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Design and Validation of Low Profile Quad-band Metamaterial Absorber for Shielding Technology for Higher Frequency Bands

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Abstract

This work presents a simple and compact Concentric Octagonal Split-Ring Resonator (COSRR) based metamaterial absorber (MMA) for microwave absorber applications in the X, Ku, and K-band. The proposed MMA has an electrical size of approximately $0.178\lambda_0 \times 0.178\lambda_0$. The MMA unit cell demonstrates transmission resonance with Mu Negative (MNG) metamaterial properties. It has an excellent absorption value of 98.88%, 90%, 99.30%, and 95.11% at absorption frequencies of 9.85, 12.8, 15.48, and 20.42 GHz, respectively. Plotting the real and imaginary components of permittivity (ϵ), permeability (μ), and normalized input impedance (Z_{in}) allows one to investigate metamaterial behavior. The structure's polarization-insensitive behavior is examined at various angles for both normal and oblique incidence. Shielding effectiveness of MMA: 38.46 dB, 19.58 dB, 51.75 dB, and 27.40 dB make this design useful for many wireless applications. Comparing the suggested structure to previously published multi-band absorbers, it was discovered that the former contains more absorption peaks and encompasses frequency spectra such as X, Ku, and K bands all at once. Validation of S-parameter/absorption is also reported through an experimental setup, and it shows good agreement with the simulated results.

Keywords: absorber, microwave, incident angle, shielding, fabrication

1 Introduction

Metamaterials have several potential applications due to their remarkable optical and electromagnetic (EM) properties. Metamaterials are used in microwave sensors, EM cloaking, high-performance antenna systems, absorbers, and superlenses. Among these, MMA is one of the most active research areas. Metamaterial absorbers are widely employed and designed across a variety of frequency ranges, depending on the applications in terahertz, optical, or microwave frequency spectra [1]. Cloaking, imaging, sensing, and lowering radar cross-section are just a few of the applications that eagerly await the ideal metamaterial absorber. Since the initial study by Landy et al. [2], a variety of MMA with many variations in structural design of the resonating patch, angular stability, polarization-independent features, and wide bandwidth have been studied.

Alongside remarkable developments in applications such as energy harvesting (EH) and wireless power transfer (WPT), the use of MMA technologies for electromagnetic interference (EMI) shielding has increased. It has been observed that as technology has advanced, electronic device improvements and advancements have increased EM radiation and interference, which can be detrimental to both human health and the gadgets themselves. In order to reduce EM contamination and create efficient EMI shielding materials and devices, researchers have given EMI shielding phenomena a great deal of attention. The shielding materials must have high electrical conductivity in order to deflect polluted EM signals. For certain specialized applications, the shielding material or device also needs to be small, light, and extremely thin. Although they were heavy, the conventional shielding materials offered good protection. Because of their tiny size, low weight, and thin thickness, metamaterial absorbers have been investigated in this aspect. MMA can function as an efficient EMI shield by absorbing energy from the incident EM wave and removing the signal's undesired reflection and transmission.

By using the Circular-ring tied arc loaded structure, Rahman et al. [3] proposed an absorber for shielding technology under 2 to 6 GHz frequency band for WI-FI application. This designed MMA produces resonance frequencies at 2.4 GHz and 5.0 GHz with absorption values of 98.88 % and 99.81 % with SE values of 54.34 dB at 2.4 GHz and 77.96 dB at 5.0 GHz, respectively. A study for quad-band MMA has been reported by Hossain et, al. [4] using the double elliptical resonator structure. This structure provides resonance frequencies at 3.46 GHz, 6.44 GHz, 7.89 GHz, and 12.44 GHz under a 2 to 14 GHz frequency range application. The simulated value of SE is 36.7 dB, 65.98 dB, 70.67 dB, and 55.63 dB at resonant frequencies. Due to the asymmetrical design of this MMA, it exhibits stability up to 60 degrees for both polarization and incident angles. As the elliptical resonator is becoming popular among researchers, the use of this resonator has been frequently used for MMA applications. Hasan et al. [5] proposed a quad-band MMA for energy harvesting applications under the 2 to 14 GHz frequency band. This design provides absorption frequency at 2.576 GHz, 5.632 GHz, 8.304 GHz, and 13.44 GHz with absorption values of 99.83%, 99.98%, 99.56%, and 99.15%, respectively. A triple-band MMA based on a double E-shaped symmetric split-ring resonator configuration for EMI shielding and stealth applications was reported in [6]. The proposed structure exhibited near-unity absorption at

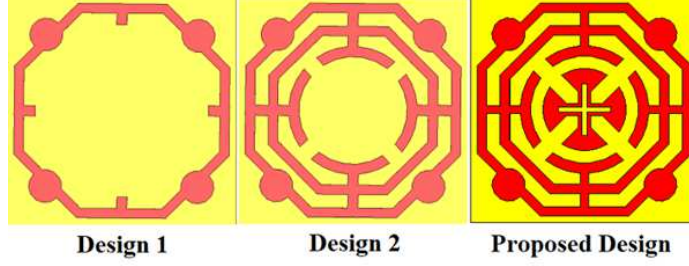


Fig. 1: Evolution of proposed MMA.

three resonance frequencies, achieving simulated absorption peaks of 99.9%, 99.9%, and 99.7%, with measured values exceeding 97%, and demonstrated stable performance for polarization and oblique incidence angles up to 60° for both TE and TM modes, indicating polarization-insensitive and wide-angle operational characteristics. Furthermore, shielding effectiveness exceeding 40 dB across the operating bands was experimentally achieved, ensuring strong attenuation of incident EM waves. Due to the rapid development of symmetrical structures for shielding technology, the X-structure type shape of MMA is highly recommended for researchers. In this regard, a perfect quad-band MMA using a double X-shaped ring resonator has been reported by [7]. It is designed for EMI shielding technology and multi-sensing applications in the C, X, and Ku frequency bands. This design demonstrates near-perfect absorption of 99.9% at 4.87 GHz, 7.49 GHz, 11.78 GHz, 99.8% at 13.09 GHz, with a magnitude of SE up to 87 dB and 101 dB, respectively. Recently, using a bold X-structure type quad-band MMA in the 4 to 14 GHz frequency band has been demonstrated by Hussain et.al. in [8] for shielding applications. It shows absorption peaks at 7.64 GHz, 8.41 GHz, 11.4 GHz, and 12.66 GHz with absorption values of 98.4%, 97%, 99.2%, and 99%, respectively. This design achieves polarization stability up to 30 while being angular insensitive for 60. In settings with many frequency sources, including 5G networks and radar installations, the SE values of 45.2dB, 65.2dB, 62.4dB, and 46.2dB support shielding.

