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Nano- and Micro- Engineering for Design of Smart Magnetic Metamaterials as Microwave-Absorbing

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Abstract

Electromagnetic (EM) wave-absorbing materials are of paramount importance in communication applications, radar stealth technology, and electromagnetic interference shielding. The design and analysis of a Smart Magnetic Metamaterial based on Split Ring Resonators (SRR) are explored in this study to achieve broadband and high absorption of Terahertz (THz) waves. Unlike conventional materials, metamaterials offer the ability to engineer their electromagnetic properties, specifically the complex permittivity and complex permeability, to achieve optimal Impedance Matching and energy dissipation. The unit cell of the absorber was designed and analyzed, and the surface current distribution was examined to determine the resonance mechanism. Simulation results indicated that high absorption is achieved by the proposed absorber in a broad band centered around 1.5–1.6 THz. The effect of geometric variations, specifically the gap width (d), on the absorption characteristics and Group Delay was also analyzed. The potential of this design for developing ultra-broadband and efficient absorbing devices in the THz range is confirmed by the results.

Keywords: Smart Magnetic Metamaterials, (SRR), EMW, HFSS., Absorption, Reflection Loss (RL) and Terahertz Range.

Introduction

Electromagnetic (EM) waves cover a wide spectrum of frequencies, with Microwaves and Terahertz (THz) waves being vital parts of this spectrum. Microwave frequencies typically range from 0.3 to 300 GHz [5]. With the accelerating development of communication and electronics technology, there is a growing need for advanced materials capable of efficiently absorbing these waves. The goal of absorption is to convert the energy of incident waves into heat, thereby minimizing unwanted reflection and transmission [3][6]. Metamaterials have emerged as a revolutionary solution to these challenges. They are artificial materials designed with periodic or non-periodic structures on a scale smaller than the electromagnetic wavelength. These structures grant metamaterials electromagnetic properties not found in nature, such as Negative Refractive Index, Electromagnetically Induced Transparency (EIT), and Fano Resonances [4][7][5]. The ability to independently control the permittivity (εr) and permeability (μr) makes metamaterials ideal candidates for designing highly efficient EM wave absorbers [19][6]. Split Ring Resonators (SRR), shown in Figure 1, introduced by Pendry in 1999 [2], are among the most prominent structures used in metamaterial design. These resonators function by generating an effective magnetic response, allowing control over the material's magnetic permeability. When these structures are combined with magnetic materials, the result is known as Smart Magnetic Metamaterials, which are characterized by frequency-dependent permeability and permittivity, enabling a wide range of absorption applications [15].

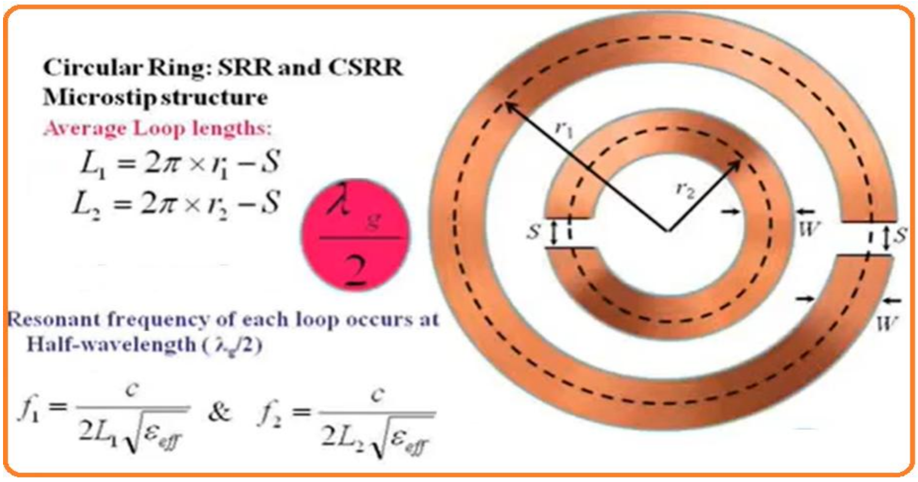

Figure 1. Metamaterials Split Ring Resonators SRR and CSRR.

