A tunable metamaterial absorber using varactor diodes

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Abstract. We present the design, analysis and measurements of a polarization-insensitive tunable metamaterial absorber with varactor diodes embedded between metamaterial units. The basic unit shows excellent absorptivity in the designed frequency band over a wide range of incident angles. By regulating the reverse bias voltage on the varactor diode, the absorption frequency of the designed unit can be controlled continuously. The absorption mechanism is interpreted using the electromagnetic-wave interference theory. When the metamaterial units are placed along two orthogonal directions, the absorber is insensitive to the polarization of incident waves. The tunability of the absorber has been verified by experimental results with the measured bandwidth of 1.5 GHz (or relative bandwidth of 30%).

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1. Introduction

Metamaterials with peculiar electromagnetic properties have attracted a great deal of interest in the last decade [1]. The metamaterial units, which are often periodically arranged and have a scale much smaller than the corresponding wavelength, satisfy the Lorentz–Drude model just as normal materials do [2]. The relationship between the particle response and the macroscopic system functions for metamaterials has been set up based on the effective medium theory [3]. By carefully choosing the shape of the metamaterial units and adjusting the structural dimensions, the required effective permittivity and permeability can be achieved. This property has been employed to design microwave and terahertz absorbers based on Snell’s law and Fresnel’s equation.

Recently, the metamaterial absorber (MMA) has become a popular topic as it is very thin and can dramatically decrease unwanted reflections, which may lead to extensive applications in microwave and terahertz engineering. Landy et al [4] first reported the concept of the perfect MMA, which consists of two resonators coupled to the electric and magnetic fields separately to absorb the incident waves. Cheng et al [5] fabricated an ‘electromagnetic black hole’ based on the composition of non-resonant and resonant metamaterial structures, which can trap and absorb omnidirectional electromagnetic waves. Chen proposed the interference theory to explain the physical mechanism of MMAs [6, 7]. A number of absorbers have been successfully realized which are either multiple band, polarization-insensitive or broadband [8–12], bringing in many potential applications. However, the operation frequencies of traditional metamaterial devices are fixed, which are inconvenient to change after fabrication. Therefore, more and more attention has been focused on the design of tunable MMAs. Mias et al investigated a varactor-diode-tunable high impedance surface with a lumped-element biasing grid based on surface mount resistors, with tunability achieved by altering the reverse bias voltages [13]. Feng et al demonstrated a switchable reflector–absorber with diodes connecting to the structure units, where the MMA can be switched between the status of total reflection and total absorption for incident waves at the given frequency band by turning the diodes ON and OFF [14]. Yang et al [15] introduced a broadband MMA made of ferrite slabs and copper wire, in which the absorption band can be shifted linearly by adjusting the magnetic bias. Further research on tunable MMAs can be found in [16–20].

In this paper, we realize an electrically controlled MMA using varactor diodes embedded between adjacent resonant units; the absorption frequency in our design can be tuned continuously by regulating the bias voltage on the varactor diodes. The experimental results...
verify the tunability of the designed MMA, ranging from 4.35 to 5.85 GHz with an absorption rate of more than 90%.

2. Design of the basic unit

The basic unit of the designed tunable MMA is illustrated in figure 1. There are two identical electric-field coupled-LC (ELC) resonators with the same orientation on the top of the dielectric substrate, which are connected by a microwave varactor diode. The ELC resonator can be viewed as a central capacitor connected with two parallel loop inductors [21]. The equivalent circuit of the basic unit is two ELC circuits connected by a microwave varactor diode, where the LC resonance is driven by the electric field parallel to the gap of the ELC unit; the resonant frequency of the above-mentioned circuit is determined by its lumped parameters. Since the capacitance of the varactor diode changes under different reverse bias voltages, the absorption frequency of the basic unit will experience a red or blue shift correspondingly, which could be utilized to adjust the designed absorption frequency.

In our design we choose FR4 as the dielectric substrate; it has a relative permittivity of 4.3\,(1 − j0.025) and a thickness of 1.6 mm. The varactor diodes are biased by the feeding network printed on the bottom of the substrate, with metallic-plated through-holes connected to each other. The back layer is a metallic film, as shown in figure 1(a), which is separated from the feeding network by a 0.05 mm thin insulating layer (\(\epsilon = 1.1\)) to avoid the dc short circuit. The dimensions of the MMA unit have been optimized to ensure that the MMA could be tuned within a wide frequency band. The final geometry dimensions are given as: \(a = 16.84\,\text{mm},\ w = 5.55\,\text{mm},\ w_1 = 0.60\,\text{mm},\ w_2 = 0.40\,\text{mm},\ w_3 = 0.70\,\text{mm},\ \phi = 0.25\,\text{mm},\ d = 2.87\,\text{mm},\ d_1 = 1.20\,\text{mm},\ d_2 = 1.0\,\text{mm}\) and \(d_3 = 0.60\,\text{mm}\).

