A simplified design of broadband metamaterial absorber covering X- and Ku-band

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Abstract
This paper developed a simplified design of broadband metamaterial absorber (MA) covering X- and Ku-band. Based analysis of its equivalent circuit model, this paper moves a step forward in terms of using COMSOL simulation software to optimize and analyze the structure parameters of the MA. The simulation results show that the absorptivity of the designed MA at the entire X- and Ku-band (8 GHz-18 GHz) is more than 90% under normal incidence for both transverse electric (TE) and transverse magnetic (TM) polarization, and with good absorption characteristics under a wide incident angle. Furthermore, compared with the previous reports, the MA designed in this paper with simple structure, and without consideration of loading lumped elements or using new materials, the absolute and relative bandwidth reach up to 10 GHz and 76.92%, respectively. This study can be applied to reduce radar cross-section, stealth and improving the electromagnetic compatibility of devices.

1. Introduction
Metamaterials are novel types of artificial electromagnetic material with sub-wavelength and periodic structures. Common electromagnetic metamaterials mainly consist of arrays of conductive patterns and dielectric substrates. The effective permittivity and effective permeability of the materials can be changed, by adjusting the unit structure and geometric parameters. Thus, they achieved the extraordinary physical properties that natural materials do not possess, such as negative refractive index [1], perfect lens [2], invisible cloak [3]. The emergence of metamaterials stimulated new ideas and methods for the electromagnetic properties of artificially controlled materials and attracted lots of attention from the academic community all over the world.

Metamaterial absorber (MA) is one of the research fields of the metamaterial. It is a novel type of artificial designed structural absorbing material, which composed of a resonant unit with sub-wavelength and periodic structure, attracted wide attention due to the advantages of thin thickness, high absorptivity, and easy adjustment, and successfully employed in imaging [4], sensing [5], antenna system [6, 7]. In 2008, Landy [8] firstly proposed the conception of MA, the MA consists of metal split-ring resonator and cutting wire located on the surface and bottom of the lossy dielectric substrate, respectively. By optimizing the unit cell reasonably, electromagnetic resonance occurs between the resonator and cutting wire at 11.48 GHz, the impedance of the MA matched with free space, cause the incident electromagnetic wave is absorbed almost without reflection, therefore, achieving absorptivity close to 100%. Subsequently, the MA operate in microwave [9], terahertz [10], infrared [11], and optics [12] have been explored in the last 10 years. For different applications, the MA of narrow-band [13], multi-band [14, 15], wide-band [16], wide incident angle [17], and polarization-insensitive [18] aroused great interest of researchers. However, it is difficult to obtain wide enough absorption bandwidth, due to the strong electromagnetic resonance characteristics of MA, which limits the practical applications. Therefore, it is particularly important to expand the absorption bandwidth of MA.

Researchers have employed different methods to expand the absorption bandwidth. The first one is to arrange multiple resonators in the periodic plane [19]. The second one is to alternately stack resonator and dielectric substrate in the vertical direction [20]. Both methods connect multiple adjacent absorption peaks in
series to achieve broadband absorption. The third method is loading lumped elements to achieve broadband absorption \[21\], it aims to match the input impedance with free space in a wide frequency range. However, these three methods have some shortcomings, which limit their applications in practice. For example, in the first method, because of the strong electromagnetic resonance, lead to the absorption band is not wide enough and with complex structure. In the second method, due to the stacking of multi-layer structures, cause the absorption bandwidth widened while the thickness increased simultaneously. In the third method, the loading lumped elements destroyed the planarity and the processing cost expensive. Moreover, the MAs of microwave broadband based on the structure of metal-dielectric-metal are mostly cover a single band, such as C-band \[22\], X-band \[23\], while the investigations of simultaneous cover multi-band are few.

This paper proposed a broadband MA based on the metal-dielectric-metal structure covering X- and Ku-band. The structural parameters of the MA optimized through the analysis of its equivalent circuit model. The absorption mechanism has analyzed by the electric field and the surface current distributions, as well as the input characteristic impedance and retrieved constitutive electromagnetic parameters. Subsequently, the oblique incidence and polarization characteristics are studied. Finally, the proposed absorber has compared with other absorbers. Results show that the proposed MA has a compact structure, without consideration of loading lumped elements or using new materials, it achieves the absorptivity is more than 90% in the range of 8GHz-18GHz, and with good broadband absorption characteristics for wide incident angles.

