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| RESEARCH ARTICLE

Recent Developments and Prospects of Electromagnetically Active Metamaterials in Biosensing

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| ABSTRACT
This paper provides an overview of the progress of research on electromagnetically active metamaterials in the field of biosensing, especially the potential of terahertz metamaterials for biosensor applications. Electromagnetically active metamaterials exhibit a negative refractive index and perfect absorption through their special structure, and their electromagnetic behavior is affected by their structure and geometry, which is different from traditional materials. The article reviews the application of terahertz technology for the bio-detection of cancer cells and apoptotic processes using periodic metal arrays by terahertz biosensors, demonstrating the advantages of terahertz biosensors, such as high sensitivity and detection without labeling. This paper presents a comprehensive overview of the advancements in research concerning electromagnetically active metamaterials within the domain of biosensing, with a particular emphasis on the potential applications of terahertz metamaterials in biosensor technology. Electromagnetically active metamaterials are characterized by their negative refractive index and perfect absorption, which arise from their distinctive structural properties. The electromagnetic behavior of these materials is significantly influenced by their design and geometry, setting them apart from conventional materials. The article examines the utilization of terahertz technology for the bio-detection of cancer cells and apoptotic processes tunability, employing periodic metal arrays in terahertz biosensors. It underscores the advantages of terahertz biosensors, which include high sensitivity and the capability to detect biological entities without the necessity for labeling. Terahertz metamaterial biosensors are promising for protein, virus, and cancer cell detection. This paper also explores the design and application of chiral metamaterials, especially indium tin oxide-based mid-infrared chiral metamaterials, to solve the problem of the large size of traditional materials and investigates their circular dichroism. Looking ahead, electromagnetically active metamaterials, especially terahertz metamaterials, are expected to improve resolving power and sensitivity, reduce costs, and expand the applications of biosensors in the biomedical field. The applications and research of these sensors will continue to advance with the advancement of micro and nanoprocessing technologies.

| KEYWORDS
Metamaterials, active materials, electromagnetically active metamaterials, terahertz technology, biosensors, chiral metamaterials, metamaterial absorbers.

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1. Introduction
Active metamaterials, which show great potential for application in modern science and technology, have unique electromagnetic properties that are highly tunable. Innovative applications of these materials continue to expand the boundaries of science and technology, from invisibility technology to biomedical detection. However, with the rapid development of science and technology, the requirements for the performance of metamaterials have become increasingly stringent, prompting researchers to continuously explore new development directions and application prospects.

By summarizing and outlining the existing literature, we find that fan-type mid-infrared chiral metamaterials based on indium tin oxide have been investigated, and their circular dichroism properties have been explored by Yexin Zhu et al. Among the experimental results, it is shown that the material exhibits significant circular dichroism with a difference in the transmittance of right- and left-hand circularly polarized light in a specific wavelength range, which provides a new idea for the design of micro- and nanostructured materials and devices. Fan-type mid-infrared chiral metamaterials based on indium tin oxide were successfully prepared. The circular dichroism properties of the material in the mid-infrared band are revealed. It provides new ideas and methods for the design of micro- and nanostructured materials and devices, especially for potential applications in optical filtering and sensing. Wang et al. (2020) introduce the research progress of electromagnetic metamaterial wave absorbers from three aspects: multi-frequency and broadband, polarization and angle insensitivity, and dynamic tunability(Ding et al., 2012)

Among them, for multi-frequency and broadband research, they explored multi-frequency and broadband wave absorber technology to enhance wave-absorbing performance. In polarization and angle insensitive wave absorbers, they mainly reviewed the solutions to the effects of polarization and incident angle changes on wave-absorbing performance. In dynamically tunable wave absorbers, they explored methods for dynamically adjusting the absorbing characteristics to adapt to different environmental requirements. Finally, it is proposed that the future research direction for the electromagnetic wave absorbing technology should focus on lightweight, strong bearing capacity, good wave-absorbing performance, intelligent adjustability, and multi-frequency band compatibility in order to meet the needs of complex environments (Wang et al., 2020).

