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Studies of Terahertz Sources and Their Applications

Sukhmander Singh, Shravan Kumar Meena, Ashish Tyagi, Sanjeev Kumar, Man Raj Meena and Sujit Kumar Saini

Abstract

The contributed chapter discuss the applications of terahertz radiations and its generation mechanism through laser plasma interactions. The methods of generation of terahertz radiations from plasma wake field acceleration, higher harmonic generation and the laser beat wave plasma frequency are reviewed. The nonlinear current density oscillate the plasma at beat wave frequency under the effect of ponderomotive force and excite the terahertz radiation at beat wave frequency. The current state of the arts of the methods of generation has been incorporated. The mathematical expression of ponderomotive force has been derived under the influence of gradient of laser fields. In additions, the future challenge and their overcomes are also been discussed.

Keywords: electromagnetic waves, THz radiation, beat wave, ponderomotive, nonlinear, plasma, harmonic, detectors

1. Introduction

THz radiation has applications in broadband THz communications, basic science, security, pharmaceutical industries, manufacturing and medicine science. The Terahertz (THz) frequency region, which was difficult accessible frequency region range (0.1–30 THz) lies between the microwave and infrared bands in electromagnetic spectrum. This THz region is also defined as borderline of high frequency region of the microwave band and long wavelength region of far infrared light. Radiation at 1 THz has a period of 1 ps, wavelength 300, wave number 33/cm and photon energy 4.1 meV. It has peak field at 100 MV/cm between 15 THz and 50 THz that provide major momentum to the investigating materials. Therefore THz waves allow direct access to molecular rotations, lattice vibrations and spin waves (low-energy excitations) in contrast to excitations of valence electrons stimulated by optical waves. The THz radiation is non-ionizing and nondangerous for living cells. These radiations can penetrate through plastics, metals, textiles, paper and woods which assists to identify the explosives and drugs. In most of the cases, the vibrational modes of oxygen, water and carbon monoxide (molecules of drugs and explosives) lies in the THz region, therefore during the investigation, those ingredients display distinctive absorption lines in the THz frequency range.

Electromagnetic waves have an applications in medical imaging, broadcasting, WiFi, and treating cancer. The Sequential arrangement of electromagnetic waves are shown in **Table 1**.

We also summarize some of the main applications for each range.

The electromagnetic spectrum				
Frequency (Hz)	Nature	Wavelength (m)	Production	Applications
10^{22}	gamma rays	10^{-13}	Nuclear decay	Cosmic rays
10^{21}	gamma rays	10^{-12}	Nuclear decay	Cancer therapy
10^{18}	x rays	10^{-9}	Inner electronic transitions and fast collisions	Medical diagnosis
10^{16}	ultraviolet	10^{-7}		Sterilization
10^{15}	visible	10^{-6}	Thermal agitation and electronic transitions	Vision, astronomy, optical
6.5×10^{14}	blue	4.6×10^{-7}		
5.6×10^{14}	green	5.4×10^{-7}		
3.9×10^{14}	red	7.6×10^{-7}		
10^{14}	infrared	10^{-5}	Thermal agitation and electronic transitions	Heating, night vision, optical communications
10^{9}	UHF	10^{-3}	Accelerating charges and thermal agitation	Microwave ovens
10^{10}	EHF	10^{-1}		remote sensing
10^{8}	TV FM	10		radio transmission
10^{6}	AM	10^{3}		radio signals
10^{4}	RF	10^{5}	Accelerating charges	

Table 1.
The electromagnetic spectrum.

2. Application of terahertz radiation

THz radiation technology have a substantial presentation in the field of engineering, science, biomedical engineering, astrophysics, environmental engineering, information science, technology and plasma physics.

2.1 In biomedicine

Terahertz waves are useful for the diagnosis of disease since every organisms have a unique response to THz wave. THz tomography get absorption rate distribution and three-dimensional distribution of the refractive index of materials in computer assisted tomography [1–29].

2.2 Quality control and safe monitoring

THz radiation is used to observer the process of food processing, weapons, drugs and explosives. THz electromagnetic waves are completely harmless to humans owing to its strong capacity of penetration [2–29].

2.3 Non damaging testing

The penetration length of radiations are measured by THz time-domain spectroscopy. The safety and penetrable properties of THz waves are useful for

nondestructive testing. THz waves can penetrate a few inches thick foam. Foam used in space shuttle has very low refractive index and absorption variation, although this change can be observed to detect the defects [1–10].

2.4 Astronomy and atmospheric research

The atmospheric molecules (nitrogen, water, oxygen and carbon monoxide) have excitation energy in the terahertz range, therefore these molecules can be detected with THz radiation to monitor the atmospheric environmental and ozone layer as well as space research [3–12]. THz technology can be employed in astronomy and Earth observation to monitor the weather. The ultra-high frequency of THz radiation provide better digital signal processing and imaging.

2.5 Wireless communication and networking

THz band has higher frequency, wider bandwidth and greater channel than the microwave and 10 Gbps wi-fi transmission speeds may be obtained by means of THz communique, which is some hundred or maybe hundreds of instances faster than contemporary ultra-Wideband technology [3–12].

2.6 Secure communication

The small power of THz radiations is used to gain long-range space communications because of its low attenuation characteristic. THz radiation has wider beam width against space optical communication, which make it suitable to pointing in the long-distance space communication [1–6].

2.7 Chemical and biological agent detection

Terahertz radiation is very sensitive to molecules and surrounding environment. Therefore, terahertz technology is used in chemical detection and identifications of the chemical and biological agents [1–16].

