TERAHERTZ RADIATION GENERATION BY LASER BEATING IN A MAGNETIZED PLASMA

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DOCTOR OF PHILOSOPHY

By

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SYNOPSIS

1. Introduction

In the past two decades, the Terahertz (THz) frequency region which was difficult accessible frequency region in the electromagnetic spectrum has been researched extensively in science and technology. The THz region is defined as borderline of photonics (i.e., long wavelength region of far infrared light) and electronics (i.e., high frequency region of the microwave band) [1, 2]. Both neighboring frequency (microwave and infra-red) regions have been extensively investigated and developed, but, the THz region remained the least region, commonly known as the THz gap. The THz technology has also woken the immense potential interest for its applications in many areas due to following properties: (i) most fundamental molecules (e.g., water, oxygen and carbon monoxide) and chemical substances have their rotational and vibrational absorption lines in the THz range, (ii) THz radiation can penetrate through many non-polar and nonmetallic materials such as paper, textiles, woods and plastics, (iii) THz radiation is reflected by metals, (iv) it can be absorbed by polar molecules such as water and (v) THz radiation is non-ionizing and is not harmful for living cells. Such characteristic features attract the rising interest for THz applications in basic science, manufacturing, security, medicine and broadband THz communications [3-6].

Since early nineties, the THz region of spectrum has been explored intensively. THz radiations can be generated by using various new techniques such as solid state electronic devices [7], quantum cascade laser [8], optical THz generation [9], accelerator based sources [10], optical rectification [11] and sources based on laser plasma interaction [12-20]. However, most of these methods are not efficient enough to achieve high energy pulses of THz radiation due to their lower damage limit. To overcome this limitation, plasma is utilized as a nonlinear medium in various schemes employing a strong laser plasma interaction**.** This is so because, plasma can handle very high power lasers and it has an added advantage of not having damage limit. Lasers impart their energy to oscillating electrons of the medium and in turn, these oscillating electrons constitute a time dependent current, responsible for the THz radiation generation. In order to achieve phase matching condition between the nonlinear ponderomotive force and the oscillatory current, researchers have utilized corrugated plasma [21, 22], amplitude modulated pump wave [19, 20], etc.

2. Schemes based on laser plasma interaction

THz radiation generation utilizing plasma as a nonlinear medium is widely reported in the literature [18-22]. Two schemes based on nonlinear laser plasma interaction are as follows:

2.1 Wakefield THz schemes

The laser wakefield can be considered as a conical emission in the forward direction by laser pulse induced oscillating electrons involving Cerenkov mechanism. The wakefield excitation is reported by several authors utilizing different means [23-25], where large amplitude wave is desirable. This scheme relies on the interaction of an intense laser beam with a plasma; in this case, the accelerator is referred to as the laser wakefield accelerator (LWFA). This configuration was first proposed by Tajima and Dawson[12]. Through the laser ponderomotive force, the rising edge of the laser pulse envelope pushes away the background plasma electrons. Once the laser pulse is gone, the force resulting from the charge separation initiates a density oscillation. The phase velocity of the electro-static density oscillation is roughly equal to the group velocity of the laser. This charge oscillation is referred as wake or plasma wave.

2.2 **Beat wave schemes**

Recently, various experiments based on laser beating in a corrugated plasma have reported efficient THz radiation generation at different frequencies [4, 9, 11, 18-22]. Out of various schemes based on laser plasma interaction, THz radiation generation by beating of two lasers of different frequencies and wave numbers in plasmas has shown tremendous potential in terms of amplitude, tunability, efficiency and directionality [18-22]. THz sources based on beating can also be scaled to high peak powers. The process diagram of this mechanism is shown in Fig.1.1. The basic mechanism to generate THz radiation by beating of two co-propagating laser beams is as follows: consider two laser beams co-propagating in a corrugated plasma having electric field profiles $\vec{E}_j = \hat{y}E_{00}e^{-i(\omega_j t - k_j x)}$, where $j = 1, 2$

and $k_j = \omega_j / c\left(1-\omega_p^2/\omega_j^2\right)^{1/2}$. Here $\omega_p = \sqrt{4\pi n_0 e^2/m}$ is the electron plasma frequency; $-e$ and m are the electronic charge and mass respectively.

