Design of a double-layer high transmittance broadband graphene absorbing metamaterial*

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In this paper, an optically transparent broadband absorbing metamaterial is designed for electromagnetic protection and stealth for visible parts of ships. Based on the coupling resonance loss of double-lay metamaterial structure, the new absorbing material realizes broadband characteristics. Based on the photoelectric compatibility characteristics of graphene thin films, the new absorbing material realizes high transmittance characteristics. The measured results show that when the absorbing rate is higher than 90%, the bandwidth of the absorbing metamaterial is 7.95—18.65 GHz, covering X-band (7.95—12 GHz) and Ku-band (12—18.65 GHz), and the visible light transmittance is 85%. The design and preparation of new absorbing material can solve electromagnetic compatibility (EMC) design problems of high transmittance and broadband. It can be widely used in observation windows of ships, aircraft and reconnaissance control vehicle, display terminal of the information system.

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With the rapid development of radar detection technology and wireless communication technology, efficient electromagnetic protection and stealth absorbing materials have been widely used in the fields of electronics, navigation, aerospace, communication, etc[1-3]. The visible position of a ship is one of the three strongest scattering sources to display radar features. The traditional methods mostly use transparent conductive film to realize the appearance stealth, but it cannot achieve the overall electromagnetic protection of a ship. Currently absorbing material according to the molding process and the bearing capacity is mainly divided into two categories, namely type coating absorbing materials and structural absorbing materials. The coating absorbing materials are based on the magnetic loss and electricity loss to realize porter absorption of conductive film[4-6], with a strong adaptability, easy to use, shape and density, easy to fall off. The structural absorbing materials realize coupling resonance loss based on the characteristics of periodic structural coupling resonance, and have the characteristics of light weight, broadband and ultra-thin thickness[7-9]. Therefore, the development of high efficiency absorbing materials is important in military stealth, information security, civil protection and other aspects.

The transparent electromagnetic absorbing metamaterial based on graphene, as a new type of structure with dielectric constant, permeability and operating frequency, can be designed, and has a series of strange electromagnetic properties such as negative dielectric constant, negative phase velocity and inverse Doppler effect[10-12]. GRANDE et al[13] proposed a double-sided graphene film absorbing material based on the principle of Salisbury screen, which realized the absorption of more than 80% in the 8.5—9.5 GHz band with the thickness of a quarter wavelength, and the measured light transmittance was more than 80%. LEE et al[14] proposed a transparent radar absorbing material with a composite design of metal grid and carbon nano film, which achieved a resonant frequency of 11.2 GHz, a bandwidth of 4.28 GHz and a visible light transmittance of 81.3%. JANG et al[15] proposed a reconfigurable absorbing material composed of polyethylene tereiformate cool film, polydimethylsiloxane medium and aluminum metal grid. The absorption rate in the operating band of 5.8—12.2 GHz was 90%, and the light transmittance was 62%, realizing the design and preparation of low frequency band and strong absorbing wave. LU et al[16] realized 86.69% absorption and 90% light transmittance in the working band 18—26 GHz by using the combination of metasurface graphene/PET laminate structure, which improved the light transmittance. CAI et

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al[17] used the composite of carbon nano-metamaterial structure layer, air layer and metal layer to realize the electromagnetic wave to oscillate between the metal layer and graphene metamaterial structure layer for many times to expand the absorption bandwidth, but the light transmittance was low. But the large size, narrow frequency band and low light transmittance of transparent metamaterials still cannot meet the application requirements.

In this paper, a double-layer high transmittance broadband graphene absorbing metamaterial is designed for electromagnetic protection and intelligent stealth in the visible part of a ship. A double-layer periodic composite absorbing structure is simulated by computer simulation technology (CST). The effects of metamaterial unit pattern, geometrical parameters, period size and incident angle on the reflectance performance of absorbing metamaterial were studied by the design of electrical matching between structural parameters and electromagnetic parameters. Simulation and test results show that the periodic absorbing structure based on metamaterial can form multiple absorption peaks in the microwave band, which can broaden the absorption bandwidth of the absorbing material.

