

Reconfigurable EIT Metasurface with Low Excited Conductivity of VO₂

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Abstract: The active materials-loaded reconfigurable metasurface is a potential platform for terahertz (THz) communication systems. However, the requirements of the modulation performance and the modulation rate put forward the opposite requirements on the excited conductivity of active materials. In this paper, we proposed a concept for a metal-doped active material switch that can produce an equivalent high excited conductivity while reducing the required threshold of the active material conductivity, thus balancing the conflict between the two mutual requirements. Based on it, we designed a reconfigurable electromagnetically induced transparency (EIT) metasurface driven by a low excited conductivity of vanadium dioxide (VO₂), which can achieve the amplitude modulation and amplitude coding under the control of light and electric. Simulation results validate the role of the metal-doped VO₂ switch on the metasurface. This work provides a new scheme to mediate the contradiction between the modulation performance and the modulation rate in the requirement of active material's excited conductivity, which facilitates the development of new terahertz modulators based on reconfigurable metasurfaces. In addition, the concept of a metal-doped active material switch will also provide a solution to the limitations of active material from the design layer.

Keywords: reconfigurable metasurface; terahertz; metal-doped active material switch; low excited conductivity; vanadium dioxide



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1. Introduction

The terahertz (THz) band is an important part of the next-generation communication system because of its significant broadband characteristics [1,2]. Higher requirements on modulation performance and rate put higher demands on THz devices such as THz modulators [3,4]. A metasurface can directly change the transmission properties of an electromagnetic (EM) wave, which is a potential platform for novel communication systems [5–7]. By loading active material switches onto the unit cell, a reconfigurable metasurface can actively control THz waves [8], resulting in important applications in coding communication [9,10], beamforming [11], and polarization control [12–14]. The significant conductivity changes of active materials can be excited by external stimuli, such as light [15], thermal [16], and electrical [17], which can be used to drive the modulation capabilities of reconfigurable metasurfaces.

For reconfigurable metasurfaces, the requirements of modulation performance [18] and rate [19] can be defined as the requirements for the excited conductivity of active materials. The higher THz wave modulation performance can be always supported by the higher excited conductivity. On the other hand, for active materials, the higher excited conductivity is caused by the higher free carrier density, which take a long time to return to the initial state [20]. It means that the fast modulation rate can only be supported by

the lower excited conductivity [21]. This, in turn, leads to a decrease in the modulation performance on the THz reconfigurable metasurface. Therefore, for current meta-devices, the THz wave modulation performance and rate are the two indicators that are difficult to achieve at the same time.

Vanadium dioxide (VO₂) is an interesting phase change material; it can phase transition from an insulator state to a metallic state with significant conductivity changes [22–25]. This phase transition process can be excited by light [26–28], heat [29–32], and current [33–36], which greatly enriches the external driving approaches of the reconfigurable metasurfaces. The maximum excited conductivity of the metallic state of VO₂ can reach 3×10^5 S/m [27], which is an order of magnitude higher than that of silicon, gallium arsenide, germanium, and their like. It brings better theoretical properties to reconfigurable metasurfaces and has facilitated many meta-device designs based on VO₂. However, VO₂ has various multioxidation states and polymorphic phases [37]; only insulating monoclinic VO₂ (M1) can be excited with the theoretical conductivity, which makes it difficult to prepare an ideal VO₂ (M1) film. In the preparation process, the presence of heterophases will reduce the excited conductivity of the film [38], so the measured VO₂ films in some studies have a lower excited conductivity [39].

Therefore, it is an urgent problem to find an approach to achieve high performance THz modulation based on low excited conductivity on a metasurface platform. Here, we proposed a metal-doped active material switch based on the equivalent concept and then designed a reconfigurable electromagnetically induced transparency (EIT) metasurface loaded with metal-doped VO₂ switches for amplitude modulation and amplitude coding. The required excited conductivity for the amplitude modulation function is an order of magnitude lower than that in theory. In addition, the designed metasurface supports a variety of external excitation approaches. The concept of doped switches and the proposed reconfigurable metasurface design will provide an interesting view for advanced meta-devices with high modulation performance and rate and contribute to the development of THz technology.