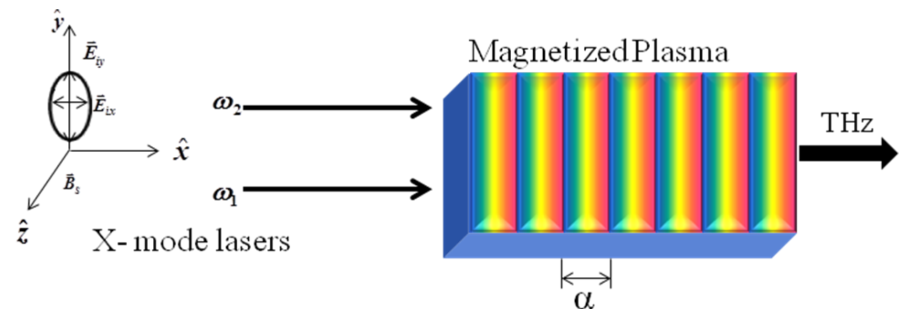

Fig. 1.1: Schamatic diagaram of THz generation

Lasers impart oscillatory velocity $v_j = e\vec{E}/mi\omega$ to plasma electrons which is given by equation of motion $m(d\vec{v}/dt) = e\vec{E}$. Lasers beat together and exert a ponderomotive force $\vec{F}_p = -m/2\,\mathrm{Re}\left[\left(\vec{v}.\nabla\vec{v} + \vec{v}^*.\nabla\vec{v}\right)\right] - e/2c\,\mathrm{Re}\left[\left(\vec{v}\times\vec{B} + \vec{v}^*\times\vec{B}\right)\right]$ on plasma electron at frequency $\omega = \omega_1 - \omega_2$ and wave vector $k' = \vec{k}_1 - \vec{k}_2$. The ponderomotive force drives space charge oscillation frequency at $\omega = \omega_1 - \omega_2$ and wave number $k' = \vec{k}_1 - \vec{k}_2$. Assuming the potential of space charge mode to be ϕ, the oscillatory velocity of electron due to space charge mode along with ponderomotive force can be expressed as $v_x = i\left[e\nabla\phi + F_{px}\right]/m\omega$. The nonlinear velocity along with continuity equation provides density perturbation $n = n^L + n^{NL}$. Here $n^L = 1/4\pi e k^2 \chi\phi$, $n^{NL} = \left[n_0 k/m\omega(\omega^2)\right]F_{px}$ and $\chi = -\omega_p^2/\omega^2$. Substituting $n = n^L + n^{NL}$ in the Poisson's equation $\nabla^2\phi = 4\pi n e$, we obtain characteristic equation for beating mode, given by $\varepsilon\phi = -4\pi e/k^2\, n^{NL}$ where $\varepsilon = 1 + \chi$. Oscillations at $(\omega, \vec{k}_1 - \vec{k}_2)$ in the presence of density ripple $n_{\alpha 0}e^{i\alpha z}$ excite nonlinear current at $(\omega, \vec{k}_1 - \vec{k}_2 + \vec{\alpha})$ which can be written as $\vec{J}^{NL} = -\frac{1}{2} n_{\alpha 0} e \vec{v}_\omega e^{i\alpha z}$. This oscillatory current is the source for the emission of THz radiation at the beating frequency (which is the same $\omega = \omega_1 - \omega_2$ as that of the ponderomotive force) and wave number $\vec{k} = \vec{k}_1 - \vec{k}_2 + \vec{\alpha}$. For strong THz radiation, plasma density ripples should be periodic, otherwise $\vec{k}(= \vec{k}_1 - \vec{k}_2 + \vec{\alpha})$ will exhibit non-periodic behavior; resonance condition can't be achieved and maximum energy transfer will not take place and consequently a weak field THz radiation will be generated.

