Laser-induced THz radiation generation in plasma

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Abstract

Overlapping zone of electromagnetic spectrum between the submillimeter and millimeter wavelength is known as terahertz (THz) region. THz waves have inherent properties of strong absorption by water molecules which is abundantly present in flora and fauna on this planet, widens the scope of this research field. This area gains lots of interest of scientists and academicians during last two decennium due sky-high increase in laser intensities and improvements in THz time domain spectroscopy techniques result into wide range applications in the field from physics to medical science and applied sciences. Researchers suggests new and innovative methods and techniques for the detection and generations of these THz photon. In this paper we will discuss the different THz generation methods especially through laser plasma interaction because plasma is more advantageous than other generation methods because it shows no sign of saturation on the upgradation of laser intensities up to pettawatt level. In this paper we discuss the different laser plasma techniques to achieve the tunable, energy efficient THz source.

Key words: Ponderomotive force, density ripple, laser, magnetic field, plasma.

Introduction

In the electromagnetic spectrum, region roughly between 0.1 THz to 10 THz is known as terahertz region which covers high frequency microwave band and long wavelength infrared region of spectrum. This zone bridges the gap between optics and electronics, so opens the wide horizons for optoelectronics stream in physics, chemistry, life sciences and applied sciences. These waves are invisible to necked human eyes and nonionizing for in nature [1].
These terahertz waves (T-waves, T-light) have hidden potential for applications in the field of explosive detection[2], short distance wireless communication and sensing, remote sensing, defense[3], material characterization[4], biological and chemical imaging[5], high field condensed matter studies[6], non-destructive testing[7], ultrafast magnetic switching[8] etc. Because of wide range applications, scientists show their keen interest in research and development of THz field generation, detection and application from the last two decades.

**Terahertz wave generation methods**

The recent time experiences rapid growth in terahertz ray generation method, i.e. electron-based accelerator, laser nonlinear crystal interaction, laser pulse and plasma interaction, quantum cascade laser, photo excited semiconductors etc. In all these above-mentioned methods laser plasma interactions gain more attention due to its inherent properties. When intense laser (greater than $10^{11}-10^{12}$ W/cm$^2$) interact with matter (i.e. nonlinear crystals, semiconductors etc.), high energy, broadband terahertz wave generation is limited by matter damage and saturation properties thus decrease the resultant THz amplitude. When laser wave of intensity $10^{11}$ w/cm$^2$ interacted with nonlinear crystal it generates up to sub mJ terahertz wave of few GV/m via optical rectification method [9-11].

In recent years laser intensities archives higher and higher values up to pettawatt (1 billion million watts) levels, plasma is only known source to handle such high energies and open up the new avenues for more effective non ionizing terahertz waves generation. In recent study A. Gopal et al. [12] uses the laser intensity up to $10^{20}$ W/cm$^2$ there is no sign of saturation in intense laser plasma interaction.

Researchers shows their immense contribution in theoretical [13-23] as well as in practical [24-28] perspective for laser plasma interaction methods in order to achieve tunable broadband THz sources. A tunable and focused terahertz source observed by Malik et al. [29] when triangular laser passes through ripple density plasma in external DC magnetic field. Two dark hollow intense laser beams interact with collisional plasma generates nonlinear ponderomotive force and hence terahertz generation. Bakhtiari et al. [30] studied the effect of laser and
plasma parameters for efficient terahertz generation. Kumar and Tripathi [31] investigated resonant terahertz generation by using optical mixing of linearly polarized two color lasers in ripple density plasma. Suitable ripple density wave vector provides necessary condition for phase matching.

Bhasin and Tripathi [32] suggested an analytical model for the resonant terahertz generation by using x-mode picosecond laser passed through magnetized ripple density plasma. They showed by optical rectification that magneto plasma increases the power of terahertz radiation. Pathak et al. [33] studies that when relativistic electron beam interacts with ripple density under dense plasma at an incidence angle produces space charge beam mode. These beam mode give velocity to the plasma electrons with density ripple results into strong THz wave radiation. The theoretical results are verified by simulations in which output frequency of radiation depends upon ripple density and electron beam energy. There is strong nonlinear coupling exists between ripple density, energy of beam, side band and electromagnetic radiation solved mathematically. Electromagnetic mode falls at high frequencies which is compensates by increase in density of plasma.