2. Theory and Design

The metal-doped active material switch, shown in the right section of Figure 1, consists of a metal patch and an active material patch with a coincident central area. In the equivalent circuit model, the metal patch will replace the excited VO₂ in the coincidence area and short-circuit its resistance. In this way, the equivalent conductivity of the entire switch σ_{quiv} can be increased, and the maximum conductivity of the active material σ_{VO_2} required for the reconfigurable metasurface design can be reduced. Since the VO₂ structure in the edge of the switch is not obscured, the doped switch can be excited by optical pump or current control in the specific design of the reconfigurable metasurface. The equivalent conductivity σ_{quiv} follows

$$\sigma_{quiv} = \frac{S_{switch} \times \sigma_{VO_2}}{S_{switch} - S_{dopedMetal}}, \quad (1)$$

where S_{switch} and $S_{dopedMetal}$ are the areas of the whole switch and doped metal patch, and σ_{VO_2} is the excited conductivity of VO₂.

In this study, because the metal-doped active material switch reduces the excited conductivity requirement of VO₂, the phase transition only needs to be carried out to the metallic state with a lower conductivity. In this process, the dielectric constant of metallic state VO₂ can be expressed as a Drude model

$$\varepsilon_{VO_2}(\omega) = \varepsilon_{\infty} - \frac{\omega_p^2(\sigma_{VO_2})}{\omega^2 + i\omega\gamma}, \quad (2)$$

where $\varepsilon_{\infty} = 12$ is the relative dielectric constant at the highest frequency, and $\gamma = 5.75 \times 10^{13}$ rad/s is the collision frequency. The plasma frequency $\omega_p(\sigma_{VO_2}) = \sqrt{\sigma_{VO_2}/\sigma_0} \times \omega_p(\sigma_0)$ is a function of VO₂ conductivity σ_{VO_2} with $\sigma_0 = 3 \times 10^5$ S/m and $\omega_p(\sigma_0) = 1.4 \times 10^{15}$ rad/s.

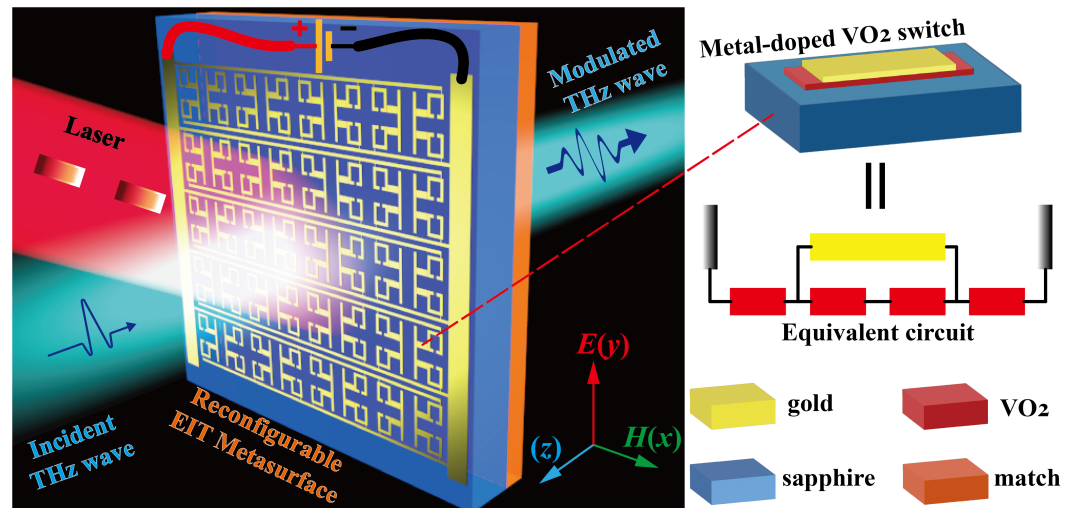


Figure 1. Schematic of the metal-doped active material switch concept and the reconfigurable metasurface.

