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Review of Microplasma's Use in Terahertz Technology

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Abstract: *Terahertz functional devices are essential for advanced terahertz radiation applications in biology, medicine, nanotechnology, and wireless communications. Due to its small size and high plasma frequency, the interaction between terahertz radiation and microplasma presents opportunities for developing functional terahertz devices. This article discusses the use of microplasma as terahertz generators, amplifiers, filters, and detectors. The advantages and drawbacks of transdisciplinary research using microplasma and terahertz technologies are underlined.*

Keywords: Microplasma, Terahertz, Applications

I. INTRODUCTION

Terahertz (THz) spectroscopy, imaging, and technology have grown significantly during the last three decades as a result of potential THz uses in radio astronomy [5, 6], biology/medicine [3, 4], wireless communication [4, 5], and explosives detection [1, 2]. The THz frequency range, which is in the range of frequencies between microwaves and infrared light, is often used [4,6]. With typical lifetimes in the picosecond range and energetic transitions in the meV range, such as chemical reactions, dielectric relaxation and vibrational spectroscopy of liquids, weak collective excitations in solids, and biomolecular collective motions, THz radiation interacts strongly with these materials [7]. These characteristics make THz radiation a unique tool for a range of applications. For instance, since THz radiation does not ionize molecules owing to its low energy, it offers a significant advantage over X-rays in medical imaging [8]. THz spectroscopy may function as spectroscopic fingerprints for material identification since molecular crystals have vibrational absorption bands in the THz range [9]. In comparison to microwave frequencies, the THz spectral region offers a wider theoretical bandwidth, which might meet the growing need for higher data transfer rates in wireless communications [10]. THz images also have improved spatial resolution as a result of the shorter wavelength [11]. When compared to infrared frequencies, many ordinary materials, such as traditional packaging materials like paper, plastics, and composites, are quite transparent to THz radiation [1]. The THz sector, which is unexplored but available for growth, has been labeled the ultimate unmet scientific gap in the electromagnetic spectrum. One of the main issues is the lack of functional devices in the THz frequency band. Terahertz sources, amplifiers, filters, and detectors are crucial functional elements in THz spectroscopy, imaging, and technology. Proof-of-concept experiments and simulations show that microplasma interacts strongly with THz radiation, enabling it to be utilised in THz functional devices. Microplasma sources have been used successfully in plasma medicine, material processing, light sources, and electromagnetic wave control [12]. Microplasma is a term often used to describe plasma having features smaller than 1 mm. At atmospheric pressure, microplasma has a high electron density and a low gas temperature. Because of its size and plasma frequency in the terahertz range, microplasma is theoretically best suited to interact with THz radiation [13]. According to the well-known Drude model [14], the plasma frequency, the frequency of incoming electromagnetic waves, and the frequency of collisions between electrons and molecules or atoms all affect the relative plasma permittivity. It is easy to change the relative plasma permittivity by applying voltages or input electric power, which may be positive or negative. Microplasma has a nonlinear refractive index from the perspective of dielectrics and serves as a metamaterial for the modulation of THz radiation [15]. It provides advantages of rapid dynamic reaction, reconfigurability, and adjustability in contrast to other techniques based on

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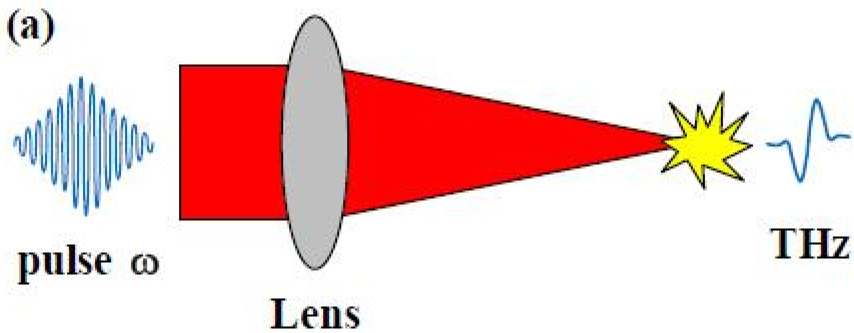
temperature [16], magnetic field [17], and pressure [18]. The crucial part that microplasma plays in THz functional devices such THz sources, amplifiers, filters, and detectors has now been shown in several investigations. Despite several research on the development of THz spectroscopy and imaging [11], THz clinical application [8], THz communication [19], and extreme THz science [20], there isn't an overview of microplasma applications in the THz sector. As a consequence, the focus of this work is on a few recent developments and how they could affect future THz-related microplasma applications.

