Terahertz Radiation Generation via Laser Plasma Interaction: An Overview

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Abstract. The radiations sources of THz-waves are nowadays become indispensable tools for applications in different branches of science, industry, and medicine. Many large and expensive facilities involving laser plasma interaction have been established worldwide and in India to meet the growing demand for safe, non-ionizing, non-destructive sources of THz waves. THz radiation sources based on laser wakefield accelerator is of great interest due to its compact size and unique tunability of frequency and energy for several application purpose. However, there are other types of radiations also being generated on interaction of ultra-intense laser with plasma viz. Synchrotron radiation, Betatron radiation, Bremsstrahlung radiation, Recombination radiation, Line radiation, Cyclotron radiation etc. Therefore, one needs to devise a mechanism that brings out the dominance of THz radiation emission from plasma. The main approach that we deal with is the beat wave excitation and wake field excitation in plasma on laser irradiation. The dynamics of plasma is controlled by tailored pulses along with external applied electric and magnetic fields. This is the nonlinear currents which are excited resonantly in the plasma which give rise to the excited longitudinal and transverse fields within the plasma that causes electron acceleration and emit radiation in terahertz frequency range. If one could be able to tune the frequency, field amplitude and efficiency of these THz radiation sources, this will open up a novel way of enormous opportunity to the researchers across the globe to improve the available radiation sources in the frequency regime and to exploit them for their better applications.

PLASMA: A FOURTH STATE OF MATTER

Plasma is an ionized and electrically neutral gas which is most often described as the fourth state of matter. This can be understood with the simple example such as in most of the cases, when energy is added to a solid (first state) it becomes a liquid (second state), which with more added energy takes the form of gas (third state) and when further energy is added to gas it eventually dissociates to become a plasma. It is said that the universe comprises more than 99% in the form of plasma and less than 1% includes solids, liquids and neutral gases. Any ionized, neutral gas is said to be plasma if it is abided by the following conditions i.e. quasi-neutrality ($\lambda_D << L$), collective behaviour ($N_D >> 1$) and the plasma approximation ($\omega_p\tau > 1$); here λ_D is the electron Debye length, and N_D is the number of species in the Debye sphere, ω_p is the plasma frequency and τ is the relaxation time between two collisions in the plasma species. In non-compliance of the above conditions, the plasma more like behaves as a neutral gas rather than the plasma. Based on the above parameters the available plasmas exhibits several characteristics, therefore classified further to different types as follows.

Underdense and Overdense Plasmas

Based on the plasma density, a plasma having density below a critical plasma density is said to be under-dense whereas the plasma having density above the critical density is called to be over-dense. In laser produced plasmas [1], critical density depends on the intensity of laser pulse. When the laser frequency (ω) is less than the plasma frequency, i.e. $\omega < \omega_p$, the refractive index of the plasma becomes complex and so the wave vector. Under this situation, the laser pulse is reflected back (no propagation) and this signifies the formation of over-dense plasma [2]. The over-dense plasma acts like a mirror. On the other hand if the laser frequency is more than the plasma frequency, i.e. $\omega > \omega_p$, the refractive index of the plasma and wave vector are real quantities. Hence, the laser propagates upto critical surface into the plasma, this signifies the formation of under-dense plasma.

