URSI-RCRS 2024, ARIES/GEHU, Bhimtal, India, 22 - 25 October, 2024

Ultra-thin Quad Spiral Metamaterial Absorber for Multi-band Microwave Applications

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Abstract

The design, analysis and fabrication of a novel Quad spiral metamaterial absorber in the microwave regime has been presented in this paper. The proposed structure is based on two square like spiral resonators that exhibits near perfect absorption at five distinct frequencies ranging from 1.45 to 8.09 GHz. The absorber is composed of periodic array of resonant structure fabricated on a dielectric layer with thickness of only 0.008λ which unveils its ultra-thin nature and is compact with unit cell dimension of 0.06λ. Absorption mechanism of the absorber is studied by analyzing electric field and surface current distributions of the structure at each frequency. Investigation done for different incident and polarization angle shows polarization insensitivity at all resonant frequencies of the proposed absorber. These exceptional features highlight its potential application in various advanced fields of communication and technology.

1. Introduction

Metamaterials, engineered with unique properties, have garnered significant attention in recent decades. They find diverse applications in antennas, cloaks, filters, absorbers, and as perfect lenses due to their ability to achieve negative refractive index. These properties stem from resonant structures composed of periodic arrays of unit cells, which can be finely tuned to create absorbers with tailored characteristics. Unit cells are much smaller than the wavelength of incident electromagnetic waves, influencing their interaction and behavior through effective medium parameters like permittivity and permeability. Metamaterial-based absorbers (MMA) leverage these properties to achieve near-total absorption, surpassing conventional absorbers. They maintain consistent performance across different polarizations of incident waves, known as polarization independence. MMAs can incorporate additional functionalities such as frequency tuning, polarization-independent absorption, multi-band absorption, and energy harvesting. Applications of these absorbers span wireless and satellite communications, electromagnetic shielding, stealth technology, and imaging.

In the present paper, an ultrathin quad spiral metamaterial absorber with thickness 0.008λ is designed. The proposed absorber combines dual band and triple band spiral resonant structures. The absorption mechanism is studied by analyzing the propagation of electromagnetic wave inside the proposed absorber. From the simulated results, the structure exhibits resonance at five different frequencies: 1.44 GHz, 2.95 GHz, 4.42 GHz, 6.65 GHz and 8.09 GHz with percentage of absorption 84.2%, 99.3%, 97.8%, 94.3% and 99.4% respectively. The structure is polarization insensitive due to its symmetric nature and has mu near zero characteristics. Fabrication is done using photolithography and the experimental result shows close correspondence with simulated result reveals that the structure is indeed a perfect absorber.

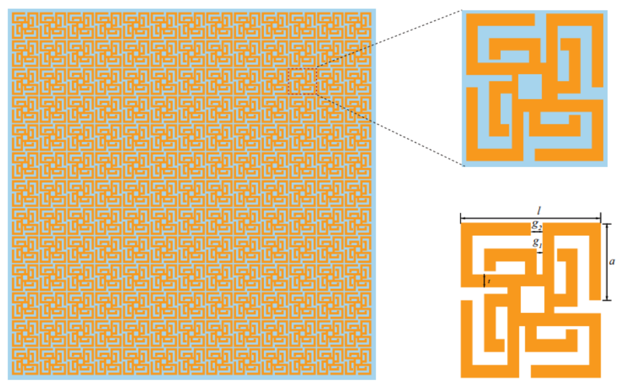

Figure 1: Proposed metamaterial absorber.

2. Design and Simulation

The unit cell of proposed metamaterial absorber (MMA) is a three-layered structure composed of two square like resonators and a metallic ground sheet separated by a dielectric substrate, as depicted in Fig. 1. The top and bottom layer is made up of copper with thickness 0.01 mm of which top layer is periodic metallic patterns etched on copper and bottom layer (ground plane) is a continuous metallic plate. Dimension of the unit cell is 12.5 mm x 12.5 mm. The middle layer is FR4-lossy Glass Epoxy having dielectric constant ε_r= 4.4, loss tangent tan δ = 0.02 and substrate thickness 1.6 mm having the same dimension as that of the ground plane. Geometrical parameters of the proposed metamaterial absorber is: a= 12 mm, g_1 = 1 mm, g_2 = 2 mm, t = 2 mm.

The proposed absorber structure MMA3 is composed of two structures: MMA1, which produces two absorption peaks while MMA2 with three absorption peaks. The final structure in Fig. 2 has five absorption peaks at distinct frequencies. The absorptivity of MMA1 and MMA2 is given in Fig. 3.

Figure 2: Unit cell of the proposed absorber.

