Terahertz Metasurfaces Research Progress and Applications

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Abstract: Terahertz waves have strong penetration, wide frequency bands, and non-ionizing properties, and have received extensive attention from both the industrial and scientific communities in recent years. Metasurfaces, as two-dimensional planar metamaterials, possess three properties: subwavelength structures, lightweight, and flexible regulation. The combination of the two has led to better development in both research and application fields. This paper focuses on the breakthroughs in the core design of terahertz metasurfaces, including materials, structures, and manufacturing technologies, as well as the realization of functions such as wavefront regulation and imaging technology, polarization and mode control, and dynamically adjustable functions. It also summarizes the current challenges faced by terahertz metasurfaces, such as how to balance manufacturing precision and cost, and the need to optimize the power consumption of existing dynamic metasurfaces. In addition to the current application fields, future research and development directions also include potential solutions such as interdisciplinary communication and integration with artificial.

1 INTRODUCTION

Terahertz waves (0.1-10 THz) connect the special frequency bands of photonics and electronics with their unique penetrating, non-ionizing, and high-bandwidth characteristics, showing revolutionary potential in communications, imaging, and biomedicine. However, due to the weak response characteristics of natural materials in the terahertz band and the difficulty in achieving efficient regulation with traditional optical devices, terahertz technology has long faced bottlenecks and has been difficult to apply. With the rapid rise of new application areas such as 6G communication and high-resolution non-destructive testing, there is an urgent need for breakthroughs to enable the efficient application of terahertz. The development of metasurface technology offers new opportunities for the design and application of terahertz functional devices.

The rise of metasurface technology offers a new way to solve this problem. Metasurface materials are two-dimensional planar structures that allow for flexible manipulation of the phase, amplitude, and polarization state of electromagnetic waves through the precise arrangement of sub-wavelength-scale units. Their lightweight and customizable features not only break through the diffraction limit but also enable functional reconfiguration through dynamic tunable materials, opening up new paths for the miniaturization and intelligence of terahertz devices. Therefore, terahertz metasurfaces have broad prospects in application fields. However, terahertz metasurfaces still face technical bottlenecks and challenges, and in the future, they can also be combined with the current popular artificial intelligence and interdisciplinary research to achieve breakthroughs.

This article focuses on the innovative breakthroughs of terahertz metasurfaces in the past five years, using a two-dimensional analytical framework of "design manufacturing-function realization". The paper aims to summarize the future development trends and research directions of terahertz metasurfaces, providing ideas and references for further research in related fields.

2 PROGRESS IN TERAHERTZ METASURFACE DESIGN

Conventional static materials have problems such as high loss and limited adjustable parameters in the

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terahertz band. Therefore, improvements are needed in two directions: optimizing static metamaterial surfaces and developing dynamic metamaterial surfaces. This article will specifically analyze how core design drives the performance improvement of terahertz metasurfaces from three dimensions: material innovation, structural design breakthrough, and manufacturing technology progress.

2.1 Material Innovation

2.1.1 Static Materials

Static materials refer to those whose electromagnetic properties remain unchanged under external stimuli such as electric fields, magnetic fields, or light. Early studies relied on metallic materials such as gold and aluminium and dielectric materials such as silicon and titanium dioxide, but the loss of materials and structures and the frequency dependence limited the ability to control.

To overcome these issues, Li et al. modified silicon wafers with monolayer gold nanoparticles (AuNP/AuNR) and found that the modulation depth of terahertz waves reached 10-20 times that of bare silicon, and the modulation rate was 8 times that of silicon-based (Li, 2021). When modulating the phase of terahertz waves with a mixture of gold nanoparticles and toluene through laser irradiation, the tunable bandwidth of (0.3-1.5 THz) was superior to that of conventional liquid crystal technology. It has been demonstrated that a new system composed of static materials and other materials can also optimize the performance of terahertz wave regulation. Therefore, static materials still have significant value in future terahertz metasurface studies.

2.1.2 Dynamic Tunable Materials

A single regulation method is difficult to meet the demands of complex scenarios, while dynamic tunable materials such as graphene, phase change materials (like VO_2), and liquid crystals have opened up new paths for real-time dynamic regulation and multi-functional integration of terahertz waves.

In recent years, many researchers have proposed that the combination of different static materials to form terahertz metasurface materials can enhance the performance of functional devices. Chen et al. designed a terahertz metasurface based on four materials: metal, VO2, graphene, and polyimide, combining the dynamic complementary properties of graphene (electrically modulated) and VO_2 (thermally modulated) to break through the limitations of a single regulation method (Chen et al., 2024).