Weakly Coupled and Strongly Coupled Plasmas

Based on the strength of interaction amongst plasma species, mostly standard plasmas are weakly coupled. Strength of coupling between plasma species is described in terms of Coulomb logarithm (Λ) parameter. If $\Lambda << 1$, the Debye sphere is sparsely populated that corresponds to the strongly coupled plasma. The strongly coupled plasmas tend to be cold and dense. However, the situation $\Lambda >> 1$ corresponds to the weakly coupled plasma, which is densely populated and tends to be diffusive and warm. In strongly coupled plasma, the charged particles are dominated by one another's electrostatic influence more or less continuously. Also their kinetic energies are small compared to the interaction potential energies [3]. On the other hand, in weakly coupled plasma, the strong electrostatic interactions between individual particles are occasional and relatively have rare occurrence. Here, typical particle is electrostatically influenced by all of the other particles within its Debye sphere, but this interaction very rarely causes any sudden change in its motion. Generally inertial fusion experimental plasma, arc discharges, white dwarf and neutron star plasmas are strongly coupled. On the other hand ionospheric plasma, magnetic fusion devices, plasma ball etc. are weakly coupled plasmas. In a weakly coupled plasma, collision frequency (ν) is much smaller than the plasma frequency (ω_p) i.e. $\nu << \omega_p$. Hence, collisions do not affect plasma oscillations much. In view of this diffusive and high temperature plasmas tend to be collision-less or weakly collisional [4].

Collision-less and Collisional Plasmas

As mentioned earlier, collisions become important in partially or weakly ionized plasma. A collisional plasma is the one where mean free path the of electrons (λ_{mfp}) is much lesser than the observational length scale (L), i.e. $\lambda_{mfp} << L$. Collisions between charged particles in plasma differ fundamentally from those between molecules in a neutral gas because of the long range of the Coulomb force existing amongst plasma species. In fact the binary collision processes corresponding to larger Λ are defined for weakly coupled plasmas that are between electrons and neutral atoms. A collisional frequency ν is defined as a rate at which the electrons strike with neutral particles in weakly ionized plasmas. It is noteworthy to learn that the collision frequency measures the frequency with which an electron trajectory changes due to interaction with neutral particles. Therefore, the collision frequency is not the inverse of the typical time between collisions of electron with neutral, rather it is the inverse of the typical time needed for enough collisions to occur that the particle trajectory is deviated [5]. It makes little sense to talk about a collision-less neutral gas. Many astrophysical and space plasma are collision-less to a very good approximation. Collision affects the plasma properties such as the dielectric constant of the plasma. Because of these nonlinear propagation characteristics of laser pulse in plasma also gets modified. Thermal motions of the electrons in plasmas also alter the collision frequency and results new thermo-collisional effects.

LASER PLASMA INTERACTION

There are various types of plasmas existing in nature corresponding to the plasma density, plasma frequency and plasma electron temperature [6] and their respective Debye lengths (λ_D). The laser plasma lies in the range of plasma frequency of the order of 10^{12} - 10^{18} rad/sec, plasma density of 10^{18} – 10^{34} per cm^3 and plasma electrons temperature range of 10 – 1000 eV. The interaction of laser with matter has been studied since lasers were invented. The matter may be of any state, viz. solid crystal, neutral gas and plasma. The plasma is an electrified neutral gas which has high degree of sustainability even at very high power of the lasers, though ordinary crystal and gases suffer breakdown [7, 8]. The gaseous target like plasma offer certain advantages over solid target, Therefore, the interaction of ultra-high power laser with plasma has evolved as a very interesting and innovative area of research [9, 10]. The plasma may be pre-formed [11 - 13] or it may be produced by lasers [14 - 16]. The laser plasma interaction is a highly enriched field giving rise to several regime of interaction in plasma and nonlinear phenomena.
Various applications offered by such interactions include nuclear fusion [17], particle acceleration [18 - 22], heating of ionospheric plasma and laboratory plasmas by radio waves [23] etc. along with controlled fusion applications to ITER (International Thermonuclear Experimental Reactor) [24 - 26], frequency upshifting [27 - 28], resonance absorption [29 - 31], laser focusing and defocusing [32 - 34], material processing [35], generation of X-ray [36 - 37],

THz [38 - 42] and microwave radiations, higher order harmonic generation [46], laser filamentation [43 - 45] etc. With the inclusion of plasma, the performance of some devices such as backward wave oscillator (BWO), travelling wave tube (TWT) amplifiers, gyrotrons and other microwave tubes is also being increased [46].