Liu and Tripathi [34] strengthen the path for tunable terahertz source by adjusting the magnetic field. For this purpose, a short laser wave passed through a tunnel plasma of ionized gas in density profile of axial square shape. As the pulse passed via tunnel generates free electrons with transverse drift and started oscillation at cyclotron frequency results into THz generation. Applied magnetic field (nearly100 KG) tune the THz frequency and density ripple controls the angular direction of THz radiation.

Bhasin and Tripathi [35] investigated that hen an amplitude modulated laser beam incident obliquely under mode conversion, excites the amplitude modulated surface plasma wave at modulation frequency over the surface free space boundary which exerts a nonlinear ponderomotive force on metal electrons results into nonlinear current and generates strong terahertz waves at modulation frequency. These surface plasma wave exhibit very week damping effect, shows good option for optical rectification and have highest amplitude at free space metal interface. This amplitude falls rapidly away from boundary.
Kumar and Tripathi [36] suggest an analytical model to achieve a tunable THz resource in which THz frequency controlled by laser wavelength. In this investigation when a relativistic electron beam interacted with wiggler magnetic field under laser modulation exerts a ponderomotive force and coherent THz radiation. THz yield varies linearly with electron bunch radius and as square of bunch radius, beam current and inverse square of wiggler wave vector. THz power has maximum value at THz frequency equals to 1.4 THz.

Kumar and Tripathi [37] observed the effect of ripple density plasma on resonant THz generation. When finite spot sized 2 collinear laser pulses of intensities of $10^{16}$ w/cm$^2$ launched into at an angle to density ripple wave vector produces terahertz radiation at difference frequency in unmagnatized plasma. Density ripples generates additional angular momentum for proper phase matching. They investigated the effect of pulse spot size, density ripple, laser frequency, laser amplitude on resonant terahertz radiation. Power conversion efficiency for present scheme is $2.5 \times 10^{-5}$ for laser wavelength 1 µm, ripple density ≥30%, spot size=4c/ω$_p$ and pulse duration > 100 fs.

Kumar et al. [38] compare the TE and TM mode in semiconductor waveguide in the generation of resonant terahertz radiation. They concluded that when two laser beams of different frequency propagate through semiconductor slab ripple wave vector in transverse magnetic field generates THz radiation at beat frequency. TM mode laser beating generates higher THz yield than TE mode. In this plan ripple density provides requisite phase matching. Kumar and Tripathi [39] ascertained that surface plasma wave (SPW) experiences low loss if glass coated with ultrathin metal foil. For resonant THz photon generation two nonlinear laser beams incidented normally to metal foil surface from free space to excite the SPW. As we move into glass and in free space surface plasma wave decreases away from thin metal sheet. At laser intensity $10^{12}$ w/cm$^2$ and 1µm wavelength, THz amplitude to laser amplitude is of the order $10^{-3}$. In this study metal film thickness is a critical parameter.

Kumar and Tripathi [40] examined the tunable THz source adjusted with metal film thickness. They using two nonlinear laser pulses interact with optical fiber coated with thin metal film and having dielectric ripple. Laser pulses excites the surface Plasmon waves along the laser direction. A CO$_2$ megawatt laser source is used for this
scheme to generate ratio of THz amplitude to laser amplitude of the order of $10^{-2}$. At higher frequencies, coupling between surface Plasmon decreases hence decrease in THz amplitude. Dielectric grating structure of optical fiber provides required phase matching condition for resonant wave in THz domain.