Jun Yang et al. mainly introduced the research progress of terahertz metamaterial biosensors and discussed the unique advantages of terahertz waves in biosensing, such as low photon energy to reduce the damage to biological samples and the ability of metamaterials to modulate electromagnetic waves. Terahertz waves have been widely used in medical diagnostics for protein concentration detection, virus detection, and detection of cancer cells and their markers. In food safety, the detection of aflatoxin b1 and aflatoxin b2 can be performed. In pesticide detection, the sensitivity of chlorpyrifos and organic green pesticides has been greatly improved. In other aspects, the use of terahertz metamaterials has improved the detection of yeast, fatty acids, and other substances. For terahertz metamaterials, Jun Yang et al. proposed the future development direction in distinguishing and identifying chiral molecules, improving the sensitivity of detection, and predicting the experimental results quickly and accurately. Although active metamaterials have shown their unique advantages in a number of fields, there are still some key issues that need to be resolved, such as the stability of the materials, cost-effectiveness, and optimization of performance in specific applications. The existence of these issues limits the wide application of active metamaterials.

The aim of this review is to provide insight into the recent developments in active metamaterials, especially their applications in biosensors and electromagnetic metamaterial absorbers. The main points reviewed in this paper include Active Metamaterials. The present volume, through the analysis of the existing research results and limitations, puts forward the proposition of optimizing the structure and properties of active metamaterials in order to achieve a higher degree of sensitivity and a wider range of applications.

2. Active Metamaterials

2.1 Electromagnetically Active Metamaterials

Electromagnetically active metamaterials are artificially structured materials with unconventional electromagnetic properties. Unlike conventional materials, the electromagnetic properties of metamaterials do not only depend on the nature of their constituent materials but are also influenced by their structure and geometry (Wang et al., 2020). These materials can be designed to exhibit special electromagnetic behaviors such as negative refractive indices, perfect absorption, superlens effects, etc., in specific frequency ranges.

Electromagnetically active metamaterials are a class of materials with a unique electromagnetic response, the behavior of which is determined by their microstructure rather than just the macroscopic nature of the material. These materials typically consist of a periodic arrangement of artificial units (i.e., "meta-units") that are capable of producing unconventional effects on the propagation and response of electromagnetic waves (Wang et al., 2020).

Yanzhao Wang et al. reviewed the research progress of electromagnetic metamaterial wave absorbers with the aim of exploring their potential and challenges in the field of modern stealth and electromagnetic compatibility. The research background emphasizes that traditional wave-absorbing materials have been difficult to meet modern demands, and metamaterials have become a research hotspot due to their advantages of simple structure, lightness, and thinness, as well as high absorption rate. The wave-absorbing property of electromagnetic metamaterials can be measured by the absorptivity A(w), which is related to the reflectivity R(w) and transmittance T(w) by the equation (1) (Wang et al., 2020):

$$A(\omega) = 1 - R(\omega) - T(\omega), \tag{1}$$

In order to design and optimize better wave-absorbing structures, the equivalent medium theory, the equivalent circuit theory, and the multilevel reflection interference theory have been proposed to analyze the wave-absorbing mechanism of metamaterials. The equivalent medium theory, which can be inverted from the scattering parameter by the inversion method, was initially used as an effective method to verify the negative refractive index, but it lacked the analysis of the interactions between the unit structures; therefore, the equivalent circuit method was proposed. Other analytical methods include resonant cavity theory, Fabry-Perot cavity theory, Mie scattering theory, and mode analysis methods (Wang et al., 2020). Adopting appropriate analysis methods and combining them with simulation software for algorithm optimization can guide the design and compensate for the shortcomings.

In multi-frequency and broadband, Huang et al. designed a broadband absorber, as shown in Fig. 1, where each structural unit introduces an absorption peak, which is finally realized by superposition (Huang et al., 2012). Efficient electromagnetic wave absorption was achieved in the terahertz band, demonstrating the potential of metamaterials in the field of electromagnetic wave modulation.