Theoretical Background and Metamaterial Classification

A comprehensive design and analysis of an electromagnetic wave absorber based on smart magnetic split ring resonators is presented in this paper. The theoretical basis of EM wave absorption and metamaterial classification is reviewed in Section II. The unit cell design and simulation methodology are detailed in Section III. The simulated results, including current distribution, reflection loss, and the effect of geometric dimensions, are discussed in Section IV. Finally, the key findings are summarized in the Conclusion section.

Electromagnetic wave absorption relies on three fundamental phenomena: reflection, transmission, and absorption [12]. For a material to function as an effective absorber, two main conditions must be satisfied: Impedance Matching and Attenuation.

Absorption Mechanism: Coherent and polarized microwaves obey optical laws; these waves can be reflected, transmitted, and absorbed, depending on the type of material they pass through. Generally, the use of microwaves has been based on the phenomenon of reflection and transmission only (Figure 2(a)). However, in recent decades, the phenomenon of microwave absorption has also become very popular as a core concept in the development of rapidly advancing electronic and telecommunications technology, as shown in Figure 2(b) [3-6]. A main requirement for microwave-absorbing material is that it possesses values of permeability (magnetic loss properties) and permittivity (dielectric loss properties) [12].

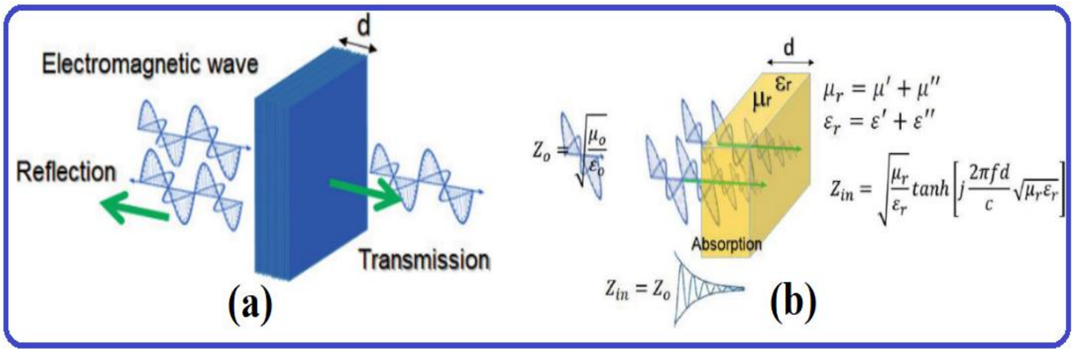

Figure 2. (a) Rules of optical law in microwaves and (b) Microwave absorption mechanism for materials [12].

A Fundamental Electromagnetic Properties: The electromagnetic properties of an absorbing material are defined by complex expressions. The complex permittivity (εr) and permeability (μr) are expressed by the following:

$$\varepsilon r = \varepsilon' + \varepsilon'' \qquad (1)$$

$$\mu r = \mu' + \mu'' \qquad (2)$$

The real parts (ε') and (μ')) represent the measure of energy stored from the external electric and magnetic fields, respectively, while the imaginary parts ((ε'') and (μ'') represent the measure of energy lost or dissipated (dielectric and magnetic loss). The Loss Tangents are defined as follows:

$$\tan \delta \varepsilon = \varepsilon'' / \varepsilon'$$

The greater the loss tangent of a material, the greater the attenuation when the wave moves through the material. The same applies to magnetic fields, namely:

$$\tan \delta \mu = \mu'' / \mu'$$

A higher value of the loss tangent indicates an increased ability of the material to attenuate the electromagnetic wave as it passes through [12].

