

Design and analysis of X-band metamaterial absorber

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Abstract. This study introduces a novel metamaterial absorber operating in X-band frequency range, characterized by two resonating peaks. The proposed structure consist of four circular sectors connected by two cross resonators enclosed by a circular strip with the dielectric between them. FR4 is used as a substrate backed by a copper ground plane. Simulation results reveal that the reflection co-efficient remains consistently below -10dB across the entire X-band, ensuring effective absorption of incident electromagnetic waves. Moreover, the absorber achieves 100% absorptivity with the gain of -25dB under normal incidence. The validity of absorber performance is confirmed through impedance plot and Voltage Stand Waving Ration (VSWR) analysis, verifying the accuracy of S_{11} parameter. Furthermore, the proposed structure has a compact size of 0.1666λ . The absorber's robust performance validated through numerical analysis, positions it as a compelling candidate for various X-band applications, including radar systems, communication devices, and stealth technology. This research establishes the proposed metamaterial absorber as a promising solution for X-band electromagnetic wave attenuation needs, offering both superior performance and compact design.

1 Introduction

In 1952, a significant advancement in the field of electromagnetic absorption was introduced by Salisbury with the development of the first nonmagnetic planar absorber. The proposed absorber consists of a resistive sheet with the impedance same as the free space, positioned at $\lambda/4$ distance from the metallic ground plane, where λ represents the wavelength at the center frequency of the operation. Salisbury screens evolved into metasurfaces with the development of the metamaterials concept. Metasurfaces are two dimensional periodic structures fabricated over planar and non-planar substrates [1]. Design parameters and selection of substrate effects the electromagnetic properties namely relative permittivity (ϵ) and relative permeability (μ) [2]. In design of an absorber bandwidth, reflection coefficient (S_{11}), and total thickness are essential parameters. Metamaterial absorber works on the principle of matching free space impedance with the metasurface impedance to resonate the structure and trap the incoming electromagnetic

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wave. Metamaterial absorber is an effective solution for impedance matching by using resistive ink deposited on a substrate layer with a metal ground metal plane [3]. Prince et al., [4] additively manufactured a microwave circuit analog absorber using two different fused filament fabrication materials namely graphite PLA and standalone PLA. For the design of the absorber, the complex permittivity of PLA, bronze, brass, copper, iron-powder-based infused PLAs, and graphite PLA composite was measured using free-space measurements. Graphite PLA and standalone PLA were found suitable materials to be used as frequency-selective surfaces and substrates respectively. For optimization of dimensions, CST microwave studio was used. At their resonant frequencies, the fabricated absorber showed absorption of at least 20 dB, with a fractional bandwidth of at least 44% and 0.1 λ . Yao et al [5] fabricated an ultra-broadband multi-material absorber with five resonant modes and a double-layer structure. Copper is used to fabricate the patterns on F4B Substrate using printed circuit board (PCB) technology. Single and dual band absorption concepts were combined, resulting inefficient performance compared to the previous studies, with a fractional bandwidth of 170% (1.4 to 17.31 GHz) and a total thickness of 20.8mm. Results were validated through simulations and measurements. The wide-angle performance of the absorber is not discussed in this study. Ghosh et al., [6] fabricated a broadband polarization-independent circuit analog absorber that utilizes multi-layer resistive frequency selective surfaces (FSS). The proposed structure consists of a periodic arrangement of square loops made of copper, loaded with lumped resistors, printed on an FR4 dielectric substrate using the screen-printing technique. Simulation shows that reflectivity is below -10 dB in the frequency range of 4.96 to 18.22 GHz (with a fractional bandwidth of 114.40%) under normal incidence covering C, X, and Ku bands. The reflection coefficient of the absorber is measured experimentally using an anechoic chamber, which shows -10 dB reflectivity with a fractional bandwidth of 112% from 5.10 to 18.08 GHz. The proposed absorber has simplified geometry, is polarization-sensitive, offers wide angular stability, and has been experimentally validated with minimal increase in overall thickness. This study does not include the performance of the absorber in the W-band. Jaiswar et al., [7] fabricated a highly efficient microwave absorber using FSS and dielectric layers. FSS is ink-jet printed on a polycarbonate (PC) sheet using carbon nanotube-based resistive ink. The absorber showed a wide fractional bandwidth of 137% (from 7.30 to 41.95 GHz) with reflectivity below -15 dB and absorption exceeding 90%. The performance is achieved with a compact thickness of 0.13 λ by tuning the number of printed layers, which determines the FSS resistivities and absorption bandwidth. The wide fractional bandwidth of the newly developed ultrawideband microwave absorber (UWMA) confirms its high efficiency as an electro-magnetic interference (EMI) shielding solution. The absorber performance outperforms state-of-the-art solutions in terms of bandwidth and compactness. The lightweight nature and ease of fabrication of UWMA make it promising for applications in space, aeronautics, and mobile wireless communications, where compactness is crucial. Cui et al., [8] presented a novel approach that integrates 3D printing and inkjet printing additive manufacturing techniques to fabricate tunable origami structures, which is a first of its kind achievement. As a proof of concept, a tunable Miura-shaped frequency selective surface (FSS) operating in a millimeter-wave (mm-wave) frequency range is demonstrated using this approach. The substrate is a 3D printed formlabs flexible (FLGR02) photopolymer using selective laser sintering (SLA). To decrease the surface roughness of the substrate, six layers of MicroChem SU-8 silver nano-particles are ink jet printed on the substrate. Simulations were carried out to evaluate the performance of the fabricated FSS and were then validated through free-space measurement. The -10 dB bandwidth of FSS increases significantly from 14% to 32% as the angle of incidence from 0° to 60°. The study demonstrates the FSS's capability to exhibit wider bandwidth with increasing angle of incidence, indicating its potential for

