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Perfect Metamaterial Absorbers in Microwave and Terahertz Bands

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1. Introduction

Recently, resonant metamaterial absorbers (MAs) at microwave and terahertz (THz) bands have attracted much attention due to the advantages such as high absorption, low density, and thin thickness [1-6]. The MA generally composed of a metamaterial layer and a metal plate layer separated by a dielectric spacer. With this kind of novel device, unity absorptivity can be realized by matching the impedance of MA to free space. Besides that, wide-angle, polarization insensitive and even multi-bands/wide-band absorption can be achieved through properly device designing [7-11]. Furthermore, our previous investigations on MA show that the absorber traps the incident electromagnetic (EM) wave into some specific spots of the devices, and then converts it into heat [9, 12]. All these features make MAs very useful in areas such as EM detector/imager, anti-electromagnetic interference, stealth technology, phase imaging, spectroscopy and thermal emission.

Tunable devices, which allow one to real-time control and manipulate of EM radiation, are emerging as an interesting issue in metamaterials fields [13]. Combined with pin diodes, switchable microwave MAs were developed and an electronic control strategy was demonstrated [14, 15]. However, the device fabrication process is complex, and the structure with pin diodes is hard to be scaled down to higher frequency such as THz and visible regimes. In this chapter, we proposed a VO₂ based switchable MA in microwave band. VO₂ is known to exhibit a transition from an insulating phase to a metallic state (IMT) when it is thermally, electrically or optically triggered. By this unique property, VO₂ films have already been used to tune the resonance characteristics of metamaterial in near IR [16] and THz regimes [17, 18]. The switchable microwave MA presented in this work is realized by placing VO₂ thin film between the electronic split ring resonator (eSRR) and the dielectric layer. It is found that by triggering the IMT of the VO₂, the absorption amplitude of the device can be significantly switched between absorber and reflector with high speed. This VO₂ based MA has the advantages such as simple fabrication, strong tunability and easy to scale to terahertz and optical bands. This tunable MA also has the potential to be a self-

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resetting “smart” EM absorber, since the absorbed wave would transfer into heat and that can also trigger the IMT of the VO₂ film.

2. Basic structure and working principle of metamaterial absorber

The first metamaterial based absorber was proposed by N. L. Landy et al in the microwave band [1]. It is called “perfect metamaterials absorber” because nearly 100% absorption can be achieved theoretically. A single unit cell of the absorber consisted of three layers as shown in Fig.1. The top layer is the electric split-ring resonator (eSRR), the middle layer is isolation layer (such as polyimide), and the bottom layer is rectangular metal strip. Due to the lithography alignment and multi-step lithography process, the preparation process of the first MA is complex. Experimentally, the maximum absorptivity only reaches to 70% at 1.3THz due to the fabrication tolerance. An improved MA was proposed by H. Tao et al, with the bottom metal strips replaced by a continuous metal film [2]. This improved absorber operates quite well for both TE and TM radiation over a large range of incident angles (0-50°), and the measured absorbance was further improved to 97%. Therefore, the MA with a continuous metal ground plane become the most commonly structure in the researches.

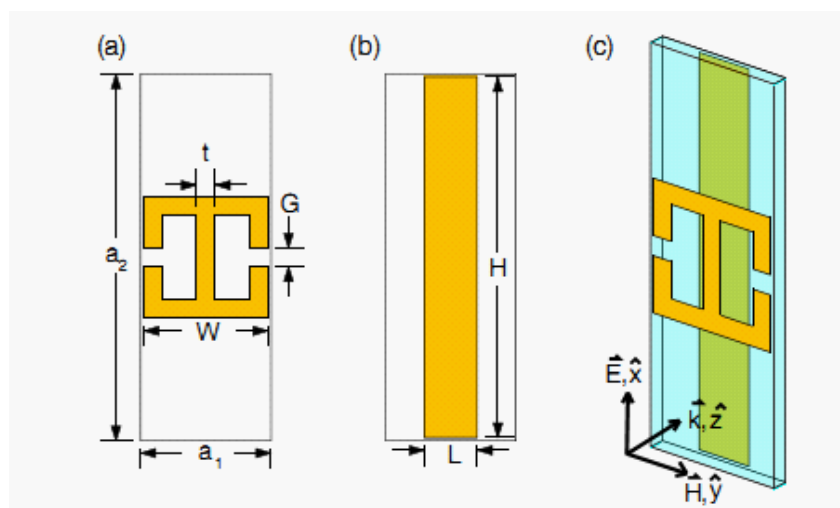


Fig. 1. Basic structure of three layers metamaterial absorber (a)the layer of metamaterial;(b) the bottom metallic layer;(c)the unit structure include the dielectric layer. Figure adapted from N. L. Landy et al. [1]

The absorption mechanism of the MA is as follows: First, by changing the geometry of the SRR and the thickness of the spacer, the impedance $Z(\omega)$ of the absorber can be designed to match the impedance of free space at a specific frequency (center frequency) resulting in zero reflection; Second, electromagnetic waves can not pass through the metallic ground plane, giving rise to zero transmission too. Thus, electromagnetic waves will be completely restricted in the device and finally be consumed. In principal, the metamaterial absorber can absorb 100% of the narrow-band electromagnetic waves. It can be used in microwave, terahertz (THz) and even light wave band by adjusting the feature size of the unit cell.

