A high absorptance wide-band metamaterial absorber with metasurface and low-permittivity dielectric slabs

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Abstract
In this paper, a new wide-band and high-absorption metamaterial absorber (WHMA), consisting of a metasurface (MS), three low-permittivity dielectric slabs, and a metal backplane, is proposed and fabricated. The unit cell of MS is concentric rings loaded with chip resistors. This structure exhibits excellent absorption property and improved stability of oblique incidence, which are difficult to be achieved in previous radar absorbing materials. The functions of MS and different dielectric slabs are analysed. At normal incidence, the simulated results indicate that $-10$ dB absorption and $-20$ dB absorption bands cover a bandwidth of $4.8–14.3$ GHz and $5.70–13.57$ GHz, respectively. The measured results show that $-10$ dB and $-20$ dB absorption are achieved with the bandwidth of $4.6–16.3$ GHz and $5.5–14.4$ GHz respectively at normal incidence; below $50^\circ$ angle of oblique incidence, WHMA can still have wide-band $-10$ dB absorption. The agreement between simulation and measurement validates the proposed design. Finally, since the structure is made of foam and thin dielectric layers, the area density is relatively low.

Keywords: metamaterial absorber, metasurface, low-permittivity dielectric slabs, wide-band absorption, stability of oblique incidence, high absorption

(Some figures may appear in colour only in the online journal)

1. Introduction
Radar absorbing materials (RAMs) can reduce reflection energy of the object [1–3]. It is used in versatile applications such as satellite navigation systems, electromagnetic energy harvesting, stealth fields and so on. However, traditional RAMs usually have narrow absorption bandwidth which cannot meet specific requirements. To solve this problem, two types of new RAMs are created and developed including all-dielectric metamaterial absorbers (ADMAs) and metasurface [4–6] absorbers [7] (MSAs).

Our research group studied ADMAs in the past several years. Zhang et al [8] proposed a binary-structured metamaterial absorber (BMA) based on a 3D cross-shaped dielectric periodic array and a metal backplane. The thickness of the structure is $30.0$ mm, where the raw material is FR4 with $\varepsilon_r = 4.8$ and $\tan\sigma$ of $0.025$. It generates six absorption peaks at $10.004$ GHz, $12.192$ GHz, $14.304$ GHz, $15.456$ GHz, $15.7060$ GHz and $17.600$ GHz, which corresponding reflection coefficients are $-28.58$ dB, $-12.8$ dB, $-10.21$ dB, $-24.64$ dB, $-18.6$ dB, and $-11.23$ dB, respectively. Wang et al [9] proposed a two layers BMA based on FR4 with $\varepsilon_r = 4.3$ and $\tan\sigma$ of $0.025$. The thickness of this BMA
is 30.0 mm. It has two absorption peaks at 14.65 GHz and 16.61 GHz, resulting from the magnetic and electrical responses of ADMAs, respectively. The studies prove that pure dielectric materials can be used as RAMs through controlling the interaction between microwave and material, which give us a good inspiration for this article. The biggest challenges of ADMAs are too thick and too heavy, which limit their application seriously.

Another type of new RAMs is MSAs, which have attracted a lot of attention because of their advantages of thin thickness, light weight and strong absorption. The MSAs, such as circuit-analog absorbers, usually consist of a layer of periodic elements arrays, a dielectric layer and a metal plane, whose electromagnetic characteristics can be controlled by simply changing period, size of unit cell and impedance [10–12]. To meet the requirements of broadband absorption, complicated unit cells or multi-metasurfaces (MS) structures are adopted, which lead to complex design and preparation processes [13–17]. Besides, our research group designed a ultrawide band and high absorption absorbing material with simple loop unit cell in [18]; however, the proposed UHAS uses too many chip resistors, which is expensive for large-scale applications.