An absorber intended for multiband applications in the X, Ku, and K frequency bands is presented in this paper. The suggested absorber adds a number of noteworthy features: It is built on an FR-4 dielectric substrate and has a unique resonant patch made of two concentric octagons, one split ring, and a modified cross-ring structure. With absorption values of 98.88%, 90%, 99.30%, and 95.11%, this design successfully covers the X, Ku, and K bands with four absorption peaks at 9.85, 12.8, 15.48, and 20.42 GHz. Over a broad polarization and angular range, the absorber continues to operate steadily in the operating frequency range. The suggested multi-band absorber has practical uses in the Internet of Things, biological sensing, wireless power transfer (WPT) systems, energy harvesting, back lobe reductions in antennas, WI-FI devices, and many other fields.

2 Unit cell design

2.1 Technical Background

One of the most crucial factors influencing absorption is the absorption values, which are connected to the transmission ratio $T(\omega)$, reflection ratio $R(\omega)$, and the following connection. Eq. (1) illustrates the $A(\omega)$ characteristic of microwave absorbers. As can be seen from Eq. (2) and Eq. (3), $R(\omega)$ and $T(\omega)$ are directly proportional to the reflection coefficient $|S_{11}|^2$ and the transmission coefficient $|S_{21}|^2$ [9].

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

$$R(\omega) = |S_{11}|^2 \quad (2)$$

$$T(\omega) = |S_{21}|^2 \quad (3)$$

Reducing transmission to zero in Eq. (1) is required to improve absorption $A(\omega)$, and this can be avoided by adding a metal substrate so that $T(\omega) = 0$. As a result, the absorption profile can be modified as Eq. 4

$$A(\omega) = 1 - R(\omega) = 1 - |S_{11}|^2 \quad (4)$$

The material impedance in the design is matched to the free space impedance, and absorption will reach its maximum at $A(\omega) \approx 1$ [10].

2.2 Design process and performance analysis

As seen in Fig. 1, the planned structure was evaluated step by step until the final unit cell design was attained. Fig. 2(a) displays the front view, while simulation setups with different boundary conditions are illustrated in Fig. 2(b) of MMA [11]. The absorption peak shows a four-band resonance in the 8 GHz to 22 GHz frequency range with a good magnitude in the final design. The proposed unit cell construction consists of two octagons and one split-ring resonator, along with a modified cross structure placed in the center of the unit cell. Fig. 2 illustrates the proposed structure with parameters. The substrate size is $(L) = 12 \times (W) = 12 \text{ mm}^2$ with a low dielectric constant of $\epsilon_r = 2.2$ and a thickness of $h = 1.5 \text{ mm}$, and copper is positioned on the top and bottom layers at a thickness of $t = 0.035 \text{ mm}$.

Fig. 3(a) shows the contribution of each design stage in generating different absorption peaks and the corresponding absorption values. In the initial stage of the design, a modified octagonal structure with circular elements on four sides was selected for the development of Design 1. The obtained absorption peaks were observed at 14.71 GHz, 22.55 GHz, and 29.32 GHz, with absorption values of 57.07%, 98.98%, and 97.93%, respectively. Although Design 1 provides strong absorption at the higher-frequency resonances, the number of absorption peaks and the lower-frequency absorption performance remain limited. Therefore, further structural modification was introduced to enhance the operating bandwidth and generate additional resonant modes. In

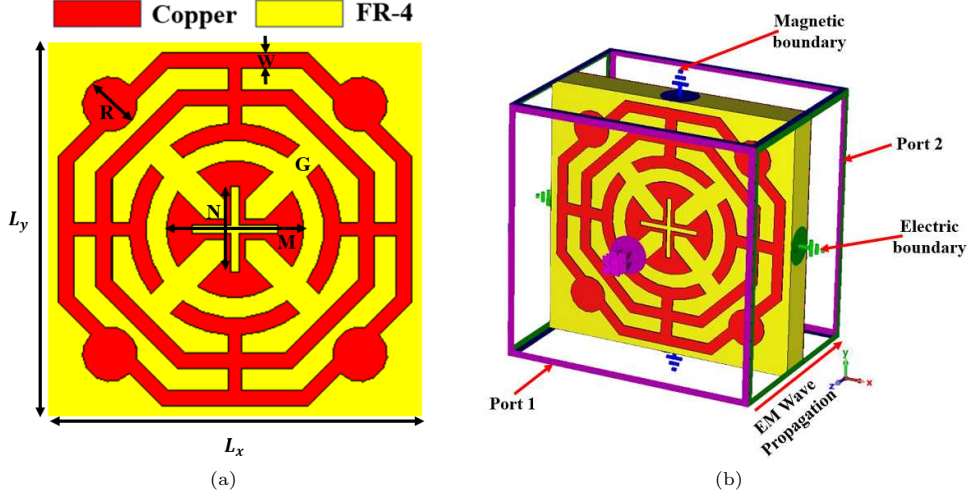
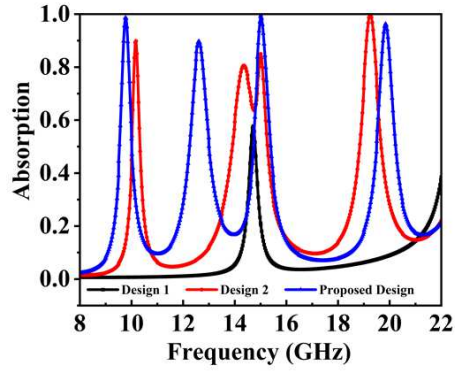
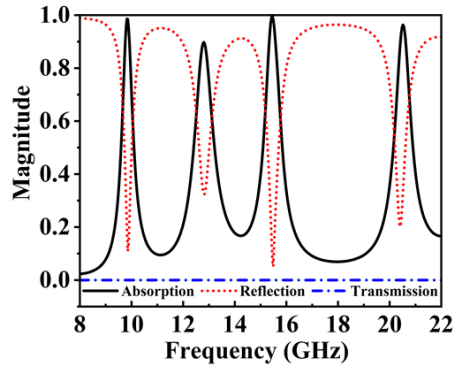