Based on the metal-doped VO₂ switch, the designed reconfigurable metasurface driven by low excited conductivity is shown in the left section of Figure 1, which can realize the amplitude modulation of THz waves. The modulator consists of a composite array of artificial microstructures, a sapphire substrate, and a dielectric match layer. The dielectric match layer is attached to the back of the substrate surface to achieve the wave impedance matching on the back of the substrate so as to avoid the Fabry–Perot reflections in the substrate to interfere with the terahertz wave modulation in the operating band. The dielectric match layer is used for non-resonant broadband wave impedance matching, its relative dielectric constant is $\epsilon_{r\ match} = \sqrt{\epsilon_{r\ sapphire}} \approx 3.4$, the thickness is $h_{match} = \lambda_0 / (4 \times \sqrt{\epsilon_{r\ match}}) \approx 340\ \mu\text{m}$, and the material type is polyimide.

The artificial microstructure array, including a metal grid network, metal resonance patterns and metal-doped VO₂ switches, is printed on the front of the sapphire substrate to achieve THz wave modulation. Figure 2a shows the composite artificial microstructure design on the meta-atom. On the surface of a 500 μm thick sapphire, the composite artificial microstructure consists of a 200 nm thick metal resonance pattern and two metal-doped switches integrated with a 200 nm thick VO₂. The metal resonance pattern includes one cut wire resonator (CWR) and a pair of split-ring resonators (SRRs), and the resonant frequencies of these two components in the spectrum are 0.1563 THz and 0.15155 THz, respectively, as shown in Figure 2b,c. The metal pattern layout forms a “bright–dark modes coupling” system, which produces an EIT-like resonance mode as the initial resonance mode. Each metal-doped switch is connected to the CWR and SRR, its length along the Y-axis is smaller than the SRR, and it is flush with the open edge of the SRR, so as to realize the active control of the resonance mode and THz wave transmission properties of the unit cell surface. To achieve a deep amplitude modulation, the artificial microstructure parameters are optimized as follows: $p = 300\ \mu\text{m}$, $q = 450\ \mu\text{m}$, $s = 340\ \mu\text{m}$, $a = 110\ \mu\text{m}$, $b = 130\ \mu\text{m}$, $g = 2\ \mu\text{m}$, $d = 80\ \mu\text{m}$, and $w = 20\ \mu\text{m}$.

The metal grid network is used to support the electrically controlled excitation of VO₂. To avoid the coupling interference between the grid network and the resonance pattern, the main stem of the grid network on the meta-atom is designed as a pair of parallel metal bias lines positioned above and below the resonance pattern, corresponding to the positive and negative poles of the external power supply bias. Based on the electrical connection point between the main line and the SRR, electrical excitation of the doped switch can be achieved, and the corresponding bias current path is “upper SRR -> upper switch -> CWR -> lower switch -> lower SRR”. In particular, the location of the connection points shown in the local structure diagram is the result of optimization. Such points are not located in the center of the SRR edge, because the presence of the connection point will

introduce potential EM resonance paths from the SRR to the grid network, which in turn disturbs the resonance EM mode on the meta-atom. To avoid the coupling interference and resonance interference from the grid network, the structure parameters of it are optimized as follows: $w_2 = 5 \text{ }\mu\text{m}$, $d_2 = 20 \text{ }\mu\text{m}$, and $d_3 = 17.5 \text{ }\mu\text{m}$.

