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Design of transparent broadband double-sided absorbing metamaterial*

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By designing the ordered structure on the key physical dimensions, metamaterial can obtain extraordinary physical properties. The method gives transparent conductive absorbing metamaterial with broadband and high absorptivity. In this paper, a kind of absorbing metamaterial with indium tin oxide (ITO) glass substrate is designed. The design method of double-sided etched an open loop and linear metamaterial periodic structures is adopted. The thickness of the absorbing metamaterial is 2.5 mm. The research shows that the working bandwidth is between 8.9 GHz and 17.4 GHz, the absorption rate is 90%, and the transmittance of visible light is 85% on average. The absorbing metamaterial has wide application value to solve the problem of visualization and absorption characteristics.

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With the rapid development of modern electromagnetic technology, the working bandwidth of electromagnetic waves has been continuously widened, which has caused serious electromagnetic interference (EMI)[1-3]. EMI has become the fourth largest source of pollution after air pollution, water and noise. Windows of aircraft are one of the strongest scatteloop sources that show the radar electromagnetic characteristics. Cockpit stealth has become the key part of overall stealth of aircraft. Existing cockpits technology mostly adopts the shape stealth design based on a transparent conductive film, which cannot achieve all-round stealth of the aircraft. Therefore, the high-performance absorbing materials is of great significance in military stealth, information security, civil protection and other aspects[4-6].

Metamaterials are referred to as a special composite material or structure[7-9]. By designing the ordered structure on the key physical dimensions of materials, metamaterial can obtain extraordinary physical properties (the negative refraction, inverse doppler effect, and perfect lens, etc.) that conventional materials do not have. In recent years, researchers have been carried out many researches on absorbing metamaterials[10-12]. Jang et al[10] designed the functional integration material of absorbing and shielding. The upper layer is butterfly-shaped metamaterial structures with a metal mesh, the middle layer uses transparent flexible material as the medium and the bottom layer is a metal mesh that prevents electromagnetic waves from passing. Experiments show the absorption rate is greater than 90% at 8—12.2 GHz. Hong et al[11] designed a single-layer dielectric absorbing metamaterial. The upper layer is square-shaped metamaterial structures based on indium tin oxide (ITO) film, the middle layer is glass, and the bottom layer is a low-resistance ITO film. Experiments show that absorption rate is greater than 90% at 7.9—9.7 GHz, and the transmittance is 89%. Cai Qiang et al[12] designed a three-layer structure of graphene metamaterial layer, air layer and metal layer. Electromagnetic waves are bound in absorbing metamaterial to realize high absorption rate and broadband characteristics. However, with the rapid development of communication systems, the working bandwidth of absorbing metamaterial still cannot meet the application requirements.

At present, the methods to broaden the bandwidth mainly include three methods: loading lumped elements[13], multi-layer stack structure[14], and multi-cell structure[15]. The first and second methods will increase the thickness of the absorbing material, and the preparation process is complicated. The third method uses the principle of multiple absorption peaks to broaden the bandwidth, and does not increase the thickness of the absorbing metamaterial. In this paper, a novel two-sided absorbing metamaterial structure is designed. The measured results show that the working bandwidth is 8.9—17.4 GHz, the absorption rate is up to 90%, and the visible light transmittance was 85%. The absorbing material has the characteristics of broadband, ultra-thin and light transparent.

The general principles of the design of absorbing materials are as follows: according to the transmission theory of electromagnetic wave and the loss mechanism in

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the dielectric layer, the electromagnetic parameters and structural sensitive parameters are reasonably selected to match the input impedance and the wave impedance of air, and the absorbing materials of specific working bandwidth are designed according to the requirements. Among them, the input impedance and air wave impedance are calculated as

$$R(\omega)=\frac{Z(\omega)-Z_0}{Z(\omega)+Z_0}, \tag{1}$$

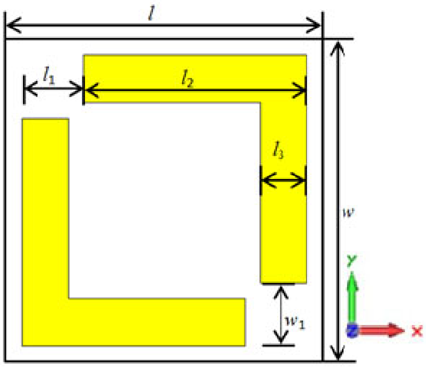
$$Z(\omega)=\sqrt{\frac{\mu(\omega)}{\varepsilon(\omega)}}, \tag{2}$$