A wide-angle stabilized terahertz tunable metasurface absorber based on liquid crystal material designed by Jing et al. The absorption frequency band and efficiency can be adjusted in real time by changing the alignment direction of liquid crystal molecules with an applied electric field and adjusting their equivalent dielectric constant (Jing et al, 2023). These dynamic tunable materials have unique physical and chemical properties that allow them to undergo significant performance changes under external stimuli (such as light, electricity, heat, etc.). It can be seen that graphene is more suitable for rapid regulation of high-frequency terahertz waves, VO2 is better for thermal drive regulation, and liquid crystals are more advantageous in low-power electronic control scenarios. The complementarity of the three expands the application boundaries of dynamic regulation.

2.2 Breakthrough in Structural Design

The traditional symmetrical resonant structure has a single function and limited bandwidth. The new structure design breaks through the physical boundaries of electromagnetic control through multi-degree-of-freedom, asymmetric, and dynamic reconfigurable units.

Gradient phase metasurfaces achieve efficient wavefront control through non-uniform element arrangement to generate vortex beams and achieve abnormal refraction; The multi-resonant coupling structure (nested, fractal geometry) excites multiple electromagnetic modes, broadens the working bandwidth and enhances the field localization effect; Tunable mechanical metasurfaces change cell parameters in real time by stretching/folding the flexible substrate, giving dynamic beam scanning capabilities.

Kou et al. summarized a variety of typical structures in the paper (Kou et al., 2019): 1. Metal resonant structures (such as open ring, H-shaped, cross-shaped, etc.) that achieve phase modulation through geometric symmetry breaking; 2. Dielectric-type structures (such as silicon columns, dielectric block) that utilize the dielectric-resonant effect to reduce ohmic loss; 3. Composite structures (metal-dielectric multilayer stacking, tunable material integration) combined with dynamic materials (such as graphene, VO_2) to achieve electrical/optical/thermal control dynamic response. The design approach emphasizes the combination of parameter optimization and full-wave simulation, satisfying a specific phase distribution by adjusting the size, shape, and arrangement gradient of the elements. In addition, to address the high loss challenge in the terahertz band, it is proposed to use a low-loss dielectric substrate and optimize the structural topology to improve efficiency. Song et al. used bilayer graphene stacks to form chiral "helical" or "Z-shaped" nanostructures, and by adjusting the Fermi level and relaxation time of the graphene, they were able to achieve dynamic control with higher circular dichroism values (more than 25%) (Song et al., 2024). Cheng et al. constructed metasurfaces using metal open rectangular ring units to efficiently control vortex electromagnetic waves in the terahertz or microwave band, achieving phase modulation by changing the structural size, with the highest mode purity reaching 90% (Chen, 2023). These designs emphasize the combination of parameter optimization and full-wave simulation, and the future trend is multi-functional integration and intelligent dynamic control. Although current polarization control devices have demonstrated excellent bandwidth and functional integration performance, there is still room for improvement in response speed, control efficiency, and device integration, which limits their widespread application in high-performance terahertz systems.

2.3 Advances in Manufacturing Technology

At present, large area nano-metasurface devices are difficult to process and costly, and

Low-cost nano-fabrication technology has become the focus of research.

Xu et al. This process has excellent performance in terms of selectivity and etching rate, with less undercutting and less damage to the material (Xu et al., 2024). Moreover, it is a clean process with high wafer etching volume, easy mask removal, and the ability to produce three-dimensional complex structures with high precision. Choi et al. 's silicon and aluminum metasurfaces were fabricated using NIL's nanolithography and 3D pattern transfer capabilities, respectively, achieving nanoscale line width uniformity, sub-200 nm translation coverage accuracy, and <0.017 rotational alignment error, while significantly reducing manufacturing complexity and surface roughness (Choi et al., 2024). This method is suitable for the scalable production of large-area functional structures for ultra-compact optical, electronic, and quantum devices.

Femtosecond laser micro-nano processing technology, as a non-contact technique, has great potential for application in the fabrication of flexible electronic devices due to the combined advantages of high peak power and low thermal effect of femtosecond lasers, high processing accuracy, strong controllability, high efficiency, and high integration (Wang et al., 2024). Yin et al. proposed a three-dimensional print-based ultra-sensitive terahertz (THz) sensor composed of periodically arranged strip-shaped metamaterials with a high sensitivity of 325 GHz/RIU, which can be produced through a simple three-step manufacturing process and is suitable for detecting a variety of analytes (Yin et al., 2022). It demonstrates the advantages of 3D printing in terms of process and design freedom to a certain extent.

Emerging manufacturing technologies are constantly innovating in response to existing problems. Reactive ion etching, nanoimprint technology, femtosecond laser micro-nano processing, and 3D printing have improved the manufacturing level of terahertz metasurface in various aspects, while also noting that technology migration can provide more possibilities for development.