2. Design and simulation

2.1. Structure design

The proposed MA structure as shown in figure 1. The periodicity of the unit cell is \(p\). The green part in the middle uses the lossy FR-4 dielectric substrate with the relative dielectric constant of 4.4, loss tangent of 0.02, and thickness of \(d\). The yellow parts at the top and bottom are coppers with the conductivity of \(5.8 \times 10^7\) Sm\(^{-1}\) and thickness \((h)\) of 0.035 mm, which is far greater than the skin depth of 8 GHz-18GHz. Among them, the bottom is a copper film so that the electromagnetic wave unable to pass through, while the top is a copper strip resonator with 45° rotation, its length and width are \(s\) and \(w\), respectively, and the short side is semi-circle with radius \(w/2\).

High absorption can be achieved by minimizing reflectance and transmittance. The bottom layer of the metamaterial absorber designed in this paper is a copperplate larger than the skin depth, lead the transmittance is 0, so we only need to minimize the reflectance. To optimizing structural parameters of the MA unit cell, this research utilized a transmission line theory \[24, 25\] to analyze the proposed structure and characterized the transmission characteristics of the MA by the impedance of the circuit model. The equivalent circuit model of the MA shown in figure 2. The left part is the transmission line of free space with a characteristic impedance of \(Z_0\). The middle part between the dotted lines represents the equivalent series RLC circuit corresponding to the copper top layer. Where \(R\), \(L\), \(C\), and \(Z_{in}\) represent equivalent resistance, inductance, capacitance, and the input characteristic impedance of the MA, respectively. The right part is a shorted transmission line modeling for the lossy FR-4 dielectric substrate with a thickness of \(d\) and equivalent impedance of \(Z_d\). The absorptivity of the absorber expressed as follows:

\[
A(\omega) = 1 - \left| \frac{Z_{in}(\omega) - Z_0}{Z_{in}(\omega) + Z_0} \right|^2
\]  

(1)

Figure 1. The proposed MA unit cell: (a) 3D-view, (b) top-view.
Where

\[
Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi
\]  \hspace{1cm} (2)

\[
\frac{1}{Z_{in}(\omega)} = \frac{1}{R + j\omega L - \frac{j}{\omega C}} + \frac{1}{Z_d(\omega)}
\]  \hspace{1cm} (3)

\[
Z_d(\omega) = j\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r} \tan \left( \frac{k_0d}{\sqrt{\varepsilon_r\mu_r}} \right)
\]  \hspace{1cm} (4)

In the above formulas, \(\varepsilon_0, \mu_0, k_0\) are the relative permittivity, permeability, and wavenumber of free space, \(\varepsilon_r, \mu_r\) are the relative permittivity and permeability of the FR-4 dielectric substrate, respectively.

From equation (1), the perfect broadband absorber can be achieved when \(Z_{in}\) is equal to \(Z_0\) (the imaginary part of \(Z_{in}\) is 0, and the real part is equal to \(Z_0\)). Equations (2)–(4) shows that \(Z_{in}\) is determined by \(R, L, C, \) and \(Z_d\) when the material parameters are determined. That is, \(Z_{in}\) is related to the \(p, s, w, \) and \(d\). Therefore, by varying the structure parameters, the input characteristic impedance of the MA can be adjusted to match the characteristic impedance of free space to obtain the higher absorbance in the entire X and Ku bands.