$$\varepsilon(\omega)=\varepsilon'-\mathrm{j}\varepsilon'', \tag{3}$$

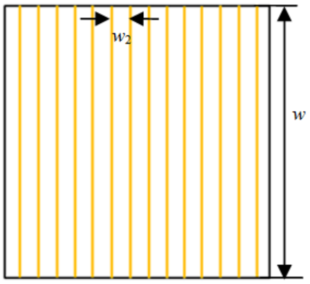
$$\mu(\omega)=\mu'-\mathrm{j}\mu'', \tag{4}$$

where $R(\omega)$ is the reflectivity, $Z(\omega)$ is the wave impedance, Z_0 is the wave impedance in the air, $\varepsilon(\omega)$ is the permittivity, $\mu(\omega)$ is the permeability, ε' and μ' are respectively represents the degree of magnetization and polarization, ε'' and μ' represent the measurements of magnetic loss and electrical loss, respectively. Therefore, the energy loss of the absorbing material is closely related to ε'' and μ''. When selecting the absorbing material, the larger the ε'' and μ'', the better.

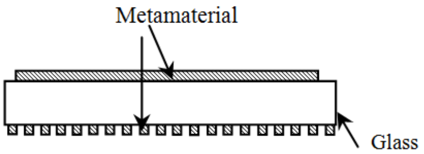
In this paper, an open-loop and linear metamaterial periodic structure ITO film-based light-transmitting broadband absorption material is designed. Through electromagnetic simulation and sensitive parameter analysis, the broadband characteristics of the absorbing material are obtained. The schematic diagram of double-sided absorbing metamaterial is shown in Fig.1. The absorbing material includes three layers. The first layer uses a open-loop structure based on ITO film, the second layer uses a glass substrate, and the third layer uses many liners structure based on ITO film. The permittivity of the substrate is 4.8, the thickness is h, and the loss tangent is 0.005 4. The square resistance of ITO film is S. The unit structure parameters are: h=2.5 mm, S=30 $\Omega/\square$, l=8.4 mm, w=8.4 mm, l_1=1.6 mm, l_2=5.8 mm, l_3=1.2 mm, w_1=1.6 mm and w_2=0.6 mm.



(a) Top view



(b) Bottom view



(c) Side view

Fig.1 Structure of double-sided absorbing metamaterial

The absorption rate is an important parameter that reflects the quality of the absorbing material. The higher the absorption rate and the wider the absorption bandwidth is, the better the absorption performance. For the absorbing metamaterial, the absorption rate is:

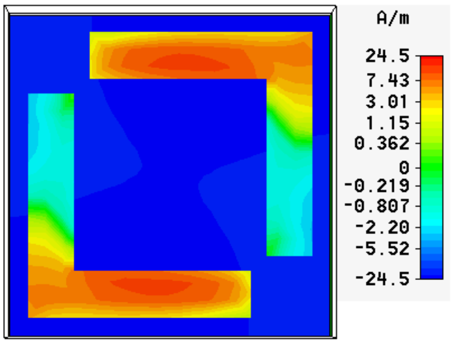
$$A(\omega)=1-T(\omega)-R(\omega), \tag{5}$$

where $A(\omega)$ represents the absorption rate, $T(\omega)$ represents the transmittance, and $R(\omega)$ represents the reflectivity. $T(\omega)=|S_{21}|^2$, $R(\omega)=|S_{11}|^2$, where S_{11} is determined by the matching between input impedance and air wave impedance, and S_{21} is the loss of electromagnetic waves in the absorbing material. The back is made of metal, so $T(\omega)$ is approximately 0. In the same working bandwidth, if S_{11} all approaches 0, then $A(\omega)\approx 1$ can achieve high absorption.

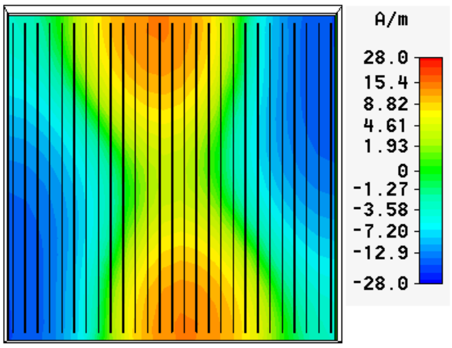
Based on Computer Simulation Technology (CST) as shown in Fig.1(a), the X-axis and Y-axis are set as periodic boundaries, the Z-axis direction is set as an open boundary, and the electromagnetic wave incident direction is along the Z-axis. Through modeling and electromagnetic simulation of the double-sided absorbing metamaterial, the current distribution and sensitive parameters were obtained by the simulation.

