Application Of Terahertz Electromagnetic Waves in The Field of Detection

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Abstract. Among all kinds of electromagnetic waves, terahertz (THz) waves are those with frequencies varying from 0.1 to 10 THz (with wavelengths ranging from 3000 to $30x10^{-6}$ m). Millimeter waves in the long wavelength range overlap with electromagnetic waves, as well as infrared light in the short wavelength range. The THz gap in the electromagnetic spectrum is the crossover between electronics and photonics, and between macroscopic classical theory and microscopic quantum theory. The THz wave band has the same characters as spectrum of substances such as semiconductors, plasmas, organisms, and biomolecules, having the characteristics of quantum energy and low blackbody temperature. The time-domain spectral signal-to-noise ratio of THz is very high, making it excellent for applications involving images. Because of the extremely large instantaneous bandwidth (0.1-10THz), high-speed transmission is possible. Therefore, utilizing THz can deepen and broaden humans' knowledge of some fundamental scientific issues in physics, chemistry, astronomy, informatics, and life sciences. At present, technology related to THz wave is widely used in temperature sensors, biosensors, communication, astronomy, and safety inspection fields.

Keywords: THz wave; Electromagnetic wave; THz sensor.

1. Introduction

New advances in the latest technologies provides the opportunities for the previously unused THz waves now being accessible for application in different areas. terahertz (THz) wave is a kind of electromagnetic wave with frequencies ranging from 0.1 to 10 THz (with wavelengths ranging from 3000 to 30 um) within a certain range overlap with millimeter in the long wavelength range and with infrared light in the short wavelength range. The THz wave band is also called sub-millimeter, far infrared and near-millimeters wave. They are the crossover from macroscopic classical theory to microscopic quantum theory, as well as that from electronics to photonics, known as the THz gap in the electromagnetic spectrum. The THz wave band can include the similar characteristics to the spectrum of substances such as semiconductors, plasmas, organisms, and biomolecules, having the characteristics of quantum energy and low blackbody temperature. What makes THz wave very suitable for imaging applications is its property of having high time-domain spectral signal-to-noise ratio of THz. THz waves have other kinds of properties as well. For instance, THz waves have high penetration, as THz waves have less scattering and better penetration depths since is wavelength is longer than infrared wavelength. THz waves are safe as well, as the photon energies in the THz band are much lower than X-rays, which means THz radiation is non-ionizing.

The instantaneous bandwidth is very wide (0.1-10THz), which is conducive to high-speed communication. Therefore, utilizing THz can deepen and widen human understanding of some fundamental scientific issues in areas like physics, chemistry, astronomy, informatics, and life sciences. For now, THz technology is widely used in temperature sensors, biosensors, communication, astronomy, and safety inspection fields. This article summarizes the above applications and looks forward to more researchers and technicians paying attention to the development of THz technology, aiming to introduce theories of some different detection areas, including temperature sensor, biological sensor, THz sensing and communication, detectors for astronomical applications and detection in field of safety inspection, providing summaries of the latest advance in technology and looking into the future.

2. Applications

2.1. THz Temperature Sensor

THz wave has a frequency ranging from 0.3 THz to 10 THz in the electromagnetic spectrum, lying between microwave and infrared wave. What makes it differ from other electromagnetic waves is its unique feature, including high penetration and low photon energy.

As an important type of functional device, THz absorbers can achieve perfect absorption of incident THz waves as well as serving as temperature sensors to capture and monitor changes in surrounding environmental information. In general, through optimizing the surface metal resonant unit structure and changing the material and morphology of the dielectric layer to investigate the influence of intermediate dielectric layers on the sensing characteristics of THz absorbers in depth, the sensing characteristics of THz absorbers are improved [1]. At present, various forms such as metal layers and insulation layers are mainly used internationally to prepare THz temperature sensors. The research results will have significant implications for THz fiber optic communication and sensing fields. In 2017, Keshavarz A theoretically described a nano THz metamaterial temperature sensor composed of an indium antimonide substrate and an H-type graphene structure [2].

The transmission spectrum of this metamaterial structure has a filtering effect, and within a certain frequency band, the percentage of electromagnetic waves passing through the structure will significantly decrease. The electromagnetic properties of materials such as graphene and InSb have a strong dependence on temperature, and their resonant frequency will change with temperature. The temperature sensor has a sensing range of 24-31°C and a sensitivity of 0.0271 THz/°C, which is higher than other design structures. One of the major advantages of this temperature sensor is that through changing the geometric parameters of the structure, it can change the resonance frequency of the device. Illuminating the piece of grapheme placed on the semiconductor substrate with THz frequency light will induce surface plasmon. It is a great idea to use the proposed temperature sensor for medical applications as well as being used for high-precision temperature measurement in the environment due to the nanoscale, sensitive reaction, and structure in the THz range. In 2021, Luo proposed a tunable ideal absorber (PA) based on a combination InSb resonator structure [3]. The absorber can be used as a dual band temperature sensor. The proposed PA can achieve absorption rates of 99.4% at 1.598 THz and 98.7% at 1.926 THz, both at temperatures of 290 K. The sensing range is 270K-295K, and its sensitivity is about 8.54GHz/K and 16.25GHz/K, respectively.

