Analysis of Innovative Methods for Terahertz Wave Production Using Laser-Plasma Interaction

Interest of the research in terahertz (THz) wave has been strongly motivated by its wide applications in the fields of physics, chemistry, biology, and engineering. Developing efficient and reliable THz source is of uttermost priority in these researches. Plasma is a quasi-neutral medium composed of electrons and positive ions, exhibiting long-range collective behavior. It has garnered significant attention as a promising source for generating THz electromagnetic wave, primarily due to the ease with which it can tolerate very high power laser and provide strong THz beams in comparison with other media. This review focuses on the various key aspects of THz mechanisms in laser-plasma interactions and also examines the characteristics of the emitted THz waves under different laser and plasma parameters.

Contents

The feature of THz waves

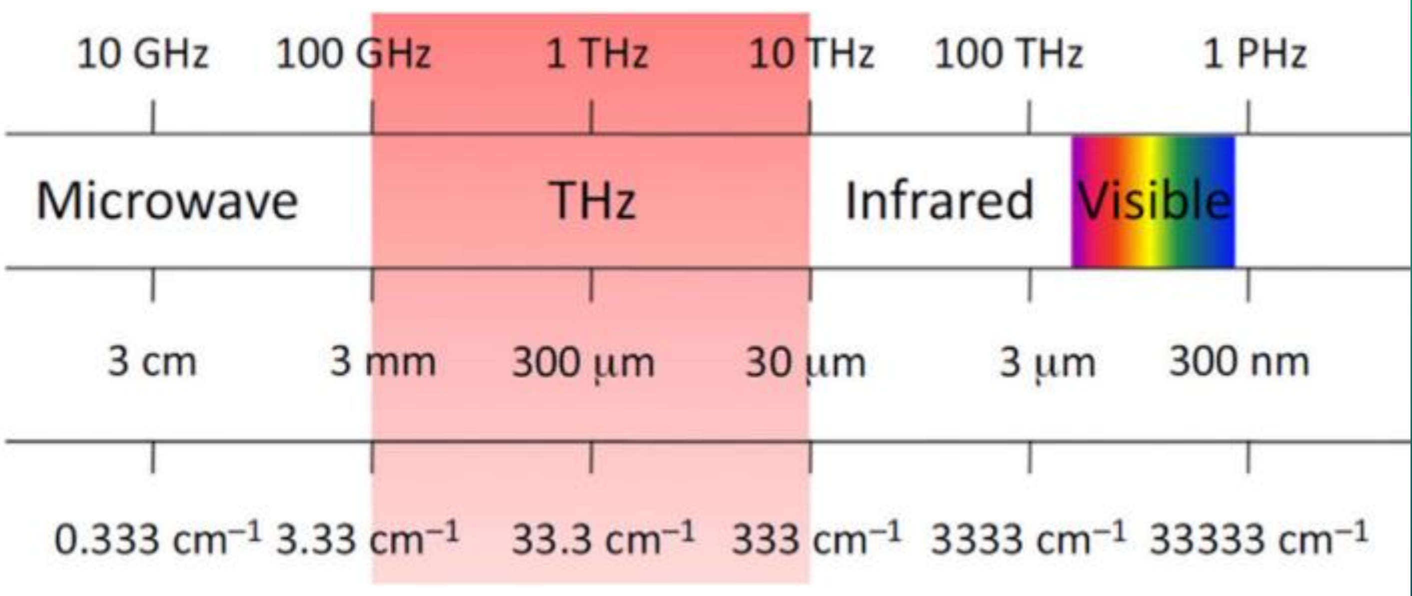
The THz rays are defined in different units, in the electromagnetic spectrum, radiation at 1 THz has a period of 1 ps, a wavelength of 300 μm, a wave number of 33 cm–1, a photon energy of 4.1 meV, and an equivalent temperature of 47.6 K

The intense THz fields at a special frequency can stimulate lattice resonance coherently and resonantly, thereby inducing novel electronic structures so new states are distinguished

THz radiation couples resonantly to numerous fundamental motions of ions, electrons, and electron spins in all phases of matter

THz technology has attracted great worldwide interest in recent years to explore scientific and engineering phenomena that lie in the THz spectral region.