The surface current distribution of the double-sided absorbing metamaterial is shown in Fig.2. Among them, Fig.2(a) and Fig.2(b) show the current intensity when the resonance point is at f_1 (9.0 GHz) and f_2 (15.0 GHz), respectively. It can be seen from Fig.2(a) that the current intensity is concentrated on the open-loop structure, so the first resonance point f_1 is generated by the split loop structure; the current intensity is concentrated on the linear metamaterial structure in Fig.2(b), so the second resonance point f_2 is generated by the linear structure. Therefore, by changing the sizes of split loop structure and linear structure, the current intensity can be changed and the absorption rate of f_1 and f_2 can be regulated.

By changing the structural parameters l_1, l_2, l_3, w_2, S and h of the metamaterial structures, the influence of sensitive parameters on the absorption characteristics is studied in Fig.3. When the gap length l_1 is gradually increased from 1.4 mm to 1.8 mm in steps of 0.2 mm, the matching performance at f_1 becomes better, and the working bandwidth of 90% absorption rate first became wider and then narrower. when the length l_2 increases from 5.4 mm to 6.2 mm in steps of 0.4 mm, the matching performance and working bandwidth are almost not affected. When the width l_3 is gradually increased from 0.8 mm to 1.6 mm in steps of 0.4 mm, the matching performance and working bandwidth are almost not affected. when the distance w_2 is gradually decreased from 1.0 mm to 0.2 mm in steps of 0.4 mm, the matching performance at f_2 becomes better, the working bandwidth of 90% absorption rate first becomes wider and then narrower. when the square resistance S gradually increases from 20 Ω/□ to 40 Ω/□ in steps of 10 Ω/□, the matching performance of the absorbing material gradually becomes better, 90% absorption rate working bandwidth first widens and then narrows. when the thickness h is gradually increased from 2.0 mm to 3.0 mm in steps of 0.5 mm, the matching performance becomes better, the working bandwidth of 90% absorption rate first becomes wider and then narrower. The research shows that the slot length l_1, the distance w_2, the square resistance S and the thickness h of the metamaterial structures are the main parameters that affect the absorption characteristics.

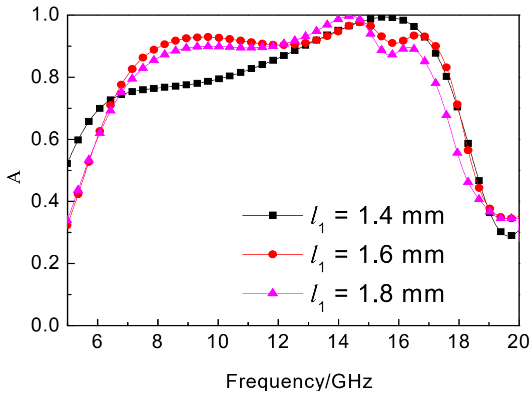


(a) f_1

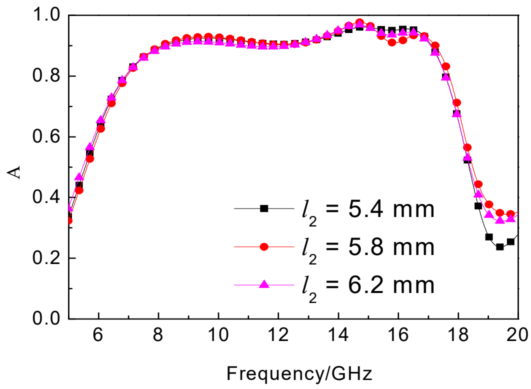


(b) f_2

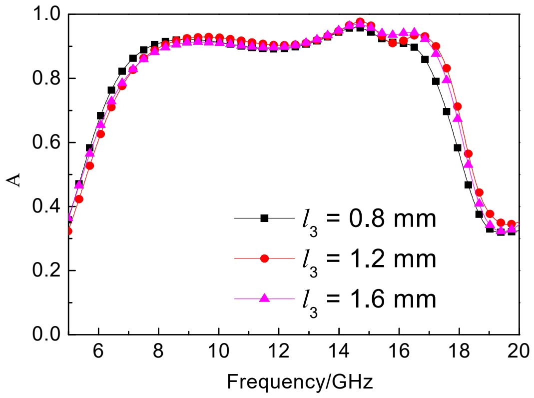
Fig.2 Surface current distribution of double-sided absorbing metamaterial