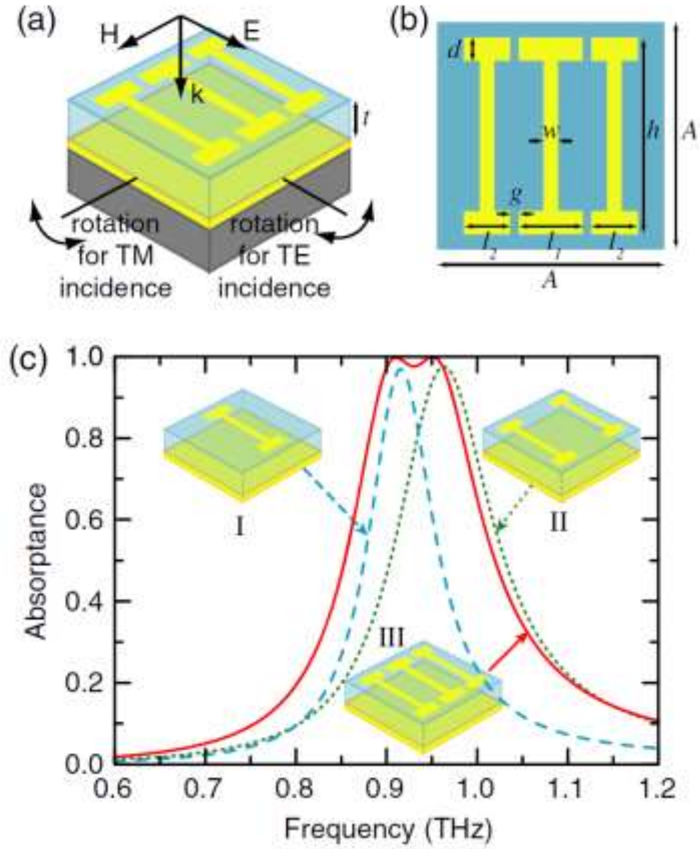

Fig. 1. Wideband terahertz metamaterial wave absorber

A polarization-independent, wide-angle, three-band metamaterial absorber, realized by a three-layer nested closed-ring resonator, was presented by Shen et al. The absorber exhibits near-perfect absorption at both TE and TM polarizations, and its thickness is only 2.4% of the shortest operating wavelength. The design is polarization-insensitive, wide-angle absorbing (absorptivity over 0.9 at incidence angles up to 50°), ultra-thin, and is expected to be used in applications such as spectroscopic detection and phase imaging (Shen et al., 2011).

Xu et al. (2012) employed a three-band polarization-insensitive wide-angle ultraminiature metamaterial transmission line absorber to achieve efficient absorption by optimizing the electromagnetic resonance properties of a three-layer structure (a dielectric layer sandwiched between two metal layers). The absorber design takes into account impedance matching and shielding effects to reduce reflections and transmission, thus converting all incident power into ohmic and dielectric losses. It is characterized by insensitivity to the polarization of the incident wave and a wide-angle absorption capability (Xu et al., 2012).
Ding et al. designed an ultra-wideband microwave absorber based on metamaterials with a multilayer pyramid structure, as shown in Fig. 3. The absorption properties of the microwave absorbing material were significantly enhanced and tuned by the design of

metamaterials. The absorptivity remains above 80% at an incident angle of 60°, and an absorptivity close to 1 is achieved over a wide bandwidth from 8 GHz to 14 GHz, and it is effective over a wide angular range. The absorption band can be easily tuned by changing the width gradient of the tetragonal pyramid. The results verify the great potential of metamaterials in the field of microwave absorption and provide new ideas and methods for the design of microwave absorbing materials, which are expected to be widely used in the fields of radar stealth and electromagnetic shielding. (Ding et al., 2012)