2.2. Simulation and optimization

According to the above theoretical analyses, the MA unit cell simulated and optimized by the simulation software COMSOL Multiphysics 5.4 based on the finite element method. The simulation model showed in figure 3. The top and bottom of the MA are air layers. Port 1 and port 2 set in the \(x-y\) plane, \(d_1\) is the distance from port 1 to the surface of the MA, and \(d_2\) is the distance from port 2 to the bottom of the MA. To obtain the accurate phase information, \(d_1\) and \(d_2\) must be as small as possible. The boundary conditions in the \(x\) and \(y\) directions are set as periodic boundary conditions to simulate the periodic structure of the MA. The electromagnetic waves incident along with the \(z\)-direction, TE polarization defined as the electric field direction is perpendicular to the \(x-z\) plane and TM polarization defined as the electric field direction is parallel to the \(x-z\) plane. The \(S\) parameter can be conveniently obtained by the simulation software, include the reflection coefficient \((S_{11})\) of the port 1 and the transmission coefficient \((S_{21})\) of the port 2. The absorptivity \(A(w)\) can be calculated by formula \(A(w) = 1 - R(w) - T(w)\), where \(R(w) = |S_{11}|^2\) is reflectivity, \(T(w) = |S_{21}|^2\) is transmissivity, and \(w\) is the electromagnetic wave angular frequency. Due to the barrier of the bottom copper plate, the electromagnetic wave cannot pass through \((T(w) = 0)\), therefore, the formula can be simplified as \(A(w) = 1 - R(w)\).

This research optimized structural parameters of the MA under TE-polarized normal incidence. It aims to achieve the absorptivity larger than 90% in the entire X and Ku bands. The absorption spectra of the proposed MA is simulated at different geometric dimension parameters, as shown in figure 4. The thickness \((d)\) of FR-4 dielectric substrate changes in the range of 2.2–3 mm, as \(d\) increases, the absorption band moves to low
frequency, and the second absorption peak changes in a wide range, as shown in figure 4(a). The thickness $d = 2.6$ mm is chosen for the smoothest absorbance and widest bandwidth. Once determined the thickness of the FR-4 substrate, the planar dimension of the unit cell is optimized. The periodicity ($p$) in the range of 7.6–9.2 mm and width ($w$) in the range of 1.2–2.4 mm, the change of $p$ or $w$ has a great influence on the high-frequency part of the absorption band. With the increase of $p$, the first and second absorption peaks move to the high frequency, and the third absorption peak shift towards the low frequency, thus the absorption bandwidth is narrowed. The effect of changing $w$ on the absorption band is just opposite to that of $p$. When $p = 8.4$ mm and $w = 1.8$ mm, the upper limit frequency of the absorptivity above 90% is 18 GHz exactly, as shown in figures 4(b), (c). Finally, the influence of different length ($s$) in the range of 7–8.6 mm on absorption spectra are studied, as shown in figure 4(d). The first absorption peak toward the low frequency with the increase of $s$, and
the positions of the second and third absorption peaks remain substantially unchanged, and the bandwidth broadens towards to low frequency. When $s = 7.8$ mm, the lower limit frequency of the absorptivity above 90% is 8 GHz. As a result, the optimized geometric dimension parameters of the MA unit cell that completely covers X- and Ku-band are as following: $d = 2.6$ mm, $p = 8.4$ mm, $w = 1.8$ mm, $s = 7.8$ mm.

3. Results and discussion

3.1. Theoretical analysis

As illustrated in figure 5, this research explored the absorption spectra of the proposed broadband MA structure under normal incidence for TE and TM polarizations. The figure shows that the absorptivity larger than 90% in the broadband of 8 GHz to 18 GHz, and the absolute bandwidth is 10 GHz, completely cover X- and Ku-band. There are three distinct absorption peaks at 8.6 GHz, 12.8 GHz, and 17.3 GHz, corresponding to the maximum absorptivity of 99.8%, 99.9%, and 99.7%, respectively. Moreover, the absorption spectra consistent for TE and TM polarization. It shows good broadband characteristics. Lots of previous papers have reported the consistency between simulations and experimental results \cite{14, 16, 17, 26–28}. Therefore, simulation is an appropriate method to analyze the absorption performance of the MA.

