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ШИРОКОПОЛОСНЫЙ СОВЕРШЕННЫЙ ПОГЛОТИТЕЛЬ ИЗ МЕТАМАТЕРИАЛА НА ОСНОВЕ ФРАКТАЛЬНОЙ СТРУКТУРЫ

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BROADBAND PERFECT METAMATERIAL ABSORBER BASED ON FRACTAL STRUCTURE

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Широкополосный совершенный поглотитель из метаматериала имеет широкие перспективы применения для обеспечения невидимости цели для радара, в областях конструирования антенн и электромагнитной защиты. Существующий многочастотный поглотитель увеличит размер или толщину структуры. В этой статье представлен широкополосный нечувствительный к поляризации совершенный поглотитель из метаматериала на основе фрактальной структуры. Благодаря комбинации фрактальной и круговой структур, рабочая полоса частот расширяется без увеличения размера структуры. Предложена простая модель эквивалентной схемы, описывающая явление поглощения, для оценки частоты поглощения предлагаемого поглотителя. Рассчитанный результат показывает, что относительная полная ширина полосы поглотителя на уровне половинной амплитуды составляет 11.7%. Рабочие углы, при которых структура метаматериала может поддерживать 50% коэффициента поглощения, равны 50 градусам. Обладая структурой с вращательной симметрией, поглотитель нечувствителен к поляризации. Эта структура создана и измерена в X-диапазоне, результаты эксперимента хорошо совпадают с результатами моделирования.

Ключевые слова: *метаматериал, широкополосный совершенный поглотитель, фрактальная структура*.

Broadband perfect metamaterial absorber has broad application prospects in the fields of radar target stealth, antenna design and electromagnetic protection. The existing multi frequency absorber will increase the size or thickness of the structure. This paper presents broadband polarization insensitive perfect metamaterial absorber based on fractal structure. Through the combination of fractal and circular structures, the bandwidth is extended without increasing the size of the structure. A simple equivalent circuit model has been proposed describing the absorption phenomenon to estimate the frequency of absorption of the proposed absorber. The simulated result shows that the absorber's relative full width half maximum is 11.7%. The operating angles which the metamaterial structure can maintain 50% of the absorbance are 50 degrees. With rotational symmetry structure, the absorber is insensitive to the polarization. This structure is made and measured at X-band, the experimental results coincide well with the simulation results.

Keywords: *metamaterial, broadband perfect absorber, fractal structure*.

Introduction

Artificial stealth materials have wide applications in areas such as radar target stealth, antenna design and electromagnetic protection etc. However, absorber based on traditional structures for the radar targets stealth application face big challenges on absorbing frequency, bandwidth, bulky and poor flexibility and other practical problems. Fractal structures different from the traditional structures, it has self-similarity, can have fine structures in any small scale , if it can be used in the designing of microwave absorber combined with characteristics of surface filling curves and will break through existing barriers.

The design of broadband absorbers is the main problem that needs to be solved in applications. Bao [6], Zou [7], Li [8], etc. use the same absorbing structure of different scales to periodically align in the plane to achieve the effect of broadband absorbing. Such a structural plane utilization rate is not high, which is equivalent to expanding the size of a single periodic structure.

Wen Qiye [9] Wang [10], Ghosh [11], Ding [12], etc. using multi-layer structure, superposition or multi-layer metal nesting in the thickness direction to achieve broadband absorption, but it has high processing precision, complicated preparation process and high processing cost. The thickness affects the application of the absorbing screen. Huang [13], Liu [14], Luo [15], etc. had a variety of absorbing structures in the periodic unit, and reduced the double absorbing peak spacing to achieve a single-layer absorbing body bandwidth expansion. Mainly using a number of small size structures to absorb electromagnetic waves, the principle and the first method do not differ much. Qu Shaobo [16], [17] teams achieve wide-band absorbing by loading lumped resistance or magnetic absorbing materials. Although this method greatly increases the absorbing band width, it is difficult to process and it has a heavy structure.