Application of Microplasma in THz Functional Devices

Terahertz Source

Electronics and photonics are often the foundations of the methods used to create terahertz sources [21]. Electronics often makes use of solid-state semiconductors and vacuum electronic devices. Due to the power and working frequency restrictions of electronic devices, it is often challenging to obtain a powerful THz source with a frequency spectrum up to tens of THz. Laser-induced microplasma, optical rectification, and photoconductive antenna (PCA) are frequently utilized photonics sources [22]. THz radiation intensity is controlled by the carrier lifetime and is computed using PCA. The optical rectification is constrained by the nonlinear crystal, which has photon absorption and a damage threshold. The damage threshold of the medium is relevant since the frequency range of THz generators based on laser-induced microplasma is wide. It makes it possible to employ THz sources with high-intensity laser input. THz generators based on laser-induced microplasma might thus create super terahertz radiation with a wide frequency range.

A THz generator based on laser-induced plasma may be used to produce short, ultra-broadband pulses with a large frequency range that reach deep into the infrared in order to identify the spectral "fingerprints" of molecular crystals. The diameter of the laser-induced plasma is between 10 and 100 m, with an electron density of over 1017 cm3. The terahertz radiation spectrum is shown in Figure 1 [23] to span the frequency range of 0.1 to 10 THz, and the electric field of THz waves is shown to be kV/cmMV/cm [24–27]. Figure 2 [28] illustrates the measurement of the ultrabroadband pulse's spectrum from the far infrared to 200 THz through a plasma using a 10 fs laser pulse. Hamster et al. first provided a description of the THz generation from the ionized helium gas in 1993 [29]. A 50 mJ near-infrared pulsed laser is focused at a helium gas target. Microplasma is created when the helium gas is ionized and has an electron density of 2.5 1017 cm3. Less than 106 percent of optical energy is converted to THz energy. Cook and Hochstrasser improved the infrared-terahertz conversion efficiency in 2000; as a result, it now increases by at least one order of magnitude when an ultrafast laser field composed of the fundamental wave and its second harmonic is used [30]. The "one-color" and "two-color" approaches, which are often characterized by the laser wavelength, are shown in Figure 3. A femtosecond or picosecond infrared laser is utilized to focus on the gas targets. When the gases are ionized by the powerful laser electric field, microplasma is produced. The accelerated ultrafast oscillating electrons in the microplasma create broad-band electromagnetic waves, including THz waves, in the presence of a strong electric field.



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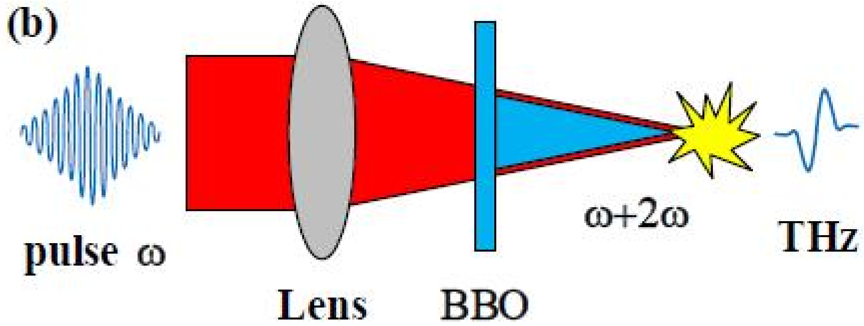

Figure: Schematic diagram of laser-induced plasma radiation terahertz wave. (a) single-colormethod; (b) two-color method.

