

# ***Matamaterial Development for Terahertz Absorber with Dynamic Tunable Property***

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**Abstract:** Typical metamaterials which could achieve dynamic tunable property of terahertz absorption such as VO<sub>2</sub>, STO and graphene were reviewed. VO<sub>2</sub>, STO, Graphene are typical terahertz dynamic tunable absorbing metamaterial. Their unique optoelectronic properties can alter the properties of the material itself under changing external conditions, thereby achieving dynamic modulation of absorbed terahertz waves. The reasons of metamaterials could be used as terahertz dynamic absorbers were analyzed from the aspects of lattice structure, material properties, and electrical properties. The adjustable properties of each of the three materials and the external conditions required for tunable properties were explained. Simultaneously demonstrate the structure of metamaterials composed of three materials and their respective terahertz absorption properties. The advantages and disadvantages of three materials as terahertz dynamic absorbers were analyzed and discussed. The future development of three materials as terahertz dynamic absorbers was discussed, and the challenges and development of metamaterials in terahertz absorption dynamic modulation were reviewed.

**Keywords:** Metamaterial, Terahertz Wave-absorption, Tunable

## **1. Introduction**

Terahertz (THz) band is located between microwave and infrared spectral ranges and is at the forefront of interdisciplinary research connecting electronics and photonics. Terahertz wave with low photon energy, wide band spectrum, and strong penetration ability is attracting interests in information application and communication technology[1], biomedical imaging[2], genetic diagnostics, food and agricultural quality inspection[3], and national defense security[4]. With the development of high-power wave sources and high-sensitivity detector technology, terahertz wave source technology and detection technology have gradually matured, while the development of terahertz functional device technology is still relatively slow, such as terahertz absorbers, modulators, filters, etc. In the applications of terahertz, there is an urgent need for broadband high absorption electromagnetic absorbers to eliminate electromagnetic pollution, suppress electromagnetic interference, reduce radar cross section, and improve information security. As a key part of terahertz wave technology, terahertz absorber technology must be improved. The electromagnetic response generated by the interaction between natural materials and terahertz waves is weak, which is the fundamental reason affecting the development of effective terahertz wave absorbers. By natural

materials, The issue of weak electromagnetic response is hard to be solved and limits the absorption of terahertz waves.

After restless research and development, The artificial composite material was conducted and the test showed these material could exhibit a strong electromagnetic response in interaction with terahertz waves. These artificial composite materials were named as metamaterials[5]. The discovery of metamaterials extremely accelerate the development to terahertz absorbers. Metamaterial is a type of artificially synthesized electromagnetic materials with periodic structure. Metamaterial devices has been gradually applied in terahertz band due to their strong responses to terahertz (THz) waves. The special extraordinary electromagnetic properties of metamaterial aompletely surpassed the natural substances. Metamaterials overcome the weak interaction between natural materials and terahertz waves, and have effective control of terahertz waves[6]. In addition, metamaterials have other superior characteristics, such as negative refractive index and ultra-high refractive index[7], electromagnetic induced transparency, and inverse Doppler effect[8]. By utilizing metamaterials, various structures of terahertz absorbers can be realized, even enabling dynamic tuning of terahertz absorption.

Lin et al. prepared a dynamic terahertz metamaterial based on vanadium dioxide ( $\text{VO}_2$ ). The top layer consists of four identical  $\text{VO}_2$  resonators. A dielectric continuous metal substrate layer is made to support the resonators. Based on the unique phase transition property,  $\text{VO}_2$  can achieve adjustable functionality through thermal control[9]. Wu and his colleagues developed an actively tunable terahertz absorber using single - layer graphene. By adjusting the Fermi energy ( $E_f$ ) of graphene, this absorber demonstrates excellent adjustability[10]. Cheng and his team designed a temperature - regulated dual - frequency terahertz metamaterial absorber (MMA). This absorber is based on a resonator structure made of strontium titanate (STO), whose absorption performance can be altered by changing external temperature of MMA[7].

However, though metamaterials are feasible for dynamic modulation of terahertz wave absorption and has broad application prospects, its special properties deserve further exploration and exploration. This article introduces the material selection, device structure, and modulation methods for dynamic modulation of terahertz absorption using metamaterials, and looks forward to the challenges and development of metamaterials in terahertz absorption dynamic modulation.