When electron bunches impinged periodically on the TM mode resonators loaded with dielectric, Kumar and Tripathi [41] investigated the Cherenkov mechanism for generation of waves in THz domain. These electron bunches excite the slowly moving forward wave via phase synchronization. THz energy conversion efficiency can be enhanced by 10% with the help of suitable parameters. THz amplitude can be enhanced by seed THz signal as every electron bunch losse significant amount of energy per unit length which is stored in the resonator. Yoshii et al. [42] examined the Cerenkov wakes radiations in magnetized plasma. Yugami et al. [43] investigated experimentally and find out that laser waves excite the Cherenkov wake in the presence of transverse magnetic field there was generation of sub terahertz radiation.

Its reported by Mori et al. [44] that if two non collinear laser pulses pass via Argon clustered plasma results into linearly polarized terahertz pulse with five times more terahertz yield.

Kumar et al. [45] examined that when two laser pulses incident obliquely at hot plasma having step density profile result into terahertz wave in reflected direction at difference frequency. When plasma density equals to critical density of difference frequency there is resonant coupling observed between plasma wave and THz wave. PCE of terahertz wave is maximum at optimum angle of incidence due to strong coupling between Langmuir wave and electromagnetic wave.

Mehta et al. [46] mathematically investigated the terahertz generation driven by two p-polarized Gaussian electromagnetic waves incident obliquely on collision less hot plasma with density ripple on its surface. As laser pulse interacts with density profile, it generates ponderomotive force on plasma electrons. Electrons starts oscillating due to nonlinear ponderomotive force. So at beat frequency irrotational current density arises, which generates terahertz wave. This theoretical investigation is very useful in the formation of tunable terahertz sources. In this paper researcher neglected the effect of kinetic and Landau damping. Amplitude of terahertz radiation
depends not only on beating frequency of laser, angle of incidence but also on plasma density. In this study power of radiated terahertz wave fall with terahertz frequency, varies as square of ripple amplitude and obtain optimum value at a particular incidence angle.

Varshney et al. [47] Studied the generation of THz wave by interaction of two cosh - Gaussian laser beams (slightly different frequency) with clustered plasma. Researcher studies the variation of resultant THz amplitude with laser decentered parameter, beam width, ripple density amplitude and plasma density. They concluded in their studies that electric field of THz amplitude is highly dependent upon decentered parameter. Increase in decentered parameter results into increase in terahertz amplitude by order of 3 which is higher for hollow Gaussian beam (b=5) than Gaussian beam (b=0). Researcher notice the increase in terahertz amplitude with decrease in laser beam width. There is increase in terahertz amplitude due to clustered plasma. As laser interacts with cluster plasma which results into nonlinear ponderomotive force. This nonlinear force oscillates the plasma electron to maintain the plasma neutrality. This oscillatory velocity oscillates in resonance with ripple density plasma to generate transient nonlinear current. These transient current converts into strong terahertz radiation at beat frequency.

Mehta et al. [48] studied the effect of frequency chirp in the presence of transverse static magnetic field on terahertz amplitude. In their studies researcher shows that tunable THz source can be achieved by adjusting the value of chirp parameter and transverse magnetic field. Chirp parameter increases the interaction time between laser and plasma electron which results into broadband terahertz pulse. In this scheme two laser beams interact with under dense plasma in the presence of transverse static magnetic field. THz amplitude has maximum value when terahertz frequency approaches upper hybrid frequency at resonance. Without magnetic field there is a dip in terahertz amplitude when terahertz frequency equal to 1.36 plasma frequency because of destructive interference. By applying the sufficient magnetic field this dip disappears because of resonant condition.

Mehta et al. [49] investigated the effect of frequency chirp in the presence of ripple density plasma on THz generation. There is a linear relationship between laser pulse amplitude and terahertz amplitude. Ripple density plasma provides background for proper phase matching condition so that maximum momentum and energy can be transfer from laser pulse to plasma which results into high efficiency of terahertz generation. Chirp parameter is
inversely proportional to group delay dispersion. Increase in chirp parameter results into decrease in group delay dispersion, hence reduces the chirp. Increase in the value of density ripple amplitude results into to increase in terahertz amplitude.

