Composite structure-based transparent ultra-broadband metamaterial absorber with multi-applications

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Abstract
In this paper, an approach is proposed to realize optically transparent metamaterial absorber (OTMA) with ultra-broadband absorption properties by using composite resonant structure. The indium tin oxide (ITO) resistive film is used to construct the resonant structure to induce high ohmic loss and broaden the bandwidth of the resonances, thus achieves more than 90% absorptivity in the wide bandwidth of 8–30.3 GHz, which can cover the X and Ku bands of the airborne and surveillance radar signal frequencies. The novelty of designed structure lies in the properties of larger absorption bandwidth (covering X, Ku, K and part of Ka bands), lower thickness, and absorption capacity over a wide range of incident angles. Moreover, by replacing the intermediate air spacer with polydimethylsiloxane (PDMS) and polymethyl methacrylate (PMMA) dielectrics, the OTMAs that can be used for conformal applications and rigid window glass of stealth armament are designed. This strategy provides more flexibility for the applications of broadband OTMA in different occasions, and has potential application prospects in radar stealth system, EM shielding and transparent RF equipment fields. The average optical transmittance of the whole structure in the visible light range exceeds 78%.

1. Introduction
Metamaterials, composed of artificial periodic unit cells, which can obtain the extraordinary electromagnetic properties that are not found in nature by changing the geometry and size of the resonant structural elements [1–3]. Metamaterial absorber (MMA) can effectively convert incident electromagnetic energy into heat energy loss, and have the properties of high absorptivity, multi-bands and polarization insensitivity [4–7]. By loading MMA, the radar reflection cross section (RCS) of the stealth targets can be effectively reduced. MMAs are widely used in various practical applications such as radar stealth system [8], EM shielding [9], RF equipment [10], etc.

In recent years, the OTMAs based on different material systems have drawn more attentions from researchers [11–13]. Compared with the traditional opaque MMA, OTMA can be applied to the occasions that require high transparency such as the window glass of stealth armament and photovoltaics [14–17]. In 2014, Tahee Jang et al [18] used an Al wire grid to construct the first OTMA to achieve more than 90% absorptivity covering a wide band from 5.8 to 12.2 GHz, the optical transmittance is over 62%. In 2016, M GRANDE et al [19] proposed a method to realize the absorber fully transparent by using multilayer graphene sheets with high transparency. The proposed OTMA can achieve over 84% absorption with a bandwidth of about 1 GHz in the X band. However, the OTMAs based on both metal wire and graphene materials usually cannot achieve high optical transmittance and large bandwidth at the same time, which limits their applications in the field of transparent electronics. In the strict sense, these designed OTMAs are still far from practical application for airborne and surveillance radar signal absorption [20–22], which usually requires the operating band to cover X (8.2–12.4 GHz) and Ku (12.4–18 GHz) bands or even wider. Therefore, it has become an urgent need to design an OTMA that combines both high optical transmittance and ultra-broadband bandwidth.

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In this paper, a resonant structure based on composite structure is designed by using transparent conformal materials, which provides an approach for the above problems. ITO resistive film with good transparency is used to absorb incident electromagnetic waves through the ohmic loss of the resistive film. The composite resonant structure is composed of cruciform and square rings in a cross arrangement, which improves the resonance quality compared with the single periodic structure, thereby exhibiting broadband absorption. The OTMA consists of a sandwich structure composed of ITO films, substrate PET and an intermediate transparent dielectric layer (AIR, PDMS or PMMA), which greatly improves the overall transparency of the OTMA. The OTMA-AIR with air as the dielectric layer achieves more than 90% absorptivity in the bandwidth of 8–30.3 GHz (covering X, Ku, K and part of Ka bands). It is worthy to note that the air as the dielectric layer makes the designed OTMA not only lightweight but also easy to fabricate. The absorption mechanism of the OTMA based on the impedance matching principle has been analyzed and the equivalent circuit model is given. In addition, without changing the pattern of the resonant structure, we replace the intermediate air layer with flexible PDMS and rigid PMMA dielectric layers, respectively. The flexible OTMA can be used for conformal applications, whereas the rigid OTMA can be applied in window glass of stealth armament. Finally, we fabricate and measure three OTMA samples based on different dielectric layers, and the measured results agree well with the simulation results.