Laser Field and Profile

A laser is a physical device that emits in a controlled manner a highly coherent amplified light with stimulated emission of radiation. A laser can operate either in continuous or pulsed mode, depending on whether the power output is essentially continuous over time or takes the form of pulses of light on one or another time scale. Laser beam whose output power is constant over time is known as continuous wave (CW) laser. However, the laser in which output power appears in pulses of some duration at some repetition rate is referred to as pulsed mode laser. The rate of repetition may vary from a few Hz to several kHz. The pulse energy of such lasers is taken to be equal to the rate of average power and the repetition rate. These days the maximum peta-watt (10^{15} W) laser systems are readily available. However, these powerful laser pulses last for an extremely short time that varies from a few femtoseconds ($1fs = 10^{-15}$s) to a picosecond ($1ps = 10^{-12}$s). The ultra-short pulse laser which are quite useful to study various phenomena occurring during the laser plasma interaction, are obtained based on a technique known as chirped pulse amplification (CPA).

It is also worth to talk about the intensity distribution of laser energy through the envelope of laser pulse. In general, the laser field has following distribution, represented as

$$\vec{E}_L = E_{0L}\exp\left[-\left(\frac{y}{b_w}\right)^p\right]\exp\left[i(kz-\omega t)\right]\hat{y} \tag{1}$$

Here, b_w is taken as the beam width of the lasers, y as the transverse distance from the axis of propagation of laser pulse, ω as laser frequency, k as laser wave number and E_{0L} is the laser pulse field amplitude and p is known as sG index. The index $p = 2$ represents Gaussian laser, $p > 2$ represents the sG lasers whereas the index $p >> 2$ represents the flat top lasers.

On the other hand, skew coshyperbolic-Gaussian (skew chG) lasers have been found to be more appropriate for biomedical applications [47 - 51] of THz radiation. The field of skew cosh-Gaussian (skew chG) lasers is represented as

$$\vec{E}_L = E_{0L}\cosh^n\left(\frac{ys}{b_w}\right)\exp\left[-\left(\frac{y}{b_w}\right)^2\right]\exp\left[i(kz-\omega t)\right]\hat{y} \tag{2}$$

Here, s is skewness parameter, n is the order of chG beam such that Gaussian laser is represented for $s = 0$ and skew ChG laser corresponds to $s > 0$. When laser propagates through the plasma, plasma dynamics gets modified expressed using Force equation of motion in the next section.

Quiver Velocity of Electrons

When a high power laser is focused onto plasma, the plasma electrons begin to oscillate at very high velocities (close to the speed of light sometimes) due to the laser's transverse oscillating electric field. The velocity caused by the laser fields to the electrons is termed as a quiver velocity of plasma electrons. It is assumed that the plasma electrons are initially under equilibrium state, which gets disturbed in the presence of laser field. Therefore, the force acting on plasma electrons is expressed using the following equation of motion where collisional force on the plasma electrons are also taken into account,

$$m\frac{\partial\vec{\upsilon}}{\partial t} = -e(\vec{E}_L + \vec{\upsilon}\times\vec{B}_L) - m\nu\vec{\upsilon} \tag{3}$$

Where $\vec{E}_L$ and $\vec{B}_L$ are the electric field and magnetic field of the lasers and $\nu = \nu_{en}$ is the electron-neutral collision frequency. Magnetic field of the laser field is much weaker as compared to the electric field. In view of this, the term $\vec{\upsilon}\times\vec{B}_L$ is generally neglected by the researchers. Then the equation of motion of electrons of mass m in collision-less plasma is simplified as $m\frac{\partial\vec{\upsilon}}{\partial t} = -e\vec{E}_L$. This equation gives the following expression for the quiver velocity of electrons $\vec{\upsilon} = \upsilon_q = \frac{e\vec{E}_L}{m\omega}$.