Varshney et al. [50] investigated the generation of tunable focused intense terahertz wave by photo mixing of 2 cosh - Gaussian Laser beams impinge into corrugated plasma. A DC magnetic field is applied in transverse direction. The cosh-Gaussian laser beams interact with coggurated plasma which generates nonlinear ponderomotive force. This nonlinear force provide oscillatory velocity to plasma electrons. Oscillating electrons couples with ripple density which generates nonlinear current density and strong Terahertz wave generation. Transverse static magnetic field works in two ways. On the one hand it controls the group and phase velocity of laser beam and on the other it manages the polarizability of THz wave. The author Investigate that optimum values of Plasma and Laser parameter can enhance the resultant terahertz amplitude. Efficiency of THz waves can be optimized by proper values of decentered parameter (b), beam width parameter (a_0), corrugation factor and applied magnetic field. The efficiency of resultant THz radiation have two ranges. For b <1.5 terahertz amplitude decreases with beam width and obtain maximum value for Gaussian beam (b=0) at resonance. For 1.5≤b≤5 resultant THz radiation increases with decentered parameter (b) and have maximum value for hollow Gaussian wave (b=5), the reason behind this variation is that ponderomotive force varies with laser profile. Laser profile decreases from b=0 (Gaussian wave) to b=1.4 (flat top) and attain the minimum value then it increases to b=5 (cosh-Gaussian wave). Efficiency of THz radiation increases with decentered parameter b. And decreases with width parameter (a_0). Varshney et al. attain the efficiency up to 20% for b=5, a_0= 3c/5w and for external magnetic field of 107 KG.

In this mathematical model researcher observed that When two non-linearly mixed laser pulses incident obliquely, on the density gradient hot nano cluster plasma surface, nonlinear ponderomotive force generated in cluster and plasma electrons Which results into terahertz generation in reflected wave. Amplitude of wave depends upon laser intensity, incident angle, cluster radius and electron thermal velocity. Laser intensity increases results into increase
in terahertz amplitude due to outer ionization of cluster atoms by ponderomotive force. Vij and Kant [51] observed two peaks at theta equal to 22 degree and 68 degree. Theta equal to 22 degree is optimized value for high THz amplitude. Terahertz amplitude can be enhanced by increasing value of cluster radius and electron thermal velocity. Researcher find out the relation between THz amplitude and frequency. When terahertz frequency approaches plasma frequency then there is strong coupling between Langmuir and terahertz wave which results into high terahertz amplitude. Step density profile provides essentials for phase matching condition. In this study terahertz conversion efficiency increases (1.4×10^{-4}) with resonant coupling between plasma and terahertz radiation. Amplitude of terahertz wave is maximum when laser frequency approaches one by root 3 of cluster plasma frequency and plasma frequency equals to terahertz radiation frequency. This research article studied the effect of thermal velocity of electron, cluster radius, and laser intensity on terahertz radiation generation. These cluster structure provides efficient energy absorption capacity to enhance terahertz amplitude and energies. Clusters are studied by Jahangiri et al. [52-53] to compare the terahertz radiation generation efficiency by argon cluster and argon gas. They showed experimentally that Ar cluster shows significant improvement of the order of two in magnitude in comparison with Ar gas.

**Conclusion**

This research paper intended to discuss different methods (such as free electron laser, laser nonlinear crystal interaction etc.) of terahertz generation and in special reference to relativistic laser and plasma interaction as it generates nonlinear phenomena such as self-focusing of laser beam, harmonics generation, particle accelerator and terahertz generation. In the 1990s with the invention of THZ- time domain spectroscopy, THz generation techniques gains momentum to achieve more tunable terahertz source. Everyday new trends and techniques are suggested by the researcher to realize the goal of tunable terahertz properties such as polarization, angular momentum and spectrum. All these tunable properties show new challenges and opportunities for the researchers and academicians [54].

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