Absorption Mechanism

Effective EM wave absorption is achieved when the material's intrinsic impedance (Zin) is equal to the free space impedance (Z0) at the desired frequency, minimizing reflection. The intrinsic impedance of the material is given by:

$$Z_{in} = \sqrt{\frac{\mu_r}{\varepsilon_r}}\, tanh\left[j\,\frac{2\pi f d}{c}\sqrt{\mu_r \varepsilon_r}\right]$$

where Zin is the impedance of material, (μ_r) and (ε_r) are the complex relative permeability and permittivity of the material, d is the absorber thickness, and c and f are the velocity of light and frequency of microwave in free space, respectively.

Once the wave enters the material (impedance matched), the material must be capable of dissipating the energy (attenuation) through dielectric and magnetic loss mechanisms [12].

Metamaterial Classification

Negative material is supported in the fourth quadrant ($\mu<0$, $\varepsilon<0$). As a result, it is also known as NIM (negative index material) [6].

The greater the loss tangent of a material, the greater the attenuation when the wave moves through the material. The same applies to magnetic fields, namely:

$$\tan \delta \mu = \mu'' / \mu'$$

EMW-absorbing materials can convert incident EMWS into heat through electromagnetic loss, with extremely low reflectivity and transmittance. the transmission process of the incident EMWs in the medium is shown in schematic figure 3

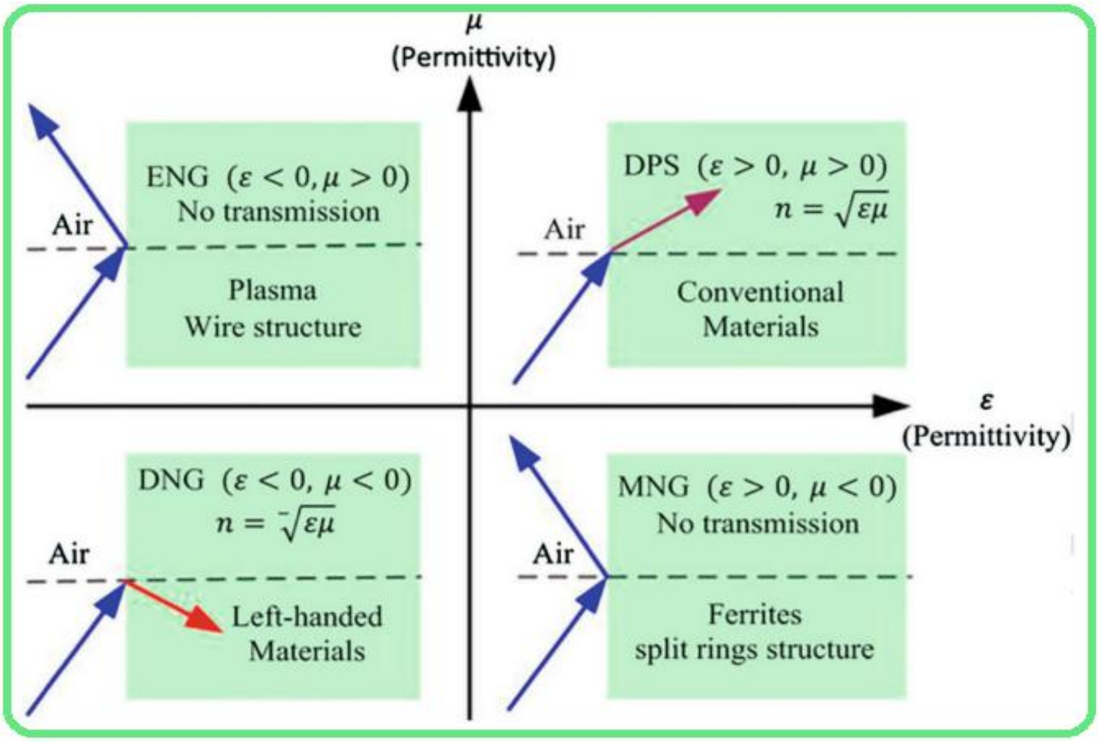

Figure 3. Metamaterial classification based on permittivity and permeability [Govindarajan et al. 2021].

The first group of materials is called double positive (DPS), as both ε and μ are greater than zero. This category primarily contains dielectrics. Permittivity is less than zero, and permeability is larger than zero in the second category, which is why it is termed epsilon negative (ENG) material. Many plasmas exhibit these properties at certain frequency regimes [12].