To obtain a simple designed RAM with properties of easily preparation, protected absorbing parts, thin thickness, light weight, wide bandwidth absorption, and stable performance under oblique incidence, a new wide-band and high-absorption metamaterial absorber (WHMA) is proposed and fabricated in this work, which combines the advantages of ADMAs and MSAs. As shown in figure 1, the WHMA can be regarded as combination of ADMA and MSA, which consists of an MS, three low-permittivity dielectric slabs, and a metal plane. The unit cell of MS is concentric rings loaded with chip resistors. Simulation results reveal that WHMA has wider −20 dB absorption band and better oblique incidence performance than most of reported MAs. Finally, a sample is fabricated and measured to validate proposed design.

2. Design and simulation

As shown in figure 2(a), WHMA has five layers, which are top FR4 layer, PMI foam, MS, PMI foam and metal backplane. Figure 2 shows unit cell of the proposed MS, that metal rings are printed on the PI film. The period, P = 20.20 mm, the radius of large ring, Rad = 8.00 mm, the radius of small ring Rad = 5.00 mm, the width of two rings, w = 0.60 mm, the resistance of resistors loaded on large ring, $R_{\text{out}} = 300 \Omega$, the resistance of resistors loaded on small ring, $R_{\text{in}} = 240 \Omega$, the height of top FR4 layer, $h_1 = 0.30$ mm, the height of top PMI foam, $h_2 = 2.80$ mm, the thickness of PI film, $h_3 = 0.13$ mm, the height of bottom PMI foam, $h_4 = 6.80$ mm. The absorptivity of WHMA can be calculated by:

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

where $R(\omega)$ is reflectivity; $T(\omega)$ is transmissivity; $S_{11}$ is reflection coefficient; $S_{21}$ is transmission coefficient. If the bottom layer is metal backplane, the transmission is zero. Under different incidence, the reflection coefficients for the perpendicular and parallel polarizations are given by [19]

$$\Gamma_\perp(\omega) = \frac{Z(\omega)\cos\theta - Z_0\cos\theta_i}{Z(\omega)\cos\theta + Z_0\cos\theta_i}$$

$$\Gamma_\parallel(\omega) = \frac{Z(\omega)\cos\theta - Z_0\cos\theta_i}{Z(\omega)\cos\theta + Z_0\cos\theta_i}$$

$$Z(\omega) = \sqrt{\frac{(1 + S_{11}(\omega))^2 - S_{21}(\omega)^2}{(1 - S_{11}(\omega))^2 - S_{21}(\omega)^2}}$$

where $Z(\omega)$ and $Z_0$ are the impedances of the MA and free space, respectively [20]. $Z_0 = \sqrt{\mu_0/\varepsilon_0} = 377 \Omega$. $\theta_i$ and $\theta_i$ are the incident and transmission angles, respectively.

Unit cell of the proposed MS is designed based on LC resonance, and its resonant frequency is calculated by

$$f = \frac{1}{2\pi \sqrt{L_{\text{eff}}C_{\text{eff}}}}$$

The effective inductance ($L_{\text{eff}}$) is mainly generated by the perimeter and width of the concentric rings. The effective capacitance ($C_{\text{eff}}$) is mainly determined by the gap between the rings.

The electromagnetic (EM) performance of WHMA is investigated by simulation software CST Microwave Studio. Periodic boundary conditions are applied in the basal $x$ and $y$ directions, with open boundaries in the $z$-direction.

Figure 3(a) shows reflectivity and absorptivity results of the WHMA. In the range of 4.8–14.3 GHz, the absorptivity is
higher than 90%. In the range of 5.7–13.8 GHz, the absorptivity is higher than 99%. As indicated in figure 3(b), in the range of 4.3–14.1 GHz, Real (Z) of WHMA is close to 1; in the range of 5.5–13.9 GHz, Imag (Z) of WHMA is close to 0. All of these indicate that the impedance of the WHMA matches with the free space in the above frequency range. Thus, almost all the incident EM wave can enter the WHMA, that the energy of the incident EM wave can be consumed by the MS and dielectric layers further.