THz waves have widespread potential applications in medicine, microelectronics, agriculture, forensic science, and many other fields.



Electromagnetic spectrum of waves

Applications

01

THz waves' non-ionizing nature and their ability to penetrate materials, make them suitable for security screening applications

THz waves can be employed in advanced chip inspection techniques, such as THz microscopy

02

In medicine, THz imaging technology can identify diseases that affect the skin non-invasively.

High-speed data transmission capabilities of the THz waves are most attractive for future wireless communication networks.

03

They all have their characteristic signatures, the so-called "fingerprints", in this frequency domain.

THz is possible to monitor the healing process in wounds with the help of THz imaging which gives information about the depth and stage of healing

04

THz scanners can be deployed at airports and other high-security areas to detect hidden weapons, explosives, and other illicit substances

THz waves can be employed for remote sensing applications to assess soil properties and monitor plant growth, providing valuable insights for precision agriculture techniques

Plasma medium

Advantages of plasma medium

Plasma-based sources can generate THz waves with a wide bandwidth, enabling the generation of THz radiation over a broad range of frequencies.

Plasma-based sources can produce THz pulses with ultrafast rise times

Plasma can tolerate very high power laser and provide strong THz beams in comparison with other media

These can support high-intensity fields and the properties of plasma, such as density, temperature, and electron energy distribution

When a laser pulse strikes a target (whether solid, liquid, or gas), the atoms within the target undergo rapid ionization due to the intense laser field, leading to the formation of a plasma environment. This ionization process occurs when the laser field's intensity exceeds the Coulomb field strength between atomic particles, resulting in plasma formation within the focal volume. Following ionization, the liberated electrons are accelerated by the laser field

A.A. Molavi Choobini, S. S. Ghaffari-Oskooei, M. Shahmansouri, and F. M. Aghamir. "Mechanisms of THz Radiation in Laser-Plasma Interactions." *arXiv e-prints* (2024): arXiv-2403.

One-Color Field

Optical pulses drive the first type with a single central wavelength, which is often referred to as a one-color field. This one-color field, first harmonic (FW) typically utilizes ultrafast pulses with a central wavelength of 800 nm.

Two-Color Field

optical pulses with two central wavelengths, known as a two-color field (second harmonic (SHW)). In this case, the pulses have central wavelengths of 800 nm and a second harmonic of 400 nm

One Approach

One approach to enhance the efficiency of THz radiation
Is considering the third harmonic of the laser pulse (THW), which corresponds to a central wavelength of 267 nm to enhance the efficiency and performance of THz radiation generation

THz generation from laser-induced gas-plasma

Despite some advantages and limitations of sources as mentioned above, they can not endure high-intensity laser pulses and have material damage. To overcome this obstacle, the use of plasma as an ionized medium that can tolerate very high potential gradients has been of interest. In compresence to other sources of THz radiation, plasma has a great potential to generate high-power broadband, intense, coherent, and highly directional THz waves, and it has become the subject of attention of many researchers in recent years

Mechanisms of THz Generation from laser-induced gas-plasma

Photo-Current

Known as tunneling ionization

- Particularly at relatively low laser intensities $\left(\leq 10^{15}\frac{W}{cm3}\right)$
- Is most suitable for explaining the low-frequency segment of the THz spectrum

Wave-Mixing

Four-wave mixing

- In plasma is an approach that is particularly effective for relatively high laser intensities in orders of $(10^{15} - 10^{17}\frac{W}{cm3})$
- The simultaneous propagation of first and second-harmonic laser pulses within the plasma

