Terahertz Field Excitation from a Plasma Slab with Laser Pulse Interaction

By
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Himank Sagar

DECLARATION

In accordance, I herewith certify that the document titled “Excitation of Terahertz Fields by Interaction of Lasers Pulses with a Plasma Slab,” submitted in partial fulfillment of the requirements of Master of Physics course in the Department of Applied Physics, Delhi Technological University, Delhi, is a true and correct representation of my own work. The experiment was performed during the period of August to December 2022 under the guidance of Prof. Suresh C. Sharma and Prof. D. N. Gupta. I also hereby state that I have not used the results of this experiment elsewhere or submitted the same towards another degree anywhere.

Himank Sagar

SUPERVISOR CERTIFICATE

As far as I know, the above project has not been submitted partially or wholly for the award of any degree or diploma from this university or from any other university. I further confirm that the details regarding the publication and indexing of the students are correct.

Place: New Delhi
Date: 12th December,2022

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ABSTRACT

We consider the excitation of terahertz (THz) radiation using the interaction of a Gaussian laser pulse with a plasma slab. Using the properties of the Gaussian laser pulse, the terahertz radiation is produced in the plasma slab. It is found that the ponderomotive force produced by the laser causes oscillations of the plasma electrons' velocity, and the ponderomotive potential of the laser generates the terahertz radiation in the plasma slab. The dependency of the field excited on the axial and radial dimensions of the plasma slab, as well as the duration and spot size of the laser pulse, is considered. We have found that the amplitude of the excited field increases four times for a highly focused laser pulse. It is found that the excitation of the terahertz radial fields is most effective in the case of the generation frequency close to the plasma frequency and when the duration of the laser pulse is about the same as the axial dimension of the plasma slab.

KEYWORDS WITH EXPLANATION

Terahertz Field or Terahertz Radiation

THz radiation is a part of electromagnetic spectrum, which generally refers to far-infrared or submillimeter radiations also known as sub metric linear unit radiation, T-lux, T-light, T-waves, rate waves, high frequency T-rays or terahertz. The frequency range of 0.1-10 THz usually represents the terahertz wave, whereas, in terms of wavelength, 1THz=10^{12}Hz=1000GHz corresponding to 0.3 mm in free space or the photon energy corresponding to 1THz is 4.1 milli-electron-volt and temperature, T= 4.8 to 478K. Crystalline phonon vibrations, molecular rotations, rotations of low frequency bond, H-bond stretches and torsions are the main sources of THz radiation. Since, T-rays have too low photon energy for the ionization of materials as compared to X-rays. Therefore, they do not produce harmful free radicals for living cells which means much less likely to cause cancer and genetic mutations. Thus it has an advantage over most other ionising imaging modalities that are commonly used today such as MRI, PET, planar X-rays and X-ray CT-scans due to its non ionising property. Also terahertz has the ability to penetrate many millimetres therefore it is appropriate for diagnosis of burn and cancerous cells. T-rays can also penetrate non-conducting materials (such as plastic, papers, textiles and foams) so can be used in material characterization, security screening purpose, non-destructive industrial quality checks, and for the identification of concealed explosives, weapons and drugs. However, molecules of air (including water vapour) strongly absorb T-waves at various frequencies but fast data transmission is still possible at least over short distances like couple of meters. On the other hand, T-waves can be useful for communication at high altitude such as satellite to satellite, aircraft to satellite etc because it has line of sight propagation.

