Skew symmetric structure for ultra-broadband electromagnetic absorbing

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Abstract
The paper reports the concept and design of skew symmetric structure which can achieve perfect electromagnetic absorbing in ultra-broad frequency range with the entire thickness being only 1/12 of the absorption wavelength. To prove the validity, a broadband absorber based on the structure is designed. Its absorptivity is more than 90% from 11.51 GHz to 23.75 GHz and the relative absorption bandwidth reach 69.4%. The characteristics are insensitive to the type and thickness of the metals of the structure. It keeps broadband absorption with high absorptivity in the case of oblique incidence. Besides, the design of the skew symmetric structure can be applied to other wavebands. A terahertz absorber based on the structure is proposed to demonstrate the effectiveness. It can broaden the bandwidth to about 43 times that of the traditional square-ring metamaterial terahertz absorber and the thickness is only 1/12 of the absorption wavelength (4.34 μm).

1. Introduction
Realization of broadband and perfect electromagnetic absorbing with ultra-thin and flexible materials can open a door for new generation electromagnetic functional components. In 2008, Landy et al proposed the first metamaterial-based absorber which can achieve perfect absorption at specified frequency point [1]. Since then, the metamaterial absorbers have been widely studied and their absorption spectra have covered the microwave [2, 3], terahertz (THz) wave [4, 5], infrared wave [6, 7] and visible light [8, 9]. Their advantages of ultra-thin and high-absorption provide possibility of improving the stealth performance of specific equipment [10]. However, narrow bandwidth resulting from their resonant nature has raised doubts concerning their usefulness. Therefore, the methods to achieve broadband absorption have been extensively researched over the last decade [11]. For examples, Viet et al integrated 9 different discs on one unit-cell to expand the absorption bandwidth (1.8 GHz) and achieved high absorption ratio of more than 90% [12]. Ding et al stacked multiple layers in the vertical direction to realize a broadband absorption from 7.8 to 14.7 GHz [13]. Nguyen et al achieved an absorption rate of more than 90% in the frequency range from 7 to 12.8 GHz by loading lumped elements [14]. Zhang et al replaced the metal with ITO (Indium tin oxide) film to achieve a broadband absorption with absorptivity higher than 90% in the range from 8.3 to 17.4 GHz by adjusting the surface impedance of ITO [15]. In general, there are several methods are widely used for extending bandwidth of the metamaterial absorbers, including the loading of lumped elements [12, 13], stacking of multiple layers [14, 15], the integration of multiple resonances [15, 16] and so on. However, the absorbers based on these methods are limited by the contradiction between thickness, fabrication difficulty and absorption bandwidth. Some of absorbers are thin and simple to process, but the absorption bandwidth is relatively narrow [15–19]. On the contrary, some of them have wider bandwidth [12–15], but they are too thick and difficult to process [20–22]. Finding an effective structure to solve the contradiction is important and it will be of great significance to the practical application of metamaterial absorbers.

To overcome the limitation of prior works, we propose a skew symmetric structure which can achieve ultra-broadband absorbing with the entire thickness being only 1/12 of the absorption wavelength. In the following, a 3-layer microwave absorber is designed to demonstrate the structure. According to the numerical simulation, its
absorptivity is more than 90% from 11.51 GHz to 23.75 GHz, and it has nearly perfect absorption (\(>99\%\)) at 12.392 GHz, 16.892 GHz and 22.004 GHz. Then, the characteristics at different oblique incidence angles and polarization directions are analyzed. Besides, the proposed structure can be applied to the other wavebands and a terahertz absorber based on the structure is proposed. Its entire thickness is only 4.34 \(\mu\)m and it can broaden the bandwidth to about 43 times that of the traditional square-ring metamaterial THz absorber. The ultra-broadband, high-absorptivity, ultra-thin and flexibility will make the skew symmetric structure suitable for the applications of electromagnetic stealth, imaging, communication and other fields.

2. Structure design and simulations

Figure 1(a) shows one unit-cell of the designed structure and multiple unit-cells are arranged periodically to form the absorber as is shown in figure 1(b). The unit-cell includes three layers: the top layer is the proposed skew symmetric structure; the middle layer is the flexible dielectric spacer; the bottom layer is the metal ground. The skew symmetric structure is composed of two square brackets and two square blocks. The top and bottom metal is the copper with an electric conductivity 5.8 \(\times\) 10^{7} s m^{-1}, the middle layer is polyimide (PI) with a relative permittivity 3.5 and a loss tangent 0.008. The structural parameters are as follows: \(L_1 = 4.5\) mm, \(P = 8\) mm, \(L_2 = 1\) mm, \(W = 0.5\) mm, \(G = 0.9\) mm, \(T_r = T_s = 0.035\) mm, \(T_d = 2.1\) mm.