Beating

Difference frequency generation

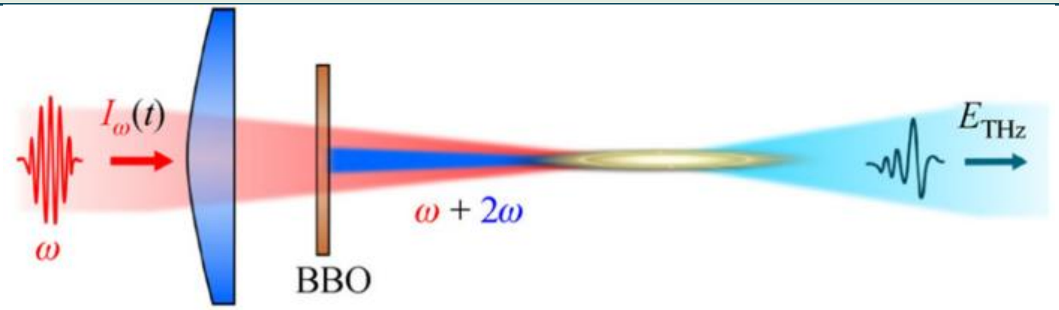
- The difference frequency generation (DFG) is a nonlinear optical process by mixing two input laser beams with different frequencies.

Wakefields

- The laser energy is coupled to the plasma via resonant absorption. In this process, a plasma wave with a large amplitude is excited, also called as laser wakefield.
- This happens at the critical density where the frequencies of plasma and laser are nearly equivalent.

Transition-Cherenkov

- An alternative practical method for generating powerful longitudinal THz radiation from plasma filaments.
- The dipole-like localized plasma current density, resembling dipole moments moving at high velocities within the medium, emits radiation via the Cherenkov mechanism.



The experimental setup for THz generation from two-color laser-induced air plasma

K. Liu, P. Huang, and X. Ch. Zhang. Terahertz wave generation from ring-airy beam induced plasmas and remote detection by terahertz radiation enhanced- emission-of-fluorescence: a review. Frontiers of Optoelectronics, 12, 2019.

Photo-Current

Mechanism

- The nonlinearity of the plasma medium causes the generation of harmonics and other nonlinear optical effects and generated photo-current is a response to the intensity and frequency characteristics of the incident two-color laser pulses

- When these harmonics are absorbed by the plasma, they can create a spatially varying electric field. This varying electric field, in turn, induces a photo-current in the plasma

THz amplitude/efficiency can be amplified by an external magnetic field, adjusting the interaction length, optimizing the pump pulse focusing conditions and considering the wavelengths/harmonics components of the laser pulse.

An external magnetic field can modifies the optical properties of the material, leading to changes in the absorption and emission of THz radiation and alter the efficiency and spectral characteristics.

By optimizing the focus of the pump pulse, the spatial distribution and intensity of the photo-generated charge carriers can be modified, leading to a more enhanced THz generation efficiency

Higher harmonic components of laser pulse can lead to enhanced THz efficiency and interaction with material, resulting in more efficient acceleration or deceleration of charge carriers and enhanced THz radiation emission

In the framework of the wave-mixing model and interaction of three-color laser pulses with plasma, based on the momentum and continuity equation in plasma, the laser fields steer plasma electrons to drift in the direction of laser fields and the electron's motion induces a nonlinear current density along the laser electric field. By utilizing this induced nonlinear current density, we can assess the THz electric field utilizing the wave equation and explore the radiated power and angular distribution of the THz wave in this process

01 By adjusting the strength of the magnetic field, one can tune the cyclotron frequency and control the THz emission.

02 Longer plasma lengths allow for a more extended interaction time between the laser pulse and the plasma, potentially leading to enhanced THz radiation.

03 Higher laser intensities can cause stronger ponderomotive forces, which push the electrons and accelerate them collectively leading to the generation of THz waves with higher field strengths and broader spectral bandwidths.

04 Collisions between charged particles in the plasma can significantly impact the dynamics and energy transfer processes.