Gaussian Laser

A monochromatic electromagnetic beam that has a Gaussian transverse amplitude profile is known as a Gaussian beam. It is possible to create different types of profiles from this beam by using proper lenses that will help in refocusing and changing the transverse phase profile of the beam. Such types of profiles include but not limited to Cosh-Gaussian, Hermite-Cosh-Gaussian, Super Gaussian, Hollow-Gaussian, and so forth, all having certain properties and being used by scientists to study nonlinear physics. Due to wide scope of plasma physics and phenomena connected with it, it is impossible to compile all the necessary information in one document. That is why this report considers only a small part of electromagnetic waves and uses only Gaussian profile for the purposes of achieving the goals. In the case of the presence of Gaussian laser beam, there will be depletion of the plasma from high field region to low field regions as a result of the ponderomotive force. This results in the movement of plasma electrons in a nonlinear way, and therefore nonlinear current appears, generating terahertz radiation. The intensity of the incident laser beam has a great impact on laser-plasma interactions. Increased intensity of the beam means increased initial ionization of the plasma and also increased nonlinearity of the system due to stronger ponderomotive force. Therefore, increased free-electron density provides appearance of more powerful THz wave. It means that it is possible to control the output wave intensity by controlling the intensity of the incident laser beams. There is a direct dependence of the THz amplitude on the intensity of the incident laser beam. The physical background of this phenomenon is increased ponderomotive force in case of increased laser intensity, and, therefore, increased initial plasma ionization. With increasing free-electron density, the nonlinearity increases and, since THz generation is a nonlinear process, it also increases.

Plasma Frequency

Electron density is the density of the electron content in the plasma. An additional parameter called the critical density of the plasma is introduced in order to distinguish between underdense and overdense plasmas. The idea behind the theory is that the laser wave can travel through the plasma only when its frequency is larger than the plasma frequency. Hence, in underdense plasma, the electron density is smaller than the critical density, while in overdense plasma, the incident beam does not propagate because of the large electron density, since the frequency of the incident laser beam is smaller than the plasma frequency. We analyze the problem of underdense plasma in this paper. As discussed above, in order to generate THz waves efficiently, the frequency of the incident laser should be considerably larger than the plasma frequency (ωp), since ions can be considered as static in this case.

Ponderomotive Force

The ponderomotive force is a nonlinear force that acts on a charge particle in an inhomogeneous oscillating electromagnetic field. The ion density fluctuations that occur in a magnetized plasma lead to the coupling between the light wave and the electron plasma wave. In the interaction of light waves with plasmas, a large ion density fluctuation can be self-consistently created due to the variation in the electric field pressure created due to the beating of the electron plasma wave and light wave. Such a gradient in the field pressure leads to a force called the nonlinear ponderomotive force.

INTRODUCTION

Terhertz (THz)field exhibit several characteristics useful in various areas of engineering and science [1,2], industry [3], food-processing [4] and related technologies such as satellite communication, atmospheric sensing, security and imaging, etc. [5-11]. Plasma is preferred as a gaining medium over mostly used conductive materials for generating THz field as plasma is an ionized medium and can sustain high electric fields [12,13], whereas conductive materials damage and have breakdown problems. Therefore, laser-plasma interaction is one of most favoured mechanisms to produce terahertz fields. The interaction between the laser pulse and the plasma electrons generates a ponderomotive force, which produces THz fields due to the potential formed. THz field generation in a plasma slab depends on the laser pulse parameters as well as the plasma density. The ponderomotive potential of laser perturbs the electron plasma density, leaving behind a charge separation wave. The frequency of electrons oscillating in this charge separation wave is same as the plasma frequency and thus depends on the plasma density. A low-density plasma is therefore advantageous over the high-density plasma to excite THz fields, which becomes highly tunable [14] and desirable for many applications. Gaussian laser pulse has been used extensively for exciting THz field in plasma [15-18] as they stay collimated over long distances and their intensity distribution has minimum divergence [19].

The outline of this thesis is as follows: Firstly, the field equations are formulated for the Gaussian laser pulse using the fluid perturbation method under the quasi-static approximation. Secondly, the field equations for the THz pulse are obtained by means of the Maxwell's equations for the Gaussian laser pulse.

INSTABILITY ANALYSIS

Consider a plasma slab with electron density n_e, ion density n_i, electron mass m_e, ion mass m_i, electron charge -e and ion charge e. A laser pulse with carrier frequency ω_L is incident normally on the plasma slab along positive z-axis, with electric field in the form

$$E_L(r,t) = \frac{1}{2}\exp\left(-i\omega_L t + i\frac{\omega_L}{c}z\right)E_o(r,t), \tag{1}$$

where E_o (r,t) is the amplitude of laser field given as:

$$E_o(r,t) = E_{Lo}\exp\left(-\frac{\eta^2}{2L^2} - \frac{r^2}{2{R_L}^2}\right)\hat{x}. \tag{2}$$

Here, E_{Lo} is the maximum electric field amplitude, L is the laser pulse length and R_L is the focal spot radius of laser pulse. The laser pulse is linearly polarized along x-axis and is Gaussian with spatial coordinates given as: $\eta = z - ct$ and $r^2 = x^2 + y^2$.