2.8 Medical applications

Ionizing radiation is a kind of radiation that carries photon energy large enough to detach electrons from atoms or molecules, leading to their ionization. X-ray radiation may be harmful for humans. Typical X-ray imaging systems for medical purpose involves photon energies close to 100 keV. Hence, a person may get exposures of a high dose. Since the detection resolution is restricted by diffraction, therefore due to shorter wavelength of the terahertz radiation, it provide better spatial resolution in imaging. Moreover, the vibrational and rotational transition energies of the biomolecular constituents of tissue lies in the THz frequency range, which offer good spectroscopic information of biological tissues. The low photon energy of the radiation is nonionizing and there is negligible scattering from tissues. An exposure of a high dose of ionizing radiation may damage DNA of a human body and may increases the possibility of developing cancer. When the energy is larger than ~ 10 eV, we say the radiation is ionizing. Therefore the water content presents in the tissue can provides good contrast between the healthy and diseased states of tissues using time-domain spectroscopy based on terahertz radiation. The time-domain spectroscopy provide quasi 3D information in the broad frequency range to investigate the desired information. Although terahertz technology is still young and there have been no major commercial applications in the medical science.

2.9 Quality control and pharmaceutical applications

X-ray photoelectron spectroscopy, Fourier transform infrared and laser induced breakdown spectroscopy are destructive for the medicine tablet to investigate the uniformity of the coating. The non-uniform of the coating or surface defects on the tablets leads to lacks of the desired dose delivery. THz waves have penetrating behavior because of its electromagnetic nature. Terahertz image can be optimized for performing 3D analysis on tablets to determine coating integrity and thickness.

3. Food applications of terahertz spectroscopy

3.1 Terahertz sources

An electronic and photonic materials based methods have been built to generate THz radiation in the recent years and these methods are tabulated in **Table 2**. These sources complement laser-based and other table-top THz sources, which are limited to lower average powers, lower peak fields and lower repetition rates.

Name	Source type	References
Gas	Lasers	Dodel [25]
Semiconductor	Lasers	Chassagneux et al. [26]
Frequency multiplication	Solid-state electronic	Maestrini et al. [27]
Transistors	Solid-state electronic	Lusakowski et al. [28]
Gyrotrons	Vacuum electronic	Bratman et al. [29]
Free electron lasers	Vacuum electronic	Knyazev et al. [30]
Synchrotrons	Vacuum electronic	Byrd et al. [31]
Mercury lamp	Thermal	Charrada et al. [32]
Mechanical resonance	Continuous pumped lasers	Wu et al. [33]
Terahertz parametric oscillator	Pulsed lasers	Kawase et al. [34]

Table 2.
Sources of THz.

4. Ponderomotive force

The nonlinear process arise, when a very high intensity electromagnetic wave interacts with a plasma and the force due to radiation pressure is coupled to the plasma particles and it is called ponderomotive force. Self-focusing of laser light in a plasma is a direct effect of ponderomotive force. When a gas is ionized by propagating a laser thought it, a force exert on the medium at ionization front. A laser beam causes a radially directed ponderomotive force in a plasma which forces plasma out of the beam and dielectric constant becomes higher inside the beam than outside. The plasma acts as a convex lens focusing the beam to a smaller diameter. Here we derive the expression for the ponderomotive force [35].

Equation of motion of particle under the electromagnetic fields

$$m_e \frac{d\vec{v}}{dt} = -e\left[\vec{E}(\vec{r}) + \vec{v} \times \vec{B}(\vec{r})\right] \tag{1}$$

Non-linearity in the system comes partly from the $\vec{v} \times \vec{B}$ term which is a second order term and assuming that $\vec{v_0} = \vec{B_0} = 0$. The other part of nonlinearity comes from evaluating $\vec{E}$ at the actual position of the partical. Let the wave electric field is

$$\vec{E}(\vec{r}) = \vec{E_S}(\vec{r}) \cos(\omega t) \tag{2}$$

We expand E(r) about point $r = r_0$

$$m_e \frac{d\vec{v_1}}{dt} = -e\vec{E}(\vec{r_0}) = -e\vec{E_S}(\vec{r_0}) \cos(\omega t) \tag{3}$$

After integrating over time, we get

$$\vec{v_1} = \left(\frac{e}{m_e\omega}\right)\vec{E_S}(\vec{r_0})\sin(\omega t) \tag{4}$$

Again, integrating over time, we get

$$\vec{r_1} = -\left(\frac{e}{m_e\omega^2}\right)\vec{E_S}(\vec{r_0})\cos(\omega t) \tag{5}$$

Now, according to Faraday's law

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{6}$$

It implies

$$\vec{B_1} = -(1/\omega)\,\vec{\nabla} \times \vec{E} \tag{7}$$

The Taylor expansion of Eq.(2) about point $\vec{r} = \vec{r_0}$

$$\vec{E_S}(\vec{r}) = \vec{E_S}(\vec{r_0}) + (\vec{r_1} \cdot \vec{\nabla})\vec{E_s}(\vec{r} = \vec{r_0}) + \dots\dots \tag{8}$$

Putting the value in equation in (1) from Eq. (7) and (8), we get

$$m_e \frac{d\vec{v_2}}{dt} = -e\left[(\vec{r_1} \cdot \vec{\nabla})\vec{E_s}(\vec{r_0})\cos(\omega t) + \vec{v_1} \times \vec{B_1}\right] \tag{9}$$

On solving the equation and taking the average over time.

$$\left(m_e \frac{d\vec{v_2}}{dt}\right)_{avg} = -\left(e^2/4m_e\omega^2\right)\vec{\nabla}\left(E_s^2\right)_{avg} \tag{10}$$

Or

$$\left(m_e \frac{d\vec{v_2}}{dt}\right)_{avg} = -\left(e^2/2m_e\omega^2\right)\vec{\nabla}\left(E^2\right)_{avg} \tag{11}$$

So the left hand side in equation (11) is the effective force on a single electron, which can be denoted by f_{NLe}.