Wave-Mixing

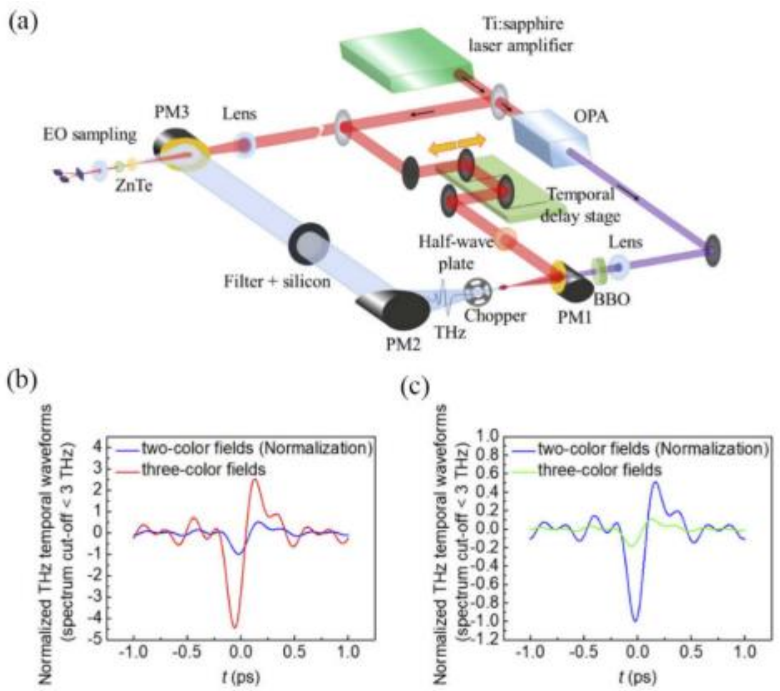


Figure 6: (a) Diagram illustrating the experimental setup, (b) THz temporal waveforms under ideal conditions, where the two plasmas perfectly overlap, (c) THz temporal waveforms under real conditions, where the two plasmas are not completely aligned [93].

D. Ma, L. Dong, M. Zhang, T. Wu, Y. Zhao, L. Zhang, and C. Zhang. Enhancement of terahertz waves from two-color laser-field induced air plasma excited using a third-color femtosecond laser. Optics Express, 28, 2020.

Laser-wakefield accelerators

An electron beam is made to cross an interface between plasma-vacuum boundary. As the electron beam interacts with the interface, it emits coherent radiation in the THz frequency range

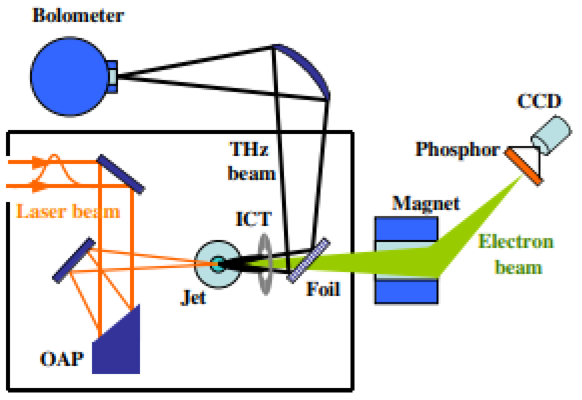


FIG. 1: Schematic of the experimental set-up. High peak power laser pulses entered the vacuum chamber and were focused onto a high pressure pulsed He gas jet using an off-axis parabola (OAP). An integrating current transformer (ICT) measured the amount of accelerated electrons (charge). A metal-coated foil directed the THz radiation outside the vacuum chamber onto a spherical mirror that focused the radiation onto a Helium cooled bolometer. The electron energy distribution was measured using an imaging magnetic spectrometer to momentum disperse the e-beam onto a phosphor screen that was imaged by a CCD camera.