The ratio of the electron quiver velocity to the speed of light c is defined as $a = \frac{eE_L}{m\omega c}$, which is termed as a laser strength parameter. Actually it is normalized laser amplitude reason being *e, m, c, ω* are constants. In view of this, the laser plasma interaction is said to be relativistic if $a \geq 1$. This region of interaction is relativistic regime otherwise it remains non-relativistic for $a < 1$ [52]. For example, the laser of intensity 2.2 × 10^{18} W/cm^2 gives $a = 1$ for 800-nm laser light. This situation is termed to be relativistic. When lasers are highly intense of the order greater than 10^{18} W/cm^2, the relativistic effects become important and are associated with the motion perpendicular to the direction of laser propagation depending on the laser field through the electron quiver velocity. The quiver energy of plasma electrons for a one oscillation period of a laser field is defined as, $E_q = \frac{1}{2} m \langle \upsilon_q^2 \rangle$ which is the same as the ponderomotive potential $\phi_p = \frac{e^2 E_L^2}{4m\omega^2}$. The ponderomotive potential results in a force $\vec{F}_p^{NL} = -e\vec{\nabla}\phi_p$, which is known as the ponderomotive force. The ponderomotive force is directed along the intensity gradient of a laser pulse envelope, and is perpendicular to the laser propagation direction. The force pushes electrons out of the region of the laser pulse, and becomes the driving force for exciting plasma oscillations in a plasma. The more details about ponderomotive force are presented in the next section.

Ponderomotive Force

A ponderomotive force is a highly specialized nonlinear force that a charged particle experiences in an inhomogeneous oscillating electromagnetic field. We know that any light wave, for instance a laser pulse, exerts a radiation pressure on the surface of its incidence. This radiation pressure force is usually very weak and hard to detect. When high-powered microwaves or laser beams are launched in the plasma, however, the radiation pressure can reach several hundred thousands of atmospheric pressure. This force is coupled to the particles in a somewhat subtle way and is referred to as the ponderomotive force. Many complex nonlinear phenomena have a simple explanation in terms of the pondermotive force [1]. The electromagnetic field of laser beam is given as

$$\vec{E}(r,t) = \hat{E}(r,t) \exp i(\vec{k}\cdot\vec{r} - \omega t) \text{ and } \vec{B}(r,t) = i\vec{\nabla}\times\hat{E}(r,t)/\omega \tag{4}$$

where $\vec{\nabla}\times\vec{E} = -\partial\vec{B}/\partial t$ are related with Maxwell's equation. It is assumed that $\hat{E}(r,t)$ describes the envelope of laser field which only have "slow" time dependence as compared to the laser period. Since time scale terms disappear upon averaging over a laser period, so we take $\partial\vec{B}/\partial t = -i\omega\vec{B}$ to high accuracy. The ponderomotive force ($\vec{F}_p^{NL}$) is expressed as

$$\vec{F}_p^{NL} = -\frac{e^2}{4m\omega^2}\vec{\nabla}\left|\hat{E}(r,t)\right|^2 . \tag{5}$$

The above force is proportional to the laser intensity and is independent of the sign of the particle's charge. Therefore, all charged particles are expelled from regions of high laser intensity to the region of low intensity irrespective of their nature. However, the effect of ponderomotive force is much weaker on the positive ions than the negatively charged electrons, owing to the larger mass of the ions than the electrons. Thus, in most of the cases it is assumed that the ions remain unaffected under the influence of ponderomtive force. The ponderomotive force is inversely proportional to the square of the laser frequency, which signifies the increased force with increasing wavelength of lasers. In the physics of laser - matter interaction, the importance of the ponderomotive force is very significant which helps us understanding the instabilities.