enhanced performance in a wider range of incident angles. For instance, it enables potential integration with 3D printed microfluidic devices, multilayer configurations, beam steering with customized 3D curves and cuts, and other innovative designs.

In this study an incident angle independent metamaterial absorber for the X-band applications is proposed. The unit cell of the proposed absorber as shown in figure 1, supports polarization insensitivity due to four fold symmetrical structure with a circular strip for gain improvement. Numerical study is carried out to observe S11 parameter of the unit cell along with the current and electric field distribution over the metasurface using HFSS 15.

2 Methodology

The methodology adopted for the development and evaluation of the proposed X-band absorber involved several key steps to ensure the effectiveness. Initially, the absorber structure is designed in HFSS to optimize the arrangement of circular sectors, cross resonators, and enclosing circular strip. The choice of materials, including FR4 substrate and copper ground plane is based on their electromagnetic properties and compatibility with X-band frequencies. Subsequently, for numerical study simulation is used to analyse the absorber performance across the X-band frequency range.

2.1 Absorber Structure

Figure 1 shows the geometry of unit cell absorber with copper printed patterns on FR4 substrate. Unit cell consists of four circular sectors connected by two cross resonators. The structure is enclosed by a circular strip with dielectric between them. The proposed absorber supports polarization insensitivity due to four fold symmetrical structure with a circular strip for gain improvement. The structure is grounded by copper metal plate. Relative permittivity (ϵ) of substrate is 4.4mm and loss tangent (ρ) 0.02. Table 1 shows the design parameters of the absorber.