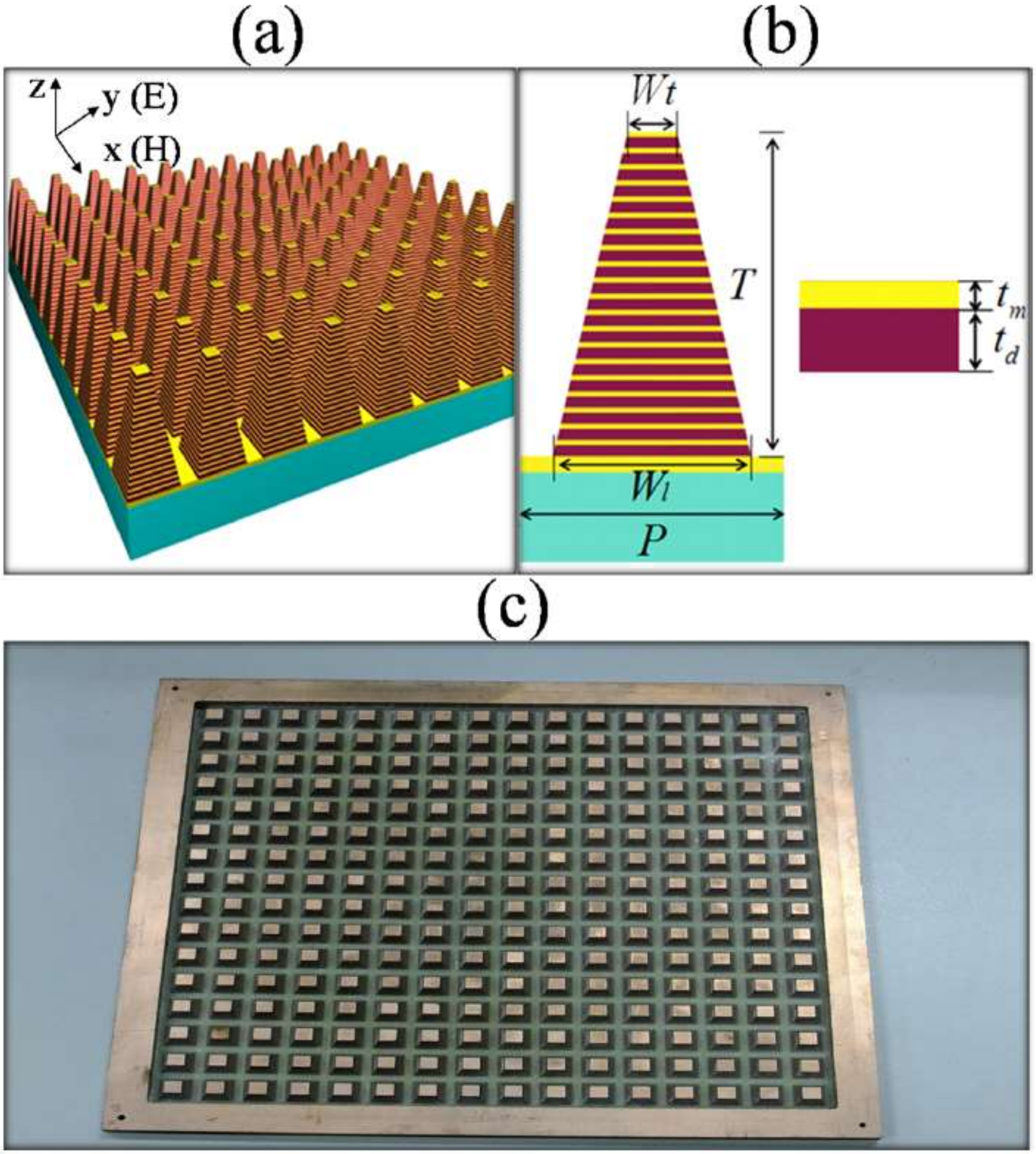

Fig. 2. (Color online) Design and fabrication of a microwave ultra-broadband MA. (a)Three-dimensional illustration of the simulated MA, (b)schematic of a MA unit cell, and (c) photograph of the fabricated sample. The optimized dimensions of a unit are W,=5mm, W=9mm, P=1lmm.tm=0.05 mm, ta=0.2 mm, and T=5 mm. Subscript "'m" represents copper, "'d" for FR4.

The current research methodology covers the exploration of key technical challenges such as multi-frequency and wide bandwidth, polarization and angle insensitivity, and dynamic tunability. Despite some progress, many challenges remain. The future direction of metamaterial wave absorbers, including low-frequency ultra-thin and broadband, multifunctional integration, and new three-dimensional structures, is highlighted, and their broad application prospects in stealth, detection, and other fields are emphasized.