3. Objectives of the present work

In scientific field, THz radiation can provide novel information in many areas e.g. quality control and monitoring in manufacturing. Three key performance factors are the peak THz electric field strength (or pulse energy), THz bandwidth, and efficiency of conversion. The enhancement of these parameters is an active area of current research in order to realize many of the envisioned THz experiments. Most of the above mentioned applications are under theoretical as well as experimental development. Although, efforts have been made for THz generation in view of these applications, still, there remain the challenging tasks of creating a proper THz radiation source that could be quite useful in these fields. For example, tunability of the radiation source, proper power of the source and directionality (collimation) of radiation are the areas where new concepts and efforts are needed in order to meet the demanding applications. Therefore, in the present thesis, we have proposed some new schemes based on laser beating in plasmas. Based on these schemes, we have been able to tune the frequency and power of emitted THz radiation. Not only this, we have given special attention to the control of the direction of emission of these radiations. Our schemes supersede several other mechanisms of THz radiation generation, explored by other researchers [18-25].

The proposed thesis has 7 chapters. In the first chapter, a basic introduction to the area is provided and motivation and objective are clearly mentioned. In Chapters 2-6, we have discussed several models of THz generation. Finally, the thesis is concluded in Chapter 7, where we have also discussed the limitations and future scope of the present work. In the following sections, the contents of chapters 2-6 are briefly described.

4. Proposed schemes for THz radiation generation

In the present study, we proposed various improved schemes for THz radiation generation. In Chapter 2, a scheme of terahertz radiation generation is proposed by beating of two **extra-ordinary lasers** having frequencies and wave numbers (ω_1, k_1) and (ω_2, k_2), respectively in a magnetized plasma. Terahertz wave is resonantly excited at frequency $(\omega_1 - \omega_2)$ and

$(\vec{k}_1 - \vec{k}_2 + \vec{\alpha})$ with a wave number mismatch factor which is introduced by the periodicity of plasma density ripples. In this process, the laser exerts a beat ponderomotive force on plasma electrons and imparts 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 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. ***[The results of this work are published in Laser and Particle Beams, vol. 31, pp.337, 2013 (Thomson Reuters I.F. =1.71, h-index =41, h5-index =16, Published by Cambridge University Press, Indexed in SCI and SCOPUS)]***

A scheme of terahertz (THz) radiation generation is investigated in **chapter 3** by photo-mixing of two **super Gaussian laser** beams having different frequencies (ω_1, ω_2) and wave numbers $(\vec{k}_1, \vec{k}_2)$ in a performed corrugated plasma embedded with transverse dc magnetic field. Lasers exert a nonlinear ponderomotive force, imparting an oscillatory velocity to plasma electrons that couples with the density corrugations ($n' = n_{\alpha 0} e^{i\alpha z}$) to generate a strong transient nonlinear current, that resonantly derives THz radiation of frequency ~ ω_h (upper hybrid frequency). The periodicity of density corrugations is suitably chosen to transfer maximum momentum from lasers to THz radiation at phase matching conditions $\omega = \omega_1 - \omega_2$, and $\vec{k} = \vec{k}_1 - \vec{k}_2 + \vec{\alpha}$. The efficiency, power, beam quality and tunaibility of the present scheme exhibit high dependency upon the applied transverse dc magnetic field along with q-indices and beam width parameters (a_0) of super Gaussian lasers. In the present scheme, efficiency ~10^{-2} is achieved with the optimization of all these parameters. ***[The results of this work are published in Journal of Applied Physics vol. 117, pp.193303, 2015 (Thomson Reuters I.F. =2.183, h-index =240, h5-index =77, Published by AIP, Indexed in SCI and SCOPUS)]***

In **Chapter 4**, a model to achieve strong THz radiation is developed by the photo-mixing of two **cosh- Gaussian lasers** pulses of different frequencies (ω_1, ω_2) and wave numbers $(\vec{k}_1, \vec{k}_2)$ and same electrical field amplitude in a corrugated plasma embedded with transverse static magnetic field. Cosh-Gaussian laser pulses having steep gradient in intensity profile along with wider cross-section exert a stronger nonlinear ponderomotive force at $\omega_1 - \omega_2$ and $\vec{k}_1 - \vec{k}_2$ on plasma electrons which imparts a nonlinear oscillatory velocity to plasma electrons. Oscillatory plasma electrons couples with the density ripple $n' = n_{\alpha 0} e^{i\alpha x}$ to produce a nonlinear current which is responsible for resonant THz radiation at frequency $\sim \left(\omega_c^2 + \omega_p^2\right)^{1/2}$. The amplitude, efficiency and beam quality of THz radiation can be optimized by choosing proper corrugation factor (α of the plasma), applied magnetic field (ω_c), decentred parameter (b) and beam width parameter (a_0) of lasers. The Efficiency $\sim 10^{-2}$ is achieved for laser electric field $E = 3.2 \times 10^9\, V/cm$. ***(The results of this work are communicated in International journal)***