3 BREAKTHROUGHS IN FUNCTIONAL REALIZATION

Based on the material and structural innovations mentioned earlier, terahertz metasurfaces have made a leap from "passive static" to "active reconfigurable" in electromagnetic wave control capabilities. This section will elaborate on its core breakthroughs in wavefront control, polarization modulation, spectrum control, and dynamic tunability, and show how these functions are achieved through underlying design innovations.

3.1 Wavefront Control

Phase control is the core of wavefront manipulation, and metasurfaces achieve precise control over the direction and mode of terahertz wave propagation through geometric phase (PB phase) and gradient phase design.

In the field of orbital angular momentum (OAM) generation, the directivity controllable OAM vortex beams generator designed by Li et al. uses metasurface and helical phase plates to efficiently generate high-order OAM modes in 0.1- 1 THz and supports dynamic direction adjustment (Li et al., 2024). Xie et al.'s (2023) silicon-based vortex beam chip enables the generation and control of circularly polarized vortex waves (topological charge ±1) through topological charge regulation. Since the Bessel beam was proposed, it has received a lot of attention due to its unique anti-diffraction and anti-disturbance capabilities, and has become a hot topic in the study of non-diffractive beams (Li et al., 2024). Terahertz Bessel beams can also be generated through metasurfaces. To meet the requirement of diffraction-free transmission, Yu et al.'s (2023) double-conical axial pyramid structure extended the diffraction-free distance of terahertz Bessel beams to 110m, and Yang et al.'s (2023) dispersive-regulated metasurfaces enabled long-distance colimation transmission in the 0.3-1.0 THz band, solving the diffraction limitation of traditional Gaussian beams. The focusing of terahertz waves relies on lenses. Compared with traditional optical lenses, planar metasurface lenses are thinner and lighter in weight, which is conducive to the miniaturization and integration of imaging systems (Fu et al., 2020). Ma et al.'s (2022) all-dielectric double-sided lens, which is only 500μm thick, focuses 1THz waves to a wavelength-level spot, increasing the electric field energy density by 44 times. Wang et al.'s (2021) graphene metasurface lens enables reconfigurable switching focusing over a wide frequency range with a focal length accuracy of 2.03mm (preset 2mm) and a spot half-peak width of 0.196mm, promoting the miniaturization of imaging systems. Terahertz metasurfaces have also made a breakthrough in holographic imaging. In 2022, Dong et al. (2022) proposed a terahertz metasurface composed of vanadium dioxide C-ring resonators and pure gold C-ring resonators, which presents different holograms at different temperatures. Zhang's (2023) high-resistance silicon rectangular column structure, which addresses the ohmic loss and low polarization efficiency of metal metasurfaces, uses Mie resonance and waveguide effects to achieve wavefront control for transmission-based holography.

Metasurfaces have achieved breakthroughs in the generation of OAM for terahertz waves, the generation of Bessel beams, focusing, and holographic imaging. By effectively controlling the wavefront through various structural designs, they have promoted the development of related applications.

3.2 Polarization Modulation Class

Terahertz polarization is mainly divided into linear polarization and circular polarization. Linear polarization has the advantage of being direction-sensitive and easy to control, while circular polarization has the advantage of strong anti-interference ability and uniform penetration. In recent years, to meet the different application requirements of various scenarios, the conversion between linear polarization and circular polarization has been necessary.

Tao's (2023) metal wire-grid-" Z "structure metasurface achieved wire-circular and wire-linear polarization converters in the 0.34-0.48 THz and 0.53-0.85 THz bands, respectively, for the first time, integrating both functions into a single device. Chen et al.'s (2025) liquid crystal birefringence modulator enables dynamic programmable control of linear/circular polarization in 1.6- 3.4 THz, breaking through the narrowband limitations of traditional devices. In contrast, linear polarization is suitable for direction-sensitive scenarios, circular polarization is better for anti-interference penetration, and multifunctional integration meets the application requirements in complex environments.

3.3 Spectrum Control

Spectrum control, which encompasses filtering and absorption, is crucial for terahertz devices to achieve signal filtering and energy management.

In terms of filter design, Wang et al. 'S multi-layer S-shaped structure filter improves performance through the superposition principle, with a modulation depth of -62 dB, bandwidth extended to 1.24 THz, and Angle insensitivity (Wang, 2023). The development of filters has evolved from single-stop narrowband to wideband, multi-band, and adjustable to meet the demand for wideband signal processing in communication and sensing.