Figure 4 shows the simulation results of proposed WHMA. At normal incidence, −10 dB absorption band is from 4.8 to 14.3 GHz (fractional bandwidth (FBW) = 101.1%); and the reflection coefficient below −20 dB is in the range of 5.70–13.8 GHz (FBW = 81.6%). At TE polarization, the proposed WHMA remains wide −10 dB absorption band whose bandwidth is greater than 7.7 GHz (FBW ≥ 84.3%) for 50° of oblique incidence. At TM polarization, the oblique incidence stability of −10 dB absorption is kept from 0° to 20°.

To understand the physical mechanism of its excellent absorption property and improved stability of oblique incidence, the interference model of the WHMA is studied in figure 5. According to the interference theory [21], WHMA has three interfaces, which are top dielectric layer, MS and copper backplane. Multireflection interference will happen among them. As mentioned in [16–20], top dielectric layer can divide incident EM energy $E$ into reflection energy $E_r$, transmission energy $E_t$ and absorption energy $E_{abs}$. Then, MS will divide $E_t$ into absorption energy $E_1$, reflection energy $E_{2_r}$ and transmission energy $E_3$.

Copper backplane act as a perfect reflection layer. It can be concluded that the reflection energy of WHMA is produced by multiply-reflection among top dielectric layer, MS and copper backplane; then the multiply reflected energy can be multiply-dissipated by top dielectric layer and MS.

To maximize the electrical dissipation in MS and top dielectric layer, the thickness of two PMI foam layers is important. According to the Poynting’s theorem, the thickness of PMI layers $h_2$ and $h_4$ will be designed corresponding to a quarter wavelength of different frequencies. The wavelength $\lambda$ can be calculated by

$$\lambda_m = \frac{\lambda_0}{\sqrt{\varepsilon_r\mu_r}}$$

where $c_0$ ($2.99 \times 10^8 \text{m s}^{-1}$) is velocity of light; $f$ is frequency point; $\lambda_0$ is wavelength corresponding to the $f$; $\lambda_m$ is the wavelength in dielectric materials.

The aim of this work is to design a WHSA for X band application, so the reflection coefficient below −20 dB in the range of 6.0–14.0 GHz is necessary to ensure the stability of the performance. The initial parameters of MS are determined by the below rules. The radius of large ring Radr approximately satisfy $2\pi^*\text{Rad}_r \sim \lambda_L$, where $\lambda_L$ is the wavelength of starting frequency of −20 dB reflection. The radius of small ring Radm approximately satisfy $2\pi^*\text{Rad}_m \sim \lambda_M$, where $\lambda_M$ is the wavelength of centre frequency of design purpose. The width $w$ should be greater than the width of the chip resistor’s package. The period $P$ needs to satisfy $2^*\text{Rad}_m < P < 2^*\text{Rad}_r + \lambda_U$, where $\lambda_U$ is the wavelength of ending frequency of −20 dB reflection to avoid onset of free space grating lobes. Literature [18] mentioned the guidance of high absorption MS absorber design that 40% absorption of MS is the key factor. After assigning the initial values, by using the full-wave simulation software, the values of $P$, Radm, Radr, $w$, $R_m$, $R_{out}$ achieve about 40% ohmic consumption of the incident plane wave energy in the designed frequency, are sequentially determined. The final parameters are $P = 20.20 \text{ mm}$, $\text{Rad}_m = 8.00 \text{ mm}$, $\text{Rad}_r = 5.00 \text{ mm}$, $w = 0.60 \text{ mm}$, $R_{out} = 300 \Omega$, $R_m = 240 \Omega$, $h_3 = 0.13 \text{ mm}$.