The structure of the paper is organized into several sections, including introduction, design and fabrication methods, analysis the challenges, solution and conclusion. Introduction shows the basic background of tunable terahertz absorbers based on metamaterials. Design and fabrication methods is related to different design and fabrication techniques used in manufacturing terahertz metamaterials and dynamic terahertz absorbers. Analysis explains the advantages and challenges of the mainly metamaterials used in the production of dynamic terahertz absorbers. Conclusion would summarize the whole essay.

## 2. Design and Fabrication

Metamaterials are artificial engineering composite materials composed of regularly aligned subwavelength unitcells. These materials exhibit extraordinary electromagnetic properties that are not found in natural materials. Due to their significant electromagnetic properties, metamaterials have become a hot topic in various fields. Metamaterial devices have attracted widespread attention due to their strong response to terahertz waves. Since Randy proposed the first perfect metamaterial absorber [11], many devices have been explored, including absorbers, filters, and converters[12]. In recent years, significant progress has been made in the research of terahertz metamaterial absorbers[13]. The operating range has progressively extended to the microwave, terahertz, infrared, and visible light regions, and the absorption mode has changed from single band to multi band. Conventional terahertz metamaterial absorbers are passive and difficult to operate; the absorption performance is

unchangeable once the structure is fixed. Dynamic tunable terahertz metamaterial absorbers in conjunction with active materials have been extensively constructed and investigated as a solution to this problem. These days, different kinds of functional materials are added to structures, and different stimulation techniques are employed to change the terahertz band's absorption characteristics.

Vanadium dioxide is a reversible phase change material. At room temperature it is at insulating phase. When temperature reaches 67 °C, it becomes a material at metallic phase. When temperature rises, usually reaching 340 K, its lattice structure changes from monoclinic to tetragonal. Vanadium dioxide has a high absorption rate in the terahertz region, which allows it to absorb incident terahertz wave energy and show important electromagnetic response due to its lattice and electronic band structures.

Strontium titanate (STO) material is one of the widely used dielectrics because it has the ability to integrate passive components into modules and can be easily miniaturized LTCC technology. STO has special qualities like exceptional chemical stability, high dielectric constant, low dielectric loss, and excellent insulation. The most attractive feature of STO is high dielectric constant. The dielectric constant of STO can be dynamically adjusted by changing the external ambient temperature, which can be applied to dynamic tunable devices in the terahertz range. Therefore, due to its excellent performance, STO can be considered a potential candidate material for designing adjustable MMA. However, these adjustable MMA based on STO materials typically require units with complex sandwich structures, which increases manufacturing difficulty and cost. Therefore, the large-scale application of STO based MMA is also limited by complex manufacturing geometries and high costs.

Graphene is a two-dimensional material composed of a single layer of carbon atoms stacked together. By changing the Fermi level of graphene, its conductivity can be altered. As a material with tunable property, graphene exhibits ultra-high charge mobility in an ideal state. The Fermi level of graphene can be tuned continuously by technique such as doping or the application of external bias voltage. This allows changes of the surface conductivity, making the development of graphene-based metamaterial absorbers adjustable.

### 3. Analysis and Challenge

#### 3.1. VO<sub>2</sub>

Vanadium dioxide (VO<sub>2</sub>) belongs to the category of phase - change materials. When the temperature generally reaches approximately 340 K, it experiences a lattice structure transformation from monoclinic to tetragonal. This lattice - structure alteration is a distinct feature of VO<sub>2</sub> as a phase - change material. During this process, VO<sub>2</sub> shows a transition from an insulating state to a metallic state [14]. Song et al. reported a wide-angle absorber based on VO<sub>2</sub>, which has adjustable intensity and bandwidth. Its broadband absorption rate can achieve 90% through four square vanadium dioxide coplanar rows [15]. To overcome the existing challenges, VO<sub>2</sub> needs to be patterned to achieve various structures such as slot resonator. As shown in Figure 1, a patterned slotted VO<sub>2</sub> absorber is designed. Employing patterned vanadium dioxide (VO<sub>2</sub>) to improve the impedance matching between the absorber and free space can boost absorption and broaden the spectrum. This structure makes use of the phase - transition properties of VO<sub>2</sub> to realize tunability within the terahertz band. The three-dimensional structure of the absorption tank is shown in Figure 1 (a), which is a three-layer structure. The top layer consists of a patterned slotted VO<sub>2</sub> resonant layer. The middle layer is a Topas dielectric layer, and the bottom layer composed of a metal ground plane with specific conductivity. Figure 1 (b) shows the top view of the device. The entire absorption structure is arranged periodically along the x and y directions, as shown in Figures 1 (b) and 1 (c) [16].