The proposed dual frequency PA has the potential to be applied in thermal emission, sensing, and detection in the THz region thanks to its excellent performance. The full electromagnetic spectrum, including the THz, is illustrated in Fig. 1.

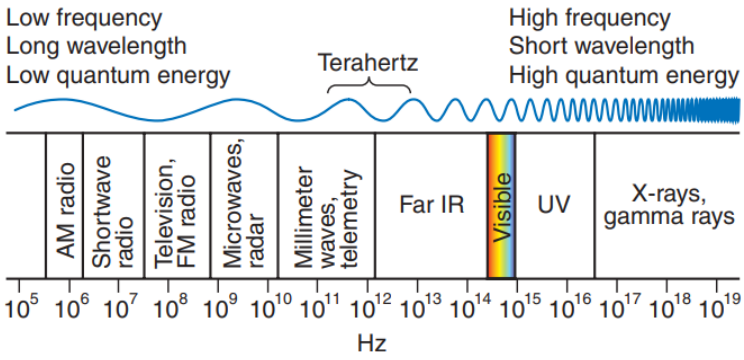


Fig. 1 The electromagnetic spectrum.

2.2. THz Biological Sensor

In recent years, THz metamaterials have made certain research progress in the application of biosensors. Yuan Xin et al. and some other scholars think that through specific binding, it can be said that single molecule detection has been achieved [4]. Ultra-thin silicon nitride substrate with a

perceptiveness of 4.05×10^{-2} GHz•nm^{-1}. The minimum concentration of glucose detected on commercial paper substrates is 0.35mmol•L^{-1}, which can meet commercial needs. A further optimized metamaterial structure called CB substrate, can detect a thin-film thickness of up to 12.5 m, with a thickness of approximately over 10×10^{-6}M basically reaches saturation. Finally, multiple resonant THz band fractal metamaterial biosensors were explored. These results provide a new opportunity for the development of biosensor technology. However, further research is needed to truly move towards practical applications. The author believes that the future can be roughly divided into the following research directions [4]. Firstly, many biological macromolecules such as DNA and protein molecules have collective oscillation modes in the THz band, but there is little research on truly combining the characteristics of metamaterials with biological molecules. If these two aspects are combined, the sensitivity of the sensor will be further enhanced, which also reflects the advantages of THz wave biosensors compared to other bands. Improving the resolution of THz time-domain spectroscopy is also an effective way to increase the detection limit of biosensors [4]. By designing special metamaterial structures and using ultra-thin, low dielectric constant substrates such as silicon nitride and commercial paper, the sensitivity of sensors can be greatly improved. However, it is difficult to achieve nanomolar level detection when detecting changes in solution concentration. Therefore, in order to meet practical needs, sensitivity and accuracy need to be further improved. At present, most of the designed metamaterial structures are planar structures. If the metamaterial structure can be processed into a three-dimensional structure and then combined with molecular specific binding techniques, it may better meet practical needs. At present, most THz metamaterial sensors are based on the transmission or reflection spectral lines of THz, and the characteristics of sensors are studied using resonance offset. If the changes in amplitude and phase measured by THz are combined with the characteristics of metamaterials, it is also an effective way to study metamaterial sensors. By combining metamaterials with THz spectroscopy through specific binding, single molecule detection can be achieved, but most results are measured in non-aqueous solutions, and every biological cell is composed of these important biomolecules and water. For practical needs, it is necessary to study metamaterial sensors working in liquid environments. Aiming to make the sensors more accurate, the identification of substances requires the matching of multiple characteristic frequencies of metamaterials and detection objects. Therefore, research on electromagnetic metamaterials with multiple resonances will also be increasingly valued.

Hence, combining the advantages of THz and metamaterials, it is essential to develop unmarked, highly sensitive, and liquid environment-based metamaterial sensors. The most important thing is to push current sensors into practical applications, which is the development trend in this direction.

2.3. THz Sensing and Communication

Wang et al. believed that as wireless cellular connectivity has advanced quickly from 1G to 5G, not only has the connection between people become closer, but more and more intelligent devices have also achieved interconnection, including automobiles, sensors, home appliances, and industrial equipment. This development tendency will continue until 2030 and beyond, when intelligent interconnection of all things will be achieved anytime, anywhere [5]. If smart devices can perceive the surrounding environment and share environmental information with other smart devices, the connection will become more intelligent. To achieve this vision, joint radar communication technology has been taken into consideration.