Though more and more attentions have been paid to MA, the mechanism of the near-unity absorption is still under studying. It has been suggested the matching between the effective

permittivity and permeability may be able to interpret the perfect absorption. However, the effective medium theory has some problems in describing MA because the three-layer structured device doesn't exactly satisfy the homogeneous-effective limit, according to Caloz [20]. A typical case is that the strong asymmetric absorption phenomenon cannot be fully explained by effective medium model [21]. The simulation results show dramatically different behaviors when the electromagnetic waves incident from the two opposite directions. For example, when light is incident from the front to the resonators the device acts as a perfect absorber, while when light is incident from the back to the ground plane the device behaves like a perfect mirror. Furthermore, the MA consists of only two metallic layers, thus are strongly inhomogeneous in the wave propagating direction, which is obviously in contrast to the effective medium model.

Q.Y. Wen et al have proposed a transmission line (TL) mode based on the equivalent RLC model [12]. In the TL model, it is assumed that the transverse electromagnetic (TEM) wave propagates through free space and the substrate with intrinsic impedances Z_i and Z_o respectively. There are two assumptions for constructing the TL model. One is that coupling capacitor or coupling inductor between the eSRR layer and wires layer should be ignorable, so that these two layers can be individually modeled, as demonstrated in Fig. 1. Another is that the THz wave normally incidents on the absorber plane with the electrical field parallel to the split gap of the eSRR. The TL model of eSRR proposed by A. K. Azad [22] is used to describe the eSRR layer, in which the LC resonance and dipole resonance each is represented by one group of L, C and R respectively, and the coupling between these two resonances is specified by the parameter M. The wires layer part is mimicked by the TL model developed by L. Fu [23], with the only resonance expressed by one group of L, C and R. The function of isolation layer is modeled by a transmission line which contains all EM related properties of the isolation layer such as ϵ , μ and thickness. It connects the eSRR part and wire part. All the parameters are needed to be optimized until the S-parameters calculated by the TL model fit the simulation results.

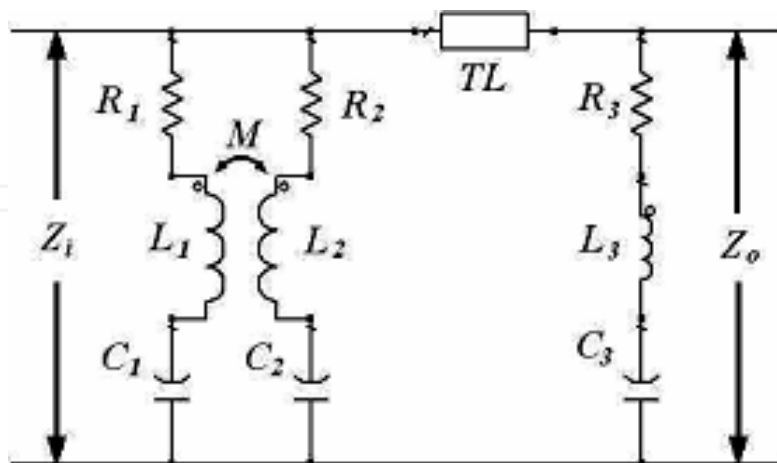


Fig. 2. Transmission line model of metamaterial absorber

By this TL model, the asymmetric phenomenon of THz absorption is unambiguously demonstrated and explained. The strong absorption is found to be mainly related to the LC resonance of the eSRR structure. The isolation layer in the absorber, however, is actually an impedance transformer and plays key role in producing the perfect absorption. The studies

by TL model also show that the electromagnetic wave is concentrated on some specific location in the absorber. It indicates that the trapped electromagnetic wave in the absorber can be converted into thermal energy, electric energy or any kinds of other energy depending on the functions of the spacer materials. This feature as electromagnetic wave trapper has many potential applications such as radiation detecting bolometers and thermal emitter.

3. Progress in metamaterial absorber

The perfect absorber first proposed by N. L. Landy is an anisotropic absorber. They further proposed a polarization independent absorber, as shown in Fig.3 [5]. One of the main features of the structure is that the eSRR has fourfold-rotational symmetry about the propagation axis and was therefore polarization insensitive. The measured absorptivity of this absorber is 65% at 1.145 THz. Experimental results confirmed that the polarization-independent metamaterial absorber can be realized by chosen a fourfold rotational symmetry SRR structure.