Design and Methodology

The third group of materials possesses a permittivity greater than zero and permeability less than zero. Gyrotropic magnetic materials display these characteristics and are called mu negative (MNG) material. The fourth group contains the double negative (DNG) material, which can only be produced artificially. This class of material has both permittivity and permeability less than zero, or negative. When an EM wave enters such media, the direction of wave propagation reverses. No naturally available material has both negative permeability and permittivity [6].

Unit Cell Design

The proposed absorber is based on the Double Split Ring Resonator (DSRR) structure, which is a modification of the basic SRR structure (Figure 4). This structure was chosen for its ability to generate a strong magnetic resonance in the high-frequency range [12].

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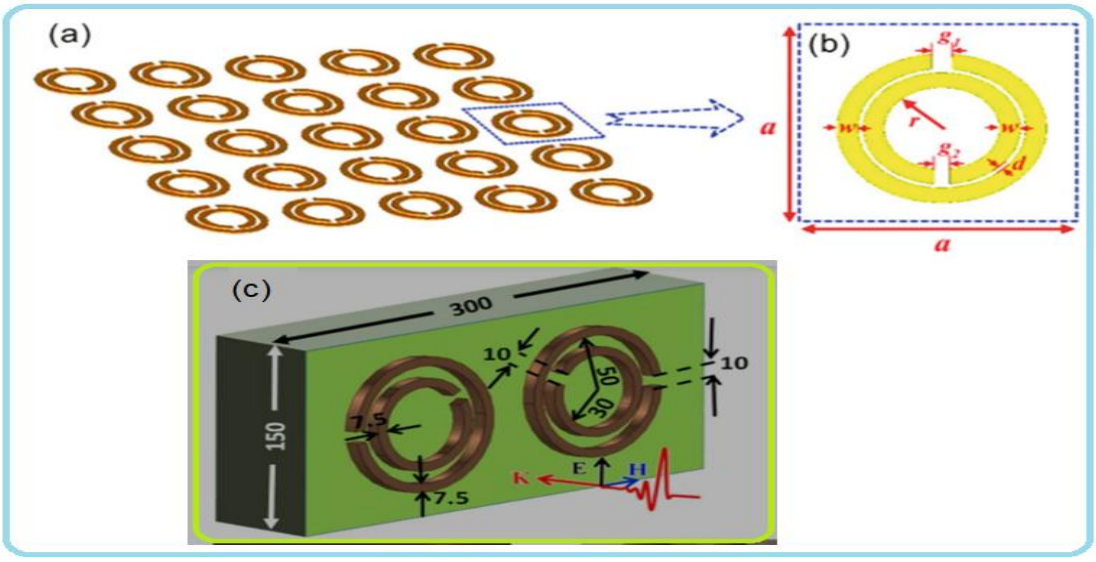

Figure 4. Dubell nuit cell of the SRR with the following geometric parameters for (a, b and c): inner ring (r), ring with (w), gap between inner and outer ring (d), and inner and outer ring gaps ($g_1$and g_2) [8].

Simulation Methodology

Electromagnetic simulations were performed using the HFSS (High-Frequency Structure Simulator) software, which relies on the Finite Element Method (FEM). Periodic Boundary Conditions were applied to the four sides of the unit cell to simulate an infinite array of absorbers. The structure was excited by a Wave Port representing a normally incident plane wave.

Results and Discussion

The performance of the proposed absorber was analyzed by studying the surface current distribution, absorption characteristics, and the effect of geometric variations on the frequency response.

