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ABSTRACT
This paper proposed a V-shaped metamaterial absorber to enrich the structure of the absorber and improve its absorbing efficiency. The structure is to print an inclined V-shaped copper-plated layer on the FR4 substrate and arrange them periodically. The absorber has two large absorption peaks, and the bandwidth with an absorption rate of more than 90% is 1.3 GHz. The origin of absorption mainly comes from reflection cancellation, followed by dielectric loss. The basic type of V-shaped absorber has excellent promotion space and application prospects. It can further optimize and expand the performance of absorber through three main forms: unit nesting, multi-unit array and multi-layer stacking. Based on the structure of unit nesting combination, the processing of experimental samples and the measurement of electromagnetic parameters were completed. The experimental results are in good agreement with the simulation results.

I. INTRODUCTION

The metamaterial is an artificial composite media with super physical properties.1 Its structure is generally composed of sub-wavelength size array elements that can tailor propagation characteristics of electromagnetic waves.2 Metamaterials have extraordinary electromagnetic properties that natural materials do not possess, using dielectric substrates and metal elements on both sides of the surface as the basic structure form,3 including split ring resonators (SRRs) or other types of current loops.4 They have broad application prospects and development potential in electromagnetic wave absorbing and shielding, communicating and imaging, sensing and detecting, information security, etc, pushing forward global advances in high-tech.5,6 Special electromagnetic properties such as negative refractive index, electromagnetic stealth,7 perfect prism8 and super absorption9 have been realized by using metamaterials. Since Landy et al. proved in 2008 that metamaterials can be used as electromagnetic wave absorbers, the concept of using metamaterials as electromagnetic wave absorbers has been popular in many fields such as radiation protection, radar stealth, electromagnetic interference prevention, etc. At present, various kinds of metamaterial absorbers have been designed. The working frequency bands of these absorbers are very wide, ranging from microwave,10,11 terahertz12 to light wave.13 According to the absorbing mechanism, metamaterial absorbers are mainly divided into dielectric loss type, resistance loss type and reflection cancellation type. Artificially designed metamaterial absorbers can achieve single-frequency, multi-frequency, broadband and even frequency modulation absorption effects in a specified frequency range by ingenious use of various losses. The common structural forms of metamaterial absorbers include metal resonant rings,14 cross-shape,15 petal-shape,16 H-shape,17 and ring-shape.18 But there are few basic types, complex structures and narrow base bandwidth, and other forms are mostly deformation or combination. In this paper, a V-shaped metamaterial absorber is proposed, which has excellent absorbing properties, and is easy to extend the application, so as to further improve its absorbing ability.

II. METHOD

As shown in Fig. 1, we plated copper on the upper and lower surfaces of FR4 substrates with a thickness of v=0.035 mm. The upper surface is a V shape. The external contour is an equilateral triangle with a side length b =4.56 mm. The internal contour is also
an equilateral triangle with a line width $c = 1.14$ mm. The geometric center coincides with the center of the unit and the rotation angle is $45^\circ$. The lower surface is completely copper plated to simulate the working interface. The FR4 substrate with a dielectric constant of 4.4 and a loss coefficient of 0.02 has a length and width $a = 8$ mm, and its thickness is 1.6 mm.

The frequency domain periodic analysis method of CST software was used to carry out simulation analysis. The boundary conditions are that the $x$ and $y$ directions are set as periodic boundaries and the transmission direction $z$ is set as open boundary. The $S$ parameters are obtained by simulation. Absorption rate of absorber is calculated by equation (1)

$$A(\omega) = 1 - R(\omega) - T(\omega),$$

where $R(\omega)$ and $T(\omega)$ represents reflectance and transmittance separately, and the corresponding expressions are $R(\omega) = |S_{11}|^2$, $T(\omega) = |S_{21}|^2$. For the absorber, the bottom layer is metal and the transmittance $T(\omega)$ is zero, so the absorption rate equation is simplified as $A(\omega) = 1 - R(\omega) = 1 - |S_{11}|^2$.

III. RESULTS AND DISCUSSION

When incident vertically, the simulated reflectance and absorption curves are shown in Fig. 2(a) at 10-30 GHz band. It can be seen that the absorption rates at 15.52 GHz and 27.24 GHz are 98.38% and 80.07% respectively, forming two large absorption peaks. From the main peak, the absorption rate at 14.92-16.22 GHz is more than 90%, the bandwidth is 1.3 GHz, the absorption rate at 14.64-16.66 GHz is more than 80%, and the bandwidth is 2.02 GHz. The bandwidth of common metamaterials is 0.25 GHz when the absorption exceeds 90% and 0.5 GHz when the absorption exceeds 80%, which shows the advantage of V-shaped absorber. At the same time, the absorption rate of the second absorption peak reaches 80%, and the bandwidth of V-shaped absorber is 4.62 GHz with the absorption rate exceeding 50%.