2. Design and analysis

2.1. Theoretical analysis and structure design

To achieve optical transparency, the ITO with good mechanical elasticity is used as the conductive material. The designed OTMA consists of three parts: the top is a periodic ITO resonant structure sputtered on a polyethylene terephthalate (PET) substrate, the middle is a transparent dielectric layer (AIR, PDMS or PMMA), and the bottom is a continuous ITO ground sputtered on another PET substrate. Thus, the sandwich structure of ITO-PET-DIELECTRIC-PET-ITO is formed. All constituent materials have excellent optical transmittance property, which greatly improves the overall transparency of the OTMA.

Different from the materials used in conventional MMAs, ITO is a resistive material. The OTMA mainly achieves the high absorption through the ohmic loss generated from ITO. By designing the composite ITO resonant structure, it is possible to achieve the effective absorption of incident electromagnetic waves instead of polarization conversion. According to the electromagnetic field theory, the absorption of OTMA can be written as:

\[
A(\omega) = 1 - R(\omega) - T(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2
\]  

Here, \(R(\omega)\) represents the reflectance and \(T(\omega)\) represents the transmittance. \(S_{11}\) and \(S_{21}\) are the reflection and transmission coefficients of the electromagnetic wave, respectively.

It is worthy to note that the perfect absorption requires minimal reflection and transmission. The reflection coefficient can be calculated by equation (2):

\[
R(\omega) = |S_{11}|^2 = \left(\frac{Z_{in} - 1}{Z_{in} + 1}\right)^2 = \frac{[(\text{Re} \{Z_{in}\}) - Z_0 \cos \theta]^2 + [\text{Im} \{Z_{in}\}]^2}{[(\text{Re} \{Z_{in}\}) + Z_0 \cos \theta]^2 + [\text{Im} \{Z_{in}\}]^2}
\]  

where \(Z_{in}\) is the equivalent input impedance of the OTMA, \(Z_0 = 377 \, \Omega\) is the characteristic impedance of the free space, \(\theta\) is the incident angle of electromagnetic wave. In general, the equivalent input impedance \(Z_{in}\) can be close to 1 by optimizing the geometric dimensions of the top patterned ITO film, thus minimizing the reflectance \(R(\omega)\). Besides, a nearly perfect conductive material (continuous ITO film) is used as the ground layer, the transmittance \(T(\omega)\) is almost zero.

Due to the periodic resonant structure of the top ITO metasurface is the key to determine the absorption property of OTMA, many different structures were simulated and optimized, and the final choice is shown in figure 1(a). The unit cell structure of the top composite resonant structure consists of cruciform and square rings which are arranged in cross but not in contact. A detailed structural illustration of the unit cell can be found in figure 1(b), designed dimensions of geometric are as follows: \(P = 12.2 \, \text{mm}, L = 5.1 \, \text{mm}, D = 3.35 \, \text{mm}, a = 3.8 \, \text{mm}, b = 5 \, \text{mm}, d = 3 \, \text{mm}, \omega = 0.5 \, \text{mm}, d_{\text{PET}} = 0.175 \, \text{mm}. Figure 1(c) shows side view of the proposed OTMA.

The surface resistance of the top and bottom ITO films is selected to be 35 \(\Omega\)/sq under the optimum absorption property, and the sputtering thickness of the ITO film is 75 nm. The relative permittivity and loss tangent of the PET substrate supporting the ITO film are \(\varepsilon = 3.2\) and \(\tan \delta = 0.003\), respectively.