The plasma frequency ω_p [$\omega_p = (4\pi n_e e^2 / m_e)^{1/2}$] is considered much smaller than the pulse carrier frequency ω_L , so that the plasma permittivity remains close to unity and the pulse propagates through the plasma slab without reflection.

The equation of motion governing the response of plasma electrons to laser pulse is:

$$\frac{\partial}{\partial t}\mathbf{V} = \frac{e}{m_e}\mathbf{E} - \frac{1}{m_e}\nabla\phi. \tag{3}$$

ϕ is the ponderomotive potential on electrons due to laser pulse averaged over high frequency oscillations given as:

$$\phi(r,t) = \frac{1}{2}m_e\left\langle {\mathbf{V}_L}^2\right\rangle, \tag{4}$$

where $\mathbf{V}_L = (e/m_e)\int_{-\infty}^{t} \mathbf{E}_L(\mathbf{r}, t')dt'$ is the electron velocity in laser field.

Using Eqn. (1), the ponderomotive potential may be expressed as:

$$\phi(r,t) = \frac{e^2}{4m_e\omega_L{}^2} |\mathbf{E}_o(r,t)|^2 . \tag{5}$$

The Maxwell's equations governing the motion are written as:

$$\nabla\times\mathbf{E} = -\frac{1}{c}\frac{\partial}{\partial t}\mathbf{B}, \tag{6}$$

$$\nabla\times\mathbf{B} = \frac{1}{c}\frac{\partial}{\partial t}\mathbf{E} + \frac{4\pi e}{c} n_e(z)\mathbf{V}. \tag{7}$$

where $n_e(z) = n_e$ in the plasma slab and vanishes out of the plasma slab in vacuum.

Taking curl of Eqn. (6) and using Eqns. (3) and (7), we get

$$\frac{\partial^2\mathbf{E}}{\partial t^2} + \omega_p{}^2(z)\mathbf{E} + c^2\nabla\times\nabla\times\mathbf{E} = \frac{\omega_p{}^2(z)}{e}\nabla\phi. \tag{8}$$

Using Eqns. (2) and (5) in eqn. (8), we get the transverse and axial electric field as

$$E_r(r,z,t) = \frac{2r\omega_p^2 eE_{Lo}^2}{\left[(\omega^2-\omega_p^2) + \frac{c^2}{L^2}\left(\frac{\eta^2}{L^2}-1\right)\right](4m\omega_L^2)R_L{}^2} \exp\left(-\frac{\eta^2}{L^2} - \frac{r^2}{R_L{}^2}\right), \tag{9}$$

and $$E_z(r,z,t) = \frac{2\eta\omega_p^2 eE_{Lo}^2}{\left[(\omega^2-\omega_p^2) + \frac{c^2\eta}{rL^2}\left(1-\frac{r^2}{R_L{}^2}\right)\right](4m\omega_L^2)L^2} \exp\left(-\frac{\eta^2}{L^2} - \frac{r^2}{R_L{}^2}\right). \tag{10}$$

RESULTS & DISCUSSION

We have used typical parameters of laser-plasma experiments for estimation of excited THz field. The laser length L varies from 15μm to 90 μm and the focal spot radius R_L takes the values 42 μm, 84 μm and 126 μm. Maximum amplitude of incident laser $E_{Lo} = 10^{10}$ V/m and pulse carrier frequency $\omega_L = 10^{15}$ Hz. The plasma electron density $n_e = 10^{17}$ cm^{-3}.

A ponderomotive potential is imposed on plasma electrons due to the ponderomotive force exerted by laser pulse. The ions do not contribute in this field excitation as they remain immobile due to their heavy mass as compared to electrons. Figure 1 shows the variation of transverse electric field E_r as a function of normalized field frequency ω/ω_p, for different values of laser focal spot size R_L. A laser pulse with a small focal spot efficiently excites the radial field and an increase in focal spot size decreases the transverse characteristic wavenumber k ~ (1/ R_L), thereby decreasing the radial electric field. Therefore, a decrease in the focal spot radius enhances the excitation efficiency of the radial field. It can be seen from fig. 1 that a two-fold increase in focal spot radius reduces the radial field to 1/4th of it's initial value. The THz field excites intensely for frequency close to the plasma frequency.