By absorbing the incident electromagnetic wave directly, the absorbing material achieves the target stealth, including the impedance matching characteristics and attenuation characteristics. Based on the transmission line theory, the impedance matching characteristics of the absorbing material were calculated. By designing the multilayer material and the size of free space, the incident electromagnetic wave could enter the material to the maximum extent and realize the low reflection of electromagnetic wave. By using lossable medium or structural design, the electromagnetic wave entering the material is absorbed and attenuated, satisfying the attenuation characteristics of the absorbing material.

Transmission line theory is an important theoretical basis for the design of absorbing materials, which is widely used because of its simplicity, accuracy and reliability. According to the transmission line theory, the input impedance of the absorbing material can be calculated by establishing the transmission line model, which can conveniently calculate the input impedance and reflectance of the absorbing material in the case of vertical incidence. If the electromagnetic wave is oblique incident, it is difficult to calculate the input impedance and reflectance of the absorbing material through the traditional transmission line model. Therefore, in order to accurately calculate the impedance of the absorbing material, the vector transmission line model is proposed in this paper.

According to the transmission line theory, the input impedance of the first layer medium is $Z_{in}^{(1)}$, and the equivalent input impedance of the second layer material and the first layer medium is $Z_{in}^{(2)}$,

$$Z_{\mathrm{in}}^{(1)} = \eta_1 \tanh(\mathrm{j}k_1 d_1), \tag{1}$$

$$Z_{\mathrm{in}}^{(2)} = \eta_2 \frac{Z_{\mathrm{in}}^{(1)} + \eta_2 \tanh(\mathrm{j}k_2 d_2)}{\eta_2 + Z_{\mathrm{in}}^{(1)} \tanh(\mathrm{j}k_2 d_2)}. \tag{2}$$

The reflection coefficient at the first boundary is

$$R = \left| \frac{Z_{\mathrm{in}}^{(2)} - 1}{Z_{\mathrm{in}}^{(2)} + 1} \right|, \tag{3}$$

where η is the characteristic impedance, k is the propagation constant and d is the dielectric thickness. By substituting Eq.(1) into Eq.(2), it can be obtained that

$$Z_{\mathrm{in}}^{(2)} = \frac{\eta_1 \tanh(\mathrm{j}k_1 d_1) + \eta_2 \tanh(\mathrm{j}k_2 d_2)}{1 + \dfrac{\eta_1}{\eta_2} \tanh(\mathrm{j}k_1 d_1) \tanh(\mathrm{j}k_2 d_2)}. \tag{4}$$

The nth layer material and the medium of $Z_{in}^{(n-1)}$ can be considered as a medium with an input impedance of $Z_{in}^{(n)}$,

$$Z_{\mathrm{in}}^{(n)} = \eta_n \frac{Z_{\mathrm{in}}^{(n-1)} + \eta_n \tanh(\mathrm{j}k_n d_n)}{\eta_n + Z_{\mathrm{in}}^{(n-1)} \tanh(\mathrm{j}k_n d_n)}. \tag{5}$$

It can be seen from Eqs.(1)—(5) that adjusting the η, k and d of the multilayer material can reach $Z_{in}^{(n)} \to 1$ and a lower reflectivity. In order to design suitable metamaterial structure absorbing material, η, k and d can be changed to achieve a better matching combination and achieve the absorbing performance.