In order to achieve broadband absorption of the absorber, while having a wide angle of incidence, the polarization is independent. In this paper, a description of the designed microwave absorber with a ring and ring fractal combination structure is presented. By using the fractal structure to increase the structural length of the absorbing unit and simultaneously zooming in on the two absorbing points, the expansion of the absorbing bandwidth is realized. The ultra-thin thickness of the perfect absorber is maintained, the structure is simple and small, so that the absorber to have a wide range of applications. The research in this paper lays the foundation for further application of broadband perfect absorber in electromagnetic stealth.

2 Design and Simulation

2.1 Structural properties

The same-layer multi-frequency resonant structure is realized by tiling multiple resonant structures. According to the literature [18], the resonant frequency is related to the length of the metal wire $f \sim 1/\sqrt{\varepsilon}\mathrm{L}$. Where ε is the dielectric constant of the dielectric layer and L is the length of the metal line, so the structure size is inversely proportional to the resonant frequency. Designing multiple structures of similar size in the same plane enables broadband absorption. In order to narrow two resonance points without increasing the size of the unit, the resonant structure is usually very close, and there is coupling between the resonant structures, and the coupling is too large, which leads to detuning. The plurality of annular square rings and the like can realize multi-frequency absorption in the same unit, but it is difficult to achieve wide-band absorption due to coupling. Fractal can extend the length in a small size. Based on this, a microwave absorber with a ring and a ring fractal structure is proposed, which can achieve similar lengths in different sizes and reasonable design distances, and can close two resonance points.

The designed absorber consists of three layers, the bottom layer is a metallic copper plane, the copper thickness is 0.035 mm, and the conductivity is 5.8×10^7 S/m. The dielectric layer FR4 is in the middle (dielectric constant is 4.3, dielectric loss thickness is 0.025), and the top layer is a ring and a circular fractal structure. The structure is shown in Figure 2.1, where the parameters are $a = 10$ mm, $r_1 = 2.95$ mm, $r_2 = 1.45$ mm, $r_3 = 0.9$ mm, $h = 1.85$ mm, $t = 1.3$ mm. All copper wires have a width of 0.1 mm.

According to the calculation of the length of the ring is 18.12 mm, the length of the circular fractal structure is 19.64 mm, and the lengths of the two are very close, so that double-frequency absorption can be achieved. In order to explain the absorbing mechanism of the absorbing body, the equivalent circuit model of the designed absorber is given, as shown in Figure 2.2.

According to the equivalent circuit theory, each absorbing structure can be equivalent to a combination of RLC circuits, wherein the resistance of each path is shown as follow

$$Z_1 = \frac{1-\omega^2 L_1 (C_1 + C_p)}{2j\omega C_p (1-\omega^2 L_1 (C_1 - C_p))},$$

$$Z_2 = \frac{1-\omega^2 L_2 (C_2 + C_p)}{2j\omega C_p (1-\omega^2 L_2 (C_2 - C_p))}.$$