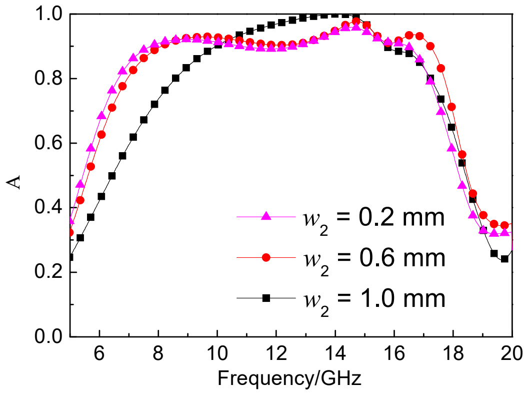
(a) Absorption rate for different l_1



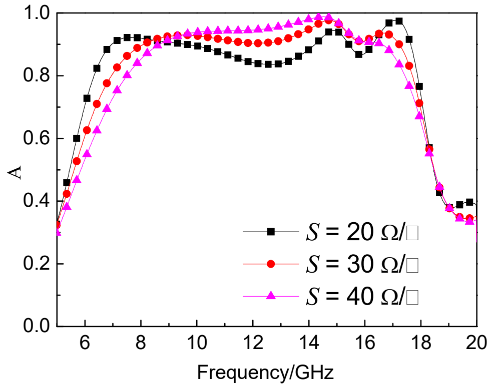
(b) Absorption rate for different



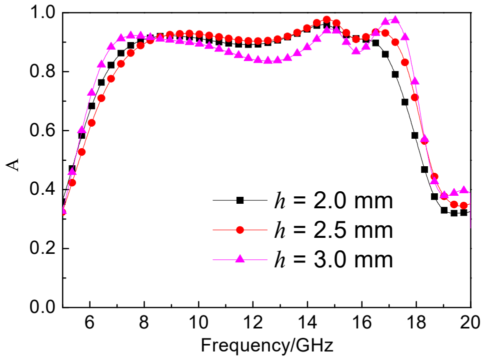
(c) Absorption rate for different



(d) Absorption rate for different



(e) Absorption rate for different *S*



(f) Absorption rate for different *h*

Fig.3 Influence of sensitive parameters on the absorbing metamaterial

The optimized parameters are h=2.5 mm, S=30 Ω/□, l=8.4 mm, w=8.4 mm, l_1=1.6 mm, l_2=5.8 mm, l_3=1.2 mm, w_1=1.6 mm and w_2=0.6 mm. The reflection coefficient of absorbing metamaterial obtained by simulation is shown in Fig.4. When the reflection coefficient meets −10 dB, the working bandwidth is 8.0—17.2 GHz. The maximum reflection coefficient is −18dB. The absorption characteristics is shown in Fig.5. When the absorption rate is higher than 90%, the working bandwidth is 8.0—17.2 GHz. The absorption rate is 99% at 15 GHz, and the working bandwidth covers the X (8.0—12 GHz) and Ku (12—17.2 GHz).