Based on the attenuation characteristics of the absorbing material, a double-layer absorbing etamaterial with double L-shaped structures on the upper layer and four L-shaped structures on the lower layer is proposed. The structure of the absorbing metamaterial is shown in Fig.1. The metamaterial comprises the double dielectric layers and the double conductive layers structure. The first conductive layer is double L-shaped metamaterial unit structure etched on the graphene film with central symmetry, and the square resistance is S_1. The first dielectric layer is glass substrate with thickness of h_1. The second conductive layer is four L-shaped metamaterial unit structure etched on the graphene film with symmetry on the X axis and Y axis, and the square resistance is S_2. The second medium layer is glass medium substrate with thickness of h_2, and the back is aluminum plate. And the square resistances S_1 and S_2 of graphene film are both 50 Ω/sq, the dielectric constant of the glass is 4.8, the thicknesses of h_1 and h_2 are 0.7 mm and 2 mm, respectively, and the tangent of the loss angle is 0.005 4. l and w represent the length and width of the periodic structure, respectively, l_1 is the upper unit arm length, w_1 is the upper unit arm width, l_2 is the lower unit arm length and w_2 is the lower unit arm width.

The electromagnetic characteristics of the double-layer absorbing metamaterials were simulated by CST, and the boundary conditions of X-axis and Y-axis were established as unit cell and that of Z-axis as open (add space). The finite difference time domain (FDTD) method is widely used in solving electromagnetic problems. By selecting the initial value conditions and boundary conditions reasonably and effectively, the four-dimensional numerical solution of Maxwell equations related to time variables can be calculated. The Fourier transform is used to get the three dimensional frequency domain solution. The high-frequency simulation software CST used in this project is developed based on FDTD algorithm, which has the characteristics of fast operation speed and accurate numerical calculation.

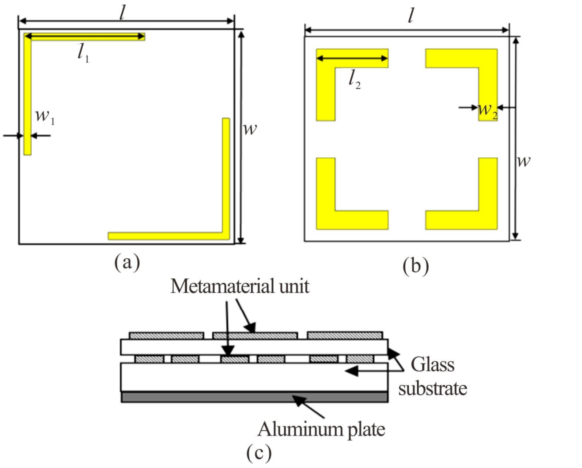
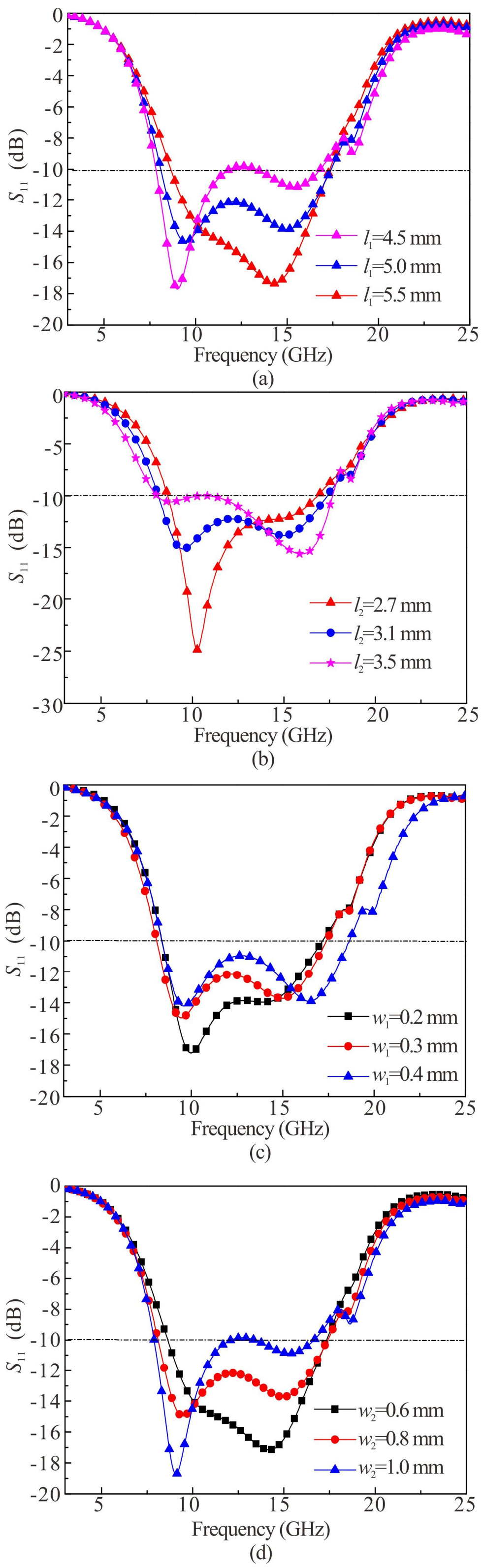