VO<sub>2</sub> can be a potential tunable absorbent based on its regulated conductivity. VO<sub>2</sub> has high sensitivity to temperature changes, and the conductivity of VO<sub>2</sub> can be indirectly manipulated by

adjusting the temperature. This provides a method for continuously adjusting the absorption rate of absorbers, which is a capability that metal structure absorbers cannot achieve. As shown in Figure 1 (d), when the conductivity of VO<sub>2</sub> increases, the absorption rate continuously tunes within the frequency band. These results indicate that the absorber is in a high reflection and low absorption state, basically functioning as a reflector. When the conductivity increases, the absorption amplitude gradually increases and the absorption bandwidth gradually expands[16].

VO<sub>2</sub> has unique electrical properties. It has phase transition characteristics, and its conductivity undergoes a sudden change of 2-5 orders of magnitude when the temperature changes. This characteristic makes it an intelligent absorbing material that can respond to temperature changes. Through temperature regulation, the absorbing performance can be "turned on" and "off", which can better adapt to complex and changing electromagnetic environments. VO<sub>2</sub> micronanorods/fibers and other structures have high dielectric constant and certain conductivity, and their rich defects also enhance the dielectric loss in absorption, thereby improving absorption performance. VO<sub>2</sub> has various shapes such as ribbon, sheet, spherical, rod-shaped, and fibrous. By designing different shapes such as three-dimensional flower, star, hollow sphere, or nanowire, multiple reflections and scattering of electromagnetic waves at material interfaces can be increased, further improving absorption performance and control ability, reducing VO<sub>2</sub> loading and composite material density. However in some cases, when VO<sub>2</sub> is used as a functional filler, its filling rate in the matrix is relatively high, and the thickness of the absorbing composite material is also large, which is not conducive to practical applications. Some VO<sub>2</sub>-based intelligent absorbing composite materials cannot shut down the entire frequency band, and there are still some effective absorption bands that can affect the signal reception and transmission of wireless communication.

However, VO<sub>2</sub> also has disadvantages when used as a terahertz absorbing material. Its phase transition conditions is limited. Vanadium dioxide requires specific conditions such as temperature, electric field or light irradiation to trigger phase transition. In practical applications, it is rather complicated to precisely control these conditions, which will increase the complexity of the system and energy consumption. The absorption bandwidth of VO<sub>2</sub> is limited. Although the absorption bandwidth can be broadened through structural design and other means, within the terahertz band, its absorption bandwidth is still not ideal enough to cover a wide frequency range, thus restricting its application in wideband terahertz devices. VO<sub>2</sub> did not show sufficient stability. Under long-term use or in specific environments, the structure and properties of vanadium dioxide might change, resulting in a decline in its absorbing performance. Moreover, the repeated expansion and contraction during the phase transition process will cause stress accumulation in the material, affecting the structural integrity and performance stability. The preparation of high-quality vanadium dioxide thin films requires complex processes such as molecular beam epitaxy and magnetron sputtering. These processes are costly and have low yields, making it difficult to achieve large-scale production. In addition, strict control of process parameters is needed to ensure the uniformity and consistency of material properties, which increases the difficulty and cost of preparation. Vanadium compounds are somewhat toxic and harmful to human beings and the environment. During the production, use and disposal processes, strict protective and environmental protection measures need to be taken to prevent adverse impacts on human health and the ecological environment. Therefore, in order to achieve tunable terahertz absorbers with simple modulation conditions, high stability, large absorption bandwidth, and simple preparation processes, it is necessary to study new metamaterial systems to replace VO<sub>2</sub> and solve the limitations of vanadium dioxide materials.