Achieve the generation of more intense THz waves

- Shorter laser pulses enable the production of ultrashort THz pulses
- Higher laser energies provide more energy to the accelerated electron bunch, resulting in increased THz intensity
- Proper focusing of the laser beam is important to achieve a well-controlled interaction between the laser and the plasma.
- Higher beam charges lead to increased THz radiation intensity.

Technical Challenge

- Low electrical charge of the electron bunches generated in LWFAs
- Achieving the required sub-micron precision in the alignment of the electron beam
- The precise synchronization between the laser pulses and the electron bunch to ensure coherent emission.

W. P. Leemans, et al. Observation of terahertz emission from a laser-plasma accelerated electron bunch crossing a plasma-vacuum boundary. Physical Review Letters, 91, 2003.

01 A laser with an energy of 4 mJ per pulse, a repetition rate of 10 Hz, a central wavelength of 800 nm, and a width of 150 fs was focused in the air using a 2 m focal length lens to create a single filament.

02 The formation of the plasma filament results from the dynamic interplay between Kerr beam self-focusing and beam de-focusing caused by air ionization

03 Throughout the filamentation, the ponderomotive force of the laser field segregates charges at the pulse's peak intensity, leaving the plasma in an excited state of oscillations trailing the laser pulse.

04 Within the plasma filament, a slight longitudinal oscillation is also stimulated by the Lorentz force but is rapidly damped by electron collisions, responsible for THz emission.

05 The dipole-like localized plasma current density, resembling dipole moments moving at high velocities within the medium, emits radiation via the Cherenkov mechanism.

Transition-Cherenkov

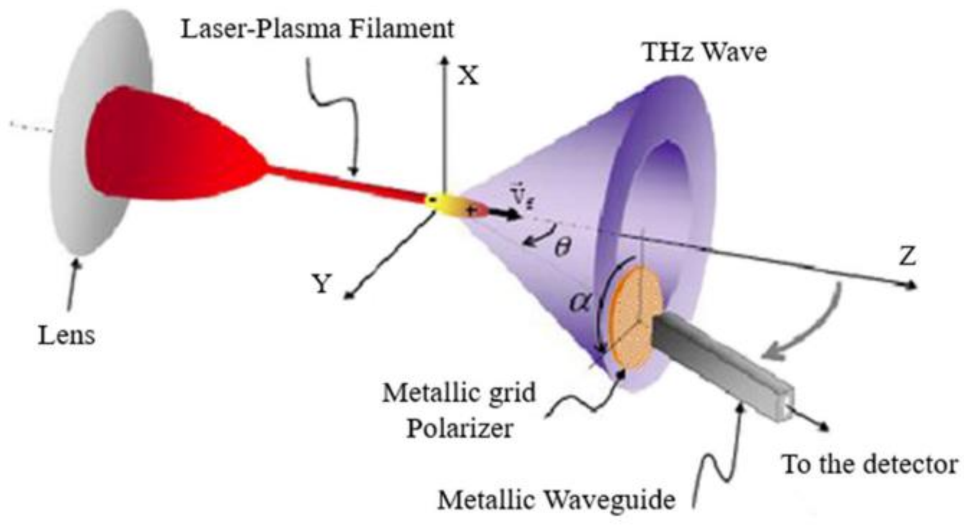


Figure 9: Experimental set-up used for THz generation and measurement [126].

The characteristics of transition radiation in the THz regime depend on various factors, such as the energy of the charged particle, its velocity, the angle of incidence, and the properties of the media involved. The emission spectrum of transition radiation can be influenced by the refractive indices of the media, the angle of incidence, and the energy distribution of the incident particles.

C. D'Amico, A. Houard, M. Franco, B. Prade, A. Mysyrowicz, A. Couairon, and V. T. Tikhonchuk. Conical forward thz emission from femtosecond-laser-beam filamentation in air. Physical Review Letters, 98, 2007.

The difference frequency generation (beating) is a nonlinear optical process used to generate THz radiation by mixing two input laser beams with different frequencies, ω_1 and ω_2.