In the innovations of absorbers, narrowband absorption (the perfect absorber) is a direction. Bai et al. 's water-based graphene absorber achieves temperature control/electric control dual tuning with absorption rate > 99% at multiple frequency points within 0-3.5THz (Bai, 2022). Li's (2023) "sandwich" structure absorber achieved broadband absorption of 1.1THz at 1.33- 2.43THz (average 95.1%), and improved sensitivity through temperature control after replacing VO_2 (0.0194/K). The graphene /VO_2 metamaterial absorber designed by Guo & Dong (2025) achieved an ultra-wideband of 6.35 THz (90% absorption rate) and a modulation depth of 99% with both polarization insensitivity and wide-angle compatibility; In the field of wideband absorption. Bindal et al. 's graphene fractal metasurface absorber has an absorption rate of over 90% in 1.2- 4.6 THz, supporting Fermi level tuning and wide-angle incident (Bindal et al., 2025).

Spectrum control is constantly innovating in filters and absorbers, evolving from narrowband to wideband, adjustable, to meet the diverse requirements of terahertz devices for signal filtering and energy management.

3.4 Dynamic Tunable Function

Dynamic control is at the core of achieving smart devices, and current research is focused on multi-physical field excitation methods such as electric control and photothermal control.

In the direction of electronic control tuning, Wang et al. (2023) proposed that dynamic tunable metasurfaces, through a multi-physics field regulation mechanism, break through the static limitations of traditional devices and demonstrate transformative potential in fields such as imaging, communication, and sensing. Zhang et al. (2025) proposed the design of L-shaped terahertz metasurface based on Dirac semimetal (DSM), achieving dynamic optical tuning through the electronically controlled Fermi level (0-0.3eV), with a reflectance adjustable range of 80% within the 1.2-2.8THz range and high sensitivity sensing characteristics (0.075THz/RIU). Wan et al. (2025) designed a graphene-based five-peak terahertz metamaterial absorber, which achieved dynamic tuning (absorption rate 70%-99%) by adjusting the graphene Fermi level (0-0.8eV) and enhanced sensing sensitivity (0.032THz/RIU) with five resonant peaks (1.2/2.1/3.0/3.8/4.5THz). This absorber is thus suitable for high-precision terahertz sensing detection.

In the direction of photothermal tuning, Dong (2023) Designed dynamic tunable terahertz metasurface based on photothermal phase change materials (silicon/indium antimonide /VO_2), achieving polarization conversion (efficiency 97%), absorption (>90%), and wavefront shaping (vortex light/hyperlens) function switching through light/thermal regulation, achieving full-space optical switching effect within the range of 0.6-1.15THz. It provides new ideas for the development of multifunctional tunable terahertz devices.

The dynamic tunable function, achieved through electronic control, photothermal control, etc., provides a direction for the development of terahertz smart devices and shows great application potential in multiple fields.

4 CONCLUSIONS

This paper summarizes the key progress of terahertz metasurfaces in core design and functional realization. In terms of materials, traditional static materials can achieve efficient terahertz wave modulation through optimized design, while dynamic tunable materials (such as graphene, liquid crystals, phase change materials) have become a key development direction for the present and future due to their real-time regulation capabilities and multi-functional integration characteristics. In terms of structural design, the bandwidth limitations of terahertz devices have been effectively broken through by multi-resonant coupling mechanisms, gradient phase distribution, multilayer stacking, and spatial multiplexing strategies, achieving wideband/multi-band response characteristics. In terms of processing technology, electron beam lithography combined with reactive ion etching can produce three-dimensional complex structures with high precision, nanoimprint technology significantly reduces the cost of mass production, and femtosecond laser direct writing expands the processing capability of non-planar substrates. 3D printing and additive manufacturing technologies, through rapid prototyping, not only shorten the R&D cycle but also promote the application of metasurfaces in emerging fields such as flexible devices and biosensing. It enables dynamic tunable metasurface technology to achieve real-time tuning and multi-functional switching based on optical, electrical and thermal excitation. The speed of dynamic adjustment of amplitude, phase and polarization mode has broken through the microsecond level. These breakthroughs provide key technical support for applications such as terahertz wavefront control, imaging communication, and intelligent perception, and will continue to move towards dynamic reconfigurability, intelligence, and multi-functional integration in the future.

It should also be noted that there are bottlenecks in the current development of terahertz metasurfaces, such as manufacturing accuracy and cost issues. How to strike a balance between the two requires further development of low-cost manufacturing processes, dynamic control response speed and stability, and the power consumption of existing dynamic metasurfaces still needs to be optimized. Also, how to achieve seamless integration of metasurfaces into existing terahertz systems remains to be broken through. It is also necessary to better translate the research results into application fields. Such as 6G communication, security imaging and non-destructive testing, biomedical sensing. Future directions include: developing intelligent metasurfaces with multi-physics field collaborative control by combining artificial intelligence with reverse design methods; Exploring new functional material systems such as two-dimensional and supramolecular materials; Developing reconfigurable metasurfaces and adaptive control technologies, and promote the in-depth application of terahertz technology in communication, sensing, imaging and other fields.

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