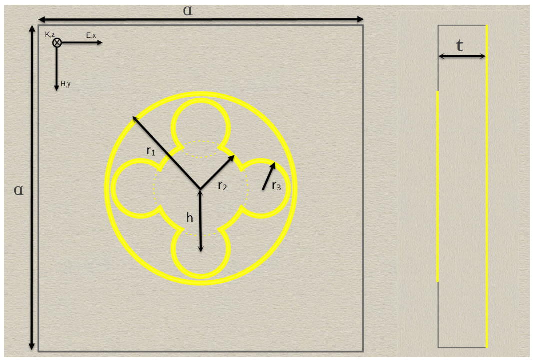


Figure 2.1 – The cell structure of the proposed absorber

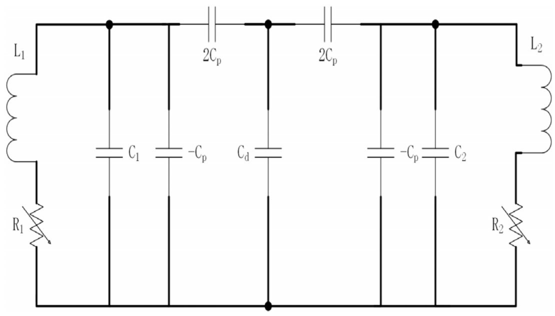


Figure 2.2 – Equivalent circuit model

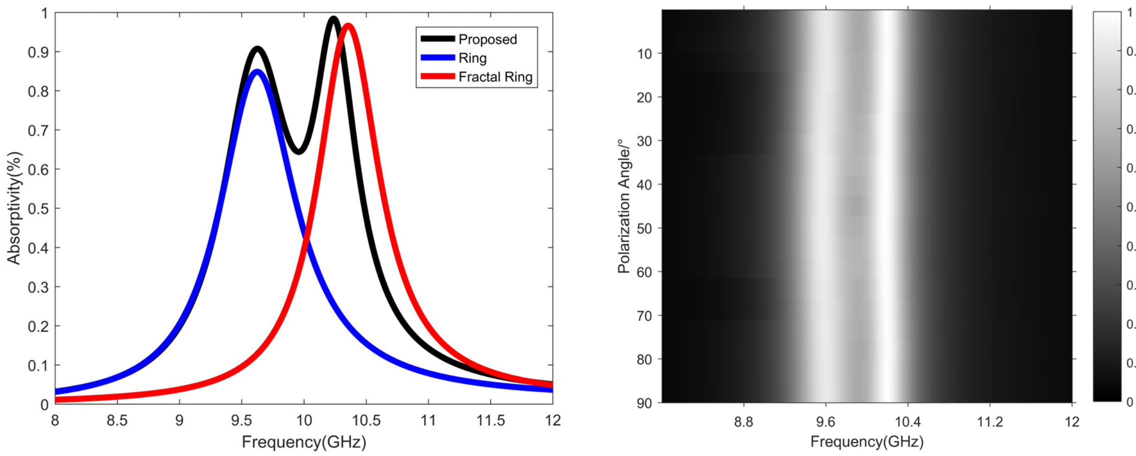
The coupling capacitance between the ring and the circle fractal is C_p, the coupling capacitance of the surface copper structure and the dielectric layer is C_d, and the equivalent impedance of the final absorber is, $Z = Z_1 // Z_2 // j\omega C_d$.

According to the literature [19], the resonant frequency point needs to satisfy the equation $\mathrm{Im}\{1/Z(\omega)\} = 0$, simplifying the equivalent impedance equation to obtain the equation

$$\omega^4 (L_1 L_2 (C_1 C_2 (4C_p + C_d) + \\ + C_p^2 (C_d - 4C_p) + C_p C_d (C_1 + C_2))) - \\ -\omega^2 ((L_1 C_1 + L_2 C_2)(4C_p + C_d) + C_p C_d (L_1 + L_2)) \\ +(4C_p + C_d) = 0,$$

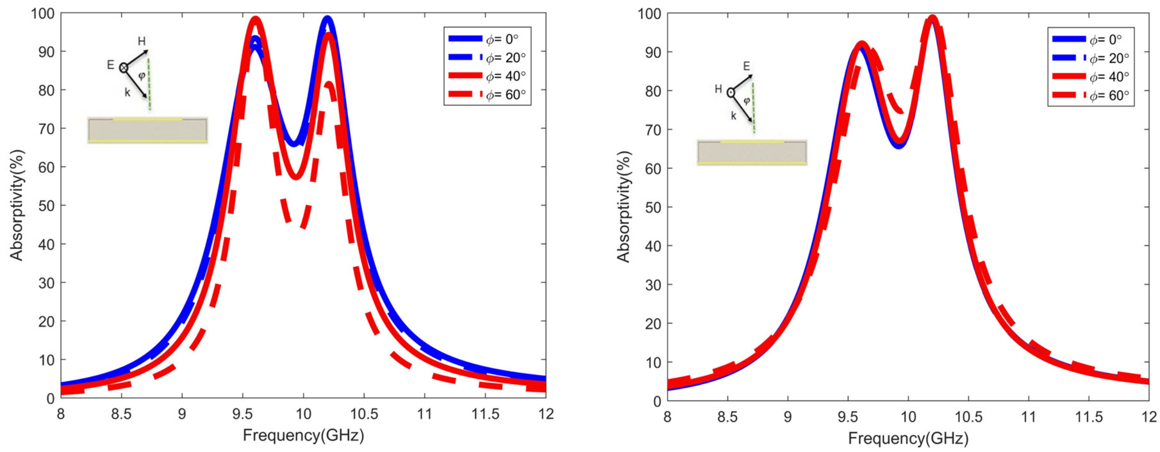
$$b^2 - 4ac = (L_1 (C_1 (4C_p + C_d) + C_p C_d) - \\ -L_2 (C_2 (4C_p + C_d) + C_p C_d))^2 + 4\cdot 16 L_1 L_2 C_p^4 > 0.$$