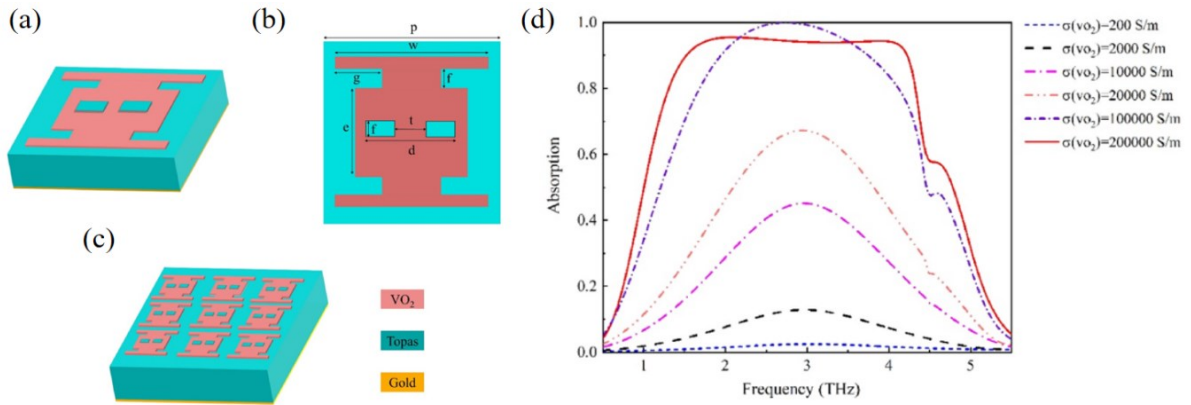


Figure 1: A schematic representation of the proposed absorber along with its geometric details is presented. (a) The schematic diagram of the unit-structure. (b) The top - view of the unit - structure. (c) The periodic structure. (d) Absorption spectra of VO<sub>2</sub> absorbers with varying conductivities [16].

### 3.2. STO

In the terahertz band, the dielectric property of the STO material is influenced by the environmental temperature [17]. The complex relative permittivity can be described using the damping harmonic oscillator model for bulk STO materials. The real and imaginary components of the relative dielectric constants ( $\text{Re}(\epsilon)$  and  $\text{Im}(\epsilon)$ ) of STO materials change with various ambient temperatures. As depicted in Figure 2, the  $\text{Re}(\epsilon)$  value of the STO material steadily declines as the ambient temperature  $T$  rises [18]. However, within THz frequency the  $\text{Re}(\epsilon)$  of the STO material changes slightly. In the lower frequency range, the magnitude of  $\text{Im}(\epsilon)$  has almost no changes when the temperature increases as shown in Figure 2(a). As the frequency shifts to the higher - frequency range, the imaginary part of the relative permittivity ( $\text{Im}(\epsilon)$ ) rises rapidly with the increase in frequency. Meanwhile, the other part (presumably referring to some aspect related to the material's permittivity characteristics) drops sharply as the temperature changes. These findings demonstrate that the complex relative permittivity of STO materials is highly sensitive to variations in ambient temperature. It suggests that the potential application prospects in temperature adjustable THz integrated devices by using STO materials. Meanwhile, due to the large  $\text{Re}(\epsilon)$ , STO materials can be a good candidate for designing large subwavelength THz devices. The structural design of STO materials can also respond to THz waves at different environmental temperatures.

Figure 2(b) presents the reflectance and absorbance spectra of the designed metamaterial terahertz absorber at a temperature of 300 K. There are two distinct resonance points visible. At these resonance points, the reflectance of the absorber diminishes. It almost achieves a perfect absorption at terahertz range[18].

STO has high dielectric constant. This property enables it to interact effectively with electromagnetic waves and cause significant dielectric loss, which helps in absorbing the incident electromagnetic energy. STO is chemically stable. It can resist corrosion and chemical reactions in a wide range of environments. This stability ensures that its wave absorbing performance remains relatively consistent over time and in different chemical surroundings. It shows good temperature stability to some extent. The wave absorbing performance of STO does not change drastically with normal temperature fluctuations, which is beneficial for applications where the temperature may vary. However STO has a relatively high density. This can be a drawback when considering lightweight requirements for many applications such as in aerospace or portable electronic devices. High density materials may increase the overall weight of the device or structure where the wave - absorbing material is used. The effective wave absorbing frequency range of STO may be relatively narrow. It

may only work well in a specific frequency band and may not provide efficient absorption across a wide range of frequencies. This limits its versatility in applications where a broad spectrum wave absorbing material is needed.