What is discussed above is the situation that the electromagnetic wave is vertically incident to the surface of the absorber. Considering the actual situation, there are some application scenarios of oblique incident of electromagnetic wave. For this reason, TM polarization is adopted to analyze the performance of the device under different zenith angles and azimuth angles in the polar coordinate.
system. As shown in Fig. 2(b) within the solid line, the group is the azimuth angle $\phi(0^\circ)$ remains unchanged, and the zenith angle $\theta$ is equal to 15° (green solid line), 30° (blue solid line) and 45° (red solid line), respectively. If the zenith angle $\theta$ increases gradually from 15° to 45°, the main peak and the second peak of absorption is decreased, but still keep clear potter absorption, even when $\theta$ is equal to 45°, the main peak absorption rate is over 70%. As shown in Fig. 2(c) within the dotted line, the group is the zenith angle $\theta(15^\circ)$ remains unchanged, and the azimuth angle $\phi$ is equal to 5° (green dotted line), 8° (blue dotted line) and 10° (red dotted line), respectively. If the azimuth angle $\phi$ increases from 5° to 10°, the peak value of the main peak decreases obviously, but the frequency point of the second absorption peak moves forward, and is divided into two stronger absorption peaks. When TE polarization is used, the results are basically consistent with the above results. Therefore, in order to maintain the excellent absorption performance of the main peak, the vertical incidence direction should be kept as far as possible, especially the azimuth angle should be as small as possible.

It should be emphasized that the absorption band of V-shaped metamaterial absorber is closely related to the size of the structure. By adjusting the structure size in equal proportion, the absorption band can be moved to the required application band. As shown in Fig. 3(a), when the size of the structure is reduced to one tenth of the size, the absorption curve at the frequency band of 100-300 GHz is exactly the same as the original basic shape; as shown in Fig. 3(b), when the size of the structure is two times of the size, the absorption curve at the frequency band of 5-15 GHz is exactly the same as the original basic shape. It also covers the commonly used X-band.

For the convenience of simulation and experiment, this paper studies the 8 mm unit structure, but the V-shaped metamaterial absorber could be adjusted in equal proportion to meet the work needs according to the application background. In addition, as shown in Fig. 3(c), when aluminium metamaterial is selected, the absorption curve is completely consistent with the original copper metamaterial, which shows that the absorber has good adaptability to different metal materials.

Based on the different absorption mechanism of metamaterial absorber, different techniques are adopted to verify the specific path of electromagnetic energy conversion. Firstly, dielectric loss comes from the imaginary part of dielectric constant of dielectric plate material, which can be set by the tangent value $\tan\delta$ of dielectric loss angle. Secondly, the resistance loss comes from the inherent resistance characteristics of conductors, which can be set by metal material parameters. Finally, the reflection cancellation comes from the phase difference between the incident wave and the reflected wave, which can be observed by the phase angle of the input reflection parameter $S_{11}$.

According to the above principles, we make the following analysis. Firstly, in order to eliminate the effect of dielectric loss on the absorption effect, assuming that the original V-shaped copper plating is matched with the lossless FR4 dielectric plate, the simulation curve is shown by the blue solid line in Fig. 4(a), which shows that the absorption effect is weakened in the area outside the wave crest, indicating that dielectric loss plays a certain role, but has little effect in the position of the wave crest. Secondly, in order to eliminate the influence of resistance loss on the absorption effect, it is assumed
that the perfect electric conductor (PEC) is combined with the original FR4 dielectric plate, and the simulation curve is shown by the green dotted line in Fig. 4(a). It can be seen that the absorption effect has no change in the whole region, indicating that the resistance loss has little effect. Finally, from the equation (2) of $S_{11}$,

$$S_{11} = \frac{U_r(z)}{U_i(z)} = \left| \frac{U_r(z)}{U_i(z)} \right| e^{j(\phi_r - \phi_i)},$$

(2)

where $U_r(z)$ and $U_i(z)$ represent the reflected wave voltage and the incident wave voltage of the input port respectively, and $\phi_r - \phi_i$ is the phase difference between the reflected wave and the incident wave voltage, that is to say, the phase of $S_{11}$ reflects the phase difference between the incident wave and the reflected wave of the input port. As can be seen from Fig. 4(b), at the 15.52 GHz frequency point where the main absorption peak is located, the phase of $S_{11}$ is -180°. Therefore, reflection cancellation can be realized when the phase of the reflected wave is opposite to that of the incident wave at the input port. This phase difference also arises from the fact that the thickness of the reflecting layer of the absorber satisfies the quarter wavelength equation (3)

$$nh = \frac{mc}{f_{AR}},$$

(3)