Since the quadratic equation satisfies $b^2 - 4ac > 0$, there are two solutions for the equation, so there are two absorbing resonance points. According to the simulation statistics, the resonant frequency is only inversely proportional to the length of a simple ring or square ring. In this type of structure, $\mathrm{C} \sim \varepsilon wl/t$, $\mathrm{L} \sim \mu tl/w$ [20]–[22], where l is the length of the wire, w is the width of the wire, and t is the thickness of the dielectric layer.



a) b)

Figure 2.3 – The simulation results of the proposed absorber (a) and absorptivity under different polarization angle (b)



a) b)

Figure 2.4 –Different incidence angles for (a) TE and (b) TM polarizations

The path of the fractal structure can extend the length of the surface current flowing, so that the resonance frequency is reduced, but the complex structure like the circular structure is not completely in accordance with the above formula. Therefore, the length of the circle is larger than the ring, but the resonance frequency is higher.

2.2 Simulation and analysis

In order to study the performance of the proposed broadband absorber, the structure was simulated by the software CST Microwave Studio based on the finite difference time domain method. On the four faces around the metal structure of the unit were set periodic unit cell boundary conditions. The transmittance is $\mathrm{T}(T=|\tau|^2=|S_{21}|^2)$, and the relationship between the reflectance $\mathrm{R}(R=|\Gamma|^2=|S_{11}|^2)$ and the absorptance A is $A+T+R=1$. The bottom layer is a copper plane, so there is no transmission wave, and the absorption ratio is $A=1-|S_{21}|^2$. The simulated absorbing rate is shown in Figure 2.3 (a).

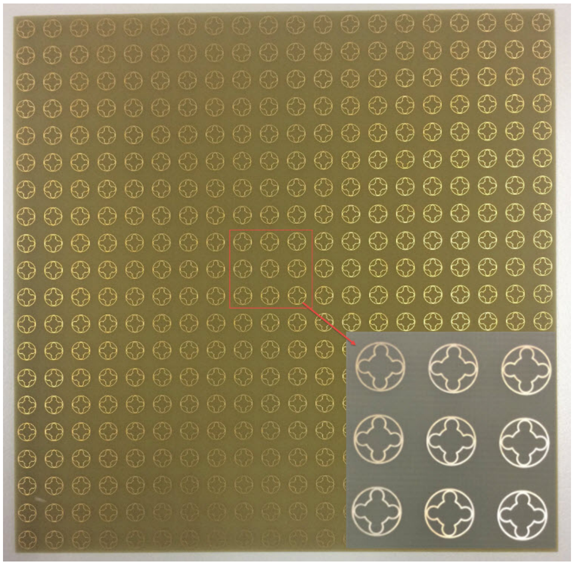
As can be seen from the figure, the perfect absorber at the frequency of 9.62 GHz, 10.24 GHz produced 90.7%, 98.4% of the peak of the absorption rate. The full width half maximum is 1.16 GHz (9.32 GHZ – 10.48 GHz). The figure also simulates a single circle and a single circular structure, each with a resonant frequency of 9.63 GHz and 10.36 GHz. A reasonable design distance can be achieved by using a coupling capacitor to reduce the resonant frequency of the circular fractal to achieve broadband absorption.

The absorptivity of the electromagnetic wave incident on the electromagnetic wave with different polarization angles is shown in Figure 2.3 (b). The polarization angle θ is the angle from the clockwise rotation to the X-axis in the electric field E direction, gradually increasing from 0° to 90°, and the absorption peak. The frequency and amplitude are basically unchanged, mainly because the absorber unit structure has rotational symmetry and thus has polarization insensitivity. The absorption of the TE polarization and TM polarization electromagnetic waves by the absorbing body at different oblique incident angles is shown in Figure 2.4 φ is the angle between the electromagnetic wave vector and the normal of the absorbing body.