When the electromagnetic wave is incident on the surface of the absorber, the top layer structure causes electrical resonance, the interaction between the top layer and bottom layer causes magnetic resonance. The electromagnetic wave is absorbed owing to the dielectric loss and ohmic loss. It’s known that the absorber’s unit size is much smaller than the wavelength, so it can be regarded as an effective artificial material characterized by a complex electric permittivity \(\varepsilon_r(\omega)\) and a complex magnetic permeability \(\mu_r(\omega)\). The complicated structure makes it difficult to use the analytical calculation method. Therefore, the reflectance and transmission are acquired by simulating the frequency dependent \(S\) parameters, i.e., \(S_{11}\) and \(S_{21}\) [1]. Then, the absorptivity \(A\) is expressed as:

\[
A = 1 - R - T = 1 - |S_{11}|^2 - |S_{21}|^2. \tag{1}
\]

Here, \(|S_{11}|^2\) and \(|S_{21}|^2\) stand for reflectance \(R\) and transmission \(T\) respectively. To maximize the absorption \(A\), the reflection and transmission must be minimized. The transmission of the absorber is zero, because the thickness of the bottom metal layer is much larger than the skin depth of the electromagnetic wave and the wave cannot penetrate the bottom layer. Therefore, the absorptivity is calculated by \(A = 1 - R\).

Moreover, as is described from equation (2), reflection \(R\) can be calculated by the impedance \(Z\) of the absorber and the impedance of free space \(Z_0\). It’s possible to design an optimized structure so that the relative permittivity \(\varepsilon_r\) is equal to the relative permeability \(\mu_r\). Then, the impedance of the absorber can perfectly match the impedance of free space to achieve zero reflection.

\[
R = \frac{Z - Z_0}{Z + Z_0}; Z = \sqrt{\frac{\mu_r\mu_0}{\varepsilon_r\varepsilon_0}}; Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\Omega. \tag{2}
\]

Two kinds of software are used to simulate the absorption characteristics of the proposed absorber to ensure the correctness of numerical simulation. The first software is HFSS which is based on the Finite Element Method (FEW); the other software is CST MWS which is based on the algorithm of Finite Integration Technique (FIT). Figure 2(a) shows the simulated absorption spectra. It can be seen that the simulation results of the two algorithms are in good agreement and the absorber has an ultra-broadband absorption with absorptivity higher than 90% in the range from 11.51 GHz to 23.75 GHz (which is located in the X, Ku, and K bands). There are three perfect absorption peaks: \(f_1 = 12.392\) GHz, \(f_2 = 16.892\) GHz and \(f_3 = 22.004\) GHz. Their absorption rates are 99.98%, 99.99%, and 99.99%, respectively. To describe the absorption bandwidth, the relative...
absorption bandwidth (RAB) is defined as:

$$W_{RAB} = 2(f_{\text{max}} - f_{\text{min}}) / (f_{\text{max}} + f_{\text{min}}).$$

Here $W_{RAB}$ is the RAB; $f_{\text{max}}$ and $f_{\text{min}}$ stand for the maximum and minimum values of the frequency range with absorptivity being above 90%. By calculation, the relative absorption bandwidth $W_{RAB} = 69.4\%$. In addition, according to the effective medium theory \cite{22}, the relative impedance $Z$ of the proposed absorber can be given by:

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

Therefore, the relative impedance of the absorber is acquired as shown in figure 2(b). The value of real part of the relative impedance is close to 1 in the frequency range from 11.51 GHz to 23.75 GHz, and the imaginary part value is close to 0, especially at the three absorption peaks which have been marked. It proves that the impedance of the absorber is perfectly matched to the impedance of free space in ultra-wide frequency range, so the reflection is near zero and the perfect absorption is achieved.

3. Analysis and discussion

To analyze the broadband absorption mechanism of the skew symmetric structure, we separate the structure into three parts: upper skew square bracket (Part A), lower skew square bracket (Part B), and center square blocks (Part C). The three parts are simulated separately and their absorption spectra are shown in figure 3(a). Furthermore, we simulated the distributions of electric field intensity at three absorption peaks as shown in figures 3(b)–(d). It can be seen that the spectra of Part A and B have absorption peaks at 12.518 GHz (absorptivity is 99.893%). There is a broadband absorption with absorptivity higher than 50% in the range from 11.384 GHz to 20.762 GHz. Meanwhile, the Part C provides absorption peak at 23.264 GHz (absorptivity = 98.141%) and the combination of three parts provides three perfect absorption peaks at 12.392 GHz, 16.892 GHz, and 22.004 GHz. Therefore, it can be inferred that the first peak (12.392 GHz) is mainly generated by the structure of Part A and B; the second peak (16.892 GHz) mainly comes from the structure of Part C; the second peak (16.892 GHz) comes from the coupling effect of the discrete parts. The combination of three parts provides an ultra-broadband absorption with absorptivity higher than 90% in the range from 11.51 GHz to 23.75 GHz.