Similarly force on ions can be written

$$\overrightarrow{f_{NLi}} = \left(m_i \frac{d\overrightarrow{v_2}}{dt}\right)_{avg} = -\left(e^2/2m_i\omega^2\right)\vec{\nabla}\left(E^2\right)_{avg} \tag{12}$$

So the resultant force on plasma due to ions and electrons is

$$\overrightarrow{F_{rslt}} = n_0\left(\overrightarrow{f_{NLi}} + \overrightarrow{f_{NLe}}\right)$$
$$= \left(\frac{n_{e_0}e^2}{2m_e\omega^2}\right)\left(1 + \frac{m_e}{m_i}\right)\vec{\nabla}\left(E^2\right)_{avg.} \tag{13}$$

Since the mass of the ions are much greater than the mass of the electrons, we get

$$\overrightarrow{F_{rslt}} = -\left(\omega_{pe}/\omega^2\right)\vec{\nabla}\left(\varepsilon_0 E^2/2\right)_{avg} \tag{14}$$

This is called Ponderomotive force.

5. Non-linear current due to laser beating

Let us consider two different color laser beams co-propagating in a corrugated plasma having electric field profiles as follows

$$\overrightarrow{E_1} = \hat{j}E_0 e^{-\left(y^2/a_0^2\right)}e^{i(k_1 x - \omega_1 t)} \tag{15}$$

$$\overrightarrow{E_2} = \hat{j}E_0 e^{-\left(y^2/a_0^2\right)}e^{i(k_2 x - \omega_2 t)} \tag{16}$$

The equation of motion of plasma electrons in a field

$$m\frac{\partial \overrightarrow{v}_e}{\partial t} = -e\vec{E} \tag{17}$$

Lasers impart oscillatory velocity to electrons

$$\overrightarrow{v_1} = e\,\overrightarrow{E_1}/i\omega_1 m \tag{18}$$

$$\overrightarrow{v_2} = e\,\overrightarrow{E_2}/i\omega_2 m \tag{19}$$

The corresponding ponderomotive force

$$\overrightarrow{f_p}^{nl} = \frac{-e^2}{2m\omega_i^2}\vec{\nabla}\left(E_{avg}^2\right) \tag{20}$$

In terms of two components of electric field

$$\overrightarrow{f_p}^{nl} = \frac{-e^2}{2m\omega_1\omega_2}\vec{\nabla}\left(\overrightarrow{E_1}.\overrightarrow{E_2}^*\right) \tag{21}$$

We know that

$$\vec{F} = -e\nabla V \tag{22}$$

By comparing the Equation (21) and (22)

$$V = \frac{e}{2m\omega_1\omega_2} \vec{\nabla}\left(\vec{E_1} \cdot \vec{E_2}^*\right) \tag{23}$$

the equation (19) deduce that

$$E_i = \frac{im\omega v}{e}. \tag{24}$$

So, from the equation (18) and (19) , we get

$$V = \frac{-m}{2e}\left(\vec{v_1} \cdot \vec{v_2}^*\right) \tag{25}$$

From the equation (22)

$$\vec{f_p}^{nl} = \frac{-e^2}{2m\omega_1\omega_2} \vec{\nabla}\left(\vec{E_1} \cdot \vec{E_2}^*\right) \tag{26}$$

Putting the values of electric filed $\vec{E_1}$ and $\vec{E_2}$ -

$$\vec{f_p}^{nl} = \frac{-e^2}{2m\omega_1\omega_2} \vec{\nabla}\left(E_0^2 e^{-\left(2y^2/a_0^2\right)} e^{i[(k_1-k_2)x-(\omega_1-\omega_2)t]}\right) \tag{27}$$

Or

$$\vec{f_p}^{nl} = \frac{-e^2 E_0^2}{2m\omega_1\omega_2} \vec{\nabla}\left(e^{-\left(2y^2/a_0^2\right)} e^{i\left(k'x-\omega't\right)}\right) \tag{28}$$

Here,

$$k' = (k_1 - k_2) \text{ and } \omega' = (\omega_1 - \omega_2) \tag{29}$$

This oscillatory current is the source for the emission of THz radiation at the beating frequency.

6. Generation of terahertz radiation

A wide range of THz sources are now commercially accessible, although they are big and relatively expensive to run. As a result, much research is being done in order to develop appropriate THz sources. Various organizations across the world have devised various techniques for producing THz sources [5, 6]. Traditional THz sources are based on electro-optic crystals such as ZnSe, GaP, LiNbO3, or photo conductive antennas as well as super-luminous laser pulse interactions with large band gap semiconductors and dielectrics [7–13]. Laser plasma interaction, optical recitation, solid state electronic devices and many complex methods are being used to generate THz radiations [1–20]. The output of such sources can be harmonically multiplied to the THz range. Recent improvement in the field of quantum cascade lasers, laser emission is achieved through the use of inter-sub-band transitions in a periodic repetition of layers of two different compositions, or super-lattice structure. A super-lattice is a periodic structure of quantum wells and barriers. The photon emitted by the super-lattice is due to the intersub-band transition in the

super-lattice. Such transitions can be specified by the thickness of the coupled wells and barriers. Therefore, by toiloring the periodicity of the super-lattice to specific well-barrier thickness, THz radiations of specified energy range can be generated. Although the idea of inter-band emission was known since 1971, the crystal growth technology for creating quantum cascade lasers is relatively new and expensive. Terahertz radiation in the frequency range 0.1–10 THz, lies between the MW and IR region and has potential uses in a wide range of fields. That why researchers are interested in this portion of the spectrum [1–5].