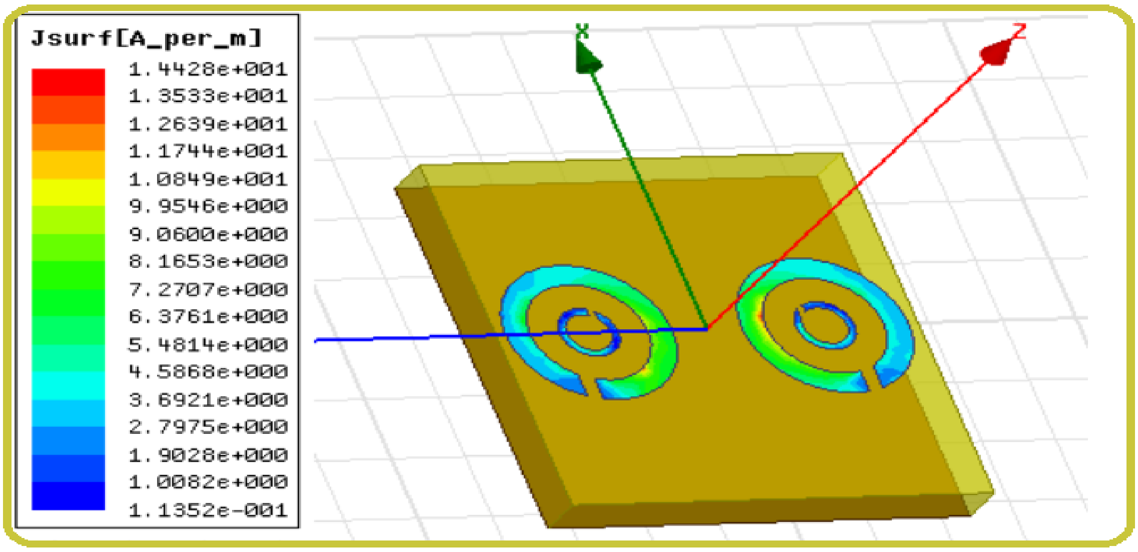

Figure 5. Calculated current distribution of the initial absorber design.

The calculated current distribution, shown in Figure 5, explains the effect of the unit cell on the surface current density, i.e., the extended current unit cell along the ring resonant dimension.

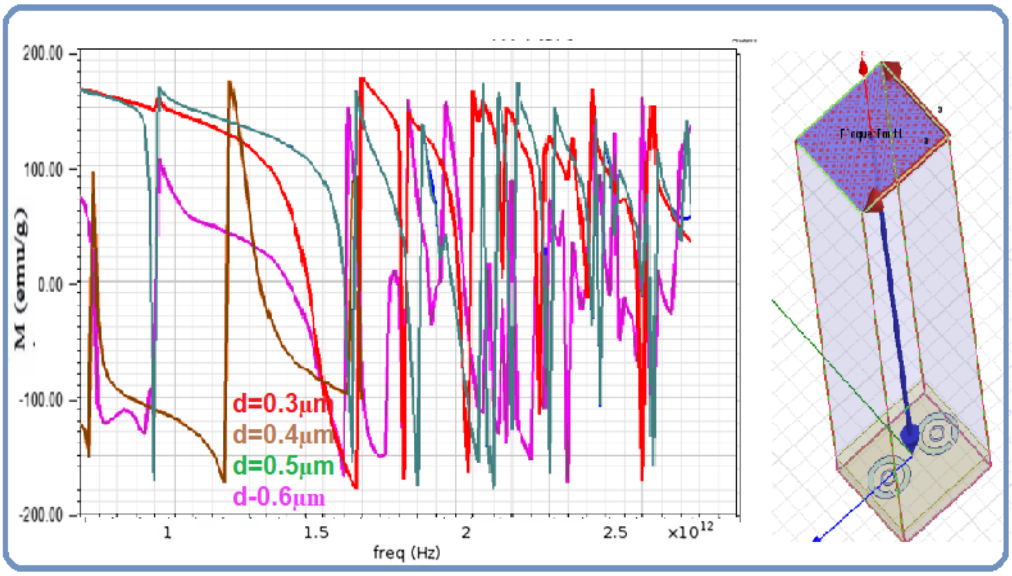

Figure 6. Understand how a material's magnetic properties change with frequency.

