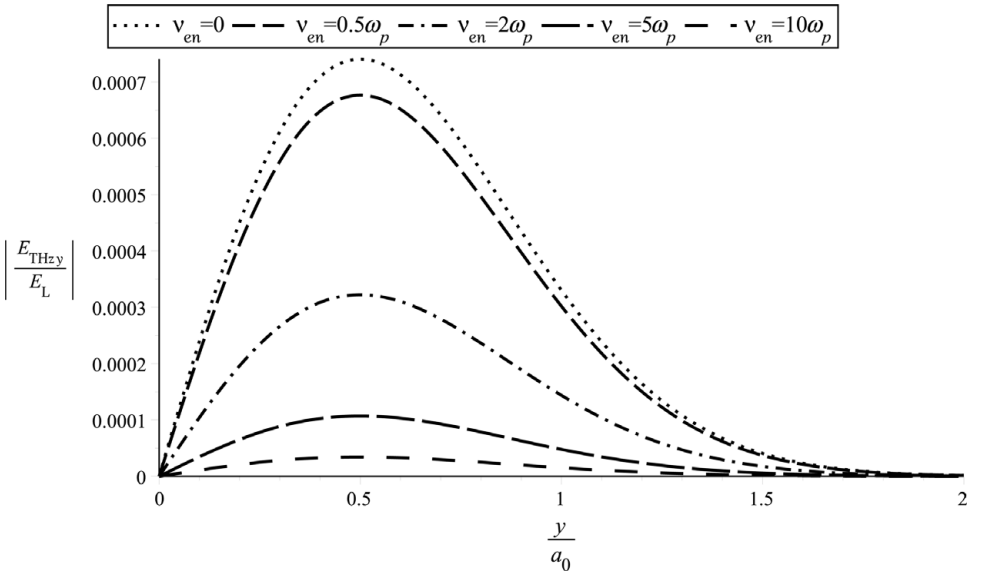


FIGURE 3. Normalized THz radiation field *vs.* transverse distance ($\frac{y}{a_0}$) from z axis for different values of the collision frequencies when $\omega_1 = 2.4 \times 10^{14}$ rad/s, $\omega_p = 2 \times 10^{13}$ rad/s, $a_0 = 0.4$ mm, $v_2 = 0.3c$, $\frac{n_\alpha}{n_0} = 0.3$ and $y/a_0 = 0.9$ ($\nu_{en} = 0$, refer to non-collisional plasmas (Malik et al. 2011)).

$\frac{n_\alpha}{n_0} = 0.3$, and $y/a_0 = 0.9$. Due to the intensity variation in the transverse direction, i.e. along the y axis (see Fig. 1), there are components of nonlinear ponderomotive force parallel and perpendicular to the direction of the propagation of the lasers. In the presence of corrugation in the plasma density, the ponderomotive force gives rise to an oscillatory current that oscillates at the beating frequency of the lasers.

Figure 2(a) depicts the amplitude of the emitted THz radiation as a function of the normalized beat wave frequency ($\frac{\omega}{\omega_p}$) for different values of the normalized collision frequency ($\frac{\nu_{en}}{\omega_p}$). Comparing the results with the conclusion of the previously published paper in which plasma has been assumed collisionless (Malik et al. 2011), i.e. $\nu_{en} = 0$, shows that the amplitude of the emitted THz radiation decreases with the increase of normalized beat wave frequency. In low beat wave frequency ($\frac{\omega}{\omega_p} \approx 1$), it might be found that the amplitude of the emitted THz radiation strongly depends on the collision frequency, but this dependency decreases with increasing of the beat wave frequency. This latter result could be apparently seen in Fig. 2(b). The effect of the collision frequency on the amplitude of the emitted THz radiation for different beat wave frequencies has been shown in Fig. 2(b). It would be seen that the increasing of the collision frequency from 0.1 to 1 could not evidently change the amplitude of the emitted THz radiation at high beat wave frequency ($\frac{\omega}{\omega_p} > 2$).