Beat Wave Process

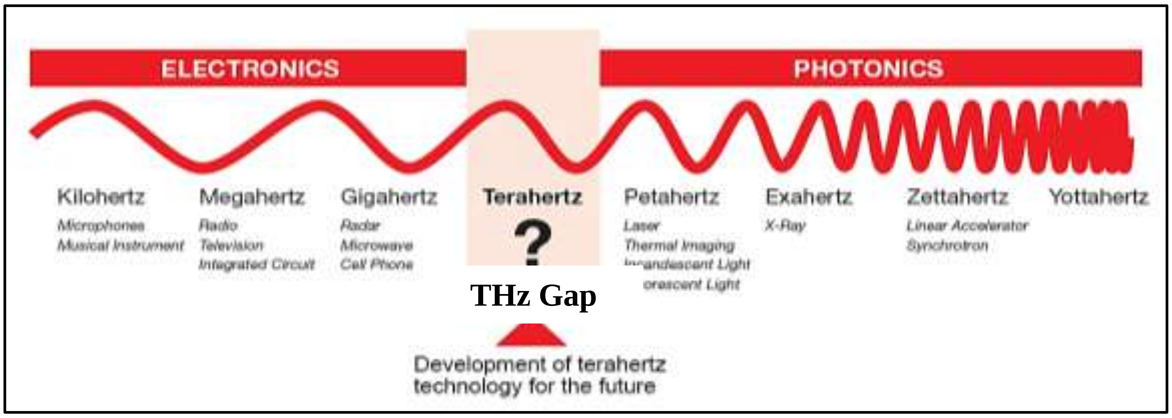
When two laser pulses of slightly different frequencies (ω_1 and ω_2) and wave number (k_1 and k_2) are collinearly launched into a plasma. A beat wave is excited that advances in the plasma with difference frequency $\omega = \omega_1 - \omega_2$. If the difference frequency is approximately equal to the plasma frequency ($\omega = \omega_p$), the ponderomotive force associated with this beat wave excites large amplitude plasma oscillations resonantly provided the energy and momentum conservations are achieved [53]. The energy conservation and momentum conservation read as $\hbar\omega_p = \hbar\omega_1 - \hbar\omega_2$ and $\hbar k_p = \hbar k_1 - \hbar k_2$ respectively. Such phase matched difference frequency generation mechanism has been employed for the THz radiation generation [54 - 55]. The schematic of THz radiation generation by beat wave mixing involves the non-linear dynamics of excited plasma oscillations by collinear mixing of laser pulses is studied in the plasma. The nonlinear ponderomotive force of beat wave excites the nonlinear oscillating currents which leads to the generation of THz radiation.

Wake Field Excitation

In beat wave process it is mandatory to match plasma frequency strictly with the beat wave frequency. For wake field excitation, one uses a short laser pulse of very high intensity of the order of 10^{15} W/cm^2. The laser pulse propagates in the plasma with a group velocity of laser envelope that is nearly equal to the speed of the light. The short laser pulse duration has a strong intensity variation in time and correspondingly in space. This causes a strong longitudinal ponderomotive force with wavenumber and frequency correspondingly the same as of the incident laser. When the length of the laser pulse matches the plasma wavelength, a high amplitude wake field is excited in the plasma. It may be understood with the example of a steamer boat sailing through the sea, causing a high gradient backward field in the wake of its motion forward. These fields are known as wake field and have acceleration gradient as high as few GV/m in plasma [56]. Under this situation, a correctly injected bunch of electrons can be accelerated by the longitudinal field of the plasma waves. Hence, plasma wake fields are mainly used for acceleration purposes [57 - 62]. But, there also exist a transverse component of wake field which give rise to terahertz radiation on matching with boundary conditions.

OVERVIEW AND SCOPE OF TERAHERTZ RADIATION

THz radiation is an electromagnetic radiation, which lies between the high frequency microwave band (MW region) and low frequency infrared band (IR region). This radiation demarcates two very important subjects, namely photonics and electronics, because of which this is also termed as THz gap [63]. The position of THz radiation in electromagnetic spectrum is shown in the following figure.