The "one-color" method depends on the laser pulse intensity being as low as possible while yet producing detectable THz waveforms. Infrared lasers produce elongated microplasma that generally has a length of several millimeters to several centimeters and a radius of tens to hundreds of microns. According to several earlier studies, the laser energy threshold is between 30 and 50 J. Where W is the laser pulse energy, NA is the numerical aperture of the focusing laser cone, is the laser wavelength, and is the pulse time, the approximate scaling law for the THz peak power is shown. Hamster et al. were the ones that created this estimate scaling rule. The equation predicts that when NA and laser intensity at the focal plane increase, the laser energy threshold will decrease. In response to this, as shown in Figure 4, Fabrizio et al. described an ambient air laser-induced microplasma as a THz emitter. The laser beam is focused into the surrounding air using a high-NA microscope objective lens, producing a microplasma with less than 40 m in diameter. [31,32]. It's possible for the electron density to exceed 1018 cm3. All that is required is a laser pulse with less than 1 J of energy. In 2018, they further demonstrated that the microplasma approach may reduce the necessary optical pulse energy by five orders of magnitude while still achieving a comparable signal-to-noise ratio for THz time-domain spectroscopy [33]. The electron density in this microplasma should be at least 1019 cm3 and ideally higher. The THz radiation typically propagates ahead as a cone. As the plasma's size diminishes, the divergence angle increases. For microplasma shorter than 40 m, the THz radiation direction is orthogonal to the optical path. It should also be emphasized that several aspects of the microplasma, including its size, electron density, gas pressure, and composition, are essential to the THz manufacturing process [34,35]. For instance, Sheng et al.'s discovery that the gas length may change the shape of the THz waveform even when the amplitude of the THz radiation remains constant opens up a new path for terahertz radiation control. In the magnetized plasmas, the maximum energy conversion efficiency is doubled, and their modeling results show that the THz radiation may be regulated by changing the strength and direction of an external dc magnetic field with a few teslas [36].

The femtosecond laser-induced microplasma has more control over THz radiation regulation in the "two-color" approach than the "one-color" method. The generation of terahertz radiation from microplasma caused by a two-color femtosecond laser was simulated by Thiele et al. [37]. It produces a microplasma with a thickness of 1 m and a length of roughly 10 m. At the focal plane, the argon gas is fully ionized, and the peak electron density approaches 3 1019 cm3. It is advantageous to increase the optical-to-THz conversion efficiency when the microplasma layer's thickness is reduced. The efficiency is more than 104 for laser pulse energy of 10 J. However, once the laser intensity reaches a certain value, the intensity of THz radiation saturates because of the plasma's defocusing effect and the absorption of terahertz waves [38]. In 2018, Thiele et al. showed that plasmonic resonance regulated by the polarization of the driving laser pulse's elliptically shaped pulse may extend the terahertz emission spectrum [39].

Terahertz Amplifier

There are currently three basic types of terahertz amplifiers: solid-state terahertz amplifiers (like InP and GaN field-effect transistors) and traveling wave terahertz amplifiers (TWAs) based on waveguides (like laser-induced microplasma). A disadvantage of solid-state terahertz amplifiers is that as working frequency increases, energy

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efficiency decreases. In comparison to solid-state terahertz amplifiers, the microplasma can achieve more power amplification and a higher operating frequency at a higher efficiency.

Laser-induced plasma amplifies terahertz wave propagation. In a 2007 article by Dai et al. [42], the four-wave-mixing parametric processes that enable the THz wave in gases generated by femtosecond laser pulses to be amplified are shown in Figure 5a. In their experiment, they use a laser beam with an 800 nm wavelength and its second harmonic to produce a nitrogen plasma. Into the plasma is introduced a 5 mm long seed THz wave. As shown in Figure 5b, the amplification factor is 65% when the total excitation intensity is 8 1014 W/cm2.