Next, we choose different metal materials to construct the skew symmetric structure (top layer of the absorber) and analyze their effects on the properties of absorber. Without loss of generality, three metals (copper, silver, and gold) are chosen. The conductivities of three materials are $5.8 \times 10^7$ s m$^{-1}$, $6.1 \times 10^7$ s m$^{-1}$, and $4.1 \times 10^7$ s m$^{-1}$, respectively. The absorption spectra are shown in figure 4(a) and there is little difference between different spectra. In addition, effects of metal thickness on spectra are simulated. Figure 4(b) illustrates the absorption spectra at various thicknesses (0.02 mm copper, 0.03 mm copper, and 0.04 mm copper) and they are almost identical. Therefore, it can be considered that the absorption characteristics of the proposed structure are insensitive to the type and thickness of the metals.
Previous simulations and analysis have demonstrated the broadband absorption of the absorber when normal incidence. Considering the practical applications, oblique incidence should also be studied. Therefore, we simulated the absorption spectra in the case of oblique incidence. Figures 5(a) and (b) show the oblique incidence of TE (Transverse Electric) radiation and TM (Transverse Magnetic) radiation. The \( \theta \) is defined as the incidence angle between wave vector \( \mathbf{k} \) and the surface normal of the absorber. Figure 5(c) shows how the absorptivity varies with the different incidence angle \( \theta \) (0 degree to 30 degree) for the TE radiation. Figure 5(d) describes how the absorptivity changes with the TM radiation. According to the Figures, although the bandwidth and absorptivity are slightly decreased, the absorber still maintains high absorptivity (>80%) from 11.384 GHz to 19.664 GHz (TE and TM radiations). It demonstrates the ultra-broadband characteristics of the absorber when oblique incidence.

In addition, the absorption spectra at various polarization directions for the normal incidence are simulated. Figure 6(a) illustrates the polarization angle \( \varphi \). Figure 6(b) shows the spectra. It can be seen that the absorptivity will not decrease when the polarization angle is from 0 to 10 degree. With the polarization angle increasing from 0 to 45 degree, the absorptivity of the absorber decreases significantly. Interestingly, the absorptivity will increase again as the \( \varphi \) increases from 45 to 90 degree. The absorption spectra of 0 to 90 degrees are symmetrically distributed at the boundary of the absorption spectrum of 45 degrees. This is due to that the unit-cell is not symmetric in respect to 90-degree rotation (C4 symmetry). In the future, it can be improved by integrating four directional unit-cells into one large unit. Although the change of polarization angle will lead to the change of absorptivity, the absorption spectra remain broadband and the position of absorption peaks are almost the same.

It is worth mentioning that the skew symmetric structure can also be applied to other wavebands. To demonstrate it, a THz broadband absorber is proposed by scale scaling (500 times) as depicted in figure 7(a). For comparison, we designed an absorber based on traditional square ring structure [23] as shown in figure 7(b). The parameters of two kinds of structure are: \( P_T = 16 \) \( \mu m \), \( L_{1T} = 9 \) \( \mu m \), \( L_{2T} = 2 \) \( \mu m \), \( G_T = 1.8 \) \( \mu m \), \( W_T = 1 \) \( \mu m \),
The thickness of the top and bottom metallic layers is both 0.07 μm, and the thickness of the intermediate dielectric spacer is 4.2 μm. According to the figure 7(a), the skew symmetric structure absorber has ultra-broadband absorption with an absorptivity higher than 90% from 5.78 to 11.86 THz and its bandwidth is 6.08 THz. By contrast, the bandwidth of the square ring structure is about 0.14 THz. The bandwidth of the
proposed structure is 43 times that of the traditional structure. The entire thickness is only 4.34 µm, which is 1/12 of the wavelength (at 5.78 THz).

4. Conclusion

In conclusion, the design, simulation, and analyses of the broadband absorber based on skew symmetrical structure are demonstrated. It offers excellent absorption (absorptivity > 90%) in the ultra-broad bandwidth (from 11.51 to 23.75 GHz), which covers the Ku band, part of the X band and K band. The entire thickness of the absorber is 2.17 mm, which is only 1/12 of the absorption wavelength (at 11.51 GHz). In addition, the absorption characteristics of the proposed structure are insensitive to the type and thickness of the metal materials. By scaling the structure parameters, the skew symmetric structure can be applied to THz waves to construct THz absorber. Its bandwidth is 43 times that of the traditional THz metamaterial absorber based on square ring structure and the overall thickness is only 1/12 of the absorption wavelength (at 5.78 THz). Therefore, we believe the skew symmetric structure has excellent properties and can serve as a promising platform to advanced metamaterials for a wide range of applications, including electromagnetic stealth cloak, microwave or terahertz imaging, communication, biosensor, and wearable photonics devices, and so on.

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