In Fig. 3, the profile of the amplitude of the THz radiation as a function of the transverse distance ($\frac{y}{a_0}$) for different values of the normalized plasma collision frequency ($\frac{\nu_{en}}{\omega_p}$) can be seen. It can be noted that the THz amplitude attains its maximum value at a particular value of $\frac{y}{a_0}$, i.e. slightly away from the z axis. One could see that the maximum value of the THz amplitude decreases with increasing

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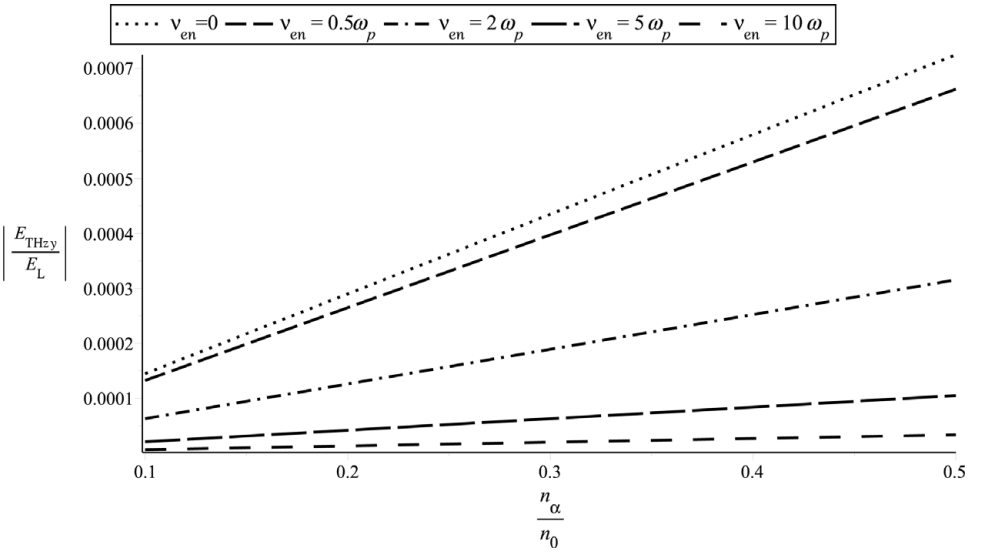


FIGURE 4. Normalized THz radiation field *vs.* normalized density ripple for different values of the collision frequencies when $\omega_1 = 2.4 \times 10^{14}$ rad/s, $\omega_p = 2 \times 10^{13}$ rad/s, $a_0 = 0.4$ mm, $v_2 = 0.3c$, and $y/a_0 = 0.9$ ($\nu_{en} = 0$, refer to non-collisional plasmas).