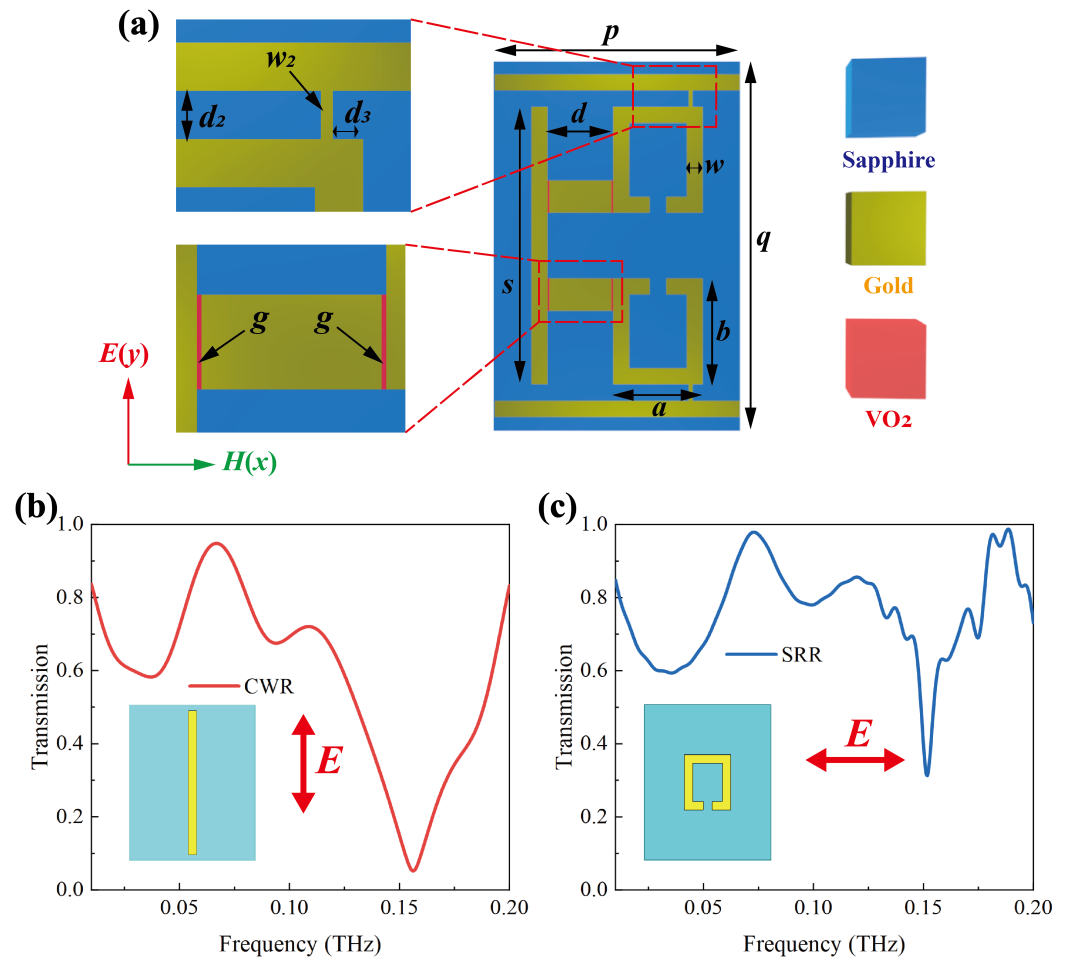


Figure 2. Design principle of the meta-atom. (a) The meta-atom design and the local structure diagram of doped switch and metal grid network. The resonance diagram of (b) CWR and (c) SRR.

In the working scenario, when the external excitation triggers the VO₂ phase transition on the metasurface, the EM resonance mode on the meta-atom will be changed, and finally modulate the transmission amplitude of an incident THz wave. In addition, a continuous change in the external power results in a continuous tuning of the transmission amplitude, allowing the encoding to be transmitted from the external stimuli to the THz band.

3. Results and Discussion

In this section, the proposed modulator design is modeled and simulated in the commercial software CST Studio Suite 2022 with a time domain solver. In the modeling, the sapphire substrate is a lossless medium with a dielectric constant of 11.5; the dielectric constant and active conductivity of metallic state VO₂ are described by the Drude model. A periodic boundary consisting of a PMC boundary in the x-direction and a PEC boundary in the y-direction is established for the meta-atom in the 3D full wave EM simulation.

Firstly, the THz wave modulation performance is verified, including amplitude modulation ability and amplitude coding. Figure 3a shows the amplitude modulation function of the designed metasurface. When VO₂ is not excited, a distinct EIT window appears in the range of 0.1192 to 0.177 THz with a bandwidth of 0.058 THz and a Q-factor of 2.37, which is caused by the destructive interference between the CWR and SRR. As the VO₂

conductivity on the metasurface is excited to 3×10^4 S/m, the excited doped switch will change the field resonance state between the CWR and SRR and creates a new EIT window in the range of 0.06 and 0.172 THz, tuning the EIT bandwidth and Q-factor to 0.1121 THz and 1.06, respectively. By comparing the transmission spectrum before and after excitation, it can be found that the transmission amplitude at 0.1192 THz changes obviously from 0.06 to 0.716, resulting in an amplitude modulation depth (AMD) of 91.6%.