Fig.1 Structure of absorbing metamaterial: (a) The first metamaterial layer; (b) The second metamaterial layer; (c) The side view

As shown in Fig.2, by changing the structural parameters l_1, l_2, w_1, w_2, h_1 and h_2 of the absorbing metamaterial, the sensitive parameters affecting the reflectivity of the absorbing metamaterial were obtained. When the upper metal arm length l_1 increases from 4.5 mm to 5.5 mm by a step length of 0.5 mm, the −10 dB operating bandwidth first becomes wider and then narrower, and the matching characteristics of the low-frequency resonant point f_1 gradually become worse, and those of the high-frequency resonant point f_2 gradually become better. When the length of the lower metal arm l_2 increases from 2.7 mm to 3.5 mm by a step length of 0.4 mm, the operating bandwidth of −10 dB reflectance first widens and then narrows, and the matching characteristics of f_1 gradually become worse and those of f_2 gradually become better. When the upper metal arm width w_1 increases from 0.2 mm to 0.4 mm by the step length of 0.1 mm, the operating bandwidth of −10 dB reflectance gradually widens, the matching characteristics of f_1 gradually deteriorate and those of f_2 almost remain unchanged. When the width of the lower metal arm w_2 increases from 0.6 mm to 1.0 mm by the step length of 0.2 mm, the operating bandwidth of −10 dB reflectance first widens and then narrows, and the matching characteristics of f_1 gradually get better and those of f_2 gradually deteriorate. When the thickness of the upper medium layer h_1 increases from 0.5 mm to 0.9 mm by the step length of 0.2 mm, the operating bandwidth of −10 dB reflectance gradually becomes narrower, the matching characteristics of f_1 gradually become better and those of f_2 gradually become worse. When the width of the lower metal arm h_2 increases from 1.8 mm to 2.2 mm by the step length of 0.2 mm, the operating bandwidth of −10 dB reflectance first widens and then narrows, and the matching characteristics of f_1 gradually get better and those of f_2 gradually deteriorate. The results show that the upper metal arm length l_1, the lower metal arm length l_2, the upper metal arm width w_1, the lower metal arm width w_2, the upper medium layer thickness h_1 and the lower metal arm width h_2 are all sensitive parameters affecting the reflectivity of the absorbing material.