Fig. 2: (a) Front view of the proposed COSRR and (b) simulation setup with different boundary conditions. [Optimized parameters: $L_x = L_y = 12$, $W = 0.5$, $G = 0.7$, $R = 0.8$, $M = 4$ and $N = 2.5$ (all in mm)]

the second design stage, a combined structure consisting of an octagonal resonator and a circular split-ring structure was incorporated. This modification significantly altered the current distribution and effective inductance–capacitance of the resonator, resulting in additional resonant modes and shifting the absorption frequencies toward the lower-frequency region. Consequently, five absorption peaks were obtained at 10.27 GHz, 15.45 GHz, 19.91 GHz, 24.34 GHz, and 26.88 GHz, with corresponding absorption values of 89.84%, 84.86%, 99.50%, 90.49%, and 95.88%, respectively. The improvement in the number of resonances demonstrates that the combined resonating elements provide additional EM coupling paths, thereby increasing the overall absorption capability of the unit cell. Finally, a modified cross structure was inserted inside Design 2 to obtain the proposed final MMA configuration. The incorporation of the cross structure further modifies the EM coupling and introduces additional resonant current paths within the unit cell. As a result, the absorption frequencies are redistributed toward the targeted frequency range, producing four distinct absorption peaks at 9.85, 12.80, 15.48, and 20.42 GHz, with corresponding absorption values of 98.88%, 90.00%, 99.30%, and 95.11%, respectively. At an absorption frequency of 9.85 GHz, the absorption value is 98%, and at 15.48 GHz, the absorption value is 99%, which means that there is good impedance matching between the MMA and the board, particularly at 15.48 GHz. These resonant frequencies are also free space at these frequencies. The gradual development from Design 1 to the proposed design shows that every structural modification is significant and has an effect on the design. Its role in controlling the resonant response and the absorption properties. The introduction of the circular split-ring and modified cross structure increases the effective inductive and capacitive loading of the unit cell, which helps to generate and move many resonant



(a)



(b)

Fig. 3: The (a) absorption performance for different designs and (b) absorption, reflection, and transmission of the proposed COSRR

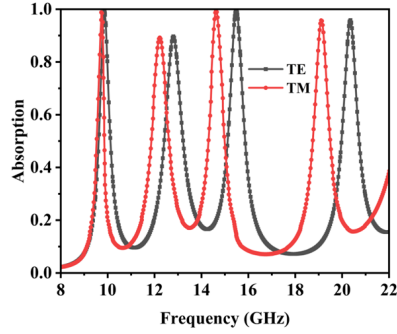


Fig. 4: The absorption performance of COSRR for TE and TM polarization of the incident wave

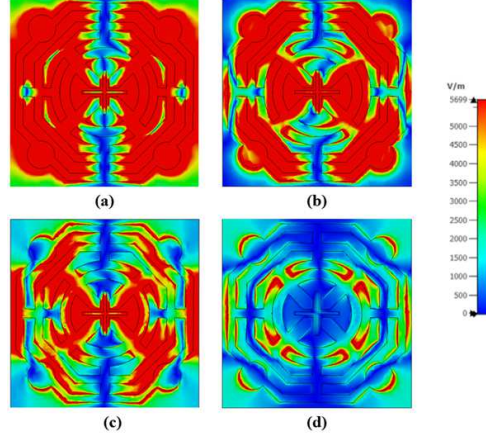


Fig. 5: Contour plot of E-field at absorption frequency of (a) 9.85 (b) 12.8 (c) 15.48 (d) 20.42 GHz

modes. Thus, the final geometry provides a better combination of compactness, multiple resonances, and high absorption compared with the initial configurations. The variation of reflection coefficient (S_{11}), transmission coefficient (S_{21}), and absorption performance of the COSRR unit cell under TEM-mode excitation is presented in Fig. 3(b). Fig. 4 further illustrates the absorption response of the proposed unit cell under TE and TM modes.

2.3 Absorption Mechanism

The absorption mechanism is explored through the distribution of the E-field, H-field, and surface current density at all the absorption frequencies [12]. The E-field distributions at 9.85, 12.8, 15.48, and 20.42 GHz are displayed in Fig. 5. As shown in Fig. 5, electric charges with opposite polarity are highly concentrated at the two opposite sides of Design 1 and Design 2 at 9.85 & 12.8 GHz, and moderately concentrated for 15.48 & 20.42 GHz. At targeted absorption frequencies, the electric resonance is triggered by an electric dipole formed on the patch by the direction of the electric charges. In the same way, in Fig. 5(b), the formation of a dipole in the second ring due to the E-field distribution along the X direction contributes to the resonance at 12.8 GHz. The distribution of the E-field at 20.42 GHz is less concentrated at the inner modified cross design, but the H-field is dominant at this design, as shown in Fig. 6(d). Due to this strong coupling formation, capacitance produces a resonance peak at 20.42 GHz with a 95.11% absorption value. The relation between E-field and H-field is clearly understood by Eq. (5). Therefore, nearly all electric and magnetic energy is absorbed when electric and magnetic resonances occur simultaneously at the desired frequencies; absorptions of 98.8%, 90%, 99.30%, and 95.11% are achieved at 9.85, 12.8, 15.48, and 20.42 GHz, respectively. To understand the correlation among E-field, H-field, and surface current, it is crucial to refer to Maxwell's curl equations as described below [13].