Different from [18], where the thicknesses of dielectric layers are calculated by the starting and ending frequencies of −20 dB designed absorption band, the thicknesses of dielectric layers in this work are designed based on other principles. As shown in figure 6(a), the starting 40% absorption frequency
Figure 4. Simulation results of the proposed WHMA. (a) Reflection coefficient under TE-polarization; (b) Absorptivity under TE-polarization; (c) Reflection coefficient under TM-polarization; (d) Absorptivity under TM-polarization.

Figure 5. The interference model and absorption mechanism of proposed WHMA. $E$ represents the total energy of the incident plane wave; $E_1$ is the energy absorbed by MS; $E_2$ is reflection energy of MS; $E_3$ signifies transmission energy of CA sheet; $E_3_R$ means the reflection energy of $E_3$ by ground; $\Theta$, $\Phi$ are positions of electrical dissipation. $\theta$ is incidence angle of plane wave. $\theta_1$ and $\theta_2$ are angles of refraction.

of large ring MS is at 5.70 GHz, that is set as the starting frequency of absorption enhancement. However, resistive small ring MS does not have 40% absorption frequency, the first absorption peak at 13.57 GHz is set as the ending frequency of absorption enhancement. The middle frequency of $-20$ dB reflection of the whole MS is 10.10 GHz, which is used to calculate PMI foam slab $h_4$. In this work, the dielectric layers $h_2$ and $h_4$ are PMI foam slabs with $\varepsilon_r$ of 1.05, top dielectric layer $h_1$ is FR4 with $\varepsilon_r$ of 4.4, the substrate of MS $h_3$ is PI with $\varepsilon_r$ of 3.5. As shown in figure 6(b), transmission and reflection coefficient of proposed MS, which is close to the $-3.5$ dB/$-9.5$ dB respectively in the range of 6.0–14.0 GHz, are like the resistive sheet with resistance 377 $\Omega$/square and corresponds well with the design principles mentioned in [18]. Figure 6(c)
Figure 6. At normal incidence, (a) Absorptivity of single resistive large loop and single resistive small loop MS; (b) Reflection/Transmission coefficients of MS and 377 Ω sheet; (c) Absorptivity of MS under four kinds of resistors configuration.

shows the absorptivity of MS under four kinds of resistors configuration. It illustrates that different configuration of resistors does not change lumped resistance while the equivalent inductance ($L_{\text{out}}$ and $L_{\text{in}}$) and capacitance ($C_{\text{out}}$ and $C_{\text{in}}$) is changed a little. So, the absorptivity changes slightly. As a result, configuration_1 is adopted as an available plan for further design.

Top FR4 layer can improve electrical dissipation around $f_{5.70\,\text{GHz}}$ and $f_{13.57\,\text{GHz}}$ at position $\oplus$, which can be used for calculating thickness whole thickness $H = \lambda_{5.70\,\text{GHz}}/4$ and thickness of top FR4 layer $h_1$. PMI foam $h_4$ is designed for electrical dissipation around $f_{10.10\,\text{GHz}}$ at position $\Box$. If all the dielectric layers of WHMA are PMI foam, $H_{\text{PMI}} \sim \lambda_{5.70\,\text{GHz}}/4 = 12.80 \, \text{mm}$; $h_{4,\text{PMI}} \sim \lambda_{10.10\,\text{GHz}}/4 = 7.22 \, \text{mm}$. Besides, in industrial production, the thickness of PI film is usually 0.13 mm, the common thickness of FR4 is 0.30 mm, which are equal to the thickness values in PMI foam: $h_{3,\text{PMI}} = 0.24 \, \text{mm}$, $h_{2,\text{PMI}} = 0.63 \, \text{mm}$. Then the thickness of $h_2$ will be estimated by two approaches: (a) $h_{2,5.70\,\text{GHz}} \sim H_{\text{PMI}} - h_{1,\text{PMI}} - h_{3,\text{PMI}} - h_{4,\text{PMI}} = 4.71 \, \text{mm}$, where $h_{2,5.70\,\text{GHz}}$ is the thickness corresponding to a quarter wavelength of 5.70 GHz; (b) $h_{2,13.57\,\text{GHz}} \sim \lambda_{\text{PMI}}(13.57\,\text{GHz})/4 \sim 5.37 \, \text{mm}$, where $h_{2,13.57\,\text{GHz}}$ is the thickness corresponding to a quarter wavelength of 13.57 GHz. It should be noticed that $h_{2,13.57\,\text{GHz}}$ is larger than $h_{2,5.70\,\text{GHz}}$. Therefore, electrical dissipation around $f_{5.70\,\text{GHz}}$ and $f_{13.57\,\text{GHz}}$ cannot be maximized together at position $\oplus$. Compared the calculated thickness with actual design, the height of top PMI foam, $h_2 = 2.80 \, \text{mm}$, the thickness of PI film, $h_3 = 0.13 \, \text{mm}$, the height of bottom PMI foam, $h_4 = 6.80 \, \text{mm}$, the values agree well with each other.