The graph illustrates how the magnetization of a material changes when exposed to varying frequencies. Material science is utilized to characterize magnetic materials for high-frequency applications. The graph appears to be a frequency response plot, showing the magnetization (M, in emu/g) as a function of frequency (freq. in Hz) for different gaps between the inner and outer ring (d=0.3mm, 0.4mm, 0.5mm, 0.6mm). It seems to illustrate magnetic properties or resonance behavior in a material. The graph shows how the magnetization (M) of the material changes as the frequency (freq.) increases for four different 'd' values. To read a specific data point, the desired frequency is found on the x-axis, a vertical movement is made to the colored line of interest, and then a horizontal movement is made to the y-axis to read the corresponding magnetization value.

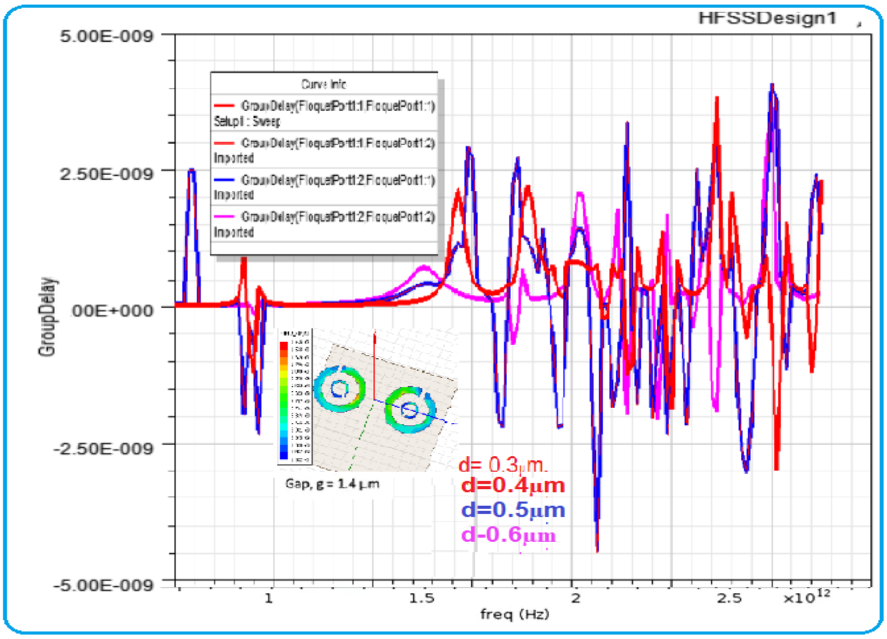

Figure 7. Groupe delay.

This measurement indicates how long it takes for the envelope of a signal to pass through a device or system at different frequencies. It is a crucial parameter in applications where signal integrity and timing are important, such as in communication systems or antenna design. The sharp peaks and dips in the curves indicate frequencies where the signal experiences significant phase distortion or variations in propagation time.

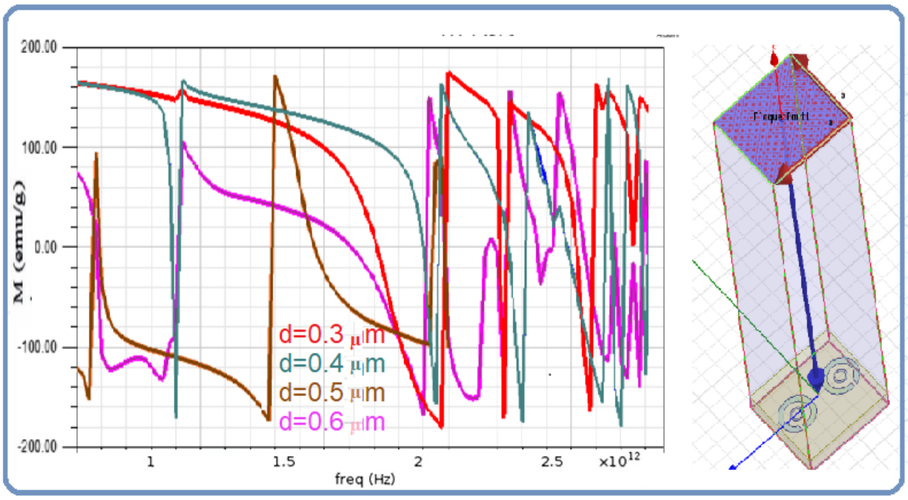

Figure 8. Frequency and reflection loss vs.