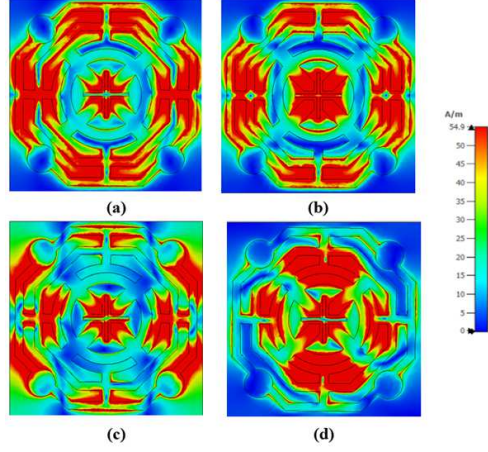


Fig. 6: Contour plot of H-field at absorption frequency of (a) 9.85 (b) 12.8 (c) 15.48 (d) 20.42 GHz

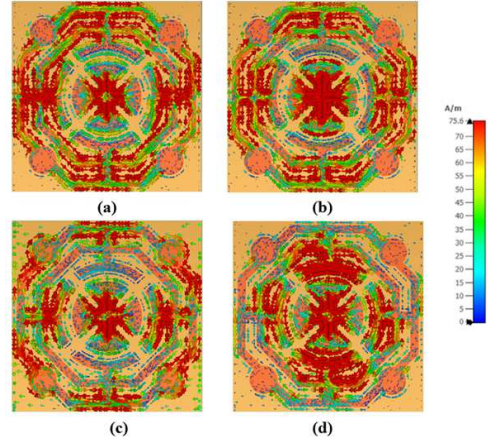


Fig. 7: Surface current distributions on patch at absorption frequency (a) 9.85 (b) 12.8 (c) 15.48 (d) 20.42 GHz

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (5)$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \quad (6)$$

The surface current distributions at different absorption frequencies are shown in Fig. 7, which also demonstrates how current travels over the structure to produce different resonances. At the first resonance, the current primarily flows along the edges of Design 1 and Design 2, as depicted in Fig. 7(a), while the modified cross structure

has the current distribution in the opposite direction of Design 1 and Design 2. For this reason, current directions form a strong magnetic dipole and produce the 98.88% absorption value at 9.85 GHz. Similar conditions are found for 12.8 and 15.48 GHz, as shown in Fig. 7(b) and Fig. 7(c). At the fourth resonance peak, the localization of current intensifies mainly at Design B and the modified cross structure of the final design, as depicted in Fig. 7(d). This anti-parallel flow between Design 2 and the modified cross structure enhances magnetic interactions. Strong absorption throughout different absorption frequencies relies heavily on anti-parallel currents and isolated high-current areas, as shown by these patterns [14].

2.4 Metamaterial characteristic analysis

The metamaterial characteristics are explored by extracting the permittivity as well as the permeability using Eqs. (7) and (8) [15]. At the frequencies of maximal absorptions, both permittivity and permeability experience a positive-negative transition, and vice versa, according to the graphs shown in Fig. 8(a) and Fig. 8(b). Additionally, it is shown that permeability turns negative while permittivity is positive and vice versa when permeability reaches a positive value. Therefore, for each given frequency, the MMA displays a single negative behavior. The normalized input impedance (Z_{in}) is analyzed for this MMA because impedance matching is essential to obtain unity absorption by using Eq. (9) [16]. From the plots presented in Fig. 9, the obtained normalized impedance Z_{in} is $0.92 + j0.020$, $0.90 + j0.035$, $0.97 + j0.012$, $0.95 + j0.022$, and $0.98 + j0.061$ at 9.85, 12.8, 15.48, and 20.42 GHz. These values indicate that there is a mismatch between the responses in terms of the impedance of the MMA and the ideal value of $1 + j0$. The impedance mismatch causes reflection at target frequencies, resulting in absorption that deviates from the ideal of 100%. As the deviation of Z_{in} in comparison to free-space impedance is high at 12.8 GHz, comparatively high reflection occurs, causing 90% absorption. On the other hand, at 9.85, 15.48, and 20.42 GHz, comparatively better impedance matching reduces reflection, leading to near-unity absorption of 98.88%, 99.30%, and 95.11%, respectively. This indicates that the suggested absorbent has low reflectivity and strong absorptivity.

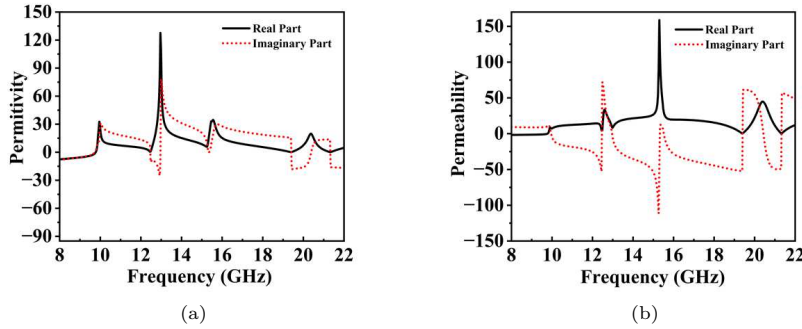


Fig. 8: The (a) permittivity and (b) permeability of COSRR structure.