STO materials needs complex preparation and high cost. Usually, it is necessary to grow crystal films on hard substrates and regulate the dielectric constant. It has strict requirements for instruments and experimental conditions, and the process is time-consuming and laborious, which leads to increased costs and is not suitable for large-scale production. The prepared metasurfaces are limited by the thickness of the substrate, usually on the order of millimeters or even centimeters, which is not conducive to the lightweight and integration of the system and it is difficult to meet the needs of efficient regulation and highly integrated equipment. Generally, good absorption effects can only be achieved within a specific frequency range when using STO as terahertz absorbing materials, and it is difficult to achieve effective absorption in the entire terahertz frequency band for electromagnetic waves.

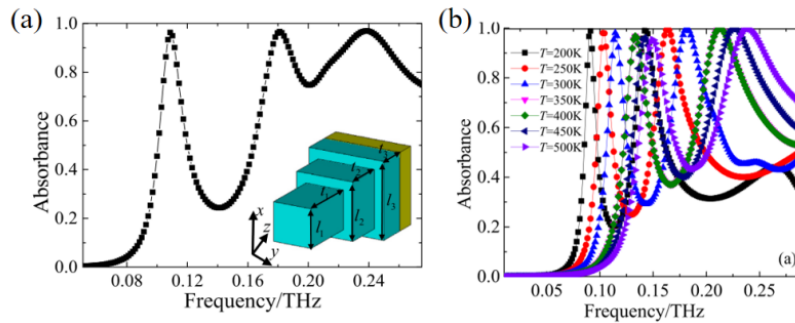


Figure 2: (a) The absorbance spectra simulated for the triple - band MMA that is based on the tri - layered STO material are presented. The inset displays the single unit - cell structure, where the axis indicates the propagation direction. (b) The absorbance spectra of the designed MMA under different temperatures are shown [18].

### 3.3. Graphene

Graphene has attracted extensive research attention as an absorbent due to its excellent performance in the terahertz range. The Fermi level ( $E_f$ ) of graphene can be dynamically tuned, and its electrical properties can be altered through the application of a bias voltage. An actively tunable terahertz absorber can be fabricated using a single - layer graphene. This absorber is composed of a layer of graphene, an optical crystal plate, and a gold substrate. These components are separated by a layer of photonic crystal plate. The top view and structural diagram of the absorber are shown in Figure3(a)[19].

Graphene has excellent  $E_f$  tuning performance, and the influence of graphene  $E_f$  variation on absorption spectra is shown in Figure 3 (b). It can be seen that when  $E_f$  increases, the absorption spectrum shifts blue and the position of the absorption peak changes. The absorption peaks of absorber shift when the  $E_f$  of graphene is increased. The findings show that when the  $E_f$  is altered, the absorption peaks will shift to varying extents. Correspondingly, both the high - absorption range and the absorption peak will undergo changes [20].

Graphene has limitations in the field of terahertz absorbing materials. Graphene only shows good absorption effect in a single frequency band, and it is difficult to meet the absorption requirements of multiple frequency bands, which greatly limits its use in multi-frequency application scenarios in the terahertz frequency band. The preparation of high-quality graphene requires complicated processes and advanced equipment, such as the chemical vapor deposition method, resulting in high costs, which is not conducive to large-scale application and promotion. Moreover, when graphene is

transferred onto substrate materials, problems like wrinkles, defects and interface contamination are prone to occur, affecting its binding force with the substrate and electrical properties, and further reducing the absorption efficiency of terahertz waves. The electrical and optical properties of graphene are easily affected by environmental factors. At present, the large-scale production technology of graphene is not mature enough to achieve the stable production of high-quality, large-area and well-uniform graphene, thus limiting its application as terahertz absorbing materials in large-scale projects.