In order to study the influence of top dielectric layer on the absorption performance, reflection coefficient and absorptivity are calculated for WHMA models with different thickness. As shown in figure 7, the parameters are $P = 20.20 \, \text{mm}$, $\text{Rad}_{\text{out}} = 8.00 \, \text{mm}$, $\text{Rad}_{\text{in}} = 5.00 \, \text{mm}$, $w = 0.60 \, \text{mm}$,
Figure 7. At normal incidence, simulation results of the proposed WHMA with different thickness of top dielectric layer. (a) Reflection coefficient under TE-polarization; (b) Absorptivity under TE-polarization. $P = 20.20 \text{ mm}, R_{\text{out}} = 8.00 \text{ mm}, R_{\text{in}} = 5.00 \text{ mm}, w = 0.60 \text{ mm}, R_{\text{out}} = 300 \Omega, R_{\text{in}} = 240 \Omega, h_2 = 2.80 \text{ mm}, h_3 = 0.13 \text{ mm}, h_4 = 6.80 \text{ mm}.

Figure 8. At normal incidence, simulation results of WHMA with different thickness $h_2$. (a) Reflection coefficient under TE-polarization; (b) Absorptivity under TE-polarization.

Layer can influence electrical dissipation around $f_{(5.70 \text{ GHz})}$, where energy is reflected by MS.

Figure 9 illustrates that the proposed top dielectric layer can improve absorption performance under oblique incidence. The mechanism can be explained by Snell’s Law. As shown in figure 5, the relationship of $\sin \theta, \sin \theta_1$, and $\varepsilon_{r_{\text{FR4}}}$ is

$$\frac{\sin \theta}{\sin \theta_1} = \sqrt{\frac{\varepsilon_{r_{\text{FR4}}}}{\varepsilon_0}}$$ (7)

The top FR4 layer with $\varepsilon_r$ of 4.4 decreases the interference angle between refracted wave $E_{r_1}$ and $E_{r_2}$, which will lead to better electrical dissipation in top dielectric layer $h_1$. It should be noted that, slab $h_1$ is mainly designed for electrical dissipation around $f_{(5.70 \text{ GHz})}$, which will improve oblique incidence stability at the same time around 5.70 GHz. In specifics, on the one hand, the $-10 \text{ dB}$ absorption band of proposed WHMA at 50.0$^\circ$ angle of incidence is similar to that of structure without top dielectric layer at 40.0$^\circ$ angle of incidence. 

Next, the effect of thickness $h_2$ are studied in figure 8. As the thickness of $h_2$ is varied from 2.5 to 5.0 mm, absorption strength is increased in the range of 5.70–13.57 GHz. Then the thickness of $h_1$ is increased from 0.4 to 0.5 mm, $-20 \text{ dB}$ reflection bandwidth is decreased; however, the proposed structure still exhibits wide $-10 \text{ dB}$ reflection bandwidth.
incidence; on the other hand, the oblique incidence stability of WHMA around 5.70 GHz is much better than that around 13.78 GHz. These are different from single square loop in [18].