Along with the four-wave-mixing parametric processes, the plasma's negative absolute conductivity acts to enhance the THz radiation in the plasma channel. Bogatskaya et al. studied and simulated the electron energy distribution function in the nitrogen, xenon, and argon plasma generated by a femtosecond laser energy pulse. It is found that the plasma has to be considerably out of equilibrium for THz amplification. The seed THz wave may be amplified up to several orders of magnitude in the nonequilibrium Xe plasma channel, according to numerical results. At atmospheric pressure, the Xe plasma is produced by a powerful femtosecond KrF laser pulse. Between 1013 and 1015 cm3 of electrons are present in the Xe plasma [43, 45].

Intriguingly, Massood et al. demonstrated for the first time that the microplasma in the capillary may boost the THz wave inside a meandering waveguide, leading to a breakthrough in terahertz traveling-wave amplifiers. A TE01 waveguide that is curved is connected to the microplasma. The microplasma is contained in a silicon capillary that has a thin dielectric layer on the inside surface wall. Typically, the microplasma is between 100 and 200 m in size. The plasma's typical density ranges from 1010 to 14 cm3. The interaction of the terahertz radiation with the plasma is linked via electric dipoles. When the phase and group velocities of the guided terahertz wave coincide with those of the microplasma, the wave absorbs energy from the latter and the terahertz signal is boosted. Since plasmas are capable of self-focusing, electrostatic lenses and magnetic focusing structures may be removed or simplified; third, bigger acceleration fields can be employed by harnessing the 104–106 V/cm space-charge electric fields of plasmas; and fourth, higher-power amplification capabilities. The following benefits apply to terahertz amplifiers based on microplasma as opposed to electron beam TWA. Their experimental results show that at a frequency of 0.9 THz, the meandering waveguide with microplasma may be amplified up to a maximum of 12 dB [46].

Terahertz Filter

The terahertz filter is a crucial component of THz spectroscopy, imaging, and technology. To improve the signal-to-noise ratio, terahertz signals are efficiently removed or filtering. In photonic crystals, photonic bandgaps are not conductive to THz waves. It is often used to regulate and guide the propagation of THz waves. To increase the tunability of photonic bandgaps for THz wave modulation, plasma is injected into photonic crystals, creating an artificial periodic structured composition of plasma and dielectrics known as a plasma photonic crystal (PPC). PPCs' wide tunability of the relative permittivity from negative to positive and their ability for fast reconfiguration are advantages over other approaches based on different external electric fields, temperatures, and pressures [12,18,47-50]. The PPCs that control THz wave propagation have recently been investigated.

Elsami et al. examined the THz PPC simulation-based characteristics of a microplasma photonic crystal for THz modulation [51]. Numerical results show that the plasma layer thickness, the electron density, and the incidence angle of the terahertz radiation all influence the characteristics of the PPC bandgaps. As the plasma layer or density rises, so does the bandgap's center frequency and the forbidden bandwidth. Although they ignore the effects of collision frequency, discharge transient process, and contact between neighboring microplasma cells, their results imply that microplasma photonic crystals may be employed for active terahertz filtering. Kushner et al. (2017) simulated an open low-pressure surface microplasma array and considered the interaction between microplasma cells to control the propagation of subterahertz waves. It reveals that the movement of metastable atoms or ions between microplasma cells has a significant impact on the transmittance of subterahertz waves and the discharge characteristics of the microplasma [52]. In 2020, Wu et al. used the transfer matrix method to examine how the collision frequency affected the terahertz bandgap structure and transmission characteristics of a microplasma photonic crystal (Figure 6a). As gas pressure increases, both the THz radiation's intensity and its core frequency decrease. Figure 6b shows that the center frequency and bandwidth of the first THz bandgap are basically unaffected by the electron density below 1015 cm3. As the electron density rises until it reaches 1016 cm3, the center frequency and bandwidth both noticeably climb [53]. Additionally, Matthew et al. investigated the effects of the plasma frequency, collision frequency, plasma column radius, lattice constant, and background dielectric permittivity on the propagation of subterahertz waves using the plane wave expansion method. The radius of the microplasma cylinder and the background dielectric are determined to be the optimum controls for the THz bandgap and its center frequency, respectively [54].