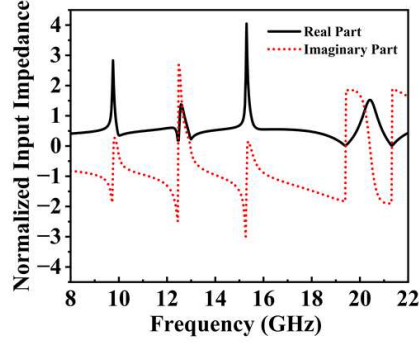


Fig. 9: Normalized Input Impedance of proposed MMA.

$$\text{Permittivity}, \epsilon_r = \frac{2}{jK_0 d} \cdot \frac{1 - S_{21} - S_{11}}{1 + S_{21} + S_{11}} \quad (7)$$

$$\text{Permeability}, \mu_r = \frac{2}{jK_0 d} \cdot \frac{1 - S_{21} + S_{11}}{1 + S_{21} - S_{11}} \quad (8)$$

$$\text{Impedance}, \frac{Z_{\text{in}}(\omega)}{Z_0} = \frac{1 + S_{11}}{1 - S_{11}} \quad (9)$$

2.5 Absorption characteristic analysis of Polarized wave

The normal-incidence wave condition is commonly considered the basis for the initial characterization of MMA. However, in practical and real-world applications, EM waves may impinge on the absorber surface at various oblique incidence and polarization angles rather than strictly under normal incidence [17]. Therefore, the angular stability of an MMA is an important performance parameter that determines its suitability for practical EM applications. An ideal MMA should maintain nearly identical absorption characteristics over a wide range of incidence angles (θ) and polarization angles (ϕ), thereby demonstrating strong angular and polarization insensitivity [18]. Such stability is particularly desirable in applications where the orientation of the absorber with respect to the incident EM wave cannot be precisely controlled. To investigate the angular stability of the proposed MMA, the incidence angle (θ) and polarization angle (ϕ) are systematically varied from 0° to 90° , and the corresponding absorption responses are presented in Fig. 10. Figure 10(a) illustrates the absorption characteristics for different incidence angles, where (θ) is varied from 0° to 90° . The resonance frequencies remain almost unchanged with increasing incidence angle, while the absorption magnitude exhibits only a gradual variation over the investigated angular range. This indicates that the resonant modes of the proposed structure are relatively insensitive to changes in the direction of the incident EM wave. Similarly, Fig. 10(b) presents the absorption response for different polarization angles. The absorption characteristics remain highly stable as the polarization angle is varied, demonstrating the polarization-insensitive behavior of the proposed MMA. This

behavior can primarily be attributed to the geometrical symmetry of the proposed unit cell, which enables the structure to interact with the incident electric field in a relatively similar manner for different polarization orientations.

Although the 0° -to- 90° angular study provides an overall assessment of the absorber's angular response, the oblique-incidence performance is further investigated separately under transverse electric (TE) and transverse magnetic (TM) polarization modes. This analysis provides a more realistic evaluation of the absorber under practical operating conditions, where the incident EM wave may arrive at the absorber surface from different directions. The absorption performance for oblique incidence angles ranging from 0° to 60° is presented in Fig. 11 for both TE and TM modes. Figure 11(a) shows the absorption response under TE polarization for incidence angles varying from 0° to 60° . The proposed absorber maintains near-perfect absorption, with absorption levels exceeding 99%, up to an incidence angle of approximately 30° . With a further increase in the incidence angle, a gradual reduction in absorption is observed; nevertheless, the absorber maintains an absorption level above 90% even at an incidence angle of 60° . The observed reduction at larger incidence angles can be attributed to the variation in the effective EM path, field distribution, and impedance-matching condition between the absorber and free space under oblique illumination. Despite this reduction, the overall absorption response remains sufficiently high over the investigated angular range.

The corresponding TM-mode response is presented in Fig. 11(b). In this case, the proposed MMA exhibits excellent angular stability, with absorption values remaining above 99% over a wide range of incidence angles and maintaining high absorption performance up to 60° . The comparatively stable TM response indicates that the proposed unit-cell configuration can effectively preserve its resonant behavior even when the EM wave impinges on the structure at a significant oblique angle. The combined TE- and TM-mode analysis confirms that the proposed MMA possesses strong angular robustness and maintains high absorption over a broad range of practical incidence conditions. The enhanced angular stability can be associated with the symmetric geometry and optimized EM coupling of the proposed unit cell. The symmetric arrangement reduces the dependence of the induced surface currents and electric-field distribution on the orientation of the incident wave. Furthermore, the resonant metallic elements and dielectric substrate collectively contribute to maintaining effective impedance matching over a wide range of incidence angles. As a result, the proposed MMA exhibits relatively stable resonance characteristics and high absorption under both normal and oblique illumination.

Overall, the results presented in Figs. 10 and Figs. 11 demonstrate that the proposed MMA has a high degree of polarization stability and strong angular robustness. In particular, the absorber maintains absorption above 90% at an incidence angle of 60° under the investigated TE and TM conditions, while several resonant bands retain absorption levels close to or above 99%. These characteristics make the proposed structure promising for practical applications in EM-wave absorption, EMI/EMC control, radar cross-section reduction, sensing, and other scenarios where the direction and polarization state of the incident EM wave may vary during operation.

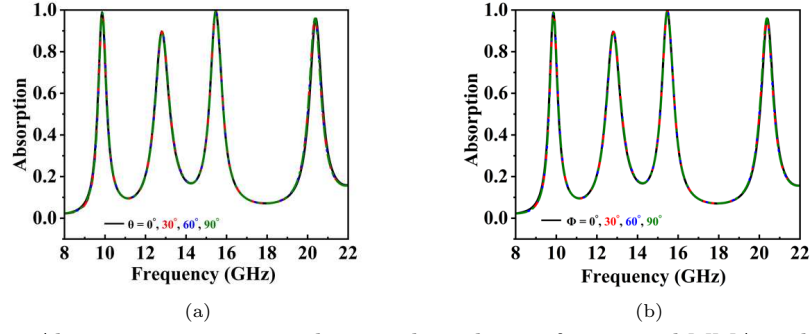


Fig. 10: Absorption response with normal incidence of suggested MMA under diverse (a) incidence angles (θ) and (b) polarization angles (ϕ).