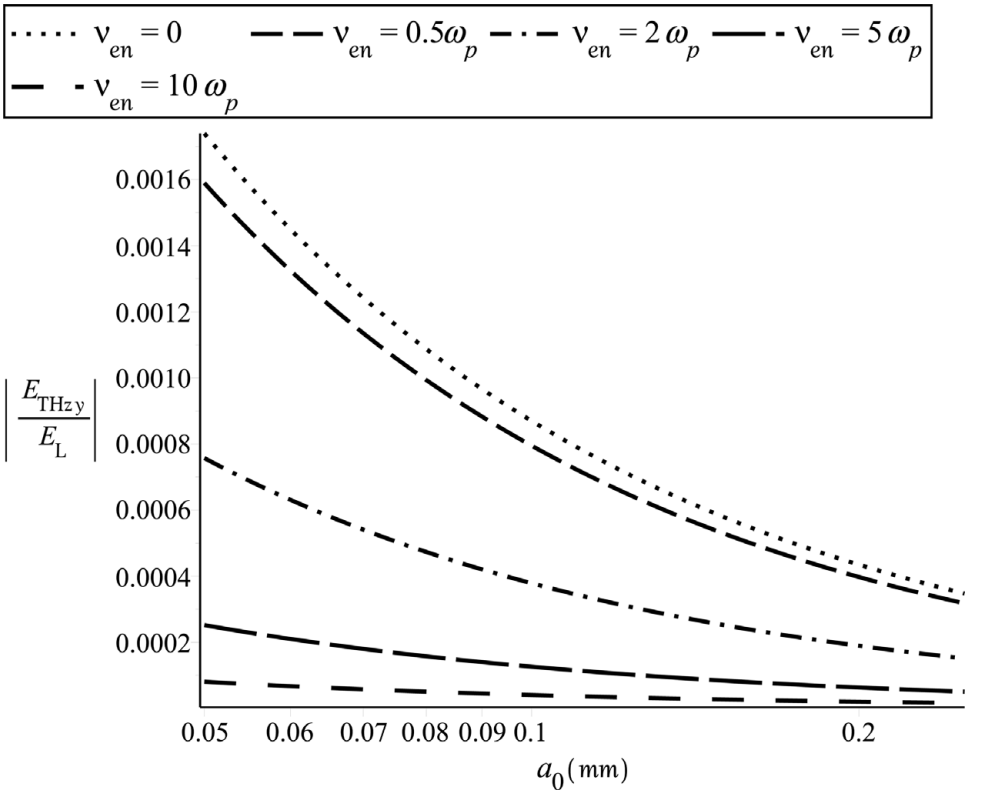


FIGURE 5. Normalized THz radiation field *vs.* laser beam width (a_0) for different values of the collision frequencies when $\omega_1 = 2.4 \times 10^{14}$ rad/s, $\omega_p = 2 \times 10^{13}$ rad/s, $a_0 = 0.4$ mm, $v_2 = 0.3c$, $\frac{n_\alpha}{n_0} = 0.3$ and $y/a_0 = 0.9$ ($\nu_{en} = 0$, refer to non-collisional plasmas (Malik et al. 2011)).

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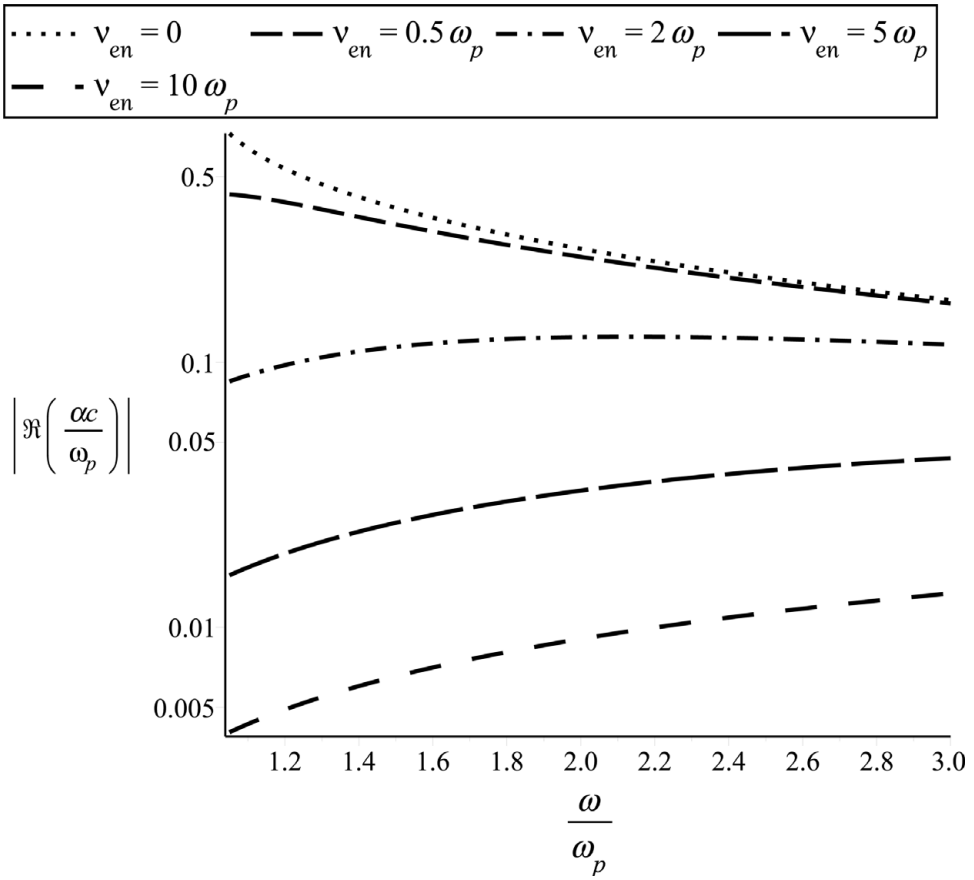