The normalized input impedance ($Z_{\text{eff}}$) of the MA is calculated by equation (5) \cite{29} in the case of vertical incidence of electromagnetic waves, as shown in figure 6. At the resonant frequency range of 8 GHz-18 GHz, the real part and imaginary part of $Z_{\text{eff}}$ are approximated to 1 and 0, respectively, the impedance of the MA and free space matches well, which explains the reason for the broadband and high absorption in figure 5. Especially at the frequencies of 8.6 GHz, 12.8 GHz and 17.3 GHz corresponding to the three absorption peaks, $Z_{\text{eff}}$ is $0.9553 + 0.0752j$, $0.9579 - 0.0102j$, and $0.9302 - 0.0853j$, respectively, the matching degree with free space is the highest. Therefore, near-perfect absorption is achieved at these three resonance frequencies.

$$Z_{\text{eff}} = \frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2} = \frac{1 + S_{11}}{1 - S_{11}}$$

To investigating the absorption mechanism of the proposed MA, this research studies the electric field and surface current distributions at these frequencies corresponding to the three distinct absorption peaks. As shown in figures 7(a)–(c), the electric field mainly concentrates on the edge of the copper strip. At 8.6 GHz, the electric field concentrates on the short side of the copper top layer. With the frequency increasing to 12.8 GHz and 17.3 GHz, the electric field gradually converges to the long side. Therefore, with the change of frequency, there is a current with directional moving, and the electric field distribution caused by a large amount of charge accumulation indicates that resonance occurs in the MA unit cell. The surface current distributions at the top and bottom of the MA are illustrated in figures 7(d)–(i). It is worth to mention that the top surface current flows upward at 8.6 GHz and 12.8 GHz, indicating that the combined field generated by the applied electric field and the induced electric field is consistent with the direction of the external electric field, that is, the induced electric field is smaller than the applied electric field, resulting in a smaller electrical response, and the top contrary to the direction of the surface current at the bottom, according to Ampere’s law, it is known that the combined
magnetic field generated by the applied magnetic field and the induced magnetic field is opposite to the direction of the applied magnetic field, which means that the generated induced magnetic field is larger than the applied magnetic field, thereby exciting the magnetic response. At the high frequency of 17.3 GHz, the surface currents at the top and bottom of the MA are antiparallel, but the direction of induced magnetic field is downward, which

Figure 6. Normalized input impedance ($Z_{\text{eff}}$) of the proposed MA under normal incidence.

Figure 7. Distributions of electric field (a)–(c) and surface current on (d)–(f) the top layer and (g)–(i) bottom layer of the MA unit cell for normal incidence with various resonant frequencies of 8.6 GHz, 12.8 GHz and 17.3 GHz, respectively.
is perpendicular to the external magnetic field, so the magnetic response is small, while the direction of surface current at the top is downward, which indicate that the direction of the synthetic electric field is opposite to the external electric field, which means that the induced electric field generated is greater than the external electric field, so as to stimulate the electric response. It is clear that the peaks at the lower resonance frequencies of 8.6 GHz and 12.8 GHz are mainly due to the excitation of electrical resonance, while the peak at the higher resonance frequency of 17.3 GHz mainly due to the excitation of strong magnetic resonance, so that the energy of electromagnetic waves bound to the interior of the MA and consumed, so as to achieve the purpose of absorbing electromagnetic waves.

The constitutive electromagnetic parameters of the MA are retrieved under normal incidence, to further understood the physical mechanism of the proposed structure. The effective permittivity ($\varepsilon_{eff}$) and effective permeability ($\mu_{eff}$) are calculated by surface electrode susceptibility ($\chi_{es}$) and surface magnetic susceptibility ($\chi_{ms}$) as shown in equations (6)–(9), where $k_0$ is the wavenumber of the free space and $d$ is the distance to be traveled by the incident wave [14, 30]. This method is superior to the traditional S-parameter inversion method [29] because it does not involve the extraction of $S_{21}$ parameters.