7. Schemes based on laser plasma interaction

Terahertz can be generated from nonlinear plasma medium. The following below mentioned schemes are commonly used for the generation of THz radiations.

1. Self-focusing of Laser Beam

2. Wake field Terahertz scheme

3. Beat wave Schemes

The high power laser beams changes the index of refraction of the plasma medium due to non-linear processes, called Self-focusing of laser beam. The increasing intensity of electric field enhances the index of refraction of plasma and the plasma shows similar behaves as a converging lens (**Figure 1**). Further, intensity of self-focusing region rises as the beam enters into medium, until the divergence effect occurs.

A work has been done to investigate terahertz generation in magnetized plasma using self-focusing of hollow Gaussian laser beam [36]. The hollow Gaussian filamented laser propagates parallel to magnetic field and interact with electron plasma wave to produce terahertz radiations. The study shows that intensity of emitted radiations is highly sensitive to the order of hollow Gaussian laser beam. Terahertz generation by amplitude-modulated self-focused Gaussian laser beam in ripple density plasma has also been studied in Ref. [37]. In this system, a current is generated by transverse component of ponderomotive force on electrons as a result the radiation is being driven at the modulation frequency (taken into terahertz domain). It is found that in comparison to without self-focusing to self-focusing an enhancement has been seen in terahertz generation which supported by numerical
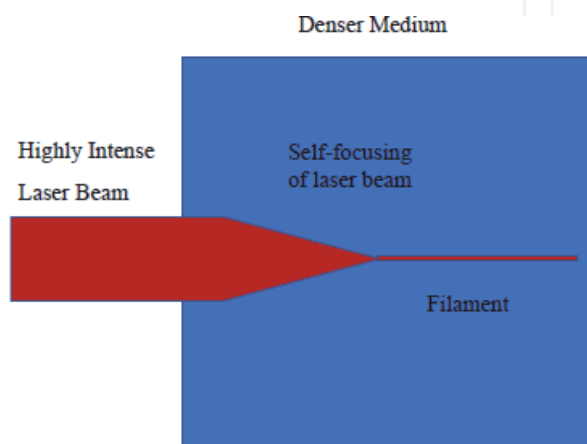

Figure 1.
Self focusing of LASER beam in plasma.

simulation. In rippled density plasma by using cosh-Gaussian lasers terahertz generation has been studied in Ref. [38]. The laser exerts a ponderomotive force along the transverse direction as a result electrons oscillate which get coupled with the density ripple to generate terahertz radiation. It is found that by changing the decentered parameter of laser there exist a notable change in magnitude, amplitude and conversion efficiency of terahertz radiations. Terahertz radiations can also be generated by using relativistic self-focusing hollow Gaussian laser in magnetoplasma [39]. Due to relativistic effect the change in electron mass occurs at high intensity which leads to produce nonlinear effects in plasma leading to the self-focusing of hollow Gaussian laser beam. Hassan et al. defined that when two Laguerre-Gaussian laser beam is gone through the cross-focusing then it generates THz [40]. The amplitude of THz can be enhanced with the help of large amplitude density ripple.

Kumar et al. [41] numerically investigated that THz yield increases sufficiently under the effect of self-focusing and defocusing of amplitude-modulated Gaussian laser beam in rippled density plasma. Hong et al. [42] studied the propagation of a Gaussian and hollow Gaussian laser beam in a tapered plasma to figure out the ponderomotive self-channeling and relativistic self-focusing effects. It has been concluded that, when transverse plasma density is homogeneous, its focusing ability is robust than that of the hollow Gaussian laser. Vhanmore et al. [43] used asymmetric elegant Hermite-cosh-Gaussian to study the self-focusing in magnetized plasma. Kumar et al. [44] analytically studied relativistic self-focusing and particle-in-cell simulations, which reveals that the self-focusing is less sensitive to laser amplitude variation in deeper plasma channels for millimeter range plasma channels present scheme is being valid.

7.1 Wake field terahertz scheme

Laser wake field scheme depends on the interaction of a laser beam with a plasma. A conical emission in the forward direction is produced by laser pulse under the influence of oscillating electrons which involve Cerenkov mechanism is called the laser wake field. Tajima and Dawson explained this scheme [45] as follows. The ponderomotive force originated by laser pulse envelope pushes away the background plasma electrons. The resulting force from the charge separation initiates a density oscillation, after the laser pulse left away the plasma. In this situation, group velocity of the laser equal to the phase velocity of the density oscillation. The same charge fluctuation is known as plasma wave or plasma wake. Self-trapped background plasma electrons produce electron bunch in the wake. Sheng et al. [46] detected powerful coherent emission of terahertz radiation in inhomogeneous plasma, when laser pulse is incident obliquely in laser wake field. It has been observed that the duration of terahertz, frequency and bandwidth depend on laser pulse duration and plasma density profile.