In Figure 8, there are four distinct curves, each representing a different physical dimension, "d", ranging from 0.3 mm to 0.6 mm. The dips in the curves (e.g., around 0.8 THz, 1.4 THz, and 2.3 THz for the red line, d=0.4mm) indicate specific frequencies where the device is well-matched, meaning most of the signal passes through and very little is reflected. The graph allows for the analysis of how changing the dimension 'd' affects the resonant frequencies and efficiency of the device.

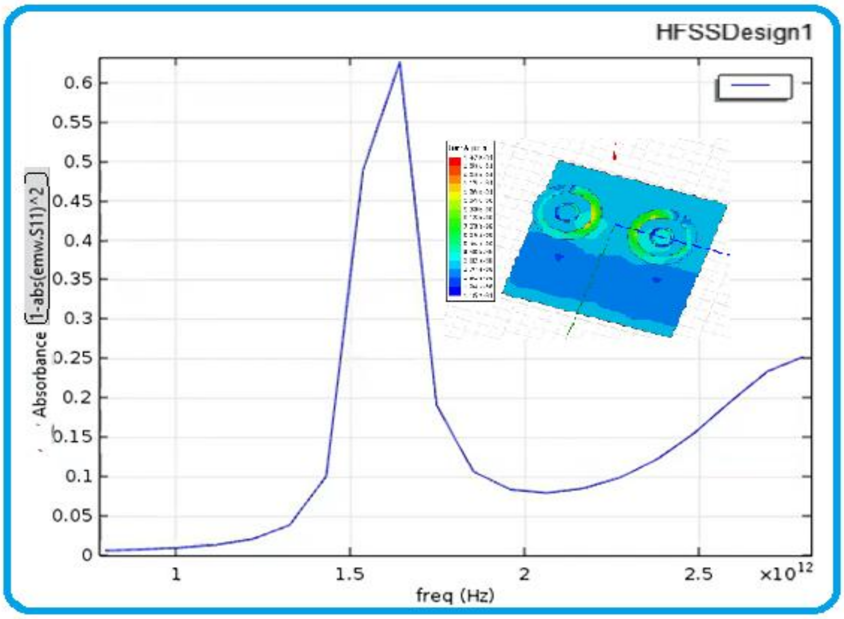

Figure 9. microwave absorption.

The graph shows S11 (input reflection coefficient) represents the amount of incident power that is reflected back from the device. The device has a strong absorption peak (a resonance frequency) at approximately 1.5-1.6 THz, where the absorbance reaches its maximum value of around 0.6.

Conclusion

This paper presented the design and analysis of an ultra-broadband electromagnetic wave absorber based on smart magnetic metamaterials and Double Split Ring Resonator (DSRR) structures. The theoretical basis for absorption, relying on impedance matching and attenuation through dielectric and magnetic loss, was confirmed. Simulation results showed that the proposed design achieves effective absorption in the THz range, with a notable absorption peak centered around 1.5–1.6 THz. The parametric study further confirmed that geometric adjustments, such as changing the gap width (d), provide an effective mechanism for tuning the resonance frequencies and controlling the absorption characteristics. These findings suggest that this design holds promising potential for developing advanced and efficient absorbing devices in the high-frequency range.