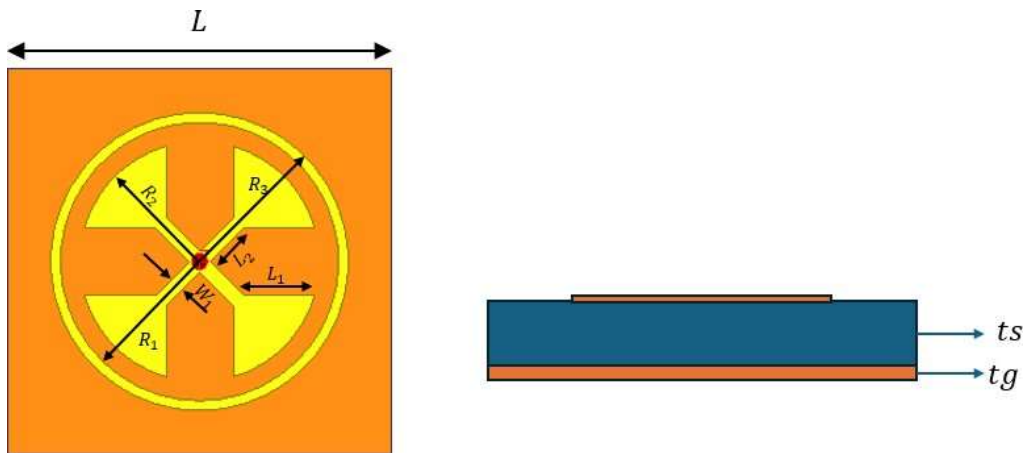


Fig. 1. Structure of proposed absorber

Table 1 Design Parameters

Parameter	L	R_1	R_2	R_3	W_1	L_1	L_2	t_g	t_s
Value	8	2.9	2.5	3.1	0.3	1.4	1.1	0.035	0.8

2.2 Governing Equations

When the electromagnetic wave is incident on a metasurface, it is transmitted as well as reflected through the surface. Reflected Power $R(\omega)$ and transmitted power $T(\omega)$ should be minimal to get the maximum absorption as defined by the equation 1.

$$A(\omega) = 1 - R(\omega) - T(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2 \quad (1)$$

Where S_{11} is the reflection coefficient and S_{21} is the transmission coefficient. Equation 2 shows the reflection coefficient under a normal incident angle.

$$v(\omega) = \frac{Z(\omega) - Z_0}{Z(\omega) + Z_0} \quad (2)$$

$Z(\omega)$ is the input impedance of the metasurface absorber and Z_0 is the free space impedance. To achieve maximum absorption the reflection coefficient must be zero. This can be achieved by changing the input impedance which depends on the resistance and capacitance of the metasurface. The values of capacitance and resistance can be tuned over a range of values and the structure is then designed to achieve the required impedance.

2.3 Boundary Conditions

A Floquet port is used to excite the absorber structure keeping phase angle and theta zero, meaning the wave hits the structure head-on as shown in figure 2. To simulate the behavior of the structure as part of an infinite array, periodic master and slave boundary conditions are used ensuring the wave interacts with the structure that represents an endless repetition of the same pattern. The structure is refined both in TE and TM mode ensuring the absorber effectively absorbs waves regardless of their electric or magnetic fields orientation.

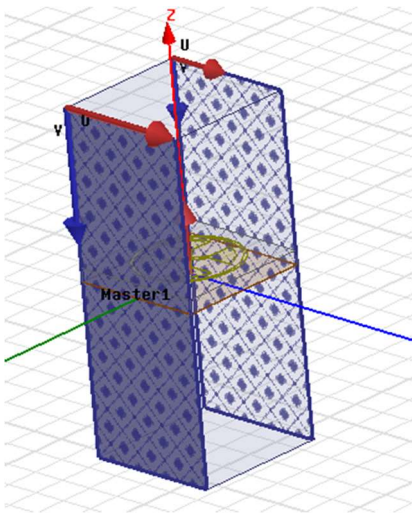


Fig. 2. Master and Slave boundary condition

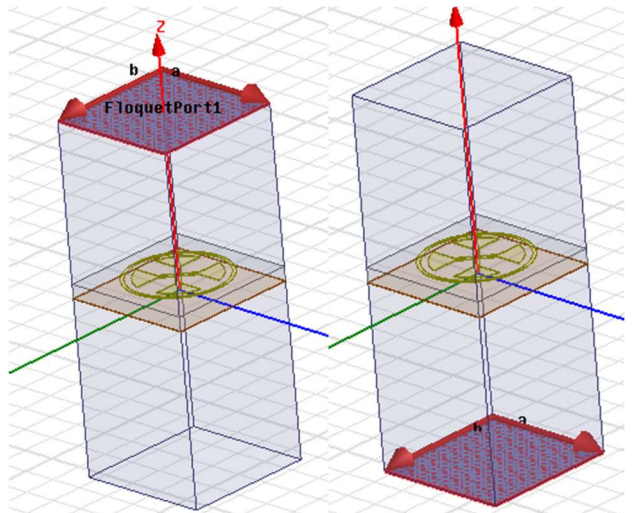


Fig. 3. Excitation

3 Results & Discussions

The electric field and surface current distribution are observed over the metasurface. Then S_{11} parameter is analysed for normal incidence. The first result indicates the ability of the structure to absorb incident wave while the later one quantifies the reflection coefficient achieved by the structure.