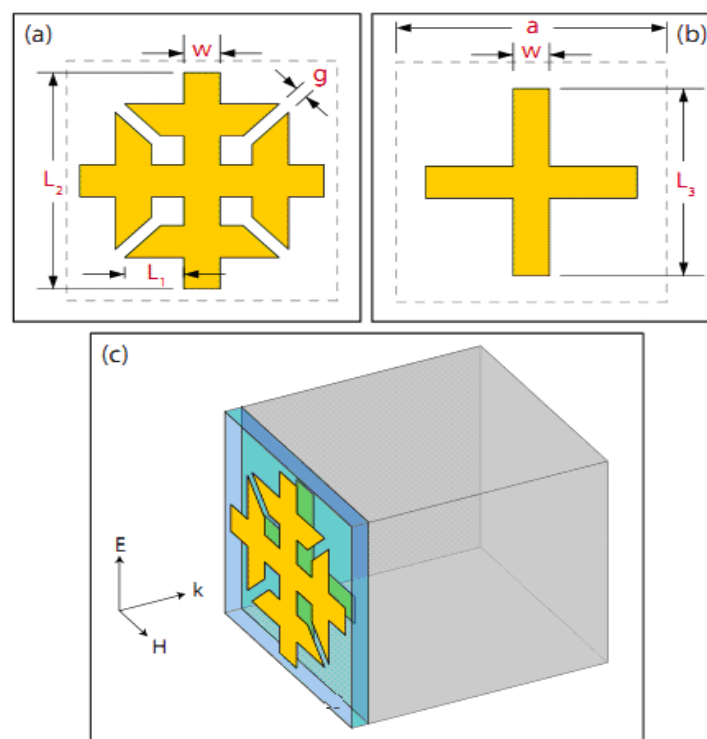


Fig. 3. Polarization-independent metamaterial absorber. Figure adapted from N. I. Landy et al. [5]

H. Tao et.al designed a wide-angle terahertz metamaterial absorber [13]. Most importantly, the device was fabricated on a highly flexible polyimide substrate with a total thickness of 16 μm . This novel design enables its use in nonplanar applications as it can be easily wrapped around objects as small as 6 mm in diameter. They demonstrated, through simulation and experiment, that this metamaterial absorber operates over a very wide range of angles of incidence for both transverse electric (TE) and transverse magnetic (TM) configuration.

Apart from single-frequency absorber, dual-band and multi-band absorbers also draw attention from researchers. A dual-band metamaterial absorber was demonstrated in terahertz band, as shown in Fig 4 [9]. The special feature of this absorber is that its eSRR unit possesses two kinds of split gaps and therefore exhibits two well-separated LC resonances. Theoretical calculation shows that there are two distinct absorptive peaks located around 0.50 and 0.94THz, each with absorptions over 99.99%. The measured absorption is 81% for low frequency absorption and 63.4% for high frequency absorption. The experimental result suggests that the design of an eSRR with multiple LC resonances is a key step toward a multi-frequency absorber. A similar result was also reported by H. Tao et al [10].

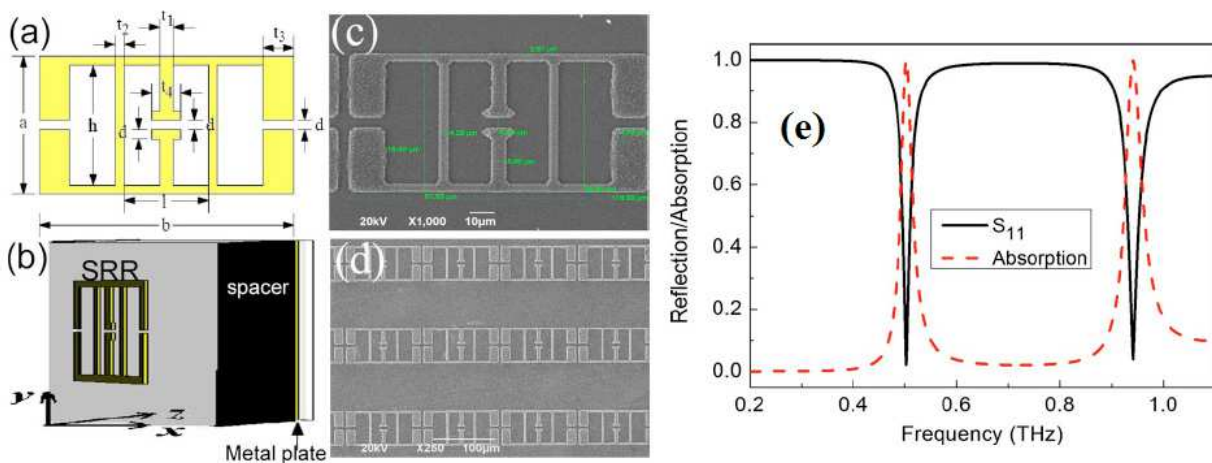


Fig. 4. Dual-band THz metamaterial absorber. (a) Designed electric split ring resonator, (b) Perspective view of the designed absorber. (c) A unit cell of the experimentally realized absorber. (d) Photograph of a portion of the fabricated absorber. (e) The simulated reflection (solid line) and absorption (dotted line) curve of the absorber.