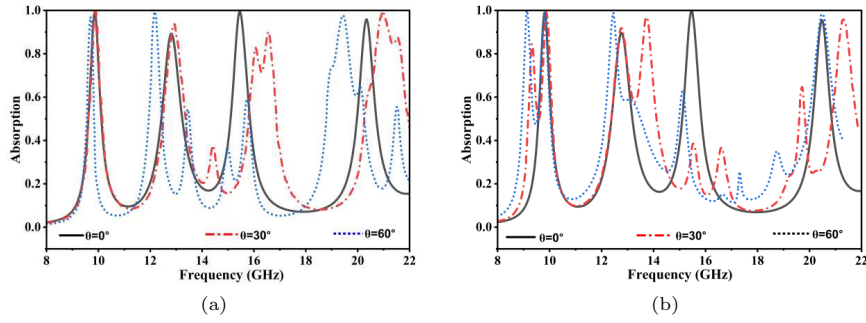


Fig. 11: Absorption response at different incidence angles (θ) for (a) TE mode and (b) TM modes

Now, by extracting the cross-polarization data, the influence of polarization conversion on the absorption performance of the proposed MMA is also investigated. Signal conversion can occur in some metasurface absorbers because of their anisotropic geometry, where a portion of the incident wave is converted from co-polarization to cross-polarization instead of being dissipated within the absorber [19]. Therefore, considering only the co-polarized reflection and transmission coefficients may lead to an inaccurate estimation of the actual absorption. To overcome this limitation, Eq. (10) considers both co-polarized and cross-polarized components and provides a more comprehensive evaluation of the absorption characteristics

$$A(\omega) = 1 - r_{xx}^2 - r_{yx}^2 - t_{xx}^2 - t_{yx}^2 \quad (10)$$

In Eq. (10), r_{xx}^2 and t_{xx}^2 represent the reflected and transmitted power coefficients corresponding to the co-polarized components, whereas r_{yx}^2 and t_{yx}^2 represent the

reflected and transmitted power coefficients corresponding to the cross-polarized components. Thus, Eq. (10) accounts for all possible reflected and transmitted polarization components and provides a reliable estimation of the actual absorbed power.

Since a continuous copper ground plane is placed on the backside of the proposed MMA, the transmission coefficient is effectively suppressed over the operating frequency range. Consequently, t_{xx} and t_{yx} approach zero, and Eq. (10) can be simplified to Eq. (11) [19]:

$$A = 1 - r_{xx}^2 - r_{yx}^2 \quad (11)$$

Fig. 12 presents the absorption spectrum calculated by considering both co-polarized and cross-polarized reflection coefficients. It can be observed that the absorption spectrum obtained from the complete polarization-dependent formulation is almost identical to the absorption response obtained for normal incidence. This close agreement is attributed to the negligible magnitude of the cross-polarized reflection coefficient throughout the operating frequency range. In other words, the incident EM energy is predominantly maintained in its original polarization state, while the remaining energy is effectively dissipated within the MMA rather than being converted into an orthogonal polarization component.

The very low cross-polarization response also indicates that the proposed structure exhibits negligible polarization conversion. This is an important characteristic for an absorber because a high cross-polarized response can artificially reduce the apparent co-polarized reflection while the EM energy is merely redirected into another polarization state rather than being absorbed. Therefore, the negligible r_{yx} observed in Fig. 12 confirms that the high absorption achieved by the proposed MMA is primarily due to EM energy dissipation and impedance matching rather than polarization conversion. Furthermore, if a significant amount of the incident EM wave were converted by the cross-polarized component of MMA, the total absorption magnitude would decrease, and the metamaterial would increasingly behave as a polarization converter rather than an absorber [20]. In contrast, the proposed MMA maintains an extremely small cross-polarized reflection coefficient, confirming that polarization conversion has a negligible contribution to the overall response. This result also validates the absorption values obtained from the conventional absorption equation based on S_{11} and S_{21} . The reduction in the cross-polarized components seen in the observations is believed to be due to the geometrical symmetry of the proposed resonating elements, which results in similar EM responses for different orientations of the incident electric field. Thus, the proposed metastructure retains its absorption properties without any appreciable polarization conversion. Hence, the proposed MMA has a good polarization-independent absorption response, which indicates its potential application in situations where the polarization state of the incident EM wave changes.

2.6 Geometric Variations Based on Parameters

The split gap(G) width strongly affects the capacitive coupling of the resonator. Increasing the split gap decreases the effective capacitance, leading to a shift of the resonance frequencies toward higher frequencies and a reduction in absorption due to weaker EM confinement, as shown in Fig. 13. Conversely, decreasing the split gap

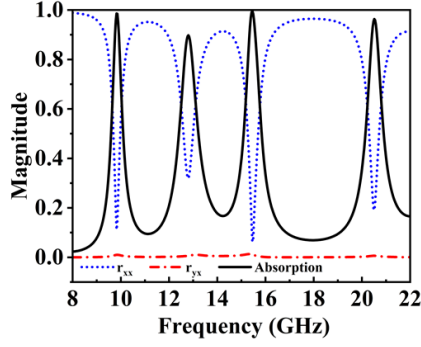


Fig. 12: The absorption behaviour of COSRR by considering the Co- and Cross-polarized reflection coefficient.

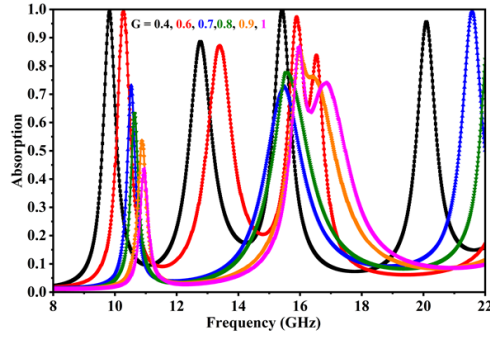


Fig. 13: The absorption behaviour of COSRR for different values of split gap(G) over the operating frequency range.

enhances capacitive coupling, improving field localization and absorption up to an optimum value. These results demonstrate that both dielectric thickness and split gap are critical design parameters for achieving high absorption and precise resonance tuning. Similarly, dielectric substrate thickness(t_s) has a significant influence on the absorption characteristics of the proposed metamaterial absorber as shown in Fig. 14. As the t_s values increase, the effective inductance and capacitance of the resonator change, causing a shift in the resonance frequencies and variations in impedance matching with free space. An optimum substrate thickness provides maximum absorption by minimizing reflection, whereas thinner or thicker substrates result in reduced absorption and slight resonance shifts, as shown.