Gupta et al. [47] reported that plasma-density modulation and magnetic field can assist in electron energy enhancement by improving the electron trapping in laser wakefield acceleration (LWFA). Gupta et al. [48] also investigated the acceleration of electrons by the plasma waves in a density rippled inhomogeneous plasma. Gopal and Gupta [49] explored the use of asymmetric laser pulses (of sharp rising front) for optimization and control of electron beam in LWFA and reported that an asymmetric laser pulse reduces the beam emittance, enhance injection and can help in controlling the beam spreading to generate a high-quality monoenergetic beam. Yoshii et al. [50] employed the particle in cell simulation to generate the Cherenkov wake field by a short laser pulse to realize THz radiation in a magnetized plasma. Gopal et al. [51] have also suggested a method of enhancing the magnetic field strength in laser pulse interaction with plasma. Esarey et al. [52] have reviewed the physics of the plasma

beat wave accelerator, laser wakefield accelerator and self-modulated laser wakefield accelerator. These sources are capable to handle the strong electric field of order 100 GV/m from an intense laser. Hofmann simulated the performance of quadrupoles and solenoids in focusing and energy selection of laser accelerated protons [53]. Döpp et al. proposed the use of longitudinal density tailoring to reduce the beam chirp at the end of the accelerator [54].

7.2 Beat wave schemes

For the Generation of efficient THz radiation at different frequencies, various experiments have been conducted on lasers beating in a corrugated plasma. THz radiation generated by beating of two lasers yields more tunability and efficiency.
The basic mechanism to generate THz radiation is as follows:
Consider two laser beams having different wave numbers and frequencies propagating in a corrugated plasma. The laser beams exert a ponderomotive force on electrons. As a result these electrons, drives longitudinal oscillations (at beat frequency) adjacent to plasma frequency as shown in **Figure 2**. The generated beat wave decays (parametrically) into a terahertz wave and a plasma wave. The generated terahertz wave is (plasma channel) transverse magnetic mode with finite longitudinal component of the electric field.
Malik et al. [55] used super-posed femtosecond laser pulses to generate the THZ from a gas jet through oscillatory current density. The emission of THz radiation occur through oscillating dipoles. Hamster et al. [56] used 100 femtosecond (1 TW) laser focused onto gas through wakefield. The electrons execute oscillatory motion and produce terahertz radiation under the influences of ponderomotive force. Yampolsky and Frainman [57] reported the four-wave coupling scheme in a plasma filled capillary for the amplification of terahertz radiation. Kukushkin has produced the THz radiations in semiconductors using crossed alternating electric field and static magnetic field [58]. The external dc magnetic field used to increase the field of emitted radiations [59]. Jafari et al. have investigated that the generation of THz radiation by nonlinear coupling of two color laser beam which have Gaussian field in a plasma with multi-ion species through ponderomotive force on laser in plasma [60]. The radiated THz emission strongly depends on the density of ionic species. Result shows that the maximum value of the amplitude of THz found in a specific range of laser intensity. Li et al.
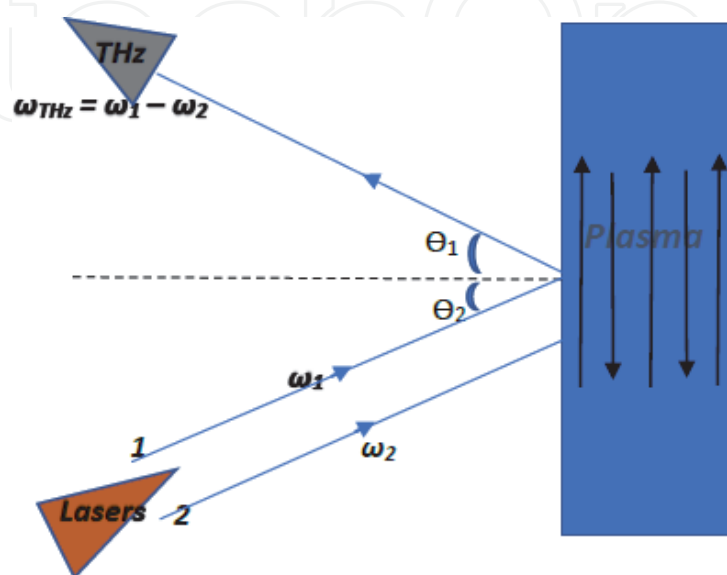

Figure 2.
THZ wave generation in beat wave mechanism.

investigated the contribution of the optical rectification for the generation of THz radiation by two color laser pulse by including the pump power of laser, rotation angle of Beta Barium Borate crystal and the numerical aperture of lens. All of the above factor dramatically affects the intensity of the radiation of THz wave [61]. Bhasin and Tripathi [62] used optical rectification of a x-mode picosecond laser pulse in rippled density magnetized plasma to generate THz radiation. Malik et al. investigated the scheme of the generation of the THz waves with two color laser in clustered plasma. The cluster plasma produces third order nonlinearity and resulted nonlinear current density produce the terahertz radiation. This scheme do not require magnetic field and the density gradient to generate the beat frequencies. The THz conversion efficiency depends on the cluster parameter. It is concluded that the surface plasmon resonance enhances the THz generation efficiency and THz power falls down with THz frequency [63].