X. P. Shen et al. have developed a wide angle triple-band absorber structure very recently, as shown in Fig.5 [11]. The top layer consists of an array of three nested copper closed ring resonator arrays, which is primarily responsible for the electric response to the incident field. The bottom layer is a copper plane, which is used to zero the transmission and is responsible for the magnetic response. The experimental results show three absorption peaks at frequencies 4.06GHz, 6.73GHz and 9.22GHz with absorptivity of 99%, 93%, and 95%, respectively, which agrees well with the simulation results.

In certain applications, broadening the absorption bandwidth is also of importance. Fig.6 shows an omnidirectional polarization-insensitive absorber with a broadband feature in the terahertz regime proposed by Q.Y. Ye et al. [8]. They demonstrated that the bandwidth of the absorption can be effectively improved by using a multilayer structure, while the wide-angle feature remains. A simple cross-shaped pattern was used as the resonator. The experimental results show that with the increasing of metamaterial layers, the absorption peak is gradually broadened. A bandwidth of nearly 1000 GHz with perfect absorption (more than 97%) was achieved in the three layer absorber.

A frequency tunable metamaterial absorber is proposed by incorporating a pin-diode between two resonators [15]. Simulation and measurement results show that by forward or reverse biasing the diodes so as to change the coupling between the resonators, the absorber

can be dynamically switched to operate in two adjacent frequency bands with nearly perfect peak absorption. It is also shown that by tuning the loading position of the diodes, it is able to adjust the frequency difference between the two switchable absorbing bands.

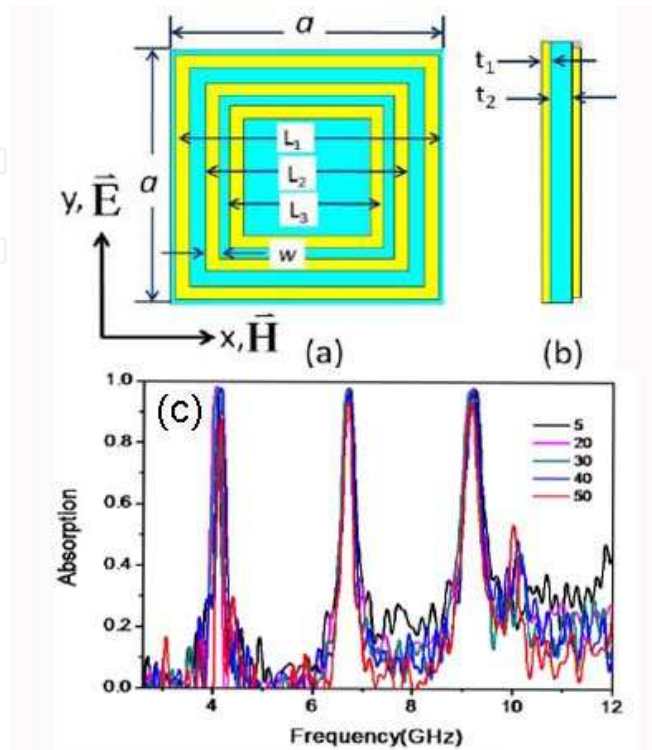


Fig. 5. (a) The front and (b) side view of the unit cell of the triple band microwave absorber, and (c) simulation and experimental results of the triple-band absorber at various angles of incidence. Figure adapted from X. P. Shen et al [11].