2.2. Simulation results and analytical verification

In order to investigate the absorption property of the designed OTMA, the absorption spectra is simulated and optimized by the commercial electromagnetic solver (CST Microwave Studio 2017). Periodic boundary
conditions are applied to both x and y direction, while open add-space boundaries are applied to z direction. Building a unit cell model and simulating through Frequency Domain Solver. We have simulated a variety of single-shaped resonant structures, including square ring, dipole, H-shape, cruciform and annulus. Their simulated absorption spectra are shown in figure 2(a). Under the same conditions, each structure can only achieve high absorption in a certain frequency band. In order to achieve the property of ultra-broadband absorption, we innovatively combine the cruciform and square ring to form a new composite structure. The OTMA-AIR using air as the intermediate dielectric layer can obtain the maximum absorption bandwidth. The simulated absorption spectrum and S parameters of the OTMA-AIR under normal incidence via full-wave simulations are presented in figure 2(b). It can be clearly seen that the simulated absorption bandwidth is from 8 GHz to 30.3 GHz with over 90% energy absorption, there are three strong absorption peaks located at 9.85 GHz, 16.2 GHz, and 24.1 GHz with nearly perfect absorption, respectively. The reflection coefficient $S_{11}$ is less than $-10$ dB in the wide band of 8 to 30.3 GHz, while the transmission coefficient $S_{21}$ is almost near to zero. Therefore, the designed OTMA-AIR has the above 90% absorptivity in the whole frequency band of interest according to the equation (1). This design exhibits a relative bandwidth of 116.4% with the center frequency is 19.15 GHz.

In order to gain a deeper understanding of the broadband absorption mechanism of the designed structure, the electric field and surface current distributions on the top of the unit cell are simulated at normal incidence of linearly TE-polarized wave. Figures 3(a)–(c) show the electric field distributions at three absorption peaks of 9.85 GHz, 16.2 GHz and 24.1 GHz, respectively. It can be seen that in the lowest frequency peak, the electric field is mainly distributed near the top square ring, and in the vicinity of the middle frequency peak, the electric field distribution gradually shifts to the cruciform portion. However, the electric field distribution again transfers to
the square ring position at the highest frequency peak. Interestingly, the distributions of surface current and that of surface electric field at three absorption peaks are almost complementary, as depicted in figures 3(d)–(f). Due to the close localization of the strong current at different positions of the cruciform and square rings, the electric resonances driven by the incident waves cause near-perfect absorption in the three bands.

We also selected the surface current distributions of the top and bottom layers at near perfect absorption peak (9.85 GHz), as shown in figure 4. The top surface current density is more concentrated and stronger than the bottom, the current will cause significant ohmic loss on the metasurface according to the equation $P_{\text{loss}} = I^2R$ (where $P_{\text{loss}}$ is the electromagnetic loss power, $I$ is the surface current, and $R$ is the surface resistance). It is obvious that the top resonant structure is the main contributor to broadband absorption. In addition, the top and bottom surface currents are in the opposite direction, which is due to the near-field coupling. This coupling is caused by the close proximity of the top layer to the ground. The anti-parallel currents form a circulating loop around the incident magnetic field, thus generating magnetic resonance. These electrical resonance and magnetic resonance simultaneously act to achieve high absorption throughout the frequency band. Due to the fourfold symmetry of the resonant structure, the electric field and surface current have the same distributions for both TE and TM incident waves.
2.3. Equivalent circuit and parameter optimization

According to the transmission-line theory, the equivalent circuit model of the proposed OTMA is established in figure 5 to understand the working mechanism from a more general prospective. As simplification, we assume that the middle dielectric is lossless and the patterned ITO metasurface is responsible for energy consumption, because the loss caused by the dielectric is negligible compared to the loss caused by the resonant structure. In the equivalent circuit model, the patterned ITO film of the top surface can be equivalent to cascaded inductance $L$, capacitance $C$ and resistance $R$. Both of the PET and dielectric layer can be treated as a transmission line with characteristic impedance $Z = \frac{Z_0}{\sqrt{\varepsilon_r n}}$ where $Z_1$ and $Z_2$ represent PET substrate, $Z_3$ represents AIR, PDMS or PMMA dielectric, $Z_0 = 377 \, \Omega$ is the characteristic impedance of the free space, $\varepsilon_r n$ is the relative permittivity of the different dielectric, $n = 1, 2, 3$. The bottom continuous ITO film is modeled as the equivalent resistance $R_g$.