FIGURE 6. Dependency of THz radiation generation efficiency on the normalized beat wave frequency ($\frac{\omega}{\omega_p}$) for different values of the normalized collision frequency ($\frac{\nu_{en}}{\omega_p}$).

of the collision frequency. Again, comparison of the results with the conclusions of the previous paper in the presence of collisionless plasma (Malik et al. 2011) shows that the maximum value of the THz field is very sensitive to the transverse distance, but in collisional plasma, this sensitivity of the amplitude profile to the transverse distance decreases with increasing of the collision frequency.

In Fig. 4, we have studied the amplitude of the emitted THz radiation versus the rippled density amplitude (n_α) at different values of the normalized collision frequency ($\frac{\nu_{en}}{\omega_p}$). It could be seen that THz amplitude increases linearly by increasing of the rippled plasma density amplitude, which is an apparent conclusion of (8), but the important matter is that increasing of the value of the collision frequency could change (decrease) the slope of the profile.

In Fig. 5, the amplitude of the emitted THz radiation as a function of the laser beam width (a_0) at different normalized collision frequencies has been depicted. It can be seen that the THz amplitude increases by decreasing the laser beam width. Also, this effect in plasma with low collision frequency is stronger than in plasma with high collision frequency.

Figure 6 shows the normalized period of the rippled density structure with respect to the normalized beat wave frequency ($\frac{\omega}{\omega_p}$) at different values of the normalized

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collision frequency ($\frac{\nu_{en}}{\omega_p}$). It can be noted that in the case with no collision, i.e. $\nu_{en} = 0$, the normalized period of the rippled density structure decreases by increasing of the normalized beat wave frequency, but in plasma with high values of the collision frequency it's vice versa, i.e. for having the best exact phase the normalized period of the rippled density structure must be increased by increasing of the normalized beat wave frequency.

4. Conclusion

The effect of the electron-neutral collision on the THz radiation generation by beating of two spatial-Gaussian lasers, co-propagating along the z direction in the presence of periodically corrugated plasma density with wave number α (parallel to the laser wave vector) has been discussed. From above results and discussions, it might be concluded that

1. In low beat wave frequency ($\frac{\omega}{\omega_p} \approx 1$), it's found that the amplitude of the emitted THz radiation strongly depends on the collision frequency, but this dependency decreases with increasing of the beat wave frequency.
2. In collisional plasma, the sensitivity of the amplitude profile to the transverse distance decreases by increasing of the collision frequency.
3. Terahertz amplitude increases linearly by increasing of the beat wave frequency, which is strongly dependent upon the value of the plasma collision frequency.
4. Terahertz amplitude increases by decreasing of the laser beam width. This effect in plasma with low collision frequency is stronger than in plasma with high collision frequency.
5. For having the best exact phase matching, the normalized period of the rippled density structure should be increased by increasing of the normalized beat wave frequency.

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