In this design, a commercial varactor diode SMV2019-079LF from Skyworks Solutions, Inc. [22] was used, whose capacitance varies from 2.31 to 0.24 pF when the reverse bias...
Table 1. The effective circuit parameters for the varactor diode SMV2019-079LF used in this design.

| VR (V) | C (pF) | R (Ω) | L (nH) |
|--------|--------|-------|--------|
| 0      | 2.31   | 4.51  | 0.70   |
| −4     | 0.84   | 4.04  | 0.70   |
| −7     | 0.55   | 3.66  | 0.70   |
| −11    | 0.38   | 3.18  | 0.70   |
| −14    | 0.31   | 2.86  | 0.70   |
| −16    | 0.27   | 2.65  | 0.70   |
| −19    | 0.24   | 2.38  | 0.70   |

Figure 2. (a) The spice model of the diode SMV2019-079LF. (b) The detection circuit model, which is used to extract the effective circuit parameters of the varactor diode based on its spice model.

Voltage changes from 0 to −19 V. The accurate effective circuit parameters of this varactor diode are shown in table 1, which are extracted from its spice model using the commercial software Advanced Design System 2008, as demonstrated in figure 2. In the following full wave simulations, the varactor diode will be replaced by the corresponding spice model for simplicity.

3. Simulation and analysis

The simulation results of the absorption rates of the designed unit under different reverse bias voltages are illustrated in figure 3, which shows that the tunable bandwidth reaches 1.19 GHz.
with the absorption rate more than 99%. We found that both electric resonances (the right seven peaks) and magnetic resonances (the left lower peaks, as circled in figure 3) are generated; the electric resonances are what we want. From figure 3, we observe that the absorption frequency is tuned from 4.45 to 5.64 GHz when the reverse bias voltage changes from 0 to $-19\text{ V}$. Figure 4 shows the simulation results for the oblique incidence of both the transverse-electric (TE) and transverse-magnetic (TM) radiations at various incident angles. We notice that the MMA unit has excellent performance even when the incident angle is up to $50^\circ$.

From figures 3 and 4 we can determine that the magnetic resonances are produced at lower frequencies, which are the result of the special unit geometry. Since the ELC units and feeding network are connected by metallic-plated through-holes, the surface current and the displacement current will form a loop at a certain frequency, as indicated by the yellow arrows in the inset of figure 5(a), which will enhance the magnetic response. The distribution of the surface current caused by magnetic resonance at 4.27 GHz is illustrated in figure 5(a), where most of the surface currents are concentrated around the plate through-holes and flow between the top and bottom metallic layers of the substrate. The distribution of the surface current caused by electric resonance at 5.64 GHz is shown in figure 5(b), where the current flowing between the ends of adjacent basic units and the current density in the centre is larger than that at the margin. To further validate our speculation, we cut off the current loop by removing the metallic-plated through-holes and carried out the simulations again under the reverse bias voltage of $-19\text{ V}$. The simulation results of the basic unit with and without the plated through-holes are plotted in figure 5(c). The lower absorption peak disappears as expected, as shown by the dashed line in figure 5(c).

In early works, it was widely believed that the impedance-matching between the MMA and the free space would minimize the reflectivity and introduce high losses due to the electric and magnetic resonances [4, 14]. However, it was pointed out that the magnetic response was too weak to contribute to impedance-matching or absorption [6]. Later, the interference theory was employed to interpret the absorption mechanism [7]. Due to the multilayer reflections from different layers, as shown in figure 6, the overall reflection can be calculated by superposition.

**Figure 3.** Simulation results of absorption rates at different reverse bias voltages, ranging from 0 to $-19\text{ V}$. The dashed circle indicates the occurrences of the magnetic resonances.
Figure 4. Simulation results of the absorption rates for oblique incidences at various incident angles for (a) TE and (b) TM polarizations under the reverse bias voltage $-19\text{ V}$.

from the classical electromagnetic theory [23]

\[ R_{\text{total}} = R_1 + R_2 + R_3 + \cdots \]

\[ = r_{12} + t_{12}r_{23}t_{21}\exp\left(\frac{-2ik_2d}{\cos(\alpha_t)}\right) + t_{12}r_{23}^2r_{21}t_{21}\exp\left(\frac{-4ik_2d}{\cos(\alpha_t)}\right) + \cdots \]  \hspace{1cm} (1)

\[ = r_{12} - \frac{t_{12}t_{21}\exp\left((-2ik_2d)/\cos(\alpha_t)\right)}{1 + r_{21}\exp\left((-2ik_2d)/\cos(\alpha_t)\right)} \]

where $r = |r|\exp(i\phi)$ and $t = |t|\exp(i\theta)$ represent the reflection and transmission coefficients, respectively, $d$ is the thickness of region 2, $\alpha$ is the incident angle, $\alpha_t = \arcsin[\sin(\alpha)]$ is the refraction angle and $k_2 = 2\pi \sqrt{\epsilon_2/\lambda_0}$. Since the lower surface of region 2 is filled with a perfect electric conductor, we have $r_{23} = -1$ in equation (1).