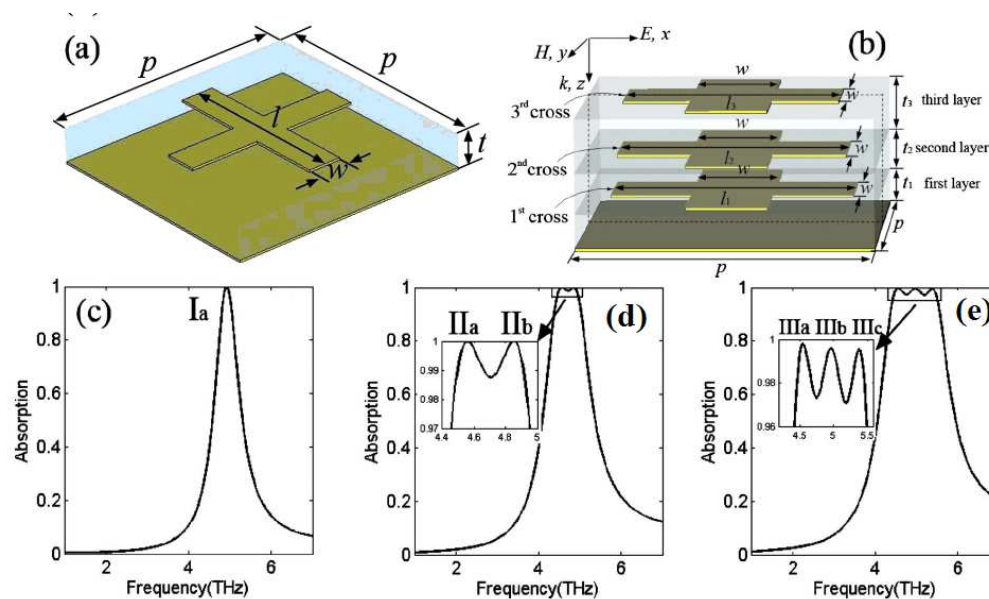


Fig. 6. (a) Unit cell of the absorbers, (b) Schematic diagram of a 3-layer cross structure, and absorption spectra for (c) 1-layer cross structure; (d) 2-layer cross structure; (e) 3-layer cross structure.

4. Switchable metamaterials absorber based on vanadium dioxides

Though tunable metamaterial absorber has been demonstrated in microwave band, the device fabrication process is complex, and the structure with pin diodes is hard to be scaled down to higher frequency such as THz and visible regimes. In this chapter, we proposed a novel switchable MA in microwave band, which is simple and can be tuned thermally, electrically and optically. The MA under studied has a similar structure to our previously designed dual band THz absorber [9] except that a thin VO₂ film is incorporated between the eSRR and the substrate, as shown in Fig.7. The eSRR unit cell is composed of two kinds of SRR with one (the inner resonator) invaginated in the other (the outer resonator pairs). It should be noted that, for the purpose of comparison, only the inner resonator has an underlying VO₂ patch and the outer resonators contact to the substrate directly. As shown in Fig.7 (b), the area of the VO₂ patch is equal to the inner resonator. Utilizing the commercial software CST Microwave Studio™ 2009, the size parameters of the eSRR marked in Fig.7 (a) was optimized to obtain two strong absorptions. In the simulation, the microwave MA is built on C-cut sapphire substrate with one side covered with metallic ground plane and another side with eSRR arrays. Both of the metallic eSRR and ground plane are modeled as copper sheet with conductivity of 5.8×10^7 S/m. A 200nm thick VO₂ film was applied in the simulation. The permittivity and the permeability of VO₂ were set to be 3 and 1, respectively. The conductivity (σ) was swept from 0.02S/m to 2000S/m to mimic the phase transition process. The incident microwave wave is normal to the devices plane with the electronic field perpendicular to the split gaps, e.g. along y axis as indicated in Fig.7 (b). The optimized parameters are: $a=2\text{mm}$, $b=4\text{mm}$, $d=0.1\text{mm}$, $h=1.8\text{mm}$, $l=1\text{mm}$, $t_1=t_2=0.2\text{mm}$, $t_3=0.3\text{mm}$, $t_4=0.5\text{mm}$ and the unit cell is $3\text{mm} \times 5\text{mm}$. The copper thickness of eSRR layer is $0.2\mu\text{m}$ and that for ground plane is $0.8\mu\text{m}$.

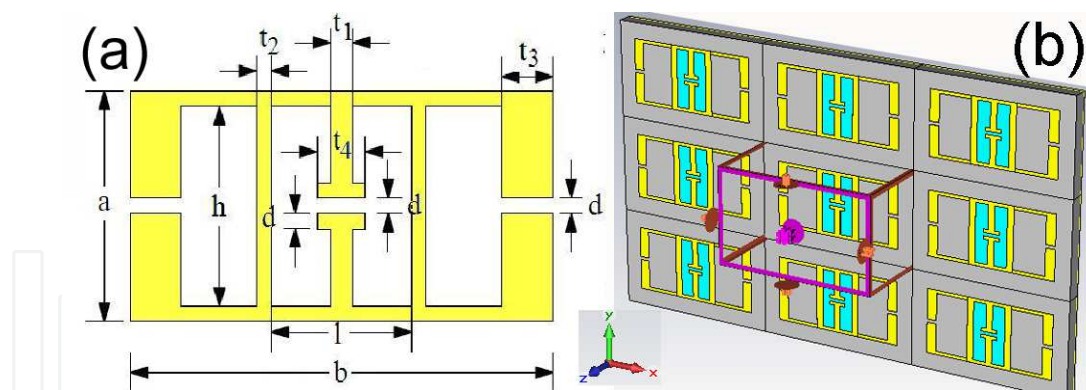


Fig. 7. Dual-band microwave metamaterial absorber. (a) Schematic of the designed eSRR unit cell. (b) Perspective view of the absorber sheet with VO₂ patterns. Gray represents the sapphire substrate, yellow the copper and dark green the VO₂ film.