In Ref. [64], spatial-Gaussian lasers has been used in a periodic density plasma to excites the radiation which shows depends on the laser-beam width and amplitude. Malik et al. employed two spatial-triangular laser beams for the excitation of terahertz radiation and reported the THz field $\sim 10^5$ kV/cm and the efficiency $\sim 10^{-2}$ correspond to the laser intensity $\sim 10^{14}$ W/cm^2 [65]. Malik and Malik [66] also suggested the mechanism for the generation of tunable terahertz radiation under the application of two femtosecond laser pulses. Dai and Liu [67] studied Terahertz emission in a gaseous plasma (generated by two lasers) with intensity of 5.00×10^{14} W/cm^2. Kumar et al. [68] studied Beat excitation of terahertz radiation from two different frequency infrared lasers of TM/TE mode propagating along z direction in a rippled density semiconductor waveguide slab in a magnetic field (applied transvers to it) and the terahertz yield is significantly higher in the TM mode laser beating than in the TE mode laser beating. Malik and Malik [69–72] investigated the role of an external DC magnetic field in tuning the frequency and power of terahertz radiation. Varshney et al. [73, 74] proposed a scheme for the generation of THz radiation from rippled density magnetized plasma by beating of extraordinary mode lasers.

Malik and Singh [74] used two super-Gaussian lasers to generate the highly focused terahertz radiation by frequency mixing. Chaudhary et al. [75] used Hermite cosh Gaussian lasers to generate the efficient intensity distribution of tunable terahertz radiation. Manendra et al. [76] used hollow sinh super-Gaussian laser beams to generate polarized terahertz wave by photo mixing of two-color laser. The efficiency and the field amplitude increases with electron temperature. Zhang et al. [77] did two-dimensional particle-in-cell simulations of ultra-intense relativistic laser plasma interaction of solid target to generate the terahertz pulses by coherent transition radiation and THz radiation energy increased by 10 times. Manendra et al. [78] investigated the effect of electron temperature on intensity and efficiency of terahertz generated by laser beating in inhomogeneous plasma [79]. Manendra et al. [78–80] used radially polarized lasers having a top-hat envelope profile [s (profile index) ≥ 1] in density modulated hot plasma and concluded that the conversion efficiency increased by 5 times, at the electron thermal velocity 0.2c, where c is speed of light. Liu et al. [81] did two-dimensional particle-in-cell simulations to study the terahertz wave propagating in the stagnation region of a reentry plasma sheath and these investigations are useful to study the attenuation of radio waves in atmosphere communication.

7.3 Resonant third harmonic generation

Higher Harmonic Generation are used to generate a highly coherent radiation sources in the soft x-ray region of the spectrum. When the electric field of the order

10^{13}–10^{14} W/cm^2 of laser interacts with a molecular gas, higher harmonics are produced through nonlinear process laser field. High Harmonic Generation sources has applications in plasma diagnostics, molecular dynamics and in solid state science [82, 83].

Some nonlinear optical crystal describes the formation of the field at the sum frequency of the source fields ω3 = ω1 + ω2, where, ω1, and ω2 are the frequencies of the sources fields. The crystal produces polarization at a combination of their frequencies and the resultant field oscillate at a frequency ω3. In second order harmonic generation the resulting field oscillate at 2ω frequency as shown in **Figure 3**.

Cook and Hochstrasser defined that, when we focus the fundamental and second harmonic laser simultaneously whose peak intensities is the order of 10^{14} then it generates the THz radiation [84]. Panwar et al. [85] studied the effect of non-uniform rippled plasma channel on resonant third harmonic laser radiation generation, strongly enhancement of the self-focusing plasma channel non-uniformity and compression of main laser pulse at lower powers and the self-focusing reduces the effectiveness of the third harmonic power because of the compression of main laser in a deeper plasma channel.

Kumar et al. [86] generated the 20 times frequency of the incident wave (high-frequency O-mode radio wave) by nonlinear reflection through ionospheric grating. Kumar and Tripathi [87] studied the parametric coupling of a high amplitude lower hybrid wave with the ion cyclotron instability in tokamak, driven by neutral beam converted ion beam and coupling would be strong when the ion cyclotron wave and the wave numbers of the pump are perpendicular to each other, advanced stage operations of a tokamak as ITER is relevant to it. Kumar [88] investigated the generation of Terahertz radiation by second-order nonlinear mixing of laser and its frequency shifted second harmonic in a rippled density plasma, and emission of THz radiation is maximized when the polarization of the lasers being aligned and also results are accordant with the recent experimental results. Surface Plasmon resonance are used in photonic devices and surface enhanced Raman scattering. Kumar et al. [89] used metal–vacuum of circular surface grating to excite the surface plasma wave and its intensity depends on dimensions of the grating. Tyagi et al. [90] investigated the procedure of third harmonic generation by laser magnetized plasma interaction, and the phase matching condition for the up shifted frequency is satisfied and the laser frequency is not too far from the upper hybrid frequency. Kumar et al. [91] investigated the process of generation of Smith–Purcell terahertz radiation of 10 mW at 10 THz by mixing of two co-propagating lasers passing over a periodic metallic grating.

Kumar and Kumar [92] proposed a scheme of a planar array of nanotube for generation of THz radiation by passing an ultrashort electron bunch. The emitted THz radiation generates at natural frequency of ωp/$\sqrt{2}$, which is the frequency of electron cylinder.
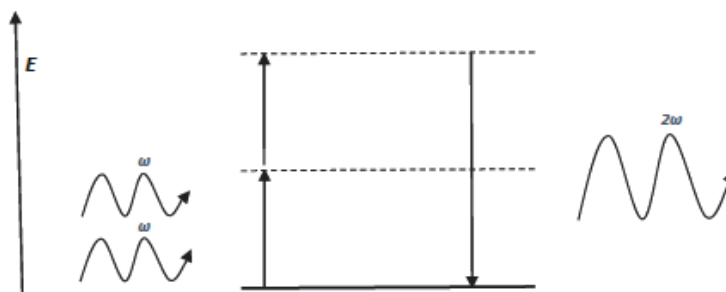

Figure 3.
Mechanics of second order harmonic generation.