However, due to the strict requirements for information exchange between radar systems and communication systems, there are many limitations in practice. An effective communication perception integrated system, including loosely coupled systems and fully integrated systems, is expected to reduce the scale of shared access radar and communication systems, and shorten the latency of information exchange between systems. Every upgrade of wireless cellular communication technology means adopting higher spectrum and larger bandwidth, which is also beneficial for perception. If THz can be applied in China, humans will have more opportunities. Compared to millimeter waves and microwaves in the low frequency range, as well as light visible to human beings'

eyes with high frequency, the features of THz are significantly different. Compared with millimeter waves, there is more selectivity of frequency in THz waves, more pronounced scattering effects, and greater transmission losses. Compared with light waves, THz waves have lower path loss, stronger volatility and reflected energy, and lower likelihood of being blocked. Due to these differences, the THz frequency band is incompatible with current millimeter wave, microwave, and visible light system channel models and measuring techniques, therefore there is an urgent need to develop specialized THz channel measurement instruments. The study by Wang et al. suggests that there are currently two methods for wireless channel modeling [6]. A statistical channel modeling method based on measurement data is a good idea, and the other one, based on ray tracing or theory of solution to electromagnetic field boundary, is a deterministic channel modeling method. However, as the new generation of mobile communication scenarios become increasingly diverse, the demand for new spectra continues to grow, and statistical channel modeling methods cannot fully fulfil the new channel requirements. So, people gradually began to study deterministic channel modeling methods and used computational electromagnetic methods for high-precision channel modeling in specific scenarios [7].

2.4. THz Detectors for Astronomical Applications

Ren et al. found that in the field of astronomy, the THz frequency band has unique advantages [8]. Firstly, the THz frequency band gathers nearly 50% of the radiation energy from various celestial bodies at different redshifts in the universe after the cosmic microwave background radiation (equivalent to the total radiation energy in the ultraviolet, visible, and near-infrared bands). Secondly, the THz frequency band is most suitable for observing cold and dark celestial bodies in the formation stage (with a typical temperature of 10 K, corresponding to spectral radiation peaks of about 1 THz frequency band), early distant celestial bodies (whose ultraviolet and visible radiation is absorbed by interstellar dust and produces longer continuous spectral radiation, which is transferred to the THz frequency band by the Doppler frequency shift effect), and celestial bodies obscured by dust (the THz frequency band interstellar medium obscuration is much weaker than visible/near-infrared, that is, the penetrability of the THz frequency band). In addition, the THz frequency band contains abundant molecular, atomic, and ion spectral lines, making it a unique frequency band for studying the physical and chemical properties and dynamic characteristics of celestial bodies. Therefore, the THz frequency band plays a particularly important role in contemporary astronomical research and is of great significance for understanding the state and evolution of the universe (including early universe evolution, star and galaxy formation, planetary and planetary system formation, etc.) [9]. Since the 1990s, significant research achievements have been made in THz frequency band astronomical observations, such as precise measurement of cosmological parameters using cosmic microwave background radiation, discovery of submillimeter wave galaxies, and fine structure observation of protoplanetary disks [10]. In addition, it also has applications in black hole imaging, characterization of water molecules in neighboring universes, and detection of ionized hydrogenated helium ions, which were the first to emerge in the universe [11].

2.5. THz Detection in the Field of Safety Inspection

Due to the enormous potential of THz wave technology in detecting explosives, knives, firearms and other hazardous materials, multiple domestic and foreign institutions are committed to THz spectral measurement and imaging research of such hazardous materials.

Representative institutions include the United States Naval Institute, Hopkins University, Syracuse University, University of Cambridge in the UK, University of Osaka in Japan, Tianjin University in China, Capital Normal University, etc. The main research direction is THz spectral characteristics of explosives in pure samples; THz spectral characteristics of mixed sample explosives; THz spectral characteristics of explosives in different states (including solid and gas phases); Explosive detection under cover; Explosive detection at different temperatures and humidity; Establishment of THz

spectral database for explosives; THz imaging and intelligent detection of prohibited items such as firearms and knives [12].

3. Conclusion

THz wave means a certain range of electromagnetic waves on the spectrum, classified by its wavelength. THz waves are now encountering wider uses in different areas, due to its good properties. This paper introduces the definition of THz wave and its characteristics, as well as summarizing the application of THz wave in temperature sensor, biological sensor, THz sensing and communication, detectors for astronomical applications and THz detection on the field of safety inspection and the theories of those applications. THz waves transcend other ways of detecting with its high sensitivity and conductivity, as well as high penetration and safety due to its unique range of wavelength. Its wide band allows the range which can be detected by THz wave to stretch over different regions, including semiconductors, plasmas, organisms, biomolecules and so on. With the use of THz wave, human beings' understanding in areas like Physics, Chemistry, Pharmacology, and life science can be improved due to deeper learning and recognition of substances' nature. THz wave will encounter a wider range of applications soon, detecting other regions, perhaps measuring coating of different materials due to its good properties and fitness of use in detection areas.

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