Fig.8 shows the simulated S_{11} parameters of the MA with different conductivity of the VO₂ patch. When σ is 0.02S/m, e.g. the insulating state of the VO₂ film, two distinct reflection peaks are observed around 9.03 GHz and 17.6 GHz. Since the transmission of MA is zero due to the metallic bottom plane, the absorptivity can be calculated using $A=1-|S_{11}|^2$. High absorptivity of 92.7% and 99.4% was obtained at 9.03 GHz and 17.6 GHz, respectively. The surface current distributions on the top eSRR and bottom plane layer at resonance frequencies were monitored, as shown in Fig.9. The results confirmed that both resonances

come from circulating currents in the eSRR resonators [9, 10]. Furthermore, it shows that the low frequency response is determined mainly by the outer ring pairs (Fig 9 (a) & (c)), while the high frequency response is induced mainly by inner resonator (Fig.9 (b) & (d)).

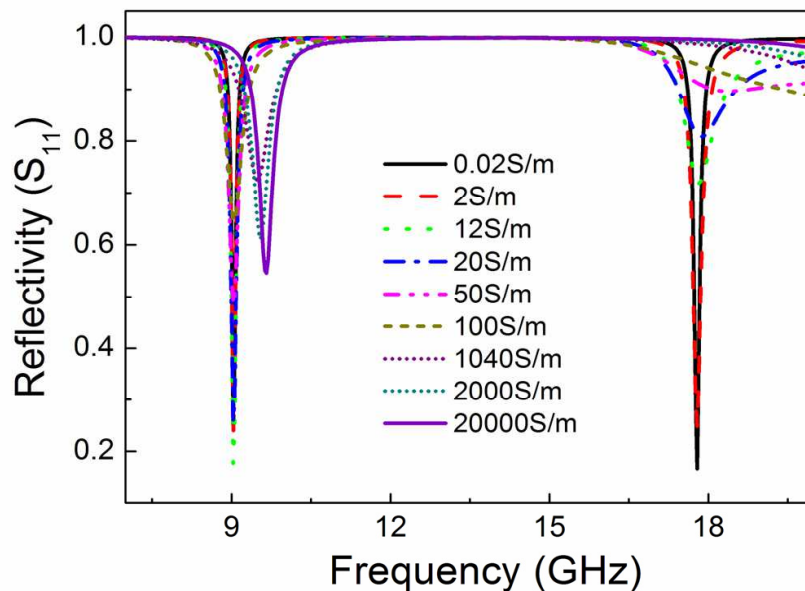


Fig. 8. Simulated reflection curve for metamaterial absorber with different conductivity of VO_2

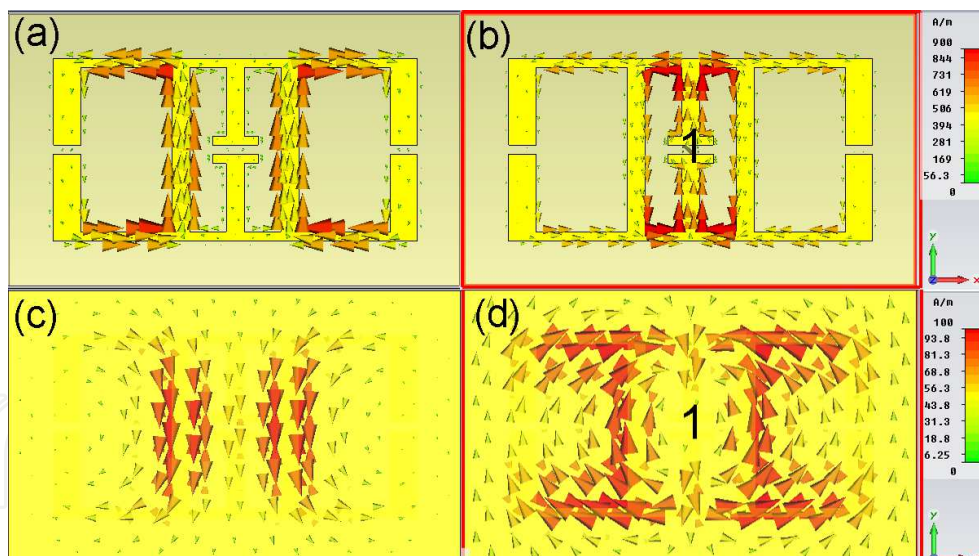


Fig. 9. Surface current distributions in the top and bottom metallic layers. (a) and (c) for the low frequency absorption, and (b) and (d) for high frequency absorption

When the value of σ increases to 2S/m , the high frequency reflectivity begins to increase. With the increase of σ from 2S/m to 50S/m , the peak reflectivity around 17.6GHz increases abruptly from 0.25 to 0.90 , corresponding to a decrease of absorptivity from 93.75% to 19% . Further increase of σ gives rise to a slight increase of the reflectivity. As to the low frequency absorption, however, the situation is different. It seems that the variation of σ from 0.02S/m to 20S/m have little effect on absorption. Further increase σ from 20S/m to 20000S/m leads

to a moderate increase of peak reflectivity from 0.26 to 0.54. Interestingly, for both absorptions a blue-shift about 0.6GHz of the peak frequency is clearly observed. All these results indicate that the IMT of VO₂ does affect the absorption of the MA, and the mechanism will be discussed later in detail.