Looking from the position $a$ towards the bottom ITO ground, the impedance $Z_a$ can be written as:

$$Z_a = \frac{Z_0 R_g}{Z_0 + R_g}$$

(3)

Here, the bottom PET substrate is treated as a transmission line with characteristic impedance $Z_1 = \frac{Z_0}{\sqrt{\varepsilon_r 1}}$, the input impedance $Z_b$ from the position $b$ to the bottom ITO ground can be derived as equation (4):

$$Z_b = Z_1 + jZ_1 \tan \beta_1 d_1$$

(4)

where $\beta_1 = 2\pi f \sqrt{\varepsilon_r 1} / c$ is the propagation constant of the incident electromagnetic wave, $j$ is the imaginary unit, $d_1$ is the thickness of the PET substrate, $f$ is the frequency of incident electromagnetic waves, and $c$ is the speed of light.

Similarly, according to equation (4), we can derive the input impedances $Z_c$ and $Z_d$ from the position $c$ and the position $d$ towards the bottom ground plane, respectively. Moreover, the impedance of the top patterned ITO film $Z_{RLC}$ can be written as:

$$Z_{RLC} = R + j \left(2\pi f L - \frac{1}{2\pi f C}\right)$$

(5)

Hence, the overall input impedance $Z_{in}$ of the OTMA can be calculated by parallel connection of the impedances $Z_d$ and $Z_{RLC}$, the $Z_{in}$ can be expressed as:

$$Z_{in} = \frac{Z_{RLC} Z_d}{Z_{RLC} + Z_d}$$

(6)

The above equations indicate that in order to obtain a high absorption, the overall input impedance $Z_{in}$ should be equal to $Z_0$ according to the impedance match principle. Therefore, we should reasonably design the shape and optimize the geometric dimensions of the top ITO resonant structure to obtain the maximum absorption.

Figure 6 investigates the angular dependence of absorption property. Under the incidence of transverse electric (TE) wave, as the incident angle $\theta$ increases from 0° to 40°, the absorptivity gradually decreases in the operating band, accompanied by additional peaks as shown in figure 6(a). This phenomenon is caused by the...
mismatched impedance at oblique incidence. Similarly, the absorptivity gradually decreases and the absorption peak shifts to the higher frequency range at the oblique incidence of transverse magnetic (TM) wave, as shown in figure 6(b). In addition, the designed OTMA is polarization-insensitive due to the fourfold symmetry of the composite resonant structure. Compared with the previous works, the structure has the advantage of higher angular stability. To be more specific, when the incident angle \( \theta \) is less than 40°, the absorption always keeps high-efficiency above 80% in operating band.

In order to demonstrate the effect of the air dielectric thickness \( d \) between the ITO films, the simulated absorption spectra with different thickness are illustrated in figure 7(a). When the dielectric thickness increases from 2.7 mm to 3.6 mm, the absorptivity increases slightly, but simultaneously the absorption bandwidth reduces caused by the highest absorption peak shifting to the low frequency. Therefore, the optimized \( d \) is 3 mm, which can take both absorption and bandwidth into consideration.

Moreover, we also simulate the absorption performance under different surface resistance values of the ITO resistive films. It is observed from figure 7(b) that with the increasing resistance of ITO films, the absorptivity increases significantly owing to the higher ohmic loss of the resonant structure. However, the lowest frequency peak and the highest frequency peak move towards each other, so the operating band gradually decreases. Therefore, the optimum surface resistance value is selected to be 35 \( \Omega \) sq\(^{-1}\).

3. Fabrication and experiment verification

To experimentally verify the absorption property of the proposed OTMA, the sample of the OTMA-AIR is prepared. First, the ITO ions are sputtered to the PET substrate by magnetron-sputtering technology. Then the top resistive film is patterned through a laser etching process, whereas the bottom film is a continuous resistive film. Due to the remarkable transparency of optical clear adhesive (OCA), the 50 \( \mu \)m thin OCA is used to adhere the top and bottom ITO-PET substrates to the '田' shaped acrylic frame, thus forming a 3 mm thick air spacer between the top layer and bottom layer. Finally, a sample consisting of 16\(^{\times}\)16 unit cells is fabricated with total size of 19.6 cm\(^{\times}\)19.6 cm, as shown in figure 8(a). The sample is placed on a white paper printed with the logo of North...
University of China. It can be seen that the fabricated OTMA-AIR has excellent transparency in the visible light band.

