Design of dual narrow-band terahertz absorber based on metamaterials

Zhongru Ren*

Faculty of Science & Technology, Communication University of China, Beijing, China

*Corresponding author e-mail: 294030535@qq.com

Abstract. Metamaterial-based absorbers are a new kind of synthetic electromagnetic materials. Because of their small thickness, easy manufacture and stable performance, they are widely used in electromagnetic wave detection in different bands. Based on the principle of equivalent LC resonant circuit, a dual-band narrow-band absorber in terahertz band is designed in this paper. The frequency domain solver based on CST software is used to study the absorption characteristics of the absorber in terahertz band. The relationship between changing different system parameters and optimizing the absorption rate and adjusting the position of resonance absorption peak is analyzed in detail. It has certain guiding significance for the detection of terahertz wave and the fabrication and optimization of terahertz wave absorbers, filters and resonators.

1. Introduction

Terahertz wave is a kind of electromagnetic wave whose frequency ranges from 0.1Thz to 10Thz. Its wavelength threshold range is between microwave band and near infrared band in electromagnetic spectrum [1]. It is also a new research field. It is widely used in modern detection imaging, stealth technology, non-destructive testing, etc [2]. At present, for terahertz wave researchers, the technical barrier that is difficult to break through is the lack of high sensitivity terahertz wave detectors in terahertz band, mainly because it is difficult to find materials with broadband response in terahertz band. Therefore, in the actual terahertz wave detection process, researchers will coat a layer of absorber on the surface of the terahertz probe to increase the absorption rate of the probe to terahertz wave.

The proposal of metamaterial dual narrowband absorber can be traced back to 2008. Landy N.I[3], first proposed the "perfect absorber" model based on resonance. The principle is to reduce the reflection of electromagnetic wave on the surface of absorber material by changing the electromagnetic parameters and physical size of the system artificially and using impedance matching principle to maximize the absorber to the specified frequency. Absorption rate of electromagnetic wave in the range of rate. Subsequently, in the field of dual-frequency absorbers, many scientists have made in-depth exploration. For example, Q-Y Wen [4] and others make use of the three-layer periodic structure of "Periodic Metal-Medium-Metal bottom plate" to form a dual narrow-band absorber, which achieves more than 98% absorption at 0.51Thz and 0.94Thz. These two typical rotationally symmetric periodic structures provide theoretical support for the development of metamaterial absorber.

In recent years, people have realized that dual-frequency absorber is a technology in the field of terahertz wave detection which needs to be developed urgently. Osman [5] et al. designed a polarization-
independent dual narrow-band metamaterial absorber. The "double-cross" periodic structure was used for the first time. The absorption rate reached 99.3% and 97.3% respectively. Its good polarization-independent characteristics also provided a new idea for the development of dual-band narrow-band absorber. At the same time, Wu Pan [6] and others found that if the unit period is different, but the top periodic structure of the same circular dual-band narrow-band absorber overlaps, making it a "pyramid" combination absorber, by optimizing the system coefficients of each layer, the bandwidth can be broadened and converted into a broadband absorber, and the absorption rate can reach more than 96%. It can be seen that the dual narrow-band absorber is closely related to terahertz detection and the development of broadband absorber. At the same time, the polarization-independent characteristics and the adjustable absorption peak frequency characteristics have become the hot research direction of dual-band narrow-band absorber in recent years.

Based on the above exploration in the field of dual narrow-band absorber, a dual narrow-band metamaterial absorber is designed by using the equivalent LC resonant circuit theory of open resonant ring (SRR). The absorber has simple structure, small thickness, stable performance, high absorption rate in the corresponding frequency band and is convenient for mass production of the absorber array, which can meet the actual needs. The CST software is used to analyze the characteristics of the "positive C" absorber. At the same time, the system parameters of the absorber are transformed. The changes of the absorber absorptivity and the position of the resonance absorption peak under different conditions are obtained. It has certain guiding significance for the production of electromagnetic wave detectors, absorbers and filters in terahertz frequency band.