Previous studies focused on the THz bandstop PPCs. If a defect layer is appropriately placed to the bandstop PPC, a THz passband PPC will occur. Wang et al. proposed a one-dimensional magnetized microplasma photonic crystal with a (AC)N(CBC)M(AC)N structure. Layer A is the plasma, Layer B is the dielectric defect layer, and Layer C is the standard dielectric layer, all of which have diameters between 0.1 and 0.2 mm. The periods of the plasma layer and the dielectric defect layer are N and M, respectively. The width of each layer of the passband—A, B, and C—is shown to alter the center frequency and transmission coefficient, however the transmission coefficient is not greatly impacted by the width of the C layer [55]. A flat passband helps the THz bandpass filter's amplitude-frequency property. It is important to note that the number of photonic crystal cycles has a favorable impact on the passband's flatness.

Sakai et al. presented a two-dimensional plasma photonic crystal based on hollow cathode discharge for THz PPCs experiments, as seen in Figure 7a. The plasma has a diameter of 0.6 mm, an electron density of around 1 1013 cm3 and a lattice constant of 1.5 mm. Around 0.1 THz, a subterahertz bandgap is seen. By altering the lattice constant, the THz bandgap's center frequency may be adjusted [56]. Eden et al. created a 5-10 microplasma jet array in 2017. The two-dimensional microplasma photonic crystal is made of the periodically aligned plasma jet and the surrounding air. The diameter of each plasma jet is 0.4 mm. The electron density is 3 1013 cm3 per electron. For the first time, a small stopband with a bandwidth of 1 GHz is found at the center frequency of 157 GHz. The modeling findings are notably different from the maximum attenuation of THz radiation, which is just 5%. The spatial nonuniformity of the collision frequency and plasma frequency caused by the mixing of air and helium gas is one of the potential causes [57]. Terahertz wave propagation in air microplasma is more significantly impacted by the nonuniformity of plasma, according to Zhou et al. [58]. The minimal attenuation of THz radiation at the PPC stopband may possibly be a result of the low electron density. The three-dimensional plasma/metal/dielectric photonic crystal bandstop filter that Eden et al. recently improved is seen in Figure 8a. At the center frequencies of 131 GHz and 138 GHz, two subterahertz stopbands are attained. The stopband's center frequency rises with increasing electron density [59]. As a consequence, it was clear from the modeling and experiment findings that the microplasma photonic crystals used as THz filters were a good choice for controlling the THz wave propagation.

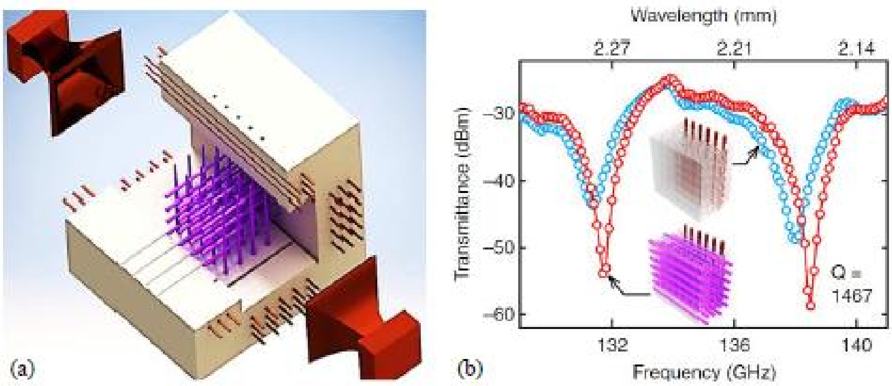

Figure (a) Three-dimensional plasma/metal/dielectric photonic crystal band-stop filter; (b) The narrowing of the 138 GHz resonance line shape with the introduction of plasma to the crystal [59].