3.1 Electric Field and Surface Current Distribution

E-field distribution and surface current as shown in figure 4 and 5 respectively, is plotted at 10 GHz frequency for TE mode to explain the absorption of the structure. Figure 5 shows that the E field is concentrated on the outer circularstrip while it is also relatively higher on the metal resonator part than the cross-linked resonators. These E fields regulate the effective permittivity and provide the electrical excitation. Figure 4 shows the current distribution over the metasurface. At the resonant frequency, current distribution at the top side of the metasurface is more than the bottom side, which results in generating circulating current which regulates the permeability and is also responsible for magnetic excitation.

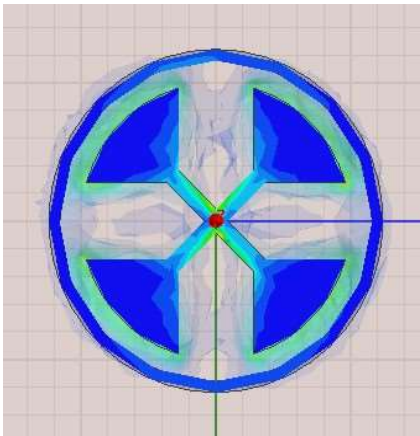


Fig.4. Surface Current Distribution

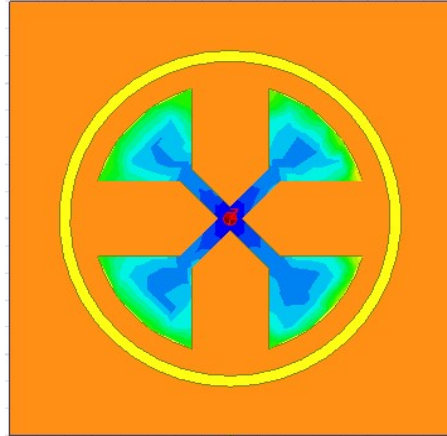


Fig.5. E Field Distribution

3.2 Reflection Coefficient (S_{11})

Metasurfaces with S_{11} parameters less than -10 dB are absorbers. Achieving higher gain and wider bandwidth requires tuning of the design parameters. The selection of an optimum absorber is also a key factor that can increase the efficiency and bandwidth of the absorber. Figure 6 shows the S_{11} parameter of the proposed absorber indicating its absorption capability. It covers the X band (8.2 to 12.4) GHz with a bandwidth of approximately 4 GHz and the highest gain, S_{11} parameter is approximately -25dB. The impedance plot and VSWR shown in figure 7 and 8 validates the absorption capability as the real and imaginary impedance value in X band is stable near zero, and voltage standing wave ratio (VSWR) is converging to zero in frequency range of 8GHz to 12GHz, which shows that the structure is resonating. As the structure resonates, it trap the incoming waves and the structure act as an absorber.