2. Design Theory of Dual-band Narrow-band Absorber

2.1. Absorption rate of absorber

In frequency domain, \( A(\omega) \) is defined as the absorptivity of the absorber; \( R(\omega) \) is the reflectivity of the surface of the absorber; \( T(\omega) \) is the transmittance of the absorber. Then the absorptivity of the absorber can be expressed as:

\[
A(\omega) = 1 - R(\omega) - T(\omega)
\]  (1)

The ultimate goal of the "perfect absorber" based on resonance is to make it as close as possible to 1. From formula (1), reflectivity and transmittance directly determine the absorptivity of the absorber. \[
R(\omega) = |S_{11}|^2
\]
\[
T(\omega) = |S_{21}|^2
\]  (2)

In formula 2, \( R(\omega) \) and \( T(\omega) \) are the reflection and transmission parameters of the absorber. The reflection and transmission parameters can be adjusted by artificially changing the system parameters of the absorber unit structure so that the reflectivity and transmittance of the material can be as close as possible to 0. In theory, the "near perfect absorption" of the absorber can be achieved.

However, the actual situation is that when the thickness of the continuous metal film at the bottom of the absorber is larger than the skin depth of the incident electromagnetic wave, the transmission parameter \( T(\omega)=0 \) [7]. For absorptivity \( A(\omega) \), there are:

\[
A(\omega) = 1 - R(\omega) = 1 - |S_{11}|^2
\]  (3)
2.2. Equivalent LC resonant circuit theory of absorber

In this paper, a "positive C" open resonant ring (SRR) is constructed by using the theory of equivalent LC resonant circuit, and an array of absorbers is constructed periodically. The incident electromagnetic wave is along the -z direction. As shown in Fig. 1, the structure unit of the metamaterial absorber is divided into four layers, the top layer to the bottom layer are: the first layer is a periodically patterned metal structure, and the material is gold. conductivity of gold is \( \sigma = 4.09 \times 10^7 \, S / m \), thickness is \( 0.2 \, \mu m \), unit period is \( p = 90 \, \mu m \), the system size is \( b = 76 \, \mu m \), \( g = 14 \, \mu m \), \( w = 13 \, \mu m \). The pattern is shown in Figure 1 (a). The second layer is the intermediate layer, the material is polyimide (PI) \( [8] \), the thickness is \( 12 \, \mu m \), the conductivity is \( \sigma = 1.05 \, S / m \), the dielectric constant is \( \varepsilon = \varepsilon_1 + i \varepsilon_2 = 2.88 + i0.09 \), the tangent value of the loss is \( \tan(\theta) = 0.031 \). The third layer is an opaque metal plane with gold and the thickness is \( 0.2 \, \mu m \). Layer IV is the substrate, the material is polyimide (PI), the thickness is \( 10 \, \mu m \), plays a supporting role. The boundary conditions are set as periodic boundary in x, y direction and open boundary in z direction.

![Figure 1](image)

**Figure 1.** (a) unit cell diagram (b) unit array diagram (c) Three-dimensional structure of the unit cell

3. Structural analysis and simulation

In high frequency circuits, conductors have a strong skin effect. If the current is equivalent to the high frequency current passing through the conductor, the current flows only in a thin layer on the surface of the conductor, resulting in an increase in the equivalent resistance of the conductor. The thickness of the layer \( \Delta \) is defined as the skin depth. The formula for calculating skin depth is as follows:

\[
\Delta = \frac{2}{\sqrt{\varepsilon \mu \omega}}
\]

In formula 4, \( \omega \) is the angular frequency of the incident electromagnetic wave. \( \varepsilon \) is the conductivity of the material, \( \mu \) is the permeability of the material. When the thickness of the metal plate at the bottom of the absorber is greater than the skin depth, the material transmittance \( T(\omega) = 0 \).

The skin depth of gold material \( \Delta = 0.12 \, \mu m \), and the thickness of opaque metal plane of layer III is greater than the skin depth of gold material, so it can be considered \( |S_{21}| = 0 \). The above model is imported into the frequency domain solver of CST software to analyze the absorption characteristics of the supermaterial absorber. The structure’s \( |S_{11}| \) and absorptivity trend image can be obtained.