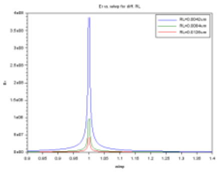

Fig. 1 Radial Electric field as a function of normalized field frequency for different focal spot size.

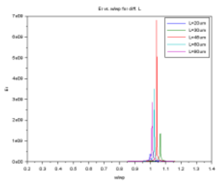

Fig. 2 Radial Electric field as a function of normalized field frequency for different laser pulse length.

Figure 2 shows the variation of radial electric field as a function of normalized field frequency for different values of laser pulse length. The intensity of the field is maximum for pulse length of 45 μm from fig. 2, for our chosen parameters η = 20 μm, R_L = 42 μm, and decreases with an increase or decrease in the value of L. It is found that when the plasma slab thickness is comparable to the pulse length, THz field of maximum amplitude is excited.

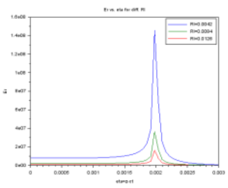

Fig. 3 Radial Electric field as a function of parameter η = z-ct for different focal spot size.

In Fig. 3, the excited electric field is plotted as a function of axial parameter η = z-ct to observe the axial dependence of radial electric field. For a constant laser pulse length L, the field shows a maxima for η = L i.e. when axial parameter is equal to the laser pulse length, for all values of laser focal spot size. Fig. 4 shows the dependence of excited THz field on laser pulse length for varying axial parameter η. As the pulse length increases, the maximum field shifts to higher values of η.

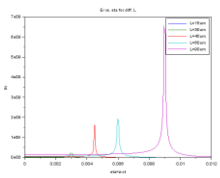

Fig. 4 Radial Electric field as a function of parameter η = z-ct for different laser pulse length.

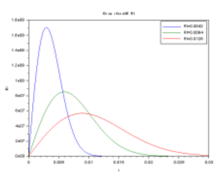

Fig. 5 Radial Electric field as a function of parameter r for different focal spot size.

In fig. 5, radial dependence of the excited fields is shown for different values of laser focal spot size. The maximum value of field decreases with an increase in the value of focal spot size, but the domain of excitation increases. A two-fold increase in spot size increases the field to more than double of it's initial value. It is also attributed to the fact that an increase in the focal spot size decreases the transverse wavenumber and the excited fields propagate predominantly in the radial direction.

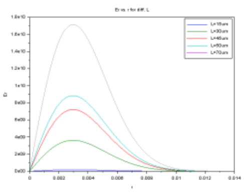

Fig. 6 Radial Electric field as a function of r for different laser pulse length.

Fig. 6 shows the THz field variation as a function of radial parameter r for different values of laser pulse length. A change in the pulse length does not alter the radial position of field where it shows a maxima. However, the maximum field increases with increase in pulse length. for a focal spot size of 42 µm, the fields are excited at r = 30 µm.

CONCLUSION

In this dissertation, the excitation of radial terahertz fields in a plasma slab subject to the ponderomotive force of a laser pulse is examined. It is observed that under normal illumination of the plasma slab by a laser pulse, there exists excitation of terahertz fields whose frequencies are close to the plasma frequency. Both axial and radial dependences of the terahertz field show that for the terahertz field to achieve its peak intensity, the axial coordinate $\eta = z - ct$ should be equal to the length of the laser pulse L, while the radial coordinate r is equal to three quarters of the radius of the focal spot of the pulse. Furthermore, the reduction of the focal spot radius results in a higher intensity of the excited terahertz fields. This implies that a tightly focused laser pulse is very efficient in the generation of terahertz fields in the plasma slab. Moreover, a laser pulse with a large pulse length is also very efficient in the generation of intense terahertz fields in the plasma slab. The effects of boundaries of the plasma slab on the excited terahertz fields are studied, and their applications in the generation of terahertz radiation from interaction of femtosecond laser pulses with gas jets which have generated megawatt terahertz radiation are investigated.

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