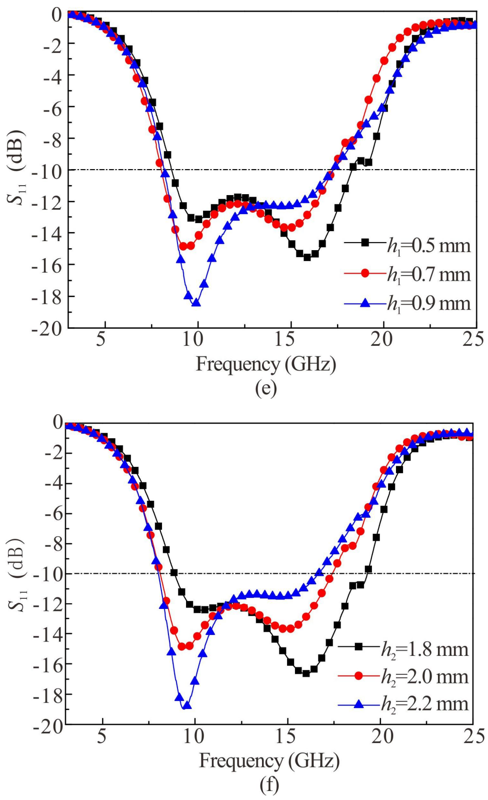


Fig.2 Reflection coefficients for (a) different l_1, (b) different l_2, (c) different w_1, (d) different w_2, (e) different h_1, and (f) different h_2

By considering the operating bandwidth and matching characteristics of the double-layer absorbing metamaterial, the optimized structural parameters of the metamaterial unit are obtained as follows, l=8.9 mm, w=8.9 mm, l_1=5.0 mm, l_2=3.1 mm, w_1=0.3 mm, w_2=0.8 mm, h_1=0.7 mm, and h_2=2.0 mm. Fig.3 shows the reflection coefficients of the material. As shown in Fig.3, the −10 dB operating bandwidth of the absorbing metamaterial is 8—18 GHz, and the peak reflection coefficient is −16 dB. Fig.4 shows the absorption curve of the absorbing metamaterial. As shown in Fig.5, the absorption rate of the operating bandwidth is higher than 90% in the range of 8—18 GHz, covering the X-band (8—12 GHz) and Ku-band (12—18 GHz).

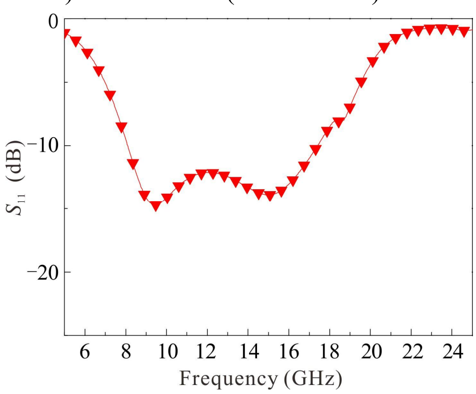


Fig.3 Reflection coefficients of the absorbing metamaterial with optimized structural parameters

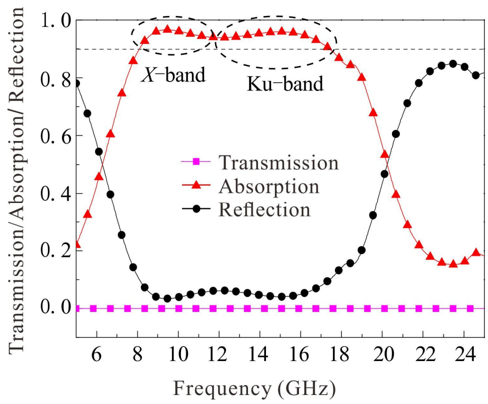


Fig.4 Transmission, absorption and reflection curves of the absorbing metamaterial

In order to explore the source of the dual-band absorption peak, the current intensity distribution of the absorbing material at the absorption peak is monitored, as shown in Fig.5. Fig.5(a) and (b) show the current intensity distribution of the upper double L-shaped absorbing metamaterial, and Fig.5(c) and (d) show the current intensity distribution of the lower four L-shaped absorbing metamaterial. According to Fig.5, when the resonant point works at 9.5 GHz, the current intensity is concentrated at the horizontal and vertical arm strengths of four L-shaped absorbing metamaterial. When the resonant point is operated at 15 GHz, the current intensity is concentrated at the horizontal and vertical arm strengths of the double L-shaped absorbing metamaterial. Therefore, the first resonant point is excited by the lower four L-shaped metamaterial, and the second resonant point is excited by the upper double L-shaped metamaterial.