3. Experiment and discussion

To validate the properties of proposed WHMA, the MS is printed on PI film initially; then a prototype is fabricated based on the thermoforming and vacuum forming method. Figure 10(a) provides view of fabricated MS; figure 10(b) shows unit cell of MS, and the chip-resistors adopt 0402 package; figure 10(c) exhibits the perspective view of WHMA. The size of the sample is 300.00 × 300.00 × 10.13 mm with 196 units. Figure 10(d) shows measurement setup of prototype.

The measured results of the tested prototype are plotted in figure 11. Under TE-polarization, below 30° angle of oblique incidence, the measured reflection coefficient remains less than −20 dB from 5.6 to 14.7 GHz; for 40° angle of oblique incidence, the measured reflection coefficient remains less than −20 dB from 8.7 to 17.6 GHz; for 50° angle of oblique incidence, the measured reflection coefficient remains less than −10 dB in the range of 5.4–16.3 GHz. Under TM-polarization, the measured reflection coefficient remains less than −10 dB in the range of 5.5–18.0 GHz, when the oblique incidence is below 40°; for 50° angle of oblique incidence, −10 dB absorption is from 6.3 to 18.0 GHz.

In order to interpret its performance, the measured −10 dB/−20 dB reflection bandwidth and oblique angle of WHMA are listed in table 1 and compared with other absorbers in literatures. WHMA exhibits better performance when the angle of oblique incidence is increased, which realizes wider −20 dB absorption caused by the combination of MS and low-permittivity dielectric slabs. In addition, MS is protected well by top dielectric layer $h_1$ and PMI foam slab $h_2$. At last, the main material of WHMA is PMI foam, that the whole structure is much lighter than all dielectric materials structures.
Figure 10. Photograph of the fabricated WHMA prototype. (a) Top view of fabricated MS; (b) Unit cell of MS. (c) Perspective view of WHMA. (d) Measurement setup.

Figure 11. Measurement results of the proposed WHMA. (a) Reflection coefficient under TE-polarization; (b) Absorptivity under TE-polarization; (c) Reflection coefficient under TM-polarization; (d) Absorptivity under TM-polarization.
4. Conclusion

This In this work, a new WHMA is proposed. Compared with most of reported designs, the proposed WHMA combines the advantages of MA and low-permittivity dielectric MA and exhibits better synthetic capability. Numerical analysis and simulation results agree with each other very well. Then a prototype is fabricated to validate the proposed design. According to experimental results, −10 dB and −20 dB absorption band of WHMA is in the range of 4.6–16.3 GHz and 5.5–14.4 GHz respectively at normal incidence. Below 50° angle of oblique incidence, WHSA can still have wide-band −10 dB absorption at TE/TM polarization. The absorbers with integration of function and structure have potential applications in the EM absorbing fields.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Table 1. Performance comparison of broadband absorbers.

| Ref. | FBW_1a | FBW_2a | TE | TM | Materials | RT (λL)b |
|------|--------|--------|----|----|-----------|-----------|
| [8]  | Six peaks | N/A | N/A | Array based on FR4 | 1.000 |
| [9]  | Two peaks | N/A | N/A | Arrays based on FR4 | 1.465 |
| [22] | 77.0% | 15% | N/A | Nylon and carbonyl iron powder | 0.130 |
| [23] | 52.0% | N/A | 30° | MA with resistors | 0.080 |
| [24] | 93.2% | N/A | <30° | Magnetic Polymer | 0.051 |
| [25] | 74.8% | N/A | 30° | Composites | 0.049 |
| Current work | 115.1% | 79.5% | 50° | Combination of MS and low-permittivity dielectric slabs | 0.156 |

a FBW of −10 dB/−20 dB reflection FBW_1/FBW_2.
b Relative thickness (λL) is the starting frequency of −10 dB reflection.

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