$\chi_{es} = \frac{2j}{k_0} \frac{S_{11} - 1}{S_{11} + 1}$

$\chi_{ms} = \frac{2j}{k_0} \frac{S_{11} + 1}{S_{11} - 1}$

$\varepsilon_{eff} = 1 + \frac{\chi_{es}}{d}$

$\mu_{eff} = 1 + \frac{\chi_{ms}}{d}$

According to the impedance matching theory, it is known that perfect absorption achieved when $\varepsilon_{eff} = \mu_{eff}$. The real parts and imaginary parts of the retrieved constitutive electromagnetic parameters are shown in figures 8(a), (b). The values of $\varepsilon_{eff}$ and $\mu_{eff}$ are close, indicate that the impedance of the MA matches well with free space in the entire X – Ku bands, which has been verified by the analyses of figure 6. At 8.6 GHz, 12.8 GHz, and 17.3 GHz, the real parts of $\varepsilon_{eff}$ and $\mu_{eff}$ are nearly equal, while the imaginary parts of $\varepsilon_{eff}$ and $\mu_{eff}$ are almost equal too, as shown in table 1. Thus, it minimizes reflection and with large electric loss angle ($\tan\delta_e$) and magnetic loss angle ($\tan\delta_m$) at the same time, so that to achieve near-perfect absorption.

Table 1. The detailed data of the corresponding frequencies of absorption peaks (include $\varepsilon_{eff}$, $\mu_{eff}$ and loss tangent $\tan\delta$).

| Frequency (GHz) | Real($\varepsilon_{eff}$) | Real($\mu_{eff}$) | Imaginary($\varepsilon_{eff}$) | Imaginary($\mu_{eff}$) | $\tan\delta_e$ | $\tan\delta_m$ |
|----------------|--------------------------|------------------|-----------------------------|-----------------------|---------------|---------------|
| 8.6            | 1.3365                   | 0.6908           | 4.3227                      | 3.9714                | 3.2343        | 5.7490        |
| 12.8           | 0.9692                   | 1.0282           | 2.9162                      | 2.6732                | 3.0089        | 2.6080        |
| 17.3           | 0.8015                   | 1.1732           | 2.2025                      | 1.9222                | 2.7480        | 1.6384        |

Figure 8. Retrieved constitutive electromagnetic parameters: (a) real parts of $\varepsilon_{eff}$ and $\mu_{eff}$, (b) imaginary parts of $\varepsilon_{eff}$ and $\mu_{eff}$.
3.2. Oblique incidence and polarization characteristics

The proposed structure has been investigated for different oblique angles ($\theta$) from 0° to 50° under both TE and TM polarizations, as shown in figures 9(a), (b). For TE polarization, in the case of the electric field parallel to the $y$-axis, the angle between the wave vector and $z$-axis is $\theta$, while the direction of the magnetic field is changed simultaneously with wave vector, as shown in figure 9(a). With the increase of incident angle, the absorption and bandwidth decrease gradually. The main reason for this phenomenon is that, as the incident angle increases, while the magnetic field component decreases gradually leads to effective magnetic resonance decrease. For TM polarization, in the case of the magnetic field unchanged along with the $y$-axis, the angle between the wave vector and $z$-axis is $\theta$, while the direction of the electric field varies simultaneously with wave vector, as illustrated in figure 9(b). Due to the electric field component decreases along with the increase of incident angle, the effective electric resonance is reduced, which leads to the absorption and bandwidth decrease. Moreover, the absorptivity remains over 80% in the frequency range of 7.9 GHz-15 GHz, even the incident angle up to 40°. Therefore, the proposed MA with good absorption performance for both TE and TM polarization under a wide incident angle.

The absorbing behavior of the structure has been further studied for polarization angles ($\varphi$) from 0° to 90° under normal incidence, as shown in figure 10. The angle between the direction of the electric field and magnetic field with the $y$-axis and $x$-axis is $\varphi$, respectively, to ensure the vertical incidence of electromagnetic waves. When $0^\circ \leq \varphi \leq 45^\circ$, as the polarization angle increases, leading to the absorptivity decreases gradually and reach the lowest value at 45°, while when $45^\circ < \varphi \leq 90^\circ$, as the polarization angle increases, contributing to the absorptivity increases gradually and reach the highest value at 90°. Moreover, the absorptivity curves are almost identical in the case of the polarization angle of 0° and 90°, 15° and 75°, 30° and 60°, respectively. The reason for this phenomenon is that the normal incidence of TE polarization occurs when the polarization angle is 0°. As the increase of polarization angle, the excitation of the electric field component and magnetic field component for
the effective electromagnetic resonance decreases. Due to the geometric structure characteristic of 45° rotation of the copper top layer, the electromagnetic resonance is the smallest as the polarization angle up to 45°, while the absorptivity decreases to the lowest level. As the further increase of polarization angle, the excitation of electromagnetic resonance by the electric field component and magnetic field component increases, the excitation converted to the case of vertical incidence of TM polarization when the angle up to 90°. It has been reported that the MA with polarization-sensitive can be well applied to radar imaging and defense system [26].