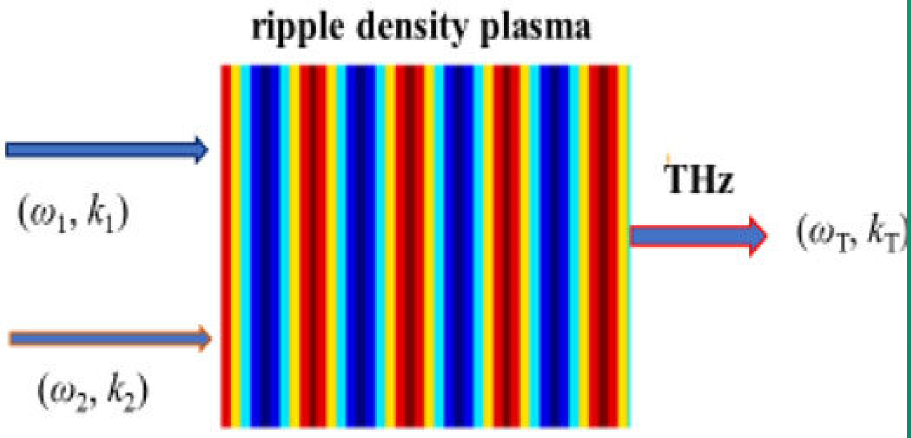
Beating

The resulting THz radiation is generated at the frequency difference between the two input lasers (ω_1-ω_2), which can fall within the THz frequency range.

The nonlinear mixing of a laser beat wave with a density-modulated plasma leads to THz emission under phase-matching conditions

The inhomogeneous electric field of the laser beat wave exerts a nonlinear force, known as the ponderomotive force, on plasma electrons that produces a strong nonlinear current at the laser beat frequency.

Phase matching is a critical aspect of efficient DFG. It ensures that the interacting waves propagate coherently and maximizes the conversion efficiency of the process



III. RESULTS AND DISCUSSION

The features of the THz electric field generated in an inhomogeneous collisional plasma irradiated by two coaxial LG and HG laser beams are obtained by using Eq. (8). For numerical illustration, we consider the following: $\omega_1 = 2.4 \times 10^{14}$ rad/s, $\omega_2 = 2.1 \times 10^{14}$ rad/s, $\omega_p = 2 \times 10^{13}$ rad/s, the normalized ripple amplitude $n_\alpha/n_0 = 0.1$, the normalized collision frequency $\nu_e/\omega_p = 0.05$, and the initial amplitude of LG and HG laser beams $E_{0L} = 2 \times 10^8$ V/m and $E_{0H} = 5 \times 10^8$ V/m, respectively. To deal with the doughnut-shaped intensity patterns, which are more attractive in a practical point of view,[68,69] we continue our investigation based on the first order of HG beam and different orders of LG beam. The effects