In order to interpret the physical mechanism of our basic unit using equation (1), we simplify our structure based on figure 6. By removing the plate through-holes, the feeding network and the insulating layer, the MMA structure model is simplified to a dielectric substrate with upper and lower surfaces coated with the basic units and the metal sheet. The reflection and transmission coefficients at the interface between region 1 (air) and region 2 (FR4) are extracted based on the decoupling system [7] with the varactor diodes biased under a randomly
Figure 5. Two types of absorptions under the reverse bias voltage $-19$ V. (a) The surface current distribution at 4.45 GHz, which is caused by the magnetic resonance. Here, the currents concentrate around the plate through-holes and flow between the top and bottom metallic layers of the substrate. The yellow arrows within the inset indicate the potential current loop, which is responsible for the magnetic resonance. (b) The surface current distribution at 5.64 GHz, which is caused by the electric resonance. Here, the current in the centre is larger than that at the margin. (c) The absorption rates with (solid line) and without plate through-holes (dashed line).

selected voltage. Figure 7 shows the calculated overall reflection coefficient (dashed line) based on equation (1), which is in good agreement with the simulated result (solid line). To further discuss equation (1), the substrate is assumed to be lossless; then we have

$$R_{\text{total}} = \frac{|r_{12}| \exp (i\phi_{12}) + \exp [i (\phi_{12} + \phi_{21} + 2\beta)]}{1 + |r_{12}| \exp [i (\phi_{21} + 2\beta)]},$$

(2)
**Figure 6.** The classical model for the interference theory. In our simplified model, region 1 is filled with air and region 2 is filled with FR4. The interface between regions 1 and 2 is placed with the basic units; the lower surface of region 2 is coated with metal sheet.

**Figure 7.** The simulated and calculated results of the overall reflection coefficients for the simplified model. (a) The magnitudes and (b) the phases.

where $\beta = -k_2 d / \cos(\alpha_t)$ and $\phi$ is the phase of the reflection coefficient. Then the conditions for non-reflection are derived as

$$|r_{12}| \to 1, \quad \phi_{21} + 2\beta \to \pi + 2N\pi, \quad N = 0, \pm 1, \pm 2, \pm 3, \ldots$$

which could be explained by the theory of an electromagnetic wave tunneling effect.

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4. Fabrication and measurement

In order to make the absorber insensitive to wave polarization, the basic units are placed orthogonally, as demonstrated in figure 8(a). The electric fields of arbitrarily polarized incident waves can be decomposed into two components along the $X$ and $Y$ directions and drive the electric resonances, respectively. A sample of MMA with the dimension $252.5 \times 257.5 \text{ mm}^2$ is fabricated in accordance with the previous design. Figure 8(b) shows the design of the feeding network, in which the positive and negative electrodes are connected to the dc source to obtain the desired reverse bias voltage.

In our experiment, the MMA sample is placed vertically, as plotted in figure 8(c). We use a transceiver horn antenna to transmit and receive electromagnetic waves, which is connected to the vector network analyzer (Agilent N5230 C) by a low-loss coaxial cable. The incident wave’s polarization is chosen to be along the vertical direction. The distance between the sample and antenna is 3.2 m, which is far enough to avoid the near-field effects of the antenna and the MMA sample being tested. We measure the reflection coefficient $S_{11}$ under different reverse
Figure 9. Experimental results of the absorption rates at different reverse bias voltages, ranging from 0 to $-19$ V. The dashed circle indicates the occurrences of the magnetic resonances.

bias voltages. Then we replace the MMA sample by a metallic plate with the same size and carry out the measurement again, which is used to remove the propagation loss and the potential interference from the surroundings.

The experimental results of absorption rates for the MMA sample are illustrated in figure 9, from which we notice that the bandwidth is 1.5 GHz (from 4.35 to 5.85 GHz) with the absorption rate more than 90% when the bias voltage changes from 0 to $-19$ V. The measured bandwidth is slightly wider than the simulation one. We also observe some small absorption peaks aroused by the magnetic resonances at lower frequencies, where the mechanism has been explained in the earlier section. By comparison, it is clear that the experimental results are consistent with the numerical simulations, which validate the tunability of the MMA.

5. Conclusions

We have designed and experimentally demonstrated an active MMA using ELC resonators and a varactor diode. The polarization-insensitive property is realized by placing the basic units orthogonally with excellent performance. The absorption frequency of the MMA can be controlled continuously by regulating the reverse bias voltage on the varactor diode. Both the simulation and the experimental results have verified the tunability of the absorber.

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