In **Chapter 5,** resonant THz radiation generation is proposed by beating of two **spatial-triangular laser** pulses of different frequencies (ω_1, ω_2) and wave numbers $(\vec{k}_1, \vec{k}_2)$ in a plasma having external static magnetic field. Laser pulses copropagating perpendicular to a dc magnetic field exert a nonlinear ponderomotive force on plasma electrons, imparting them an oscillatory velocity with finite transverse and longitudinal components. Oscillatory plasma electrons couple with periodic density ripples $n' = n_{\alpha 0} e^{i\alpha z}$ to produce a nonlinear current i.e., responsible for resonantly driving terahertz radiation at $(\omega = \omega_1 - \omega_2, \vec{k} = \vec{k}_1 - \vec{k}_2 + \vec{\alpha})$. Effects of terahertz wave frequency, laser beam width, density ripples and applied magnetic field are studied for the efficient THz radiation generation. The frequency and amplitude of THz radiation were observed to be better tuned by varying dc magnetic field strength and parameters of density ripples (amplitude and periodicity). An efficiency ~0.02 is achieved for laser intensity of $2 \times 10^{15} W/cm^2$ in a plasma having density ripples ~30%, plasma frequency ~1THz and magnetic field ~100kG. ***[The results of this work are published in Laser and Particle Beams, vol. 33, pp.51-58, 2015 (Thomson Reuters I.F. =1.71, h-index =41, h5-index =16, Published by Cambridge University Press, Indexed in SCI and SCOPUS)]***

Chapter 6 is motivated to study the resonant excitation of terahertz radiation by nonlinear coupling of two **filamented spatial-Gaussian laser** beams of different frequencies and wave numbers in a plasma having transverse static electric field. The static ponderomotive force due to filamented lasers is balanced by the pressure gradient force which gives rise to transverse density ripple, while, the nonlinear ponderomotive force at frequency difference of beating lasers couples with density ripple giving rise to stronger transverse nonlinear current which results into the excitation of THz radiation at resonance. The coupling is further enhanced by the presence of static electric field and spatial-Gaussian nature of laser beams. An increase of six fold in the normalized amplitude of terahertz is observed by applying a dc field $\sim 50KV/cm$. Effects of frequency, laser beam width and periodicity factor of modulated laser amplitude are studied for the efficient THz radiation generation. These results can be utilized for generating controlled tunable THz sources for medical applications using low filament intensities ($\sim 10^{14} W/cm^2$) of beating lasers. ***The results of this work are published in Laser and Particle Beams, vol. 32, pp. 375-381, 2014 (Thomson Reuters I.F. =1.71, h-index =41, h5-index =16, Published by Cambridge University Press, Indexed in SCI and SCOPUS)]***

5. Conclusions

We proposed various schemes for terahertz radiation generation by the beating of two laser beams having different laser profiles (x-mode, super-Gaussian, cosh-Gaussian, triangular and filamented Gaussian lasers) in the presence of magnetic field. The THz amplitude can be controlled by laser plasma parameters and applied static magnetic field. In these schemes, magnetic field plays two roles: it controls (i) the phase velocity and group velocity of beating lasers and (ii) the polarization of generated THz wave. The THz amplitude scales directly to the amplitude of density ripples and maximizes as frequency (ω) approaches to resonance frequency ($\approx \omega_h$). Results from the proposed thesis show the significant improvement in the amplitude, efficiency and tunability as compared to previous ones reported by other investigators for THz generation by laser plasma interaction.