3.3. Comprehensive comparison

Finally, this section compares the proposed MA with other broadband MA in terms of absorption frequency, absolute and relative bandwidth, plane size, and thickness, etc., as shown in Table 2. Absolute bandwidth defined as $RB = 2 \times (f_2 - f_1)/(f_2 + f_1)$, where $f_2$ and $f_1$ correspond to upper and lower limit frequencies with absorptivity higher than 90%, it often used to evaluate the absorption performance of MA [22]. The MA presented in this paper is insensitive to a wide incident angle, the absorptivity over 90% in the frequency range of 8 GHz to 18 GHz, absolute and relative bandwidth reach to 10 GHz and 76.92%, the size and thickness are small. Therefore, it can be used as one of the alternatives to reduce radar cross-section, stealth, and to improve the electromagnetic compatibility of devices.

| Ref.   | Absorption Band (GHz) | Absolute bandwidth (GHz) | Relative Bandwidth (%) | Load Lumped Element | No. of Layers | $\lambda_0$ | $\lambda_0$ | Thickness |
|--------|------------------------|---------------------------|------------------------|---------------------|--------------|----------|----------|-----------|
| [20]   | 10.8–15.8              | 5                         | 37.59                  | No                  | 13           | 0.37$\lambda_0$ x 0.37$\lambda_0$ | 0.13$\lambda_0$ |
| [21]   | 3.01–5.28              | 2.27                      | 54.76                  | Yes                 | 1            | 0.41$\lambda_0$ x 0.41$\lambda_0$ | 0.07$\lambda_0$ |
| [24]   | 7–12.8                 | 5.8                       | 58.59                  | Yes                 | 1            | 0.56$\lambda_0$ x 0.36$\lambda_0$ | 0.11$\lambda_0$ |
| [25]   | 4–8                    | 4                         | 66.67                  | No                  | 1            | 0.31$\lambda_0$ x 0.12$\lambda_0$ | 0.09$\lambda_0$ |
| [27]   | 7.8–14.7               | 6.9                       | 61.33                  | No                  | 20           | 0.41$\lambda_0$ x 0.41$\lambda_0$ | 0.12$\lambda_0$ |
| This Work | 8–18                  | 10                        | 76.92                  | No                  | 1            | 0.36$\lambda_0$ x 0.36$\lambda_0$ | 0.12$\lambda_0$ |

4. Conclusion

This research proposed a microwave broadband MA based on asymmetric structure design, which consists of copper strip resonator with 45° rotation and copperplate, located on the surface and bottom of the lossy FR-4 dielectric substrate, respectively. Based analysis of its equivalent circuit model, the structural parameters are optimized by COMSOL simulation software. The proposed structure exhibits the broadband absorption response completely covers entire X- and Ku-band ranges from 8 GHz to 18 GHz with absorptivity more than 90%. For the oblique incidence of TE and TM polarization, the absorptivity maintained over 80% in the broadband of 7.9 GHz–15 GHz even the incident angle up to 40°. The absorption mechanism is explained according to the electric field and surface current distributions of three absorption peaks under the normal incidence of electromagnetic waves, while the normalized input impedance and constitutive electromagnetic parameters are calculated to verify the impedance of the proposed structure matches well with free space in the operating frequency band. Thus, it obtains wide-band and high absorption performance. Furthermore, the MA designed in this paper is a single-layer structure with compact structure and insensitivity to the wide incident angle, it may make contributions in terms of reducing radar cross-section, stealth and improving the electromagnetic compatibility of devices.

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