The absorption performance of the proposed MMA was investigated by varying the array size from a single unit cell to finite arrays consisting of 2×1 , 2×2 , and 3×3 unit cells. The 2×1 configuration represents the fundamental resonant behavior of the designed unit cell, where absorption is primarily governed by the localized electric and magnetic resonances. However, due to the absence of neighboring elements,

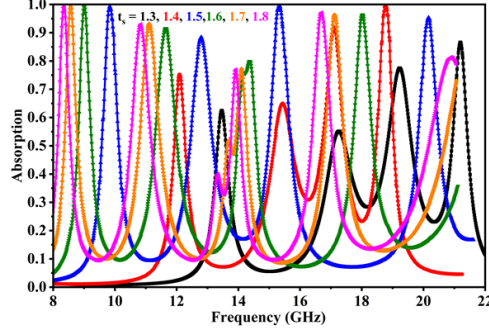


Fig. 14: The absorption behavior of COSRR for different values of substrate thickness(t_s) over the operating frequency range.

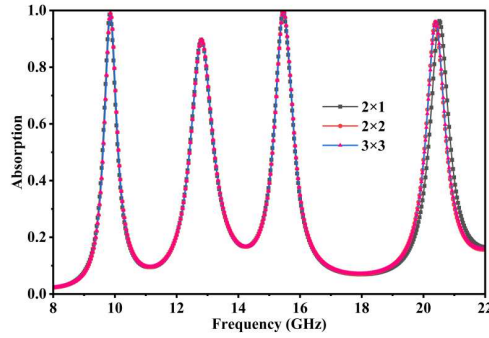


Fig. 15: Absorption performance of the 2×1 , 2×2 , and 3×3 array structure of the COSRR unit cell.

the EM coupling is minimal, which may result in slightly lower absorption and a narrower effective absorption bandwidth, as shown in Fig. 15. As the array size increases to 2×2 , mutual coupling between adjacent unit cells becomes significant. This inter-element interaction enhances impedance matching with free space, leading to improved confinement of EM energy within the dielectric substrate and metallic resonators. Consequently, the absorption peaks become stronger, and the overall absorption bandwidth may increase slightly while maintaining the resonance frequencies with negligible shift, as shown in Fig. 15. For the 3×3 array, the EM response approaches that of an infinitely periodic structure commonly assumed in full-wave simulations. The stronger periodic coupling stabilizes the resonant modes and further improves the absorption performance, resulting in near-unity absorption at the designed resonance frequencies. Beyond a 3×3 configuration, the improvement in absorption is generally marginal, indicating that the resonant characteristics have converged as shown in Fig. 15. Therefore, the 3×3 array provides a practical representation of the actual absorber performance while maintaining a reasonable computational cost. In conclusion, these

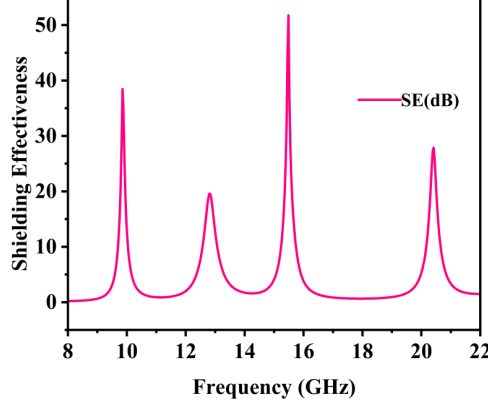


Fig. 16: Shielding effectiveness of COSRR for X, Ku, and K-band applications.

results show that the higher size of the array size will improve the absorption characteristics by having more electromagnetic coupling between cells and better impedance matching. The good absorption performance for larger array is also a proof of good robustness and scalability of the proposed MMA design in practical fabrication and experimental implementation.

3 Shielding Effectiveness

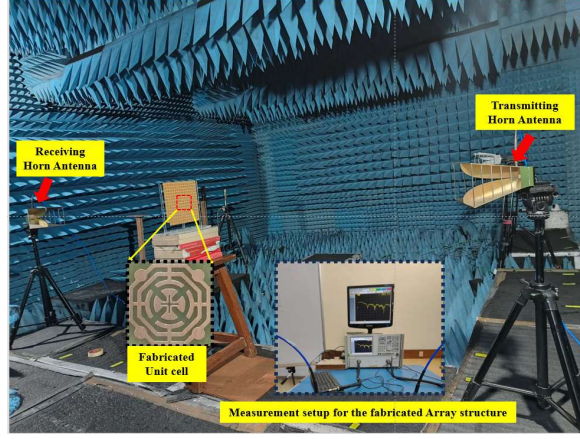
Shielding effectiveness (SE) is a key statistic for evaluating EMI shielding. A formula for calculating SE that takes into account both the absorption and reflection coefficients was put out by the authors of reference [21]. The SE was calculated using the following Eq. (12) [22].

$$SE \text{ (dB)} = -10 \log (1 - S_{11}^2) - 10 \log \left(\frac{S_{12}^2}{1 - S_{11}^2} \right) \quad (12)$$

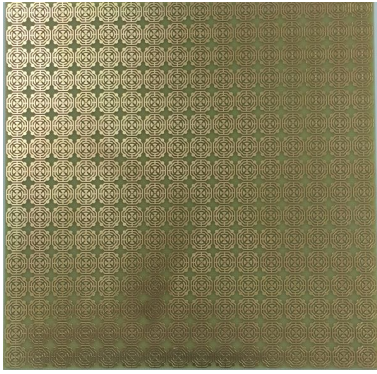
The simulated SE performance is displayed in Fig. 16, with values of 38.46 dB, 19.58 dB, 51.75 dB, and 27.40 dB, respectively, at the absorption frequencies at 9.85, 12.8, 15.48, and 20.42 GHz. This demonstrates that excellent absorption efficiency is achieved by the MMA absorber without appreciably changing the reflective response. Most applications usually require an SE of at least 30 dB, which is equivalent to a 99% decrease in EM emissions. This demonstrates its exceptional capacity to reduce EM radiation and meet EMI shielding requirements [23].