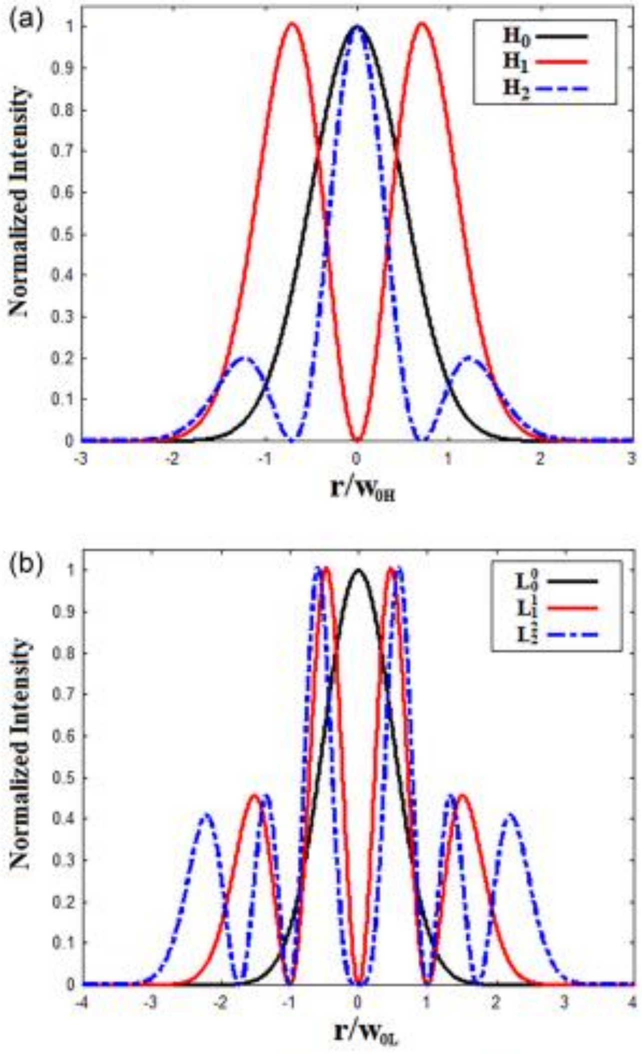


FIG. 1. Intensity profiles of (a) HG and (b) LG beams with different orders.

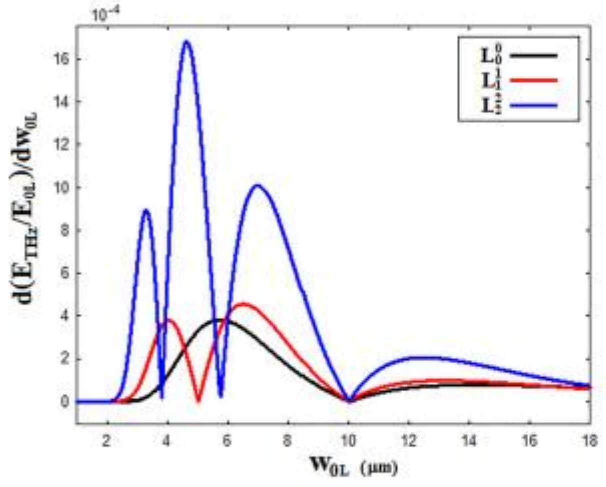


FIG. 4. Derivative of the normalized THz radiation field as a function of LG beam width to find the extreme values of THz field amplitude for different orders of LG beam.

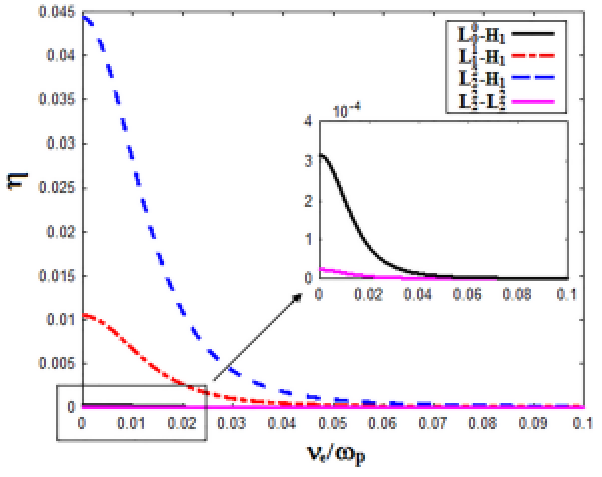


FIG. 6. Efficiency of THz radiation generated by beating of two HG-LG laser beams with different values l, p and two LG laser beams with l, $p = 2$ and $w_{0L} = 5.9$ μm as a function of normalized collision frequency when $n_\alpha/n_0 = 0.3$.

S. Safari, A.R. Niknam, F.Jahangiri, and B.Jazi. "Terahertz radiation generation through the nonlinear interaction of Hermite and Laguerre Gaussian laser beams with collisional plasma: field profile optimization." *Journal of Applied Physics* 123, no. 15 (2018).

THANK YOU

DO YOU HAVE ANY QUESTIONS !