![Figure 2](image)

**Figure 2.** metamaterial structure’s (a)\( |S_{11}| \) (b) absorption image
As can be seen from Figure 2, the absorber has only two absorption peaks in the frequency band, which are located at both locations. The absorption peaks in the x-polarization direction correspond to those in the y-polarization direction. The absorptivity of both can be guaranteed above 85%, which can meet the requirements of stability and efficiency of dual-band narrow-band absorber. It is noteworthy that the local absorption rate is close to 100%. This design can also be used as an alternative "perfect absorber" structure in this frequency band.

4. Effect of PI layer thickness $h$ on absorption rate and resonance absorption peak

According to the system parameters set by the "positive C" open resonant ring (SRR), the influence of PI layer thickness $h$ on the absorptivity is investigated, and the TE wave is incident with positive polarization. The thickness of PI medium is scanned by setting parameters according to the equal difference to determine the relationship between the thickness of PI medium $h$ and the absorption rate and resonance absorption peak. The simulation results are shown in Fig. 3. The absorption peak frequency corresponding to the x-polarization direction shifts, which is determined by $C=\varepsilon S / 4\pi kd$.

If the thickness of dielectric layer is increased, the relative distance between the top layer and the bottom plate will be increased. The change range of the equivalent capacitance can be neglected after the capacitance is connected in parallel, so the absorption peak frequency hardly changes. At this time, the dominant resonance is the dipole resonance between the top and bottom metal polar plates, referring to the dipole. In antenna theory, if the distance between the two is shortened, the electromagnetic coupling effect will be enhanced. Therefore, within a certain thickness range, the smaller the thickness $h$ of the medium in the y-polarization direction, the higher the absorptivity.

![Figure 3. Thickness of PI corresponding absorption curve](image)

5. Conclusion

In this paper, a "positive C" dual-band narrow-band terahertz wave absorber is designed, and its performance is analyzed based on the frequency domain solver in CST software. It is found that changing the system parameters of the absorber can affect the absorptivity of the absorber and the position of the resonance absorption peak. The reasons are explained. The "positive C" absorber has stable performance and high absorptivity, which has certain guiding significance for the realization of "perfect absorber" in terahertz band, and provides theoretical basis for the fabrication and optimization of terahertz electromagnetic wave detectors, absorbers and filters.

References

[1] Lee Yun-Shik. Principles of Terahertz Science and Technology[M]. NY: Springer, 2008.
[2] Tonouchi M. Cutting-edge terahertz technology [J]. Nature Photonics, 2007, 1(2): 97-105.
[3] Landy N I, Sajuyigbe S, Mock J J, et al. Perfect metamaterial absorber[J]. Physical Review Letters, 2008, 100(20): 7402-7406
[4] Q.-Y Wen, H.-W Zhang, Y.-S Xie. Dual band terahertz metamaterial absorber: Design, fabrication, and characterization (3 pages) [J]. Applied Physics . 2009
[5] Osman Ayop, Mohamad Kamal A. Rahim, Noor Asniza Murad. Dual-band metamaterial perfect absorber with nearly polarization-independent[J]. Applied Physics A, 2017, Vol. 123 (1), pp. 1-7
[6] Wu Pan, Xuan Yu. A Novel Design of Broadband Terahertz Metamaterial Absorber Based on Nested Circle Rings[J]. IEEE Photonics Technology Letters Year: 2016, Volume: 28, Issue:
Hu Tao, C. M. Bingham, A. C. Strikwerda, D. Pilon, D. Shrekenhamer, N. I. Landy, K. Fan, X. Zhang, W. J. Padilla, and R. D. Averitt Highly flexible wide angle of incidence terahertz metamaterial absorber: Design, fabrication, and characterization. [J]. Phys. Rev. B 78, 241103(R) – Published 19 December 2008

Perfect absorber metamaterial for designing low-RCS patch antenna. Y. H. Liu, X. P. Zhao. IEEE Antennas and Wireless Propagation Letters. 2014