THz radiations have several physical, chemical, biological, forensic etc. applications. These are listed below

- THz radiations have a lower frequency as compared to X-rays and therefore, the damage caused to the biological tissues is far less by them [64].
- These radiations are being used for medical imaging purposes [65 - 66].
- The present metal detectors that use eddy currents to detect materials concealed can be replaced by devices that use THz radiations.
- These radiations can easily penetrate plastic and fabrics, so these are very useful in security systems [67].
- THz radiations can be used for chemical engineering systems, instrumentation and pharmaceuticals [68].
- THz radiations can be used in communication and wireless data transmission [69 -70].
- THz radiations are also very useful in Time Domain Spectroscopy, called as THz-TDS [70 - 71].
- THz radiations are used in material characterisation [72].

THz radiations also have limitations like low penetration depth as compared to microwaves. These radiations have limited penetration through fog and clouds and cannot penetrate metals and water. In wireless data transmission, the range of THz radiations is not more than a few metres but in short distance communication, THz systems are very strong. Thus THz technology has open up a new arena of potential applications and viability.

New Research Aspect of THz Technology

At times THz technology has multiple uses in several sectors such as material sciences, medical sciences, information technology, communication, security, imaging, aerospace engineering, THz photonics, spectroscopy and food packaging etc. All are of commercial importance. THz technology has become a very active and interesting field of research. In these every aspect, it has become essential to study, generate, detect and to apply THz radiation. In this section, a brief review on the THz technology is presented discussing different aspects of THz technology and few selective important applications.

Medical Applications

Non-destructive and non-hazardous nature of THz radiation makes them more useful in the field of medical applications. THz radiations are non-ionizing unlike X-rays because THz photons energy is in the range between 0.4 to 4.1 meV which is one million times lower than that of ionizing X-ray photons and also much below the order of the required energy for molecular ionization. Therefore, THz radiation is generally considered to be safe for humans. The researchers have been showing a keen interest in applying the newly developed THz technology in the field of biological imaging and medical applications. THz wave spectroscopy is used to study molecules and proteins structural analysis in DNA. Later research focused on the study of tissue such as skin and breast cancer for diagnosis purposes. The fundamental approach for such THz based diagnosis is high sensitivity of THz to the presence of liquid water and the different water concentration between healthy and cancerous tissue. THz spectroscopy and imaging have been used to analyse skin burns and wounds. On the other hand, the THz time domain spectroscopy is served as an excellent technique to treat different types of skin-related ill tissue and its water concentration based on their characteristic optical properties. Based on this the thermal mechanism involved in burns and skin wounds have also been studied. These novel results reported in recent publications will foresee a new line of medical treatment based on THz technology. New research is still underway in order to understand that how the underlying mechanisms of the interaction between the THz waves and the behaviour of proteins and cellular structures work. However, it is a matter of concern that the THz radiations are highly absorbed by water content and biological systems are water affluent.

Optical Applications

THz optics is a new innovative field of applications. Generally optical components such as glasses are useless in THz frequency range which are most effective in the optical frequency range because the losses are too high in THz band. This led to the development of THz optical components consisting of some specialized polymers and semiconductor materials like Teflon and silicon. Teflon and silicon have high THz transmission to act effectively in THz frequency range. There are lenses and mirrors which are used to guide, focus and collimate a THz beam under paraxial optics approximation. However, diffraction, size of the source and mode characteristics of the beam need to be considered in some cases because of the larger wavelength of THz compared to the size of the optical elements. THz optical components such as lenses and windows are made up of those transmissive materials. The metal wire grids are commonly used as THz polarizers. Thin metallic meshes are also used as THz band-pass filters. Recently, meta-materials have drawn a lot of attention because of their unusual electromagnetic properties. This has given an opportunity to manipulate electromagnetic wave in different ways. Therefore, it is foreseen that meta-materials will have an important role in the development of cutting edge future THz optical technology.