It is revealed that the intensity of terahertz radiations is highly sensitive to the magnetic field and the index of super Gaussian beams [93, 94]. By using beating of two super Gaussian lasers in plasma with DC electric field in transverse direction terahertz radiation can be generated [95]. Terahertz radiation generated due to ponderomotive force which acts on electron plasma wave and make them oscillate at frequency difference of two lasers which generates a nonlinear current having frequency in terahertz domain. It is found that the amplitude of terahertz radiation can be enhanced by index of two lasers as well by DC electric field. Investigations are going on for the generation of intense picosecond THz pulses via nonlinear optical methods such as optical rectification. A work has been done to generate terahertz radiations using optical rectification of a super-Gaussian laser beam in rippled density plasma [96]. The change in intensity cause a ponderomotive force in transverse direction which makes electrons oscillates and as a consequence terahertz radiation is being produced. The phase matching is provided by ripple of plasma. In a collision less magnetoplasma terahertz radiation can be produced by using two cross focused Gaussian laser beams [97]. When the applied magnetic field is increased the focusing of lasers increases due to this a nonlinear ponderomotive force acts upon electron plasma waves causing electrons oscillations and a nonlinear current is produced at the terahertz frequency domain. It is found that the amplitude of generated terahertz radiation increases with magnetic field and the cross focusing of two laser beams. The optimization of laser-plasma parameters gives the normalized terahertz power of order 10k. The relativistic focusing of two co-axial Gaussian laser beams into ripple density plasma has been investigated by Kumar et al. [98]. When two lasers propagate into ripple density plasma, then the ponderomotive force reinforce the electrons to oscillates into the transverse direction and these oscillations gets coupled with ripple density of plasma and produce a nonlinear current at terahertz frequency. The study suggest that the amplitude of THz radiation can be enhanced by relativistic ponderomotive focusing of two lasers and also the conversion frequency of the order of 10^{-3} can be achieved. The terahertz generation in collisional plasma using two cross focused laser beams has been studied by Sharma and Singh [99]. The optimized parameters of lasers provide the radiated power of the order 0.23 MW. The applied static electric field, ripple density of plasma and the collision frequency of electron allow the generation of the terahertz radiation. Singh et al. presented a scheme for the generation of strong THz radiation through optical rectification of shaped laser pulse in magnetized plasma [100]. The THz yield increases with the increasing strength of the background magnetic field and the sensitivity depends on the ripple wave number. The emitted power is directly proportional to the square of the amplitude of the density ripple. The enhancement in terahertz generation can be achieved by increasing strength of background magnetic field. It is found that the power of emission is directly proportional to the square of amplitude of ripple. Singh et al. further employed hyperbolic-secant and Gaussian shapes of laser beam to generate the terahertz radiation through optical rectification of a laser pulse in magnetized ripple density plasma. The amplitude of the terahertz radiation shows dependence on the laser beam, laser profile index and the density ripple. When cyclotron frequency approaches to the THz frequency, the THz field amplitude reaches its maximum value [101]. The normalized amplitude of the radiation of order 10^{-2} has been realized. A work has been done to study the generation of terahertz radiations using optical rectification of an amplitude modulated super-Gaussian laser beam propagating into a periodic density plasma with a transverse magnetic field applied on it [102]. The transverse ponderomotive force arises due to the non-uniform spatial variation in laser intensity. The terahertz field amplitude increases with magnetic field strength, modulation index and ripple parameters. Efficiency of the order of 10^{-5} of terahertz wave is

achieved. The relativistic ponderomotive force and nonlinear phenomena excite the modulation instability. Jha et al. [103] studied the modulation instability due to the propagation of a laser pulse through a magnetized plasma. It has been depicted that the transverse magnetization of the plasma reduces the modulation instability. In magnetized plasma, the peak spatial growth rate of instability decreased by almost 14 percentage in contrast to the unmagnetized plasma case. Kumar and Tripathi [104] examined Rayleigh scattering of a Gaussian laser beam from clustered gases. According to the model, the clusters expand under laser-induced heating and hydro-dynamic pressure and approach towards plasma resonance. When the cluster electrons reach the plasma frequency of $\sqrt{3}$ times the laser frequency, it produces resonantly enhanced Rayleigh scattering. Magesh and Tripathi [105] investigated the laser excitation of electrostatic eigenmodes of a plasma (having parabolic density profile) in an azimuthal magnetic field. Singh et al. [106] proposed the THz radiation generation by the interaction of the pump upper hybrid wave and the laser (extraordinary wave). In this mechanism, the non-linear interaction between the two waves creates a non-linear current at their frequency difference, which can be brought in the THz range under the appropriate pump frequency and phase matching conditions. In the same research area of THz generation, Hassan et al. [107] studied the interaction of a high-intensity laser beam with density ripple in collisionless magnetized plasma under the paraxial ray approximation to produce THz radiation.