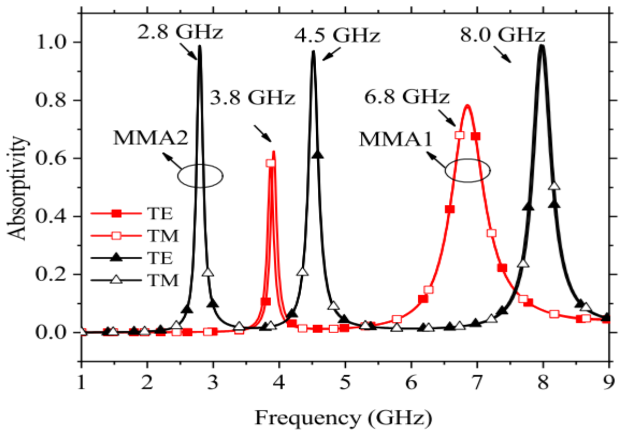

Figure 3: Absorptivity of MMA1 and MMA2.

3. Absorption Performances

The absorption rate is calculated by the equation:

$$A(\omega)=1-R(\omega)-T(\omega) \quad (1)$$

where $R(\omega)$ equals the square of the reflection coefficient $S_{11}(\omega)$ and $T(\omega)$ equals the square of the transmission coefficient $S_{21}(\omega)$. Since the bottom layer is covered by a metallic plate, the transmission coefficient is equal to zero. So, the equation for absorption reduces to

$$A(\omega)=1-R(\omega) \quad (2)$$

In terms of S parameters;

$$A(\omega)=1-|S_{11}|^2 \quad (3)$$

The structure is simulated using CST microwave studio showing five absorption peaks at 1.44 GHz (84.2%), 2.95 GHz (99.3%), 4.42 GHz (97.8%), 6.65 GHz (94.3%), 8.09 GHz (99.4%) as shown by the absorption curve in Fig. 4.

To study the polarization insensitivity of the proposed metamaterial absorber and check whether the absorption inside the material is polarization independent, TE waves are incident at varying polarization angles from $\varphi=60^0$ to $\varphi=360^0$ in increments of angle 60^0 so that the electric field vector is parallel to the x-axis and the wave propagation is along the -z direction.

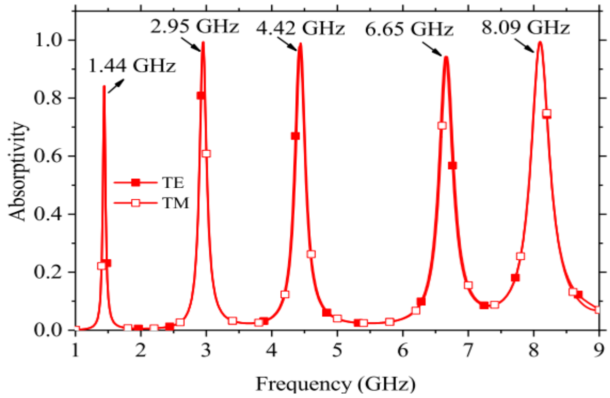

Figure 4: Absorptivity of MMA3.

Fig. 5 displays the simulation result for the absorption spectrum of various polarization angles. The findings indicates that the absorption characteristics of the metamaterial is invariant to various polarization states of the incident EM wave which means that the metamaterial absorber is a polarization insensitive. Similarly, the absorptivity dependence on the incident angle studied by changing the value of θ from 0^0 to 90^0 for MMA3 is illustrated in Fig. 6. The peaks at lower resonant frequencies in the absorption spectrum are consistent with various incident angle, while the higher resonances show variation in absorption response with incident angle. The study of power loss in the metals and dielectrics, as illustrated in Fig.7 indicates that losses in dielectric substrate is more when compared to losses in metal. This is because a major portion of the incident electromagnetic energy is trapped and dissipated by the dielectric substrate.

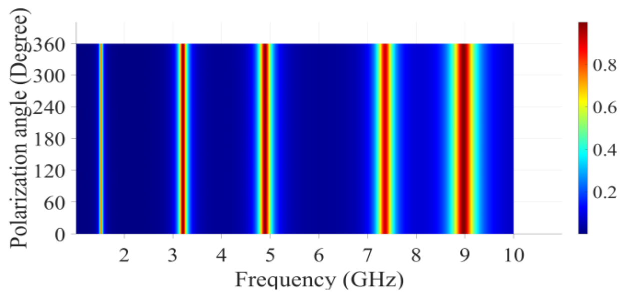

Figure 5: Absorption spectrum for different polarization angles.

To understand the physical behavior of the metamaterial absorber the electric field distributions and the surface currents are simulated at different resonant frequencies. Incident electric field induces excitation of charges in the top layer. Due to the phase change of this field, the charges on the top and bottom resonators switches polarity as depicted in Fig. 8.