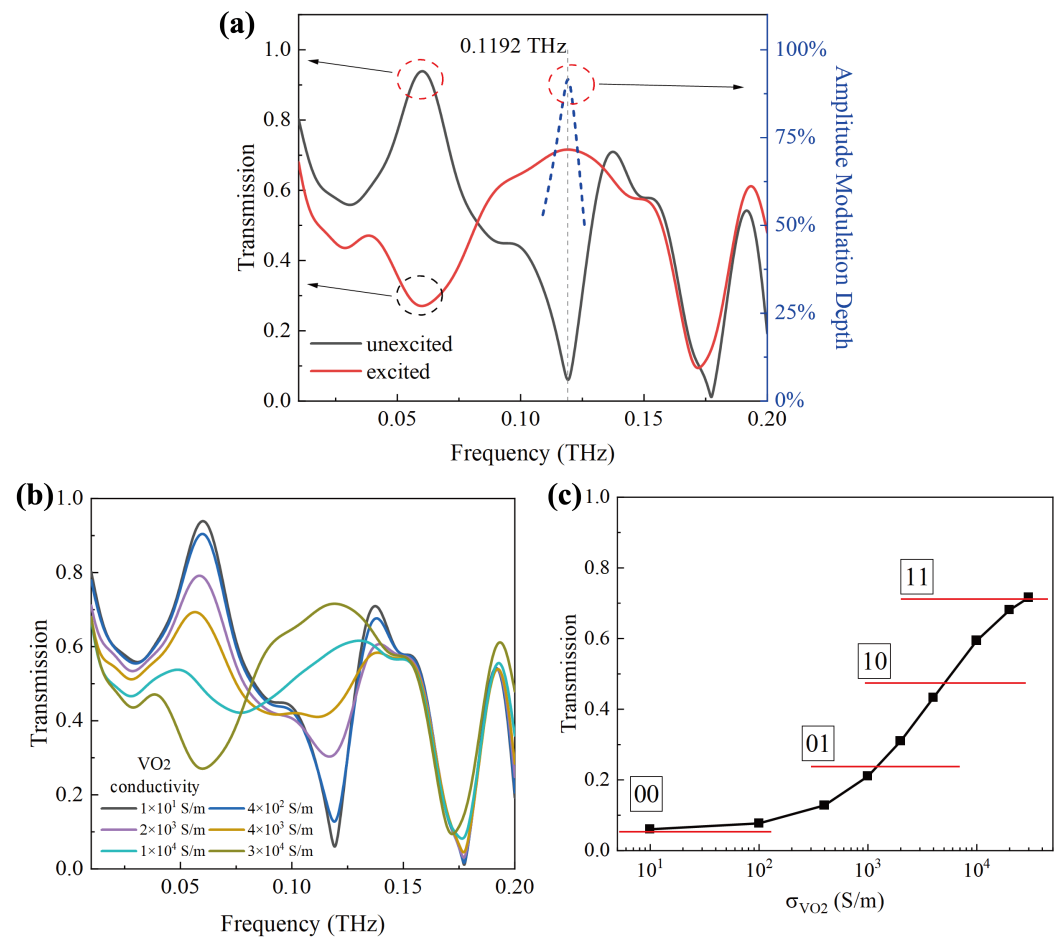


Figure 3. The amplitude modulation and amplitude coding functions of metasurface in the simulation. (a) The amplitude modulation function in the spectrum. (b) The transmission amplitude spectrum varies with the VO₂ conductivity. (c) The amplitude coding function at 0.1192 THz.

In addition, the VO₂ excited conductivity can be controlled by precisely controlling the excitation power of the external stimulus so that the transmission amplitude can be digitally encoded. Figure 3b,c show the continuous change of transmission amplitude in the spectrum and that at 0.1192 THz with the conductivity of VO₂. When the VO₂ conductivity is maintained at 10 S/m, 1.2×10^3 S/m, 5.08×10^3 S/m, and 3×10^4 S/m, respectively, the transmission amplitude at 0.1192 THz can be modulated to 0.06, 0.237, 0.474, and 0.716 in sequence. Thus, the digital codes “00”, “01”, “10”, and “11” can be achieved to form the 2-bit amplitude modulation function.

In Figure 3b, we can also observe fluctuations in the transmission amplitude spectrum beyond the frequency of 0.06 to 0.17 THz, which is a manifestation of the Fabry–Perot effect. The dielectric match layer prevents the interference of the Fabry–Perot effect on the transmission characteristics of EIT windows.