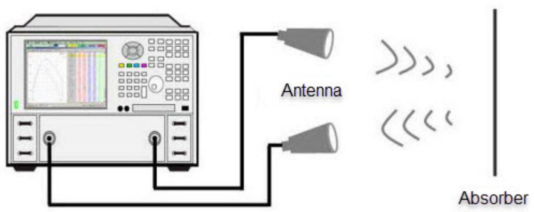
As shown in the figure, for the TE polarized wave, as the incident angle increases, the absorbing frequency does not change, and when the incident angle is 50°, the absorbing effect of 3 dB or more is maintained. For TM polarized waves, as the incident angle increases, high absorption is maintained, and after a large angle, the absorption frequency produces a certain movement. The main reason for this phenomenon is that the electromagnetic wave loss is mainly the current loss generated by the magnetic field, so that as long as the incident angle of the magnetic field is constant, high loss can be maintained at all times.

3 Experimental Verification

In order to verify the correctness of the simulation the printed circuit board technology is used. The model produced is actually 20×20 cycle units. The sample size is 200×200 mm. The sample plot and measurement schematic are shown in Figure 3.1.



a)



b)

Figure 3.1 – Photograph of the fabricated absorber (a) Photograph of measured environment (b)

In the microwave anechoic chamber, a pair of standard gain horn antennas (8–12 GHz) is connected to a vector network analyzer (PNA-XN5244A) that is used to measure the reflectivity of the proposed absorber. To ensure the remote field conditions, the distance between the absorber and the antenna is set as 1 m.

The absorber and the metal plate of the same size are sequentially measured, and the results from the metal plate are used as a reference, and the measurement results are compared with the simulation results. As can be seen from the Figure 3.2, the actual measurement and simulation are in good agreement. The measured results present two obvious absorption peaks at 9.58 GHz, 10.34 GHz with peak absorption rates of 90.47%, 95.68%, respectively. The resonant frequency of the circular structure is high, and the main cause of the difference is that it is limited by the manufacturing limit, and the partial structure is too small, resulting in an increase in the resonant frequency.

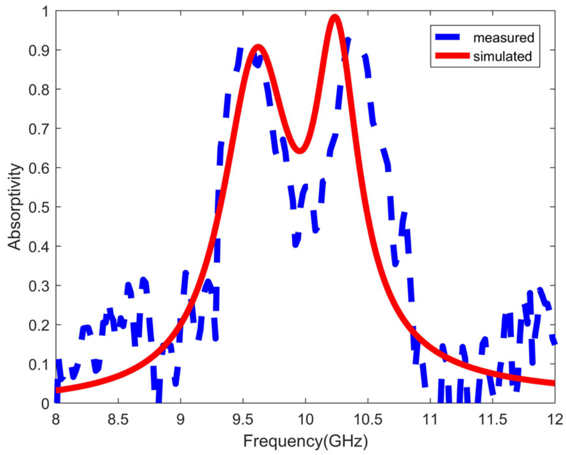


Figure 3.2 – Simulated and measured absorptivity for the proposed absorber

Conclusion

In summary, a bandwidth-enhanced metamaterial absorber is presented. Instead of using the array of scaled structures or multi-layer structures, the proposed absorber has been realized by designing multiple closed lines with similar lengths. The closed line is extended by fractal so that it can avoid mismatch due to closeness. Then, the size of the absorber became much smaller and compact compared with the similar absorber. According to the measurement results, it can be concluded that the fractal structure effectively increases the length of the resonant structure and reduces the resonant frequency. By designing the lengths of two similar structures and pulling the resonance point, the purpose of broadband absorption is achieved. At the same time, it has good rotational symmetry, so it is not sensitive to the polarization of the incident wave. When the incident angle reaches 50° in TM mode, it still maintains high absorbing rate. The absorber has a thickness of 1/25 of the center wavelength and has the advantages of large angle absorption and it is ultra-thin. The design is simple in structure, easy to manufacture and low in cost. The broadband absorber body has great application in the electromagnetic stealth of the X-band. The next step is to use a multi-partition structure to achieve ultra-wideband absorber.

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