With the optimized size parameters the microwave MA device was fabricated. Firstly, a VO₂ layer of almost 200 nm in thickness was deposited on 0.5mm-thick C-type sapphire substrates by using the reactive magnetron sputtering technique. The phase transition temperature (TP) of the films was measured to be around 340K and the conductivity exhibits nearly three-orders decrease [18]. The VO₂ film was then etched using CF₄/O₂ plasma to 1.2mm × 2mm patches in a period of 3mm × 5mm, which is the identical period of the eSRR array. After that copper film with thickness of 0.2μm was sputtering deposited on top side of the VO₂/Substrate, following by a conventional lithography process to form the designed eSRR structure with its inner resonator overlapping on the VO₂ patch. Finally another 0.8μm copper film was deposited on the backside of the substrate.

Based on the principle of Arc Tracking Test method, a vector network analyzer (Agilent 8720ES) with two horn antennas was used to transmit EM waves onto the sample sheet and receive the reflected signals. The incident and receive angle is less than 5° from normal in the experiment. Fig.10 shows the measured S₁₁ curves of the VO₂ based MA under different temperature. Two strong reflection peaks are clearly appeared and they are distinct from each other, which agrees with the simulation well. At room temperature (RT), two reflective minimums were appeared at 9.36GHz and 18.6GHz, respectively. By $A=1-|S_{11}|^2$ the peak absorptivity at low and high frequency were calculated to be 84.8% and 92.1%. For both absorptions, the measured peak frequencies and absorption amplitudes have slight derivations from the theoretical results, which are probably induced by the fabrication tolerance or the difference of the material parameter between simulation and experiment. Variations of the absorption characteristic of the MA were observed when the device temperature increased from RT to 345K. For the low-frequency absorption, the reflectivity minimum shows a small increase from 0.39 to 0.57, corresponding to an absorption decrease from 84.8% to 67.5%. Significant change of the absorption was happened in the high frequency case. With the increase of temperature from RT to 345K, the reflectivity minimum increases notably from 0.28 to 0.83, accompanying with a blue-shift of the peak frequency form 18.6 GHz to 19.12 GHz. Therefore, a deep amplitude modulation about 60% to the microwave absorption and a moderate frequency shift of about 0.5 GHz was realized. All these results agree with the simulated results very well, confirming that the VO₂ based microwave MA is thermally tunable.

In order to further clarify the tunability of MA, the temperature dependence of the reflectivity amplitude and corresponding peak frequency for high-frequency absorption was summarized and plotted in Fig.10 (b). It can be seen that the violent variation of the absorption characteristics, including the amplitude and peak frequency, occurs during a very narrow temperature range from 337K to 345K, which is the phase-transition temperature range of the VO₂ films under studied. Combining the theoretical and experimental results, we can conclude that it is the thermally triggered IMT of VO₂ that induces the tunability of the MA. To understand how the IMT of VO₂ affects the properties of MA, the distribution of the absorption at low and high frequency was examined at RT and compared in Fig.11. In the low-frequency case, the absorption mainly takes place in the

vicinity of the two outer gaps, with a small portion occurring at the four corners and inner split gap. In the high-frequency case, almost all the absorption occurs at inner gap. Therefore, the working principles of our tunable microwave MA can be explained as follows: At RT, the VO₂ is in its insulating state and allows dual band absorptions. When the temperature increase beyond T_p , the VO₂ film changes into the metallic state and electronically shorts the inner split gap of the eSRR. The impedance match for the high frequency absorption is seriously broken thus the absorption is strongly attenuated. For low frequency absorption, though the absorption from the inner resonator is also attenuated as temperature increasing, the absorption from the outer resonator pairs is still strong since there is no underlying VO₂ film. That's why the low frequency absorption is not seriously crippled. The resonance frequency of eSRR can be described as $\omega=(LC)^{-1/2}$, where L and C represents the inductance and capacitance of the resonator [19]. Therefore, the blue-shift of the peak frequencies can be ascribed to the decrease of inductance as a result of the metallization of VO₂ film. These results confirmed that by triggering the IMT of the VO₂ films both the amplitude and frequency of the absorption can be tuned.