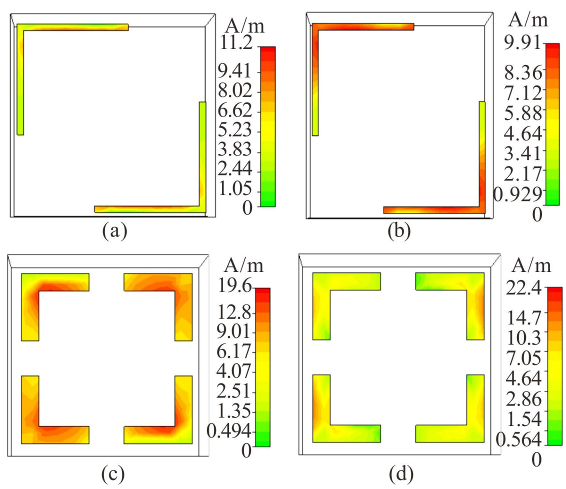


Fig.5 Surface current density distributions at (a) 9.5 GHz and (b) 15 GHz for the upper double L-shaped absorbing metamaterial; Surface current density distributions at (c) 9.5 GHz and (d) 15 GHz for the lower four L-shaped absorbing metamaterial

As shown in Fig.6, when the incident angle is 0°, 10°, 20° and 30°, the absorbing performance curve is obtained. With the increase of incident angle, the position of low-frequency resonance point f_1 does not change significantly, the resonance intensity gradually decreases from 15 dB to 12 dB, and the absorbing performance gradually deteriorates. At the high frequency resonance point f_2, the resonance intensity gradually increases from 13 dB to 14.5 dB, and the absorbing performance gradually gets better.

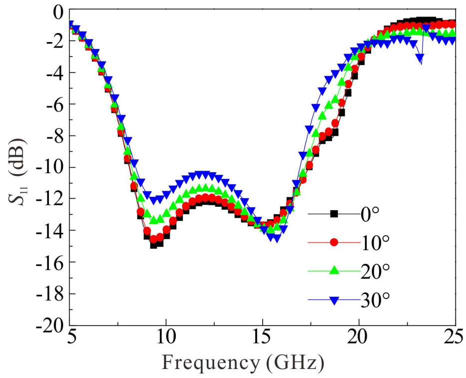


Fig.6 Reflection coefficients for different incident angles

According to the optimized parameter values above, the double-layer absorbing metamaterial samples were prepared. Monolayer/multilayer graphene was prepared based on chemical vapor deposition method. Copper was used as metal catalyst base, methane and long chain alkane were used as carbon sources, and graphene with square resistance of 50 Ω/sq was obtained. Based on laser etching technology, Computer Aided Design is used to draw the required absorbing material graphics, and the blue and white microstructure process drawings are drawn by the laser drawing machine (see Fig.7). The small power laser beam with high beam quality is used to focus into a very small spot, and a very high power density is formed at the focus, so that the blue graphics are vaporized and evaporated instantly. Metamaterial structure units are formed. The pitting technology and the conductive adhesive bonding process were adopted to achieve the pitting bonding between the upper and lower layers. The thickness of the conductive adhesive was 0.1 mm±0.05 mm, as shown in Fig.8. The sample size of the transparent wave absorbing metamaterial was 180 mm×180 mm.