Kumar and Tripathi investigated the schemes of terahertz radiation generation using different methods such as non-linear mixing of laser pulses of finite spot size in clustered gas [108–110], laser bunched electron beam in a magnetic wiggler and optical mixing of laser pulses of finite spot size in a rippled density unmagnetized plasma. In an another study, Rajouria et al. [111] proposed that the relativistic mass and non-linearity increases the resonance absorption of the laser pulse in a density gradient plasma. K K and Tripathi [112] used carbon nanotubes array to investigate the linear and non-linear interaction of laser. The surface plasmon resonance increases, when the laser imparts oscillatory velocity and excursion to electrons in the nanotubes. Kumar et al. [113] have studied the non-linear mixing of laser pulses in a rippled density magnetized plasma. It was obtained that the electron drift induced by lasers' ponderomotive force couples with the density ripple and produces a non-linear current that resonantly drives the THz at the beat frequency. Liu et al. [114], developed an analytical formalism for broadened surface plasmon resonance and enhanced X-ray emission is achieved in a non-uniform clusters with high power lasers. Kumar et al. [115] explored the laser beat wave excitation of THz radiation in a hot plasma with a step density profile, where enhanced yield is achieved due to the coupling with the Langmuir wave at plasma frequency near THz frequency.

Bakhtiari et al. [116] proposed a scheme for improving terahertz radiation efficiency by the interaction of two Gaussian laser array beams in an electron-neutral collisional plasma. They optimized that high efficiency of up to 0.07% can be achieved using array beams, which is almost three times higher than the maximum efficiency achieved by a single Gaussian laser beam. An analytical study has been presented by Sharma et al. [117] for the generation of terahertz radiation due to transverse wakefields produced by the propagation of a circularly polarized laser pulse in a homogeneous, underdense, and axially magnetized plasma. Sobhani et al. [118] demonstrated the vital role of pump depletion and cross-focusing effects in the generation of twisted THz radiation in a non-linear plasma medium. Lehmann and Spatschek [119] discussed the generation of plasma gratings in underdense plasma by counterpropagating laser pulses, which can act as plasma photonic crystals for high-power lasers. In Ref. [10, 120] review of recent progresses in the generation, detection and application of intense terahertz radiation has been reported.

8. Detection of terahertz pulses

The electro-optic sampling is used to detect the THZ radiations which is opposite of optical rectification mechanism in nonlinear crystals. Coherent detection process is normally used so that the amplitude and phase of radiation can be detected. Other way of detection of Terahertz wave is electro optic effect. This detection method is based on the process in which electric field at terahertz frequency induce a birefringence in an optically transparent material. The relation between the magnitudes of effect is directly proportional to the state of the field. Fourier transform of the temporal pulse give the THz spectrum.

The direct and coherent detectors are mainly used to identify the terahertz radiations. The direct detector measure the average power and the coherent detectors measure the instantaneous value of electric field.

8.1 Direct detectors

The Bolometer, Golay cell and the pyroelectric are used to measure the average power of broadband THz pulses. The bolometer work on the principle of temperature-dependent electrical resistivity which contains of a sensing material. As soon as it absorb the incoming photons, its shows the change of its electrical resistivity when it is illuminated by incoming radiations.

8.2 Coherent detectors

The atto-second technologies are used to measure the amplitude and phase of the electric field oscillation of an EM wave at THz frequency. Although this technique is difficult at optical frequencies, therefore it is achieved in the radio wave frequency range with the oscilloscope.

The THz radiation photon have energies of the order of few meV than the photons of optical frequencies. Therefore the ambient background and thermal noise disturb the measurement of THz radiations. So, it has become necessary to extract the background noise from the interested signals. The researcher use the Phase Sensitive Detection linked with an instrument called Lockin Amplifier.

9. Challenges in the terahertz radiation spectroscopy

There are various challenges in the field of terahertz radiation spectroscopy and imaging. The first issue is that terahertz radiation are strongly absorbed by the polar liquid (water) which presents in all the tissues, so they cannot penetrate much deeper into the moist tissues [1, 3, 4].

The other challenges in the terahertz radiation spectroscopy and imaging are resolution and its slowness mechanism in comparison to previously established ways of imaging, which produces thousands of pixels per second while the terahertz have the speed 1 pixel in several seconds. For any conventional way of imaging the diffraction is limited by wavelength of the radiation. In the case of terahertz imaging, it lies in the range of one micrometer to 3 mm which do not give enough detail images for most of the medical applications. This shortcoming can be overcome by near field imaging.

10. Conclusion

This chapter contribute the applications and generations of THz technology in the field of security, medicines, science and biomedical engineering. The biomacromolecules and certain drugs are detected by using of THz spectroscopy. THz imaging has been employed to diagnostics of cancers, treatment skin burn and dental related diagnostics. The biological effect of THz is still required to further explore the research area. The nonthermal effects of THz radiation on human DNA is needed to pay more attention. For the widespread applications of THz, we need higher-power THz sources and their THz detectors.

Author details

Sukhmander Singh[1*], Shravan Kumar Meena[2], Ashish Tyagi[3], Sanjeev Kumar[2], Man Raj Meena[4] and Sujit Kumar Saini[2]

1 Plasma Waves and Electric Propulsion Laboratory, Department of Physics, Central University of Rajasthan, Ajmer, Rajasthan, India

2 Department of Physics, Motilal Nehru College, University of Delhi, Delhi, India

3 Department of Physics, Swami Shraddhanand College, University of Delhi, Delhi, India

4 Department of Physics, Gargi College, University of Delhi, New Delhi, India

*Address all correspondence to: sukhmandersingh@curaj.ac.in

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