The prepared sample is measured by bow-frame method as shown in figure 9. In the experiment, two pairs of standard broadband horn antennas of 1–18 GHz and 18–40 GHz are used to measure the reflection coefficients $S_{11}$ of the sample by connected to a vector network analyzer (Agilent N5224A) through low loss cables, consequently. Within each sub-frequency range, a pair of horn antennas is used for signal transmitting and receiving, respectively, and the antennas are nearly perpendicular to the geometric center of the OTMA sample. The distance $d$ between the sample and the horn antennas meets the far-field criterion with $d \geq 2D^2/\lambda$ (where $D$ is the maximum dimension of the OTMA sample, $D = 196$ mm, $\lambda$ is the wavelength of incident microwaves).

Pyramidal foam absorption materials are placed surround the sample to absorb spilled electromagnetic waves outside the sample. In the measurement, an aluminum plate is used as the PEC reference reflection plane for calibration, and the aluminum plate has the same size with the sample. The difference between the measured reflection signal of the sample and the reference aluminum plate is calculated as the sample reflection coefficients $S_{11}$. Since most of incident energy is actually blocked by the bottom continuous ITO film, it can be regarded as zero transmission. Therefore, the absorptivity is finally calculated by the reflection spectrum.

The measured absorption spectra of the OTMA-AIR sample is shown in figure 8(b). Compared with the simulation result, the absorptivity and bandwidth are slightly reduced in operating band, and the absorption peaks seem to merge together toward the low frequency. This difference possibly due to the sample fabrication errors as well as measurement system errors, and the sample size is limited results in the edge effects. Considering the imperfect fabrication and tolerance, the measured result is in agreement with the simulated predictions. Finally, the optical transmittance of the sample in the visible light range is measured by the light transmittance meter, and the average transmittance is exceeding 78%, slightly below the target value 80%, as shown in figure 10.
In addition, we also fabricate the OTMA samples with dielectric layers of PMMA (the relative permittivity is \( \varepsilon = 2.25 \) and loss tangent is \( \tan \delta = 0.001 \)) and PDMS (the relative permittivity is \( \varepsilon = 2.35 \) and loss tangent is \( \tan \delta = 0.06 \)), respectively, as shown in figures 11(a) and (b). It can be seen that the OTMA-PDMS using PDMS as dielectric has excellent flexibility and bending. The manufacturing process is similar to that of the OTMA-AIR with air dielectric layer. The only difference is that we use a vacuum plasma surface treatment machine (PTL-VM500) to bond the top and bottom ITO-PET substrates to the intermediate dielectric layer, and the bonding strength is equivalent to the adhesive force of the OCA. Subsequently, the different OTMA samples are measured based on the above measurement methods, respectively.

To better compare the relative bandwidth, optical transmittance and other properties of the designed broadband OTMA, table 1 lists the main features of some related works. The relative bandwidth is defined as the ratio of the operating bandwidth to the center frequency, calculated from \( f_{oc} = \frac{2(f_H - f_L)}{(f_H + f_L)} \).
4. Conclusions

In conclusion, the ultra-broadband OTMAs based on different dielectric layers are designed, analyzed, and fabricated in this paper. OTMA-AIR can achieve 22.3 GHz wide high-absorption (absorptivity >0.9). Based on the impedance match principle, an equivalent circuit model is established and the absorption mechanism is analyzed according to the electric field and surface current distributions. The symmetrical composite structure composed of cruciform and square ring makes the OTMAs insensitive to the polarization as well as the incident angle for both TE and TM waves. Finally, we fabricate and measure three OTMA samples based on different dielectric layers, and the measured results are consistent with the simulation results. Compared to previous OTMAs, the designed OTMAs have maximum absorption bandwidth, higher transparency, and lower thickness. This design provides more flexibility for the application of the OTMA in the field of transparent stealth system and electronic RF applications.

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Author contributions

RL conducted the analytical modeling, numerical simulations, sample fabrication, and measurements. BZZ, as the principal investigator of the project, conceived the idea, suggested the designs, and planned the work. JPD and LD ran numerical simulations, and JY, ZHZ participated in the sample fabrication and measurements. All authors have reviewed the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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