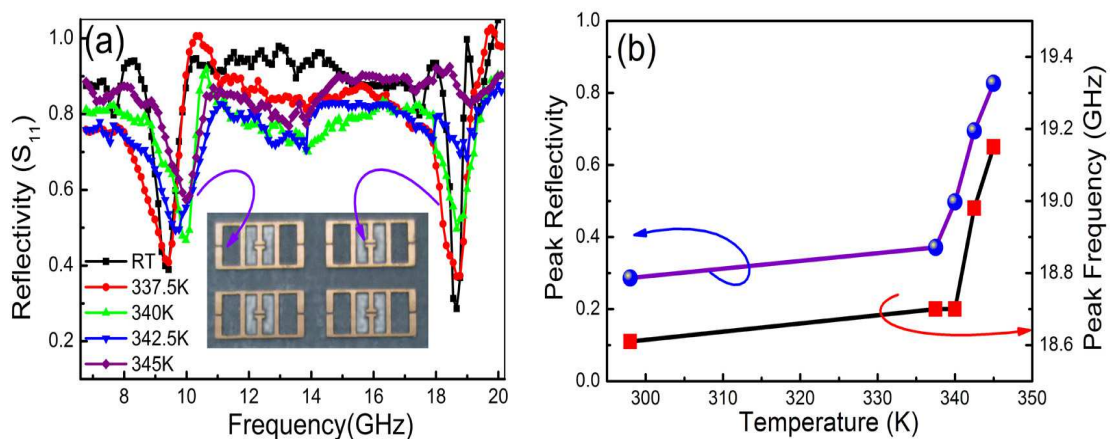


Fig. 10. (a) Measured reflectivity curves of the VO₂ based MA with respect to the devices temperature. Inset is the image of the fabricated device; (b) the temperature dependence of the reflection amplitude and corresponding peak frequency for high frequency absorption.

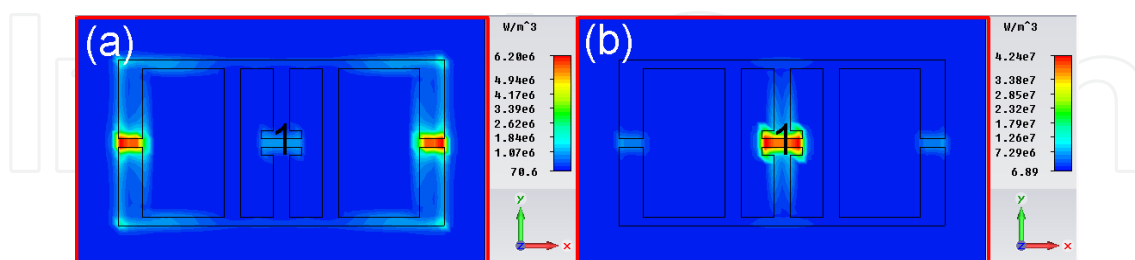


Fig. 11. Distributions of absorption densities for (a) low frequency absorption and (b) high frequency absorption.

5. Summary

Metamaterial absorbers with strong absorbance in microwave and terahertz band are very useful in many regimes such as detecting THz, creating thermal radiation, or cloaking. The metamaterial absorber could be designed to be polarization independent, broadband and

even tunable with a small volume, small thermal mass, and high absorption coefficient. In this chapter, a tunable microwave absorber was demonstrated theoretically and experimentally. It is found that by thermally triggering the IMT of the VO₂, the absorption amplitude of the device can be significantly tuned. This tunable MA also has the potential to be a self-resetting “smart” EM absorber, since the absorbed wave would transfer into heat and that can also trigger the IMT of the VO₂ film.

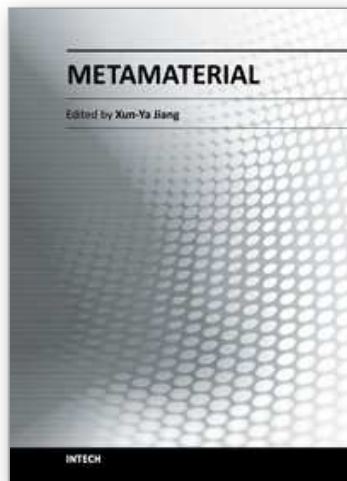
6. Acknowledgement

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Metamaterial

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In-depth analysis of the theory, properties and description of the most potential technological applications of metamaterials for the realization of novel devices such as subwavelength lenses, invisibility cloaks, dipole and reflector antennas, high frequency telecommunications, new designs of bandpass filters, absorbers and concentrators of EM waves etc. In order to create a new devices it is necessary to know the main electrodynamical characteristics of metamaterial structures on the basis of which the device is supposed to be created. The electromagnetic wave scattering surfaces built with metamaterials are primarily based on the ability of metamaterials to control the surrounded electromagnetic fields by varying their permeability and permittivity characteristics. The book covers some solutions for microwave wavelength scales as well as exploitation of nanoscale EM wavelength such as visible specter using recent advances of nanotechnology, for instance in the field of nanowires, nanopolymers, carbon nanotubes and graphene. Metamaterial is suitable for scholars from extremely large scientific domain and therefore given to engineers, scientists, graduates and other interested professionals from photonics to nanoscience and from material science to antenna engineering as a comprehensive reference on this artificial materials of tomorrow.

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