2.2 Chiral Metamaterial

Chiral metamaterials are novel artificial electromagnetic materials that possess two key properties: optical activity and circular dichroism (CD). Optical activity describes the ability of the polarization plane to rotate when linearly polarized light passes through the material, while circular dichroism reflects the difference in the absorption of right- and left-handed circularly polarized waves by the material (Zhu et al., 2020).

Zhu et al. (2020) selected ITO as an iso-isolated matrix material and designed fan-type chiral structures, as shown in Fig. 3.

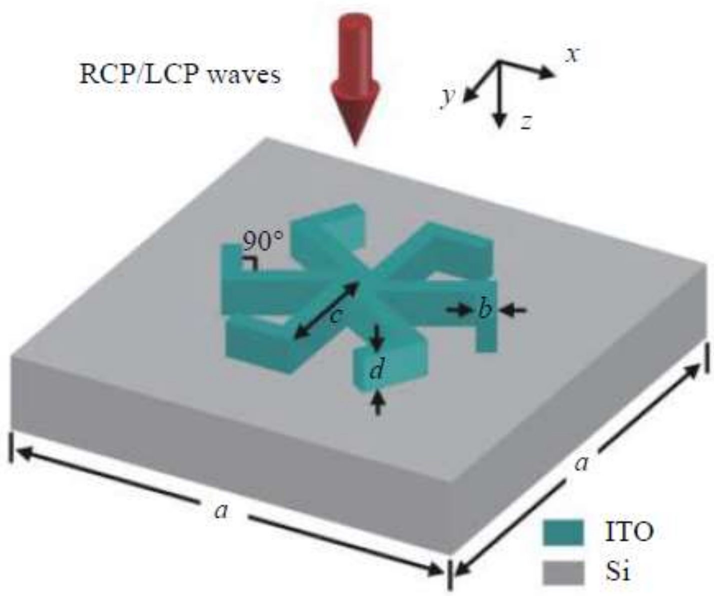

Fig. 3. Schematic diagram of a chiral structural unit consisting of six identical ITO flaps.

By varying the filler material of the flapping layer, the thickness of the flapping, the size of the flapping, the number of the flapping, and the material of the flapping, the researchers explored the variation of the circular dichroism of the structure. The simulation results show that the CD properties of chiral metamaterials can be effectively tuned by adjusting these parameters. When changing the filler material, choosing the appropriate filler layer material can achieve different intensities of CD. When the filler material is silicon, the structure ITO will oscillate due to the incidence of circularly polarized light, making the CD stronger. The CD signal reaches its maximum at a blade thickness of 400 nm, which is the optimum value for the sector thickness. There is a clear shift of the CD response wavelength towards longer wavelengths with a significant change in the dimensions of the structure. The variation in the number of fan blades has a significant effect on the CD of the structure. Finally, a novel design of mid-infrared chiral metamaterials is proposed to achieve the modulation of circular dichroism by optimizing the structural parameters of the fan blades. This material shows good performance in terms of optical activity and circular dichroism and is expected to be applied in the fields of optics, communication, and sensing (Zhu et al., 2020).

3. Biosensors

Terahertz waves have a frequency range of 0.1 to 10 THz, located between infrared and microwave. The photon energy is low: 1 THz corresponds to about 4.14 eV, which reduces the damage to biological samples (Yang et al., 2021).

By using a terahertz biosensor constructed with periodic metal SRRs arrays, oral cancer cells, and their apoptotic process were detected in detail, which verified the great potential of terahertz technology in the field of bio-detection. The literature review covers a wide range of fields, such as materials science, biomedicine, and chemical sensors, which provide a solid theoretical foundation and technical methods for the research of terahertz biosensors.

Lee et al. (2017). investigated the use of nanomaterial metamaterial sensing chips combined with terahertz spectroscopy for the detection of the terahertz optical properties of multiple types of avian influenza viruses. The multi-resonance nanoantenna sensing chip performed well in detecting viruses without unique fingerprint characteristics, and specific virus detection was achieved by optimizing the single resonance nanoantenna. Analyzing the terahertz spectra of different virus samples, combined with FDTD simulations, revealed that the spectral variations were correlated with the optical properties of the samples near the nanoantenna. Successful classification of virus subtypes and concentration-dependent virus quantification were based on complex refractive index and absorption properties. This technique provides a rapid solution for non-contact, label-free, high-precision avian influenza virus detection.