Terahertz Detector

Terahertz wave detection methods may be divided into two categories: coherent detection and incoherent detection. The temperature impact of the detecting materials on terahertz waves is often crucial for incoherent detection. Bolometers, pyroelectrics, and Golay cells are a few examples of tools that may be used to detect the average power and intensity of terahertz waves directly [60]. Terahertz imaging and terahertz wave power measurements are possible with these detectors. During the measurement procedure, the pulsed terahertz wave's phase information will be lost. However, coherent detection methods, such as photoconductivity (PC) sampling and electro-optical sampling (FS-EOS) detectors, are often used to monitor pulsed terahertz waves [61]. The antenna's resonant quality limits how quickly a PC can sample data. The balance between the detection sensitivity and the frequency response for FS-EOS detectors is greatly influenced by the kind and thickness of crystal materials. As electro-optic crystal thickness grows, the detection sensitivity rises but the detection bandwidth falls. Microplasma may be employed for THz detection in addition to the aforementioned THz detectors. This THz detector has an extremely broad detection bandwidth and great sensitivity.

A key technique for finding broadband THz waves is the use of airborne laser-induced plasma. Dai et al. first demonstrated the coherent detection of wideband THz waves in open air. Figure 9 depicts the process, which is relevant to the temporal measurement of pulsed THz pulses, as a third-order nonlinear optical process using femtosecond laser pulses through E-field-induced second-harmonic generation. For coherent detection to take place, the tunnel ionization process in gases must be dominant [62]. Liu et al. provided a description of the method for detecting THz pulses utilizing the THz-enhanced emission of fluorescence from air plasma. An air plasma with an electron density of 1014–1015 cm3 is created by a femtosecond laser. The THz-enhanced fluorescence emission is caused by the electron heating and electron-impact excitation of air molecules or ions under the THz field [63]. Clough et al. observed a 10% acoustic amplification from a laser-induced plasma under single-cycle THz radiation, revealing a viable method for coherent THz wave remote detection. It is most likely caused by the THz plasma heating, which results from the THz wave's energy being converted into the translation of gas molecules [64,65].

Due to the high complexity and high cost of the femtosecond laser-induced plasma system, a simple method for THz wave detection is required. Hou et al.'s first recommendation for a THz continuous wave detector was a weakly ionized plasma detector. To create dc neon plasma, an electrode gap of 0.15 mm is used. The responsiveness of the THz detector first increases with the increase in discharge current, peaks at 194.4 V/W at 1.4 mA, and then progressively decreases [66]. The creation of a microplasma array is also done in order to detect the THz wave [67].

Challenges

THz Radiation from Laser-Induced Microplasma

A photocurrent hypothesis put out by Kim's team that describes the process of THz waves released from laser-induced microplasma is generally accepted [68]. They thought that the asymmetric laser field drives the free electrons generated during the ionization of gas molecules, producing a quick transient current and a THz wave as a consequence. In contrast, Debayle et al. discovered that the plasma oscillation or photoionization may be the source of THz radiation, and that the strength of this radiation is influenced by the thickness of the plasma skin and its length of propagation [69,70]. Kemp et al. and Sheng et al. put a lot of work into time-domain diagnostics and effective particle-in-cell (PIC) model management of the terahertz radiation spectrum in order to comprehend the mechanism of the THz radiation from laser-induced microplasma [34,35,71-75]. However, it is yet unknown which THz radiation process dominates in laser-induced microplasma. For THz applications in 6G communications and explosives detection, the energy efficiency of the sources based on laser-induced microplasma has to be further improved.