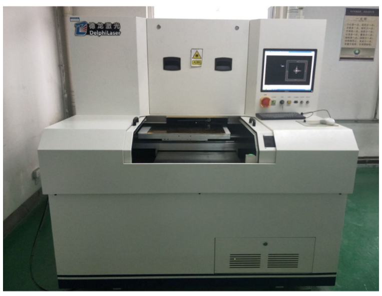


Fig.7 Photo of the laser etching machine

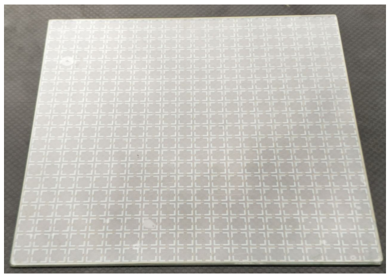


Fig.8 Photo of the transparent absorbing metamaterial

According to GJB2038A-2011 Test Method for Reflectivity of Radar Absorbing Materials, the bow method is used to test the reflectivity of absorbing materials. The test system is composed of Agilent E8386 vector network analysis instrument, rectangular horn antenna, computer, and absorbing wedge, etc. Measured reflection coefficients are shown in Fig.9. As shown in Fig.10, the −10 dB operating bandwidth of the absorbing material is 7.95—18.65 GHz, and the peak reflection coefficient is −23 dB. Fig.10 shows the test curves of absorbing properties of the double-layer absorbing metamaterial. As shown in Fig.10, the absorption rate of the operating bandwidth is higher than 90% in the range of 7.95—18.65 GHz, covering the X-band (7.95—12 GHz) and Ku-band (12—18.65 GHz). The transmittance of visible band is 85%. Compared with the simulation results, the working frequency band of absorbing material is narrowed, which is mainly caused by the dielectric constant and the tangent of the loss angle. The dielectric constant of the material itself is 4.5, the tangent of the loss angle is 0.007 8, but the tangent of the dielectric constant of the simulation material is 4.8, and the tangent of the loss angle is 0.005 4. In addition, other possible reasons are machining error, measurement error and joint welding error.

In this paper, a double-layer high transmittance broadband graphene absorbing metamaterial is designed. The broadband characteristics are designed by using different metamaterial structure units. Based on optical properties of graphene film, the high visible light transmittance is realized. The simulation curves show that the operating bandwidth of the material is 8—18 GHz,

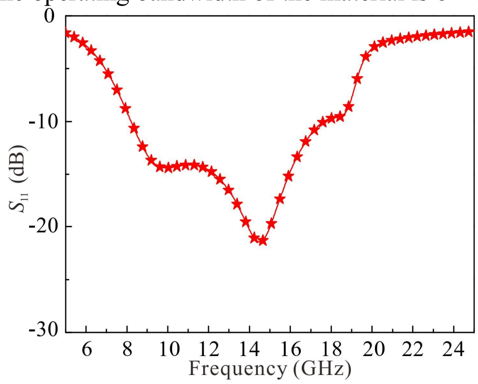


Fig.9 Measured reflection coefficients of the absorbing metamaterial

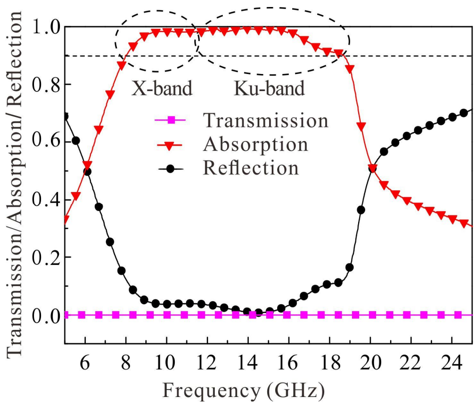


Fig.10 Measured transmission, absorption and reflection curves of the absorbing metamaterial

and the absorption rate is higher than 90%, covering the X-band (8—12 GHz) and Ku-band (12—18 GHz). The measured curves show that the materials have an operating bandwidth of 7.95—18.65 GHz, and the absorption rate is higher than 90%, covering the X-band (7.95—12 GHz) and Ku-band (12—18.65 GHz), and the transmittance in visible band is 85%. Therefore, by combining graphene film with metamaterial structure, the absorbing material can achieve high transmittance and broadband absorbing properties.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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