Then, based on Figure 4, we verified the equivalent conductivity of the metal-doped VO₂ switch in the spectrum. The proposed meta-atom design with a metal-doped VO₂ switch is shown in Figure 4a, while the reference meta-atom is shown in Figure 4b. The

reference has same structure as the design; the only difference is that the doped metal patches on the switches are replaced so that all the VO₂ switches are exposed. Figure 4c shows the comparison of transmission properties of the two meta-atoms with excited VO₂. The black curve is the transmission spectrum of the design meta-atom with excited VO₂ conductivity $\sigma_{VO_2} = 3 \times 10^4$ S/m, while the red curve is that of the reference. To better demonstrate the effect of equivalent conductivity, we improved the VO₂ conductivity on the reference meta-atom until its transmission spectrum curve is similar to that of design. Finally, we found that the VO₂ conductivity σ_{VO_2} on the reference meta-atom should be excited to 6×10^5 S/m to support the similar performance of the design meta-atom. This phenomenon in Figure 4c shows that the doped switch loaded on the meta-device can not only reduce the required excited conductivity of active material but also obtain a higher excited conductivity, which provides a new approach for the active material-based meta-device design. Based on our simulations and analysis, it is also confirmed that the designed structure has a good robustness and is tolerant to fabrication errors such as alignment errors between metal and VO₂ patterns during the micronanofabrication process.

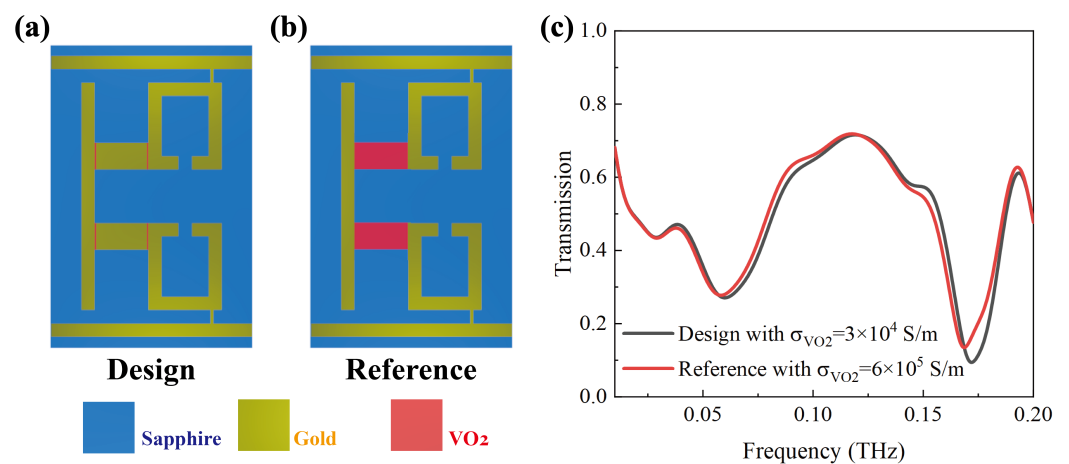


Figure 4. The characteristics of the metal-doped VO₂ switch in the spectrum. The structure of (a) the meta-atom design and (b) the reference. (c) The comparison of the transmission spectrum results between the design and reference with excited VO₂.

4. Conclusions

In this study, we proposed the doped switch design to achieve a higher excited conductivity equivalent and designed a reconfigurable EIT metasurface that can be driven by a lower excited conductivity for amplitude modulation and amplitude coding functions at the THz band. The VO₂ conductivity on the switch only needs to be excited at 3×10^4 S/m to produce an equivalent excitation effect of 6×10^5 S/m so that the metasurface can have a high AMD and digital amplitude modulation capability. The simulation results show that the design of the metal-doped active material switch can not only reduce the required excited conductivity of the active materials but also control the upper limit of the active material's excited conductivity. Our design provides a compatible solution to the contradiction between modulation performance and modulation rate requirements for the active material-loaded metasurface, and it provides new possibilities for the development of novel high-performance THz meta-devices and advanced THz technologies.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

THz	terahertz
EM	electromagnetic
EIT	electromagnetically induced transparency
VO ₂	vanadium dioxide
CWR	cut wire resonator
SRR	split-ring resonator
AMD	amplitude modulation depth

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