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List of Publications

Publications in International Journals

1. **Prateek Varshney**, Vivek Sajal, K. P. Singh, Ravindra Kumar and Navneet Sharma, **"**Tunable and efficient THz radiation generation by photomixing of two super Gaussian laser pulses in a corrugated magnetized plasma", *Journal of Applied Physics* vol. **117**, pp.193303, 2015. [Thomson Reuters I.F. =2.183, h-index=240, h5-index=77, Published by AIP, Indexed in SCI and SCOPUS]

2. **Prateek Varshney**, Vivek Sajal, Navneet K. Sharma, Prashant K. Chauhan and Ravindra Kumar, "Strong terahertz radiation generation by beating of two x-mode spatial triangular lasers in a magnetized plasma", *Laser and Particle Beams,* vol. **33**, pp.51-58, 2015. [Thomson Reuters I.F. =1.71, h-index=41, h5-index=16, Published by Cambridge University Press, Indexed in SCI and SCOPUS]

3. **Prateek Varshney**, V. Sajal, P. K. Chauhan, R. Kumar and N. K. Sharma, "Effects of transverse static electric field on terahertz radiation generation by beating of two transversely modulated Gaussian laser beams in a plasma", *Laser and Particle Beams,* **vol. 32**, pp. 375-381, 2014. [Thomson Reuters I.F. =1.71, h-index=41, h5-index=16, Published by Cambridge University Press, Indexed in SCI and SCOPUS]

4. **Prateek Varshney**, V. Sajal, K. P. Singh, R. Kumar and N. K. Sharma, "Strong terahertz radiation generation by beating of Extra-ordinary mode lasers in a rippled density magnetized plasma", *Laser and Particle Beams, vol. 31, pp.337, 2013*. [Thomson Reuters I.F. =1.71, h-index=41, h5-index=16, Published by Cambridge University Press, Indexed in SCI and SCOPUS]

5. **Prateek Varshney,** Vivek Sajal, Anil Malik, Ravindra Kumar and Navneet Kumar Sharma, "Terahertz generation by nonlinear photomixing of cosh-Gaussian laser pulses in corrugated magnetized plasma", (communicated)

Conferences

1. **Prateek Varshney,** Kanika Verma, Vivek Sajal and Ravindra Kumar "Study of THz radiation generation by Photo-mixing of two laser beams in a plasma having DC electric field" ", 29th National Symposium on Plasma Science & Technology, "Plasma-2014" at Mahtama Gandhi University, Kottayam (Kerala) page no. 195, Dec 8-11, 2014.

2. **Prateek Varshney**, Kanika Verma, Vivek Sajal and Ravindra Kumar, "Generation of tunable THz radiation by beating of two laser pulses in a rippled magnetized plasma", International conference on Recent Trends in Interdisciplinary Sciences: Opportunities and Challenges "RTISOC 2014"at M.M college Modinagar (UP). (Best Poster Presentation).

3. **Prateek Varshney**, Kanika Verma, Vivek Sajal and Ravindra Kumar, "Study of Terahertz radiation generation by beating of two spatial triangular lasers in magnetized plasma", 28th National Symposium on Plasma Science & Technology, "Plasma-2013" at KIIT University, Bhubanseshwar (Odisha) page no. 195, Dec 3-6, 2013.

4. **Prateek Varshney**, Vivek Sajal and Ravindra Kumar, "Excitation of THz radiation generation by beating of extra-ordinary lasers in a magnetized plasma", "2nd PSSI-Plasma Scholars Colloquium" in CSIR-CEERI, Pilani, page no. 49, July 22-24, 2013.

5. **Prateek Varshney**, Kanika Verma, Vivek Sajal and Ravindra Kumar, "Effects of Axial Static Magnetic Field on Stimulated Raman Scattering of a Circularly Polarized Laser Beam", "Topical conference on Laser driven charged particle acceleration and applications" in IIT Delhi, April 5-7, 2013.

6. **Prateek Varshney**, Vivek Sajal and Ravindra Kumar, "Stimulated Raman Scattering of a Circularly Polarized Laser Beam in Magnetized Plasma", 27th National Symposium on Plasma Science & Technology, "Plasma-2012" at Pondicherry University, Puducherry, page no. 118, Dec 10-13, 2012.

7. **Prateek Varshney**, Vivek Sajal and Ravindra Kumar, "Stimulated Raman Scattering of an Extraordinary Laser Beam in a Magnetized Plasma", "1st PSSI-Plasma Scholars Colloquium" in IPR Gandhinagar, page no. 55, July 3-4, 2012.

School

8. Attended 3week DST-SERB school program on "High Intensity Laser Plasma Interaction: Theory and Simulation" at Indian Institute of Technology Delhi, May 05-23, 2014.