where $n$ is the refractive index of the reflection cancellation layer, $h$ is the thickness of the reflection cancellation layer, $c$ is the speed of light in vacuum, $f_{AR}$ is the characteristic frequency, $m$ is the positive odd number. Then, after the incident and reflection inside the absorber, the electromagnetic wave generates half wavelength, that is, the phase difference of 180°. Equation (3) also shows that the characteristic frequency $f_{AR}$ is inversely proportional to the thickness of the absorber. When the thickness $h$ increases, the absorption peak moves to the left and the absorption spectrum is redshifted. In addition, we also studied the electromagnetic field characteristics at the position of the main peak of 15.52 GHz. Fig. 4(c) shows that the electric field intensity in the three sharp corners of the upper surface is stronger, the magnetic field intensity in the concave part is stronger, and the energy loss density is mainly concentrated in the position of the concave and the two arms. Therefore, there is also a
certain degree of electric resonance and magnetic resonance on the surface of V-shaped metal, and energy loss occurs. But as mentioned earlier, this is not the main factor of absorbing wave.

IV. EXTENDED APPLICATION

In view of the excellent absorbing properties of the basic type of V-shaped absorber, three common extended structures are studied. Firstly, the metal layer of the same structural unit is nested. Secondly, the units of different sizes are arrayed. Thirdly, the multi-layer of metal and dielectric layer is stacked. The first structure, as shown in Fig. 5(a) on the left, is nested by two V shapes on the base of the original unit. The original V shape moves 1 mm in the direction of 45° to the left, the second V shape is 0.645 times the original size and moves 1.8 mm in the direction of 45° to the right. The second structure, as shown in Fig. 5(a) in the middle, is planar arrays arranged in a 2-by-2 layout. This group of cells as a whole is a periodic unit. By enlarging the two V shapes on a diagonal line to 1.07 times the original size, a "1221" structural layout is formed to ensure that the structure around each V shape is different from itself. The third structure, as shown in Fig. 5(a) on the right, adopts two-layer stacked form. The substrate thickness of the underlying structure is 1.2 mm, and the dimension of the upper surface is 1.18 times the original size. The substrate thickness of the upper structure is 0.6 mm, and the upper surface is a hollow square with 45° rotation, with an outer length 2.42 mm and an inner length 1.34 mm. The distance from lower surface of the upper substrate to the upper surface of the lower substrate is 0.8 mm. All the thickness of the coating is unchanged.

The absorption curves of three extended structures are shown in Fig. 5(b). By way of unit nesting (blue dotted line), the spatial utilization efficiency of the structure is high, and the frequency range of the absorber is greatly expanded. The frequency band area with the absorption rate exceeding 50% accounts for nearly 90%, but the peak values of each absorption peak should be increased. By way of multi-unit array (red dotted line), cross-combination of different units is required, which can decompose a main peak into three absorption peaks, but the bandwidth expansion is limited. By way of multi-layer stacking (green dotted line), the frequency range of the absorber can expand while maintaining the absorption performance of the absorption peak, and the bandwidth with an absorption of over 80% increases from 2.02 GHz to 4.52 GHz. Attention should be paid to making full use of the upper structure to complete the initial large-band absorption, and create conditions for the bottom secondary absorption. For multi-layer structure, the difficulty is that the processing requirements are high and the installation and alignment are complex.

V. EXPERIMENTAL VERIFICATION

Selecting the unit nesting method of single-layer structure, a 20 cm edge experimental plate is fabricated, which is 25-by-25 V-shaped units array plates, as shown in Fig. 6(a). The free space method is used to measure the absorbing characteristics of the absorber. The electromagnetic parameters of the metamaterial are measured by KEYSIGHT E5071C vector network analyzer. Due to the limitation of experimental conditions, only 10-18 GHz frequency range is measured. The experimental results are shown in Fig. 6(b), which are in good agreement with the simulation results.

VI. CONCLUSION

The V-shaped metamaterial is an excellent basic type of absorber, which has two absorption peaks, large bandwidth and high peak value. When the structure size is reduced in equal proportion, the absorption band shifts to the high frequency region, the shape of absorption curve remains unchanged, and the bandwidth enlarges proportionally. In the case of oblique incidence, it is not sensitive to zenith angle θ, but sensitive to azimuth angle φ. Through the analysis of the absorbing mechanism, it is found that the origin of absorption mainly comes from reflection cancellation. The energy loss in the concave and arm positions of the V-shaped metal surface is relatively concentrated. The performance analysis of three main extended structures shows that the unit nesting structure has high spatial utilization efficiency and large absorption bandwidth. The multi-layer stacking structure can satisfy perfect absorption effect in a certain frequency band. For different application scenarios in the future, the improvement and optimization of V-shaped structure and its extended forms still have great potential.

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