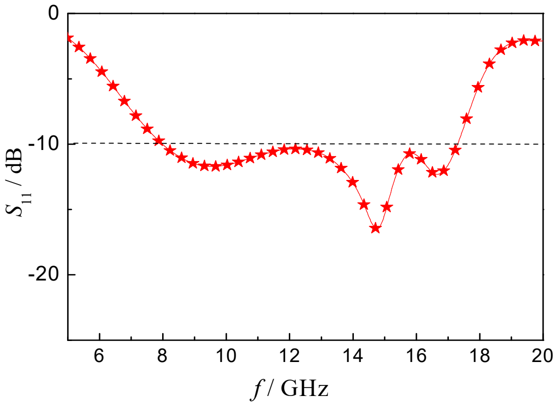


Fig.4 Reflection coefficient of absorbing material

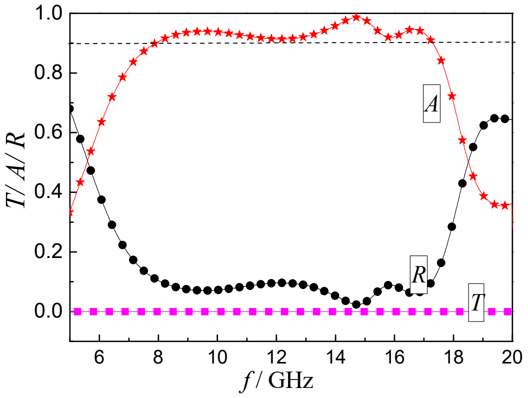


Fig.5 Absorption characteristics of absorbing material

According to the simulation optimization, the sample structure parameters of the absorbing metamaterial unit are: h=2.5 mm, S=30 Ω/□, l=8.4 mm, w=8.4 mm, l_1=1.6 mm, l_2=5.8 mm, l_3=1.2 mm, w_1=1.6 mm and w_2=0.6 mm. The two-sided ITO films with square resistance of 30 Ω/□ were deposited by magnetron sputteloop equipment. The laser etching equipment was used to accurately locate the relative position of the double-sided metamaterial structure, and the sample size was 180 mm×180 mm. The dielectric constant of the substrate is 4.8 and the thickness of the sample is 2.5 mm. The photo of double-sided absorbing metamaterial is shown in Fig.6.

Fig.6 Photo of double-sided absorbing metamaterial

The reflectivity of the absorbing material is measured by the bow device. The device is composed of Agilent E8386 vector network analysis instrument and rectangular horn antenna. The schematic diagram of the reflectivity test device is shown in Fig.7. The measured result of reflection coefficient is shown in Fig.8. It can be seen that the −10 dB working bandwidth is 8.9—17.4 GHz, and the maximum reflection coefficient is −22 dB. It covers the X-band (8.9—12.0 GHz) and Ku-band (12.0—17.4 GHz). The measured absorption characteristics are shown in Fig.9. when the absorption rate is higher than 90%, the working bandwidth is 8.9—17.4 GHz. The visible light transmittance was 85%.

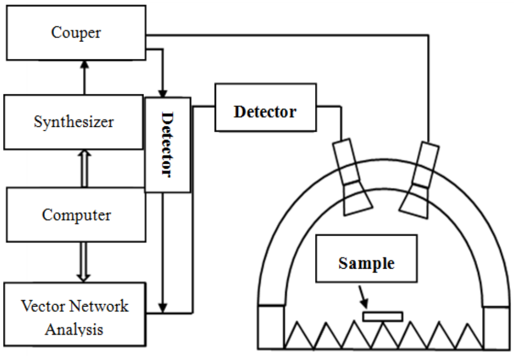


Fig.7 Schematic diagram of test device

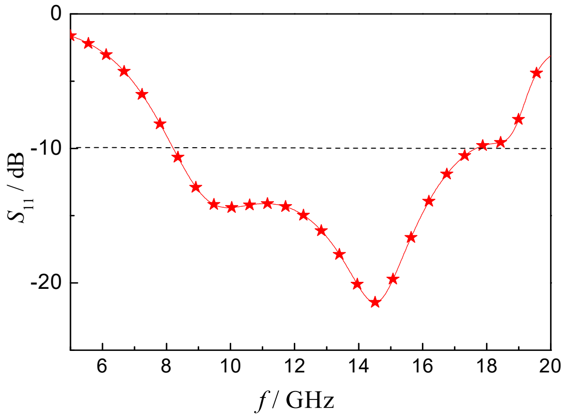


Fig.8 The measured result of reflection coefficient

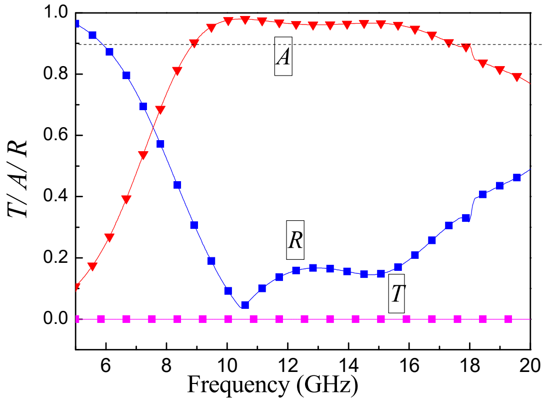


Fig.9 Measured results of absorption characteristics

Compared with the simulation results, the measured results show that the resonance points and working bandwidth all shift toward high frequency. The main reason may be the relative positional deviation from upper and lower metamaterial unit, or the insufficient machining accuracy of the metamaterial structure.

In this paper, a transparent wideband absorbing material is designed. The upper and lower layers are excited separately to produce dual-band resonance, which broadens the working bandwidth. The upper layer adopts an open-loop metamaterial structure, and lower layer adopts liners metamaterial periodic structure. The measured results show that the working bandwidth are in X-band and Ku-band, the absorption rate is up to 90%, and the visible light transmittance was 85%. The absorbing material has the characteristics of broadband, ultra-thin and light transparent.

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