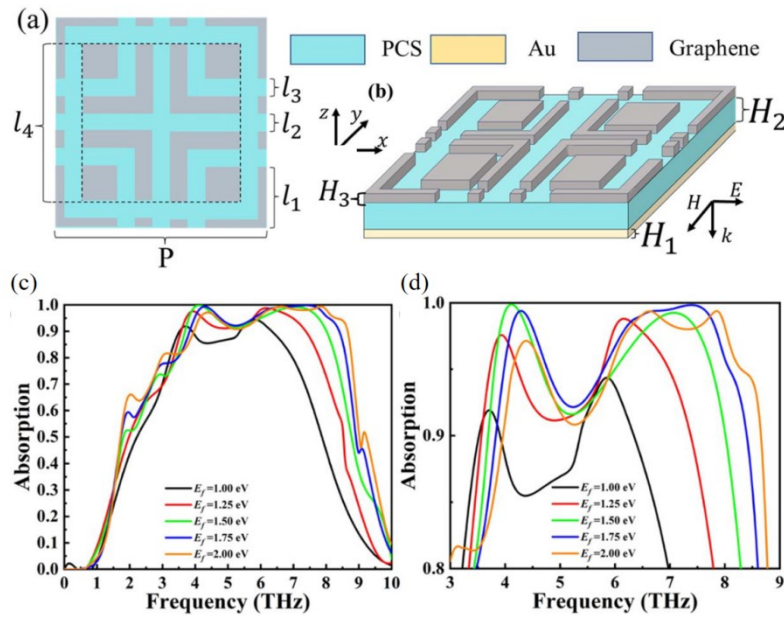


Figure 3: (a)The plane of the absorber and (b) a structural drawing of the absorber; (c) Absorber characteristics  $E_f$ .(d) Partially enlarged view of (c) [19].

#### 4. Summary & Suggestion

Table 1: Comparison of different tunable terahertz absorber

Type	Advantages	Disadvantages
VO <sub>2</sub>	-Absorbing wave advantage brought by phase change characteristics -Strong tunability -Good chemical stability	-Limitations of phase transition conditions -Limited absorption bandwidth; Insufficient material stability -High requirements for preparation process -Toxicity issues
STO	-Good dielectric property -Chemical stability -Temperature stability	-Complex preparation and high cost; - Limited integration -High density -Narrow frequency range
Graphene	-High wave absorbing performance -Broadband absorption characteristics -Stable physical and chemical properties; Strong adjustability.	-High difficulty in large-scale preparation -Poor bonding with the matrix -Great influence of factors such as thickness

The comparison of different tunable terahertz absorber was shown in Table 1.

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Graphene has a unique two-dimensional crystal structure, which can have a strong interaction with terahertz waves and has a high absorption rate of terahertz waves. It can effectively absorb electromagnetic waves within a relatively wide terahertz frequency range, enabling it to deal with terahertz waves of various frequencies. Graphene has good chemical stability and strong corrosion resistance. It can also maintain good performance under different physical environments (such as changes in temperature and humidity), which is beneficial for its use under complex conditions. By changing the electrical parameters of graphene (such as doping, applying an external electric field, etc.), the absorption frequency and intensity of terahertz waves by it can be adjusted, and it can flexibly meet different wave-absorbing requirements. However, the large-scale preparation technology for high-quality graphene still faces challenges, and the cost is relatively high, which restricts its wide application as a terahertz wave-absorbing material to some extent. When graphene is compounded with other material matrices, the problem of interfacial bonding between it and the matrix is relatively prominent, which may affect the overall performance of the wave-absorbing material. The wave-absorbing performance of graphene is relatively sensitive to factors such as its thickness and number of layers. Minor changes may lead to significant differences in the wave-absorbing effect, and it is rather difficult to precisely control these factors in practical applications.

## 5. Conclusion

VO<sub>2</sub>, STO, Graphene is a typical terahertz dynamic tunable absorbing metamaterial. Their unique optoelectronic properties can alter the properties of the material itself under changing external conditions, thereby achieving dynamic modulation of absorbed terahertz waves. VO<sub>2</sub> is a reversible phase change material that can undergo an adjustable transition between insulator phase to metallic phase. The transmittance of VO<sub>2</sub> to terahertz waves has a significant difference after phase transition, and the conductivity of vanadium dioxide can be adjusted by changing the temperature, thereby achieving active tunability of the absorber. By combining with unique absorption structures, broadband and dynamic terahertz absorbers can be achieved. The dielectric constant of STO, which is tunable, can be adjusted dynamically by modifying the external ambient temperature. Altering the ambient temperature allows for a change in the dielectric constant of STO, and this property can be utilized in tunable devices for terahertz absorption. The Fermi level of graphene can be adjusted continuously either by doping or by applying an external bias voltage. This provides the modification of the surface conductivity, making the development of graphene-based metamaterial terahertz absorbers adjustable. Analyzed and discussed the advantages and disadvantages of three materials as terahertz dynamic absorbers. The future development of three types of terahertz dynamic absorption materials was discussed.

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