4 Fabrication, measurement, and comparative analysis

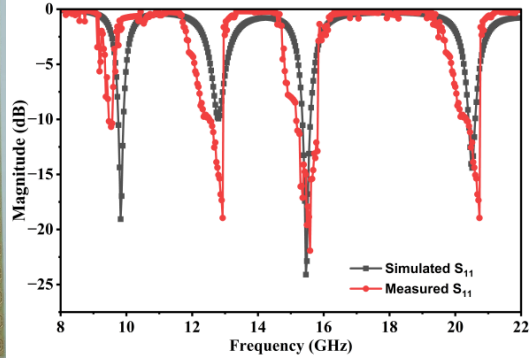
A prototype was created in order to empirically confirm the suggested MMA's performance and simulated outcomes [24, 25]. A single unit-cell model under periodic boundary conditions, which represents an ideal infinite array, was used to produce the



(a)



(b)



(c)

Fig. 17: Experimental validation (a) Measurement setup (b) Fabricated prototype of unit cell array (c) Simulated and measured S_{11}

numerical findings shown in the preceding sections. The unit cell was stretched into a finite 16×16 periodic surface for experimental realization, and full-wave simulations were run for this configuration before production [26]. Fig. 17 shows the experimental setup, the manufactured sample, and the periodic surface's simulated and measured findings. All measurements were conducted inside a fully anechoic chamber using a calibrated vector network analyzer (VNA) to accurately obtain the finite-size reflection coefficient (S_{11}) [27, 28]. The measured S_{11} response shows four distinct resonance frequencies at 9.53 GHz, 12.92 GHz, 15.58 GHz, and 20.73 GHz that are in good agreement with the simulated results as illustrated in Fig. 17(c). The black curves in Fig. 17(c) show a little difference between the S_{11} response of the ideal unit cell model and that of the finite 16×16 periodic structures. The restricted array configuration's intrinsic mutual coupling fluctuations, edge diffraction, and finite-size effects are responsible for this little discrepancy [29–31]. The performance demonstrates the

durability and scalability of the suggested design for realistic 5G energy harvesting applications by confirming that the quad-band absorption properties are successfully retained [32–34]. Additionally, Table 1 provides a detailed comparison of the proposed MMA with the corpus of recent research. This comparison demonstrates the absorber’s exceptional performance in several crucial areas, such as substrate layers, SE, unit cell size, and angular insensitivity, highlighting its enormous potential for practical applications [35, 36].

Table 1: Assessment of the presented absorber with some of the recently reported work

Ref.	Substrate Material	Unit cell dimension (mm ²)	Absorption Frequency (GHz)	Absorption value(%)	Operating Band	Remarks
[3]	FR-4	20×20	2.4, 5.0	98, 99	S and C	Sensing and RF shielding
[4]	FR-4	12×12	3.46, 6.44, 7.89, 12.44	97, 99, 99, 99	S, C and X	EMI sheilding technology
[5]	FR-4	12×12	2.5, 5.6, 8.32, 13.45	99, 99, 99, 99	S, C, X and Ku	Energy harvesting and image technologies
[6]	FR-4	10×10	5.37, 10.32, 12.25	99, 99, 99	C and X	EMI sheilding technology stealth applications
[7]	FR-4	8×8	4.87, 7.49, 11.78, 13.09	99, 99, 99, 99	C, X and Ku	EMI sheilding technology
[8]	FR-4	10×10	7.64, 8.41, 11.4, 12.66	98, 97, 99, 99	C, X and Ku	Stealth and EMI technologies
[21]	FR-4	8×8	10.76	99	X	EMI sheilding technology and radar systems
[35]	FR-4	24×24	1.8, 3.5	98, 99	L and S	EMI sheilding technology
[36]	FR-4	20×20	2.40, 3.50, 6.06	98, 99, 96	S and C	EMI shield for Wi-Fi and 5G signals
This work	FR-4	12×12	9.85, 12.8, 15.48, 20.42	98, 90, 99, 95	X, Ku, and K	EMI sheilding technology and energy harvesting

5 Conclusion

This work especially targets the shielding application by designing, fabricating, and experimentally validating a small and quad-band MMA for X, Ku, and K-band applications. The proposed COSRR-based MMA develops the resonance frequencies at 9.85, 12.8, 15.48, and 20.42 GHz, and absorption values are 98.88%, 90%, 99.30%, and 95.11% respectively. The proposed MMA was also investigated for TE and TM mode excitation in the operating frequency range and gives stable performance for different values of incidence angles. The stable performance of absorption for 0° to 90°

confirms the polarization and incidence angle stability over the operating frequency range. Surface current distributions, E and H field analysis, effective EM parameter retrieval, and impedance characterization are all used to comprehensively study the underlying absorption process. Experimental tests conducted in an anechoic chamber using a calibrated VNA validate the reliability and practical viability of the absorber and show strong agreement with the simulated results. Additionally, the suggested design is economically appealing and appropriate for large-scale manufacturing due to the use of an inexpensive FR-4 substrate. All things considered, the suggested MMA provides a balanced mix of high absorption efficiency, structural simplicity, polarization insensitivity, and angular robustness. These characteristics make it an excellent option for real-world uses such as microwave energy harvesting, EMI reduction, radar absorption, and next-generation wireless systems.