Liu et al. (2017) discuss nanoparticle-doped thin-film sensing techniques based on terahertz metamaterials aimed at improving the performance of thin-film sensors through the use of terahertz spectral properties. The study deals with the characterization of nanoparticles in polymer films and their response to terahertz waves and provides the theoretical basis and technical support for the development of new and efficient sensors.

Application in food safety is an important issue that affects a wide range of people's concerns, and the solution to the problems that arise in food safety is the rapid identification of problematic foods. Xie et al. (2015) investigated the extraordinary sensitivity enhancement of antibiotic detection in the terahertz band using a supersurface structure with a periodic array of square apertures. The hypersurface exhibited strong resonance at 0.3 THz, and the structure was found to be highly sensitive to antibiotic solutions by coating kanamycin sulfate solutions for terahertz transmission measurements. This study provides new ideas to improve the application of terahertz detection technology in the biomedical field.

The excellence of terahertz biosensors in practical applications is demonstrated through experimental studies, especially the work of Zhang et al. The novel terahertz metamaterial biosensor, which has significant advantages in the field of biosensing, can detect very small amounts of analytes. This high sensitivity and high-resolution property, enhanced by local electromagnetic resonance, allows the sensor to achieve sub-wavelength level resolution, which significantly improves detection accuracy (Yang et al., 2021).

In addition, the terahertz metamaterial sensor simplifies the detection process and reduces interference with the sample, as it does not require additional markers during the detection process. Its rapid response capability is particularly effective in applications that require immediate detection results. Terahertz metamaterial sensors have a wide range of promising applications in the biomedical field. With the development of micro-nanofabrication technology, the production cost of terahertz metamaterial sensors is gradually decreasing, which will also promote their further popularity and application in the biomedical field. In conclusion, the research on terahertz metamaterial sensors has become a very popular frontier topic internationally, and its importance and potential have been fully reflected in scientific research and practical applications.

4. Conclusions

It mainly introduces the latest research progress of electromagnetically active metamaterials in the field of biosensing, especially the application potential of terahertz metamaterial biosensors, and provides in-depth analyses of the design principles of the basic properties of metamaterials and examples of their applications in biosensing.

Firstly, unlike general conventional materials, electromagnetically active metamaterials have their own unique electromagnetic properties, such as perfect absorption with a negative refractive index. These properties are caused by their special structure and geometry, which gives them the unique advantage of controlling electromagnetic waves. In particular, terahertz metamaterials have very broad prospects for biosensing applications. Some studies have shown that terahertz metamaterial biosensors are capable of high-sensitivity detection without labeling. Additionally, terahertz metamaterial biosensors have shown good results in detecting biological samples such as protein viruses and cancer cells. Therefore, the application of electromagnetically active metamaterials is very promising in the field of biosensing.

Secondly, important progress has also been made in both optical activity and circular dichroism. Studies such as indium tin oxide-based fan-type mid-infrared chiral metamaterials have been conducted to optimize chiral structural parameters, such as the factors affecting their circular dichroism, in order to efficiently modulate the optical activity and circular dichroism of the metamaterials, which provides a new way of thinking in terms of optical filtering and sensor design.

However, although electromagnetically active metamaterials have been found to be promising in many fields, there are still challenges, such as optimizing material stability, that constrain the realization of their wide range of applications. Therefore, future research should focus on optimizing the structural design and properties of metamaterials in order to expand their applications in biomedical fields while reducing production costs. From this point of view, the main effort should currently be invested in the research on the stability of metamaterials.

To sum up, this review paper focuses on the current research status and future development direction of metamaterials with electromagnetic activity, including terahertz metamaterials, in the field of biosensing in a systematic manner. The article analyzes the progress of research on nanofabrication technology, and the practical application needs in the field of biosensing.

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