Spectroscopic Applications

THz time-domain spectroscopy (THz TDS) is the technique which is most commonly used to characterize the spectral properties of materials. THz TDS is most suited technique to study and understand the molecular structure and dynamics of materials. This is done because of the fact that rotational and vibrational modes of many molecules, especially organic ones, are distributed across the THz band. Though there are well established Raman and FTIR spectroscopy, the major difference is that both Raman and FTIR measure energy whereas THz TDS measures the electric field. It makes THz TDS a coherent detection technique that allows to extract information about both phase and amplitude data. The another interesting feature of THz TDS is the Fingerprinting. These modes of molecules can be observed as absorption peaks in the THz spectra, which can be used to identify the molecules. In the recent years, TDS systems and spectrometers are being used in security and explosive and related compounds (ERCs) detection. Early spectroscopic measurements have shown that most explosives had unique fingerprints in the THz band that could be used to identify them. Those fingerprints were measurable even with covers such as plastic, clothes, paper, and cardboard. It means THz TDS can be used in several security applications such as mail inspection and suicide bomber.

Material characterization is a basic application for THz TDS, where the “optical” constants of the material are extracted. These can be related with the complex dielectric constant. The optical constants are the index of refraction and absorption coefficient. Since the THz waveform is a measurement of the electric field of the THz wave, the absorption coefficient refers to the attenuation in electric field, which is half of the absorption coefficient in energy.

Food safety is another sector that will be benefited from the progress of THz TDS technology. Since THz waves can penetrate plastic and paper, THz TDS has the potential to analyse food that is already packaged in search of contaminants and hazardous compounds such antibiotics or pesticides. Several antibiotics commonly used in veterinary field have found to have absorption features in the THz range. These features could be used to detect the presence of such antibiotics in dry food for chicken stock.

THz TDS may also be applied for discovery and drug analysis in the field of pharmaceutical industry. THz TDS has been used to study polymorphisms and chiral symmetry in drug compounds. THz TDS has also been used to study phase transitions between different molecular configurations as a function of temperature and humidity (hydration). Depending on the temperature, it can be seed that the speed of the hydration changes. It is also possible to do spectral imaging, in which each pixel contains the spectroscopic information of that location. From an industrial perspective, THz TDS could be used to identify and classify pills based on the drug composition. This capability could be used to discard those pills that do not meet certain quality standards because they do not have the compound in the right proportion.

Other Applications

THz waves have proven their potential for non-destructive and safe imaging applications because of low frequencies close to the far IR region. Optical approaches can also be applied to design THz imaging system. As an imaging tool THz radiations may be used to detect corrosion, crack and voids in ceramic and foam materials and thickness measurements. THz systems are also being employed for chemical and security identification purpose owing to the ability of THz waves to see through the dry and non-metallic materials such as plastic, paper, cardboard and textiles. If pulsed THz imaging systems are used, then each pixel will contain spectral information that may be used to characterize and identify the material being imaged. Therefore, structural as well as chemical information about the scanned object may be extracted.

CONCLUSIONS

In the article, a complete overview of the mechanism of the THz radiation generation via laser plasma interaction is presented. There are several important aspects of the THz research that encompass the THz radiation generation, its detection and several extensive real life applications. Plasma serves as a best suitable medium for ultra-intense laser due to its limitless capability of sustainment of very strong electric fields, whereas the solid materials like nonlinear crystals suffer breakdown.

First, the THz radiation generation based on the beat wave excitation by mixing of two laser pulses in collisional plasma was presented. Here nonlinear plasma current was excited by the nonlinear ponderomotive force in the plasma. This current led to the emission of the THz radiation. On the other hand, it may also be regarded as the emission of the THz radiation generation from different approach of wake field that is also excited due to the propagation of highly intense laser through the plasma. We considered electron-neutral collisions and found their negative impact on the THz emission. Because of these collisions, the resonance frequency was also found to be altered. The effect of collision frequency was much significant in the case of super-Gaussian (sG) lasers driven THz emission. However, the amplitude of the THz field remained larger than the amplitude of the THz field obtained by using Gaussian lasers. By the use of coshyperbolic-Gaussian (chG) lasers, one could obtain bifocal THz radiation. This shall find applications in medical diagnostics. Thus, several applications of THz radiation make it evident to study the generation of THz radiation sources.

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