References:

1 J. B. Pendry, A. J. Holden, W. J. Stewart, and I. Youngs, “Extremely low frequency plasmons in metallic misstructures,” Phys. Rev. Lett. 76, 4773–4776 (1996).
2 J. B. Pendry, A. J. Holden, and D. J. Robbins, “Magnetism from conductors and enhanced nonlinear phenomena,” IEEE Trans. Microwave Theory Tech. 47, 2075–2084 (1999).
3 R. A. Shelby, D.R. Smith, and S. Schultz, “Experimental verification of a negative index of refraction,” Science 292, 77–79 (2001).
4 J. B. Pendry, “Negative refraction makes a perfect lens,” Phys. Rev. Lett. 85, 3966–3969 (2000).
5 J. B. Pendry, D. Schurig, and D. R. Smith, “Controlling electromagnetic fields,” Science 312, 1780–1782 (2006).
6 N. Liu, H. Guo, L. Fu, S. Kaiser, H. Schweizer, and H. Giessen, “Three-dimensional photonic metamaterials at optical frequencies,” Nat. Mater. 7, 31–47(2007).
7 C. Rockstuhl, F. Lederer, C. Etrich, T. Pertsch, and T. Scharf, “Design of an artificial three-dimensional composite metamaterial with magnetic resonances in the visible range of the electromagnetic spectrum,” Phys. Rev. Lett. 99, 017401 (2007).
8 H. Liu and X. P. Zhao, “Magnetic response of dendritic structures at infrared frequencies,” Solid State Commun. 140, 9–13 (2006).
9 H. Liu and X. P. Zhao, “Metamaterials with dendriticlike structure at infrared frequencies,” Appl. Phys. Lett. 90, 191904 (2007).
10 X. Zhou, Q. H. Fu, J. Zhao, Y. Yang, and X.P. Zhao, “Negative permeability and subwavelength focusing of quasi-periodic dendritic cell metamaterials,” Opt. Express 14, 7188–7197 (2006).
11 Y. Yao and X. P. Zhao, “Multilevel dendritic structure with simultaneously negative permeability and permittivity,” J. Appl. Phys. 101, 124904 (2007).
12 X. Zhou and X. P. Zhao, “Resonant condition of unitary dendritic structure with overlapping negative permittivity and permeability,” Appl. Phys. Lett. 91, 181908 (2007).
13 J. Gollub, T. Hand, S. Sajuyigbe, S. Mendonca, S. Cummer, and D. R. Smith, “Characterizing the effects of disorder in metamaterial,” Appl. Phys. Lett. 91, 162907 (2007).
14 K Aydin, K Guven, N. Katsarakis, C. M. Soukoulis, and E. Ozbay, “Effect of disorder on magnetic resonance band gap of split-ring resonator structures,” Opt. Express 12, 5896–5901 (2004).
15 C. Mitsumata and S. Tomita, “Negative permeability of magnetic nanocomposite films for designing left-handed metamaterials,” Appl. Phys. Lett. 91, 223104 (2007).
16 X. P. Zhao, Q. Zhao, L. Kang, J. Song, and Q. H. Fu, “Defect effect of split ring resonators in left-handed metamaterials,” Phys. Lett. A 346, 87–91 (2005).
17 H. Chen, L. Ran, D. Wang, J. Huangfu, Q. Jiang, and J. A. Kong, “Metamaterial with randomized patterns for negative refraction of electromagnetic waves,” Appl. Phys. Lett. 88, 031908 (2006).
18 D. Wang, J. Huangfu, L. Ran, H. Chen, T. M. Grzegorczyk, and J. A. Kong, “Measurement of negative permittivity and permeability from experimental transmission and reflection with effects of cell misalignment,” J. Appl. Phys. 99, 123114 (2006).

19 Th. Koschny, P. Markos, E. N. Economou, D. R. Smith, D. C. Vier, and C. M. Soukoulis, “Impact of inherent periodic structure on effective medium description of left-handed and related metamaterials,” Phys. Rev. B 71, 245105 (2005).

20 P. Gay-Balmaz and O. J. F. Martin, “Electromagnetic resonances in individual and coupled split-ring resonators,” J. Appl. Phys. 92, 2929–2936 (2002).
ultrathin metasurface. Sci Rep 2019; 9:1181.

21 Shen S, Henry A, Tong J, Zheng RT, Chen G. Polyethene nanofibers with very high thermal conductivities. Nat Nanotechnol 2010;5(4):251–5.

22 Fan CZ, Gao Y, Huang JP. Shaped graded materials with an apparent