The Amplification of THz Radiation by Microplasma

According to Dai et al., four-wave-mixing parametric processes are the primary causes of THz radiation amplification by laser-induced plasma. This is in reference to the amplification mechanism of THz radiation by microplasma. This differs from the Bogatskaya et al. theory, which suggested that the laser-induced plasma's negative absolute conductivity should be to blame for the amplification. Furthermore, it was suggested by Massood et al. that the mechanism based on electric dipoles is ascribed to the microplasma in the capillary amplifying the THz wave within a meandering waveguide, where the microplasma is formed by electrical discharge rather than femtosecond laser energy pulses. According to reference [44], there is a nonlinear correlation between the electron density and the gain of terahertz wave amplification. The mystery behind the THz radiation's amplification by microplasma will soon be resolved.

Microplasma Photonic Crystals

Previous experimental works have demonstrated that some specially designed mi- croplasma photonic crystals have THz stopbands at 0.1–0.2 THz, which could be used tocontrol the THz wave propagation by changing plasma parameters. Simulation results have also predicted that THz radiation with frequency up to several THz can be tuned by mi- croplasma photonic crystals as long as the plasma density increases to 10^{15} cm^{-3} or higher. Further experimental verification of this prediction is needed. In addition, the effects of the plasma uniformity, the transient discharge process, and the 3D complex structure on the THz bands of the microplasma photonic crystals are required to be investigated.

THz Detection by Microplasma

Previous studies have shown how to detect THz radiation using the second-harmonic production, fluorescence emission, and auditory signals from laser-induced microplasma. The descriptions of the qualitative applications of the detection concepts. The detection of THz waves by microplasma or a microplasma array, on the other hand, was suggested by Hou et al. Microplasma is produced by glow discharge at low pressure. The measuring process of this THz detector is still unknown, despite research on the effects of gas pressure, gas composition, and discharge current on the THz detector's responsiveness and stability.

II. CONCLUSION

This paper reviews the use of microplasma to THz functional devices from the perspectives of terahertz sources, amplifiers, filters, and detectors. Following is a presentation of the conclusions.

The "one-color" and "two-color" techniques used to produce THz sources are based on laser-induced microplasma, which has a high electron density in the range of 1017 cm3 to 1019 cm3. The effectiveness of optical-to-THz conversion is strongly influenced by the size of microplasma and the electron density. The characteristics of a wide frequency band and great power offered by THz sources make them ideal for recognizing biological macromolecules and molecular crystals.

In addition to the microplasma created by the laser, the microplasma created in the capillary by gas discharge has also been effective in boosting the THz wave. It demonstrates the potential for using the microplasma as a THz amplifier, which offers the benefits of high-power amplification at high efficiency. Diverse ampli- fication mechanisms, however, based on four-wave-mixing parametric processes, the negative absolute conductivity of microplasma, and electric dipoles are postulated, and they need to be further studied.

Microplasma photonic crystals feature THz stopbands or passbands in the frequency range of 0.1-0.2 THz, as shown by experimental and computational findings, allowing the THz wave propagation to be tuned by altering the plasma properties. Fast response and reconfigurability are benefits of THz filters based on microplasma photonic crystals. However, further research is required to determine how microplasma photonic crystals can regulate the propagation of THz waves with frequencies up to or greater than 1 THz.

The second-harmonic production, fluorescence emission, and acoustic signals from laser-induced microplasma-based THz radiation detection techniques have all been created and extensively researched. Additionally, a straightforward THz radiation detection technique is developed, based on the interaction between the THz wave and the microplasma generated by glow discharge. But as of yet, it is unclear how this approach detects objects.

In summary, the effective application of microplasma technology to the THz sector, including THz sources, amplifiers, filters, and detectors, opens up a new frontier for both THz technology and plasma research. Promoting transdisciplinary research between them is advantageous.

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