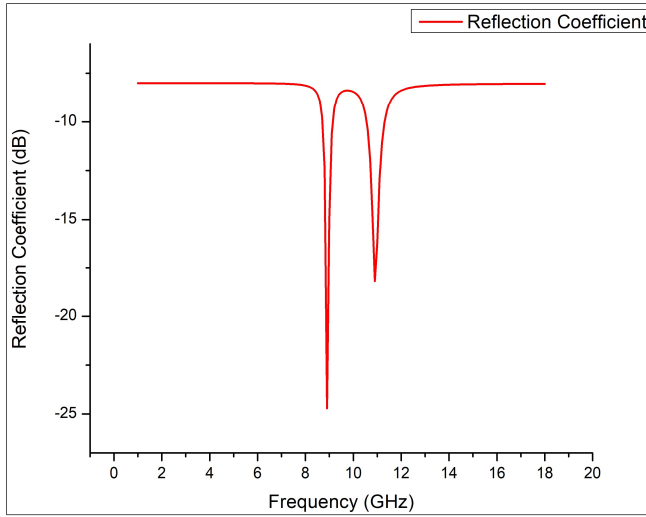


Fig.6. Reflection Coefficient of proposed absorber

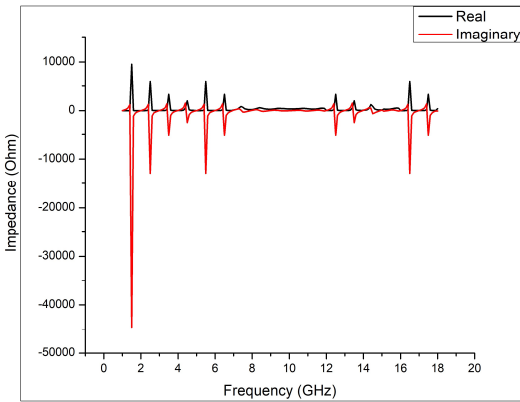


Fig.7. Impedance Plot

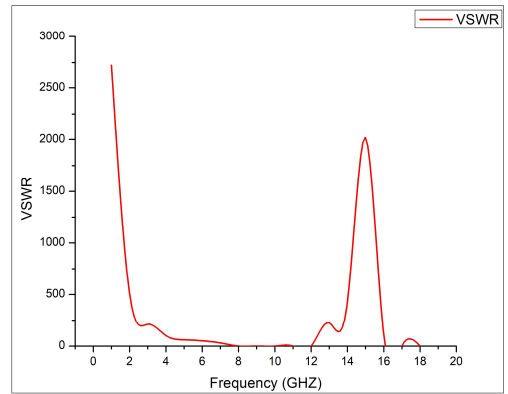


Fig.8. VSWR

3.3 Effect of Substrate Thickness

The distance between the metasurface and the ground plane determines the substrate thickness which effects the impedance matching of the absorber. In case of proposed X-band absorber the substrate thickness is $\lambda/4$ or 0.8mm. Figure 9 shows the S_{11} parameter at substrate thickness of 0.6mm, 0.7mm, and 0.8mm which shows that the S_{11} parameter is decreased with the increase in substrate thickness.

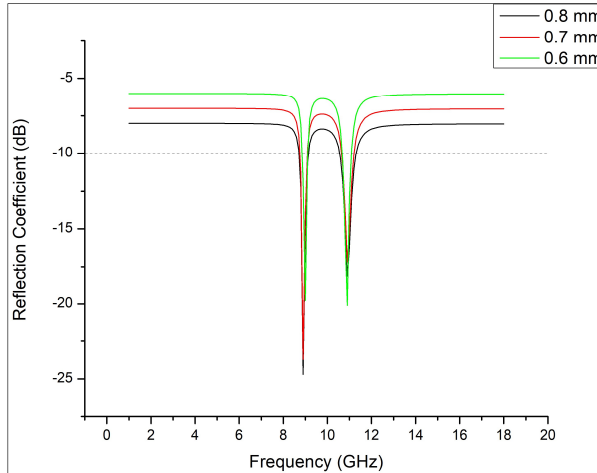


Fig.9. Effect of substrate thickness on Reflection Coefficient

4 Conclusion

This study has presented a novel X-band metamaterial absorber characterized by dual resonating peaks, offering exceptional absorption efficiency across the frequency spectrum. Through comprehensive simulation and experimental validation, the absorber demonstrated a reflection coefficient consistently below -10dB throughout the X-band, achieving 100% absorptivity with a gain of -25dB under normal incidence. The absorber’s structural design, comprising interconnected circular sectors and cross resonators enclosed within a circular strip, coupled with FR4 substrate and copper ground plane, proved to be effective in attenuating incident electromagnetic waves. Validation of the impedance plot and VSWR analysis confirmed the accuracy and reliability of the simulation results.

Further research could explore optimization techniques to enhance the absorber’s performance or investigate its compatibility with different substrates and ground plane materials. Additionally, real-world deployment of the absorber in diverse applications could provide valuable insights into its performance in practical settings. Overall, this study contributes to the advancement of metamaterial-based absorbers and underscores their potential to address the evolving needs of X-band electromagnetic wave attenuation in modern technologies.

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