This suggests the existence of an electric dipole resonance that results in a strong coupling effect with the ground plane. Therefore, a reverse current is formed indicating a magnetic dipole resonance in the proposed metamaterial structure [6].

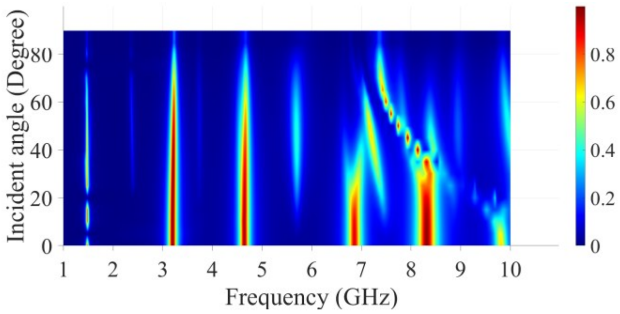

Figure 6: Absorption spectrum for different incident angles.

The surface current distribution of the metamaterial absorber is shown in the Fig. 9. Conduction current flows in opposite direction at the top and bottom conductors, with displacement current passing through the middle dielectric layer.

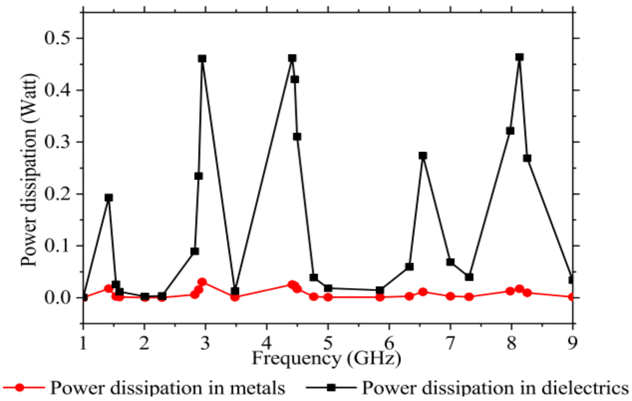

Figure 7: Power dissipation of the metamaterial absorber by the dielectric and metal.

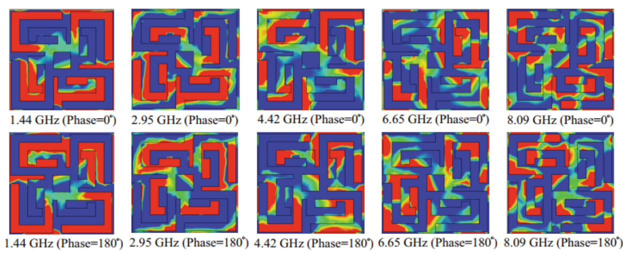

Figure 8: Z-component of the electric field (E~) distributions on the top and bottom surface of the proposed absorber.

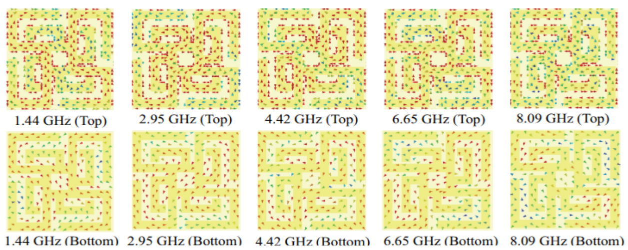

Figure 9: The surface current distribution at the top and bottom layers of the proposed absorber.

This interplay creates a current loop, resulting from the combined conduction and displacement currents across all resonant frequencies. Thus, the consumption of the incident electromagnetic energy is made possible by the simultaneous electric and magnetic dipole resonance of proposed structure at resonant frequencies 1.44 GHz, 2.95 GHz, 4.42 GHz, 6.65 GHz, 8.09 GHz respectively.

The material for which the permeability is near zero is the mu near zero material. The proposed MMA shows mu near zero characteristics. The real part of the permeability μ_r of the absorber are: 0.05, 0.05, 0.08, 0.07, 0.07 at frequencies 1.46 GHz, 2.93 GHz, 4.37 GHz, 6.65 GHz, 8.10 GHz respectively as shown in Fig.10. This mu near zero permeability at all resonant frequencies facilities effective absorption, reducing leakage of em waves and thus applicable in wireless power transfer systems (WPT).

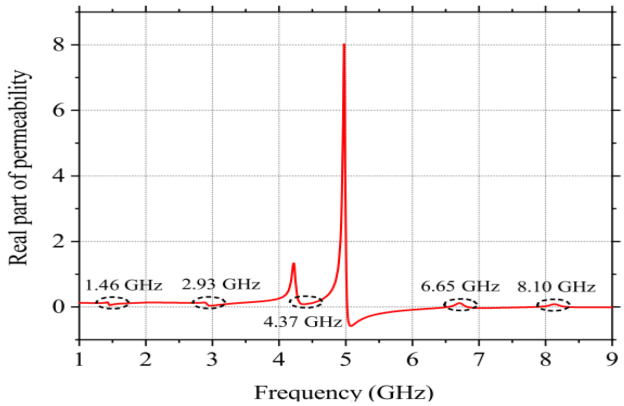

Figure 10: Real part of the permeability of the proposed absorber.

4. Experimental setup

A prototype of the metamaterial absorber with a total of 144 meticulously designed unit cells was constructed using conventional photolithography. A pair of horn antennas connected to an Anritsu MS2038C vector network analyzer was used for the free space measurements, where one of the antennas is taken as transmitter and other as receiver. To optimize measurement accuracy, a distance of 1 meter were maintained between horn antennas and prototype confirming the far field criterion. As an initial step a Through-Reflect-Line (TRL) calibration was performed to minimize the cable losses, and thus enhancing the precision. A copper sheet with the same dimension as the prototype was added to the experimental setup after calibration and reflectance S_{12}^{Ref} is measured. The fabricated prototype was used in place of the copper sheet and another measurement of reflectance S_{12}^{M} is taken. Absorbance is calculated using the equation

$$A(\omega) = 1 - (S_{12}^{M} - S_{12}^{Ref})^2$$

Fig. 11 shows the measured and simulated absorbance of the metamaterial absorber. Simulations and measurements show close correspondence as indicated in the above figure.

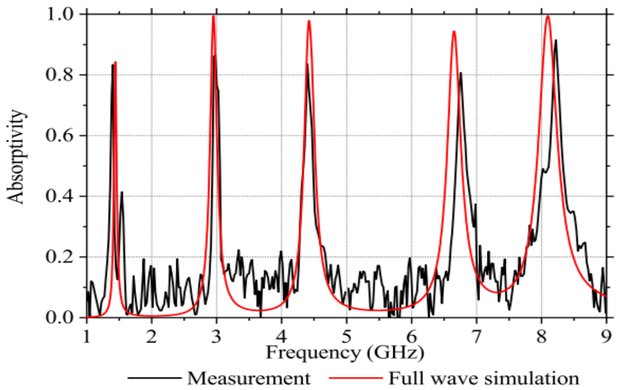

Figure 11: Measured and simulated absorptivity

Table 1 shows a comparative overview of the designed absorber performance against recent studies which portrays its unprecedented and versatile features that is suitable for an ideal absorber. The unit cell dimension of the absorber is only 0.06λ and the dielectric size is of 0.008λ at the lowest operational frequency indicating the compactness and ultrathin nature of the absorber and is applicable in many fields including communication and technology.

Work done	Resonating frequencies (GHz)	Absorption	Unit cell dimension	Dielectric thickness
Cheng et al. [1]	4.78,6.91,7.86,9.14,9.81,10.86, 11.65	98.1%,97.6%,96.2%, 99.6%,90.5%, 97.3%, 96.2%	0.16λ	0.030λ
Cao et al. [2]	8.115, 11.4, 15.125	99.95%, 99.28%, 96.36%	0.62λ	0.027λ
Jain et al. [3]	3.36, 3.95, 10.48	99.42%, 99.1%, 99.9%	0.12λ	0.018λ
Luo et al. [4]	4.44, 7.85	99.93%, 99.99%	0.21λ	0.0147λ
Singh et al.[5]	3.2, 5.32, 11.15 16.73	95.75%, 95.93%, 97.69%, 95.64%	0.11λ	0.01λ
Proposed work	1.44, 2.95, 4.42, 6.65, 8.09	84.2%, 99.3%, 97.8%, 94.3%, 99.4%	0.06λ	0.008 λ

5. Conclusion

In this work, a novel ultra-thin quad spiral metamaterial absorber has been presented. The proposed structure is designed by combining a dual band and triple band resonant structures. This absorber exhibits resonant absorption at five frequencies: 1.44 GHz (84.2%), 2.95 GHz (99.3%), 4.42 GHz (97.8%), 6.65 GHz (94.3%), 8.09 GHz (99.4%). After fabricating the absorber structure, the experimental studies were performed with Anritsu MS2038C vector network analyzer. The simulation results are consistent with experimental results, validating the reliability of the proposed absorber. It indeed shows that the absorber has nearly perfect absorption at these five different frequencies and is polarization insensitive. These attributes extend its application to a wide range of fields including electromagnetic shielding and stealth applications. Furthermore, the structure has mu near zero characteristics, suitable for flux shielding in WPT systems and ultra-thin profile ensures efficient absorption.

6. Acknowledgements

The work presented in this paper is supported by the Science and Engineering Research Board (SERB), Department of Science and Technology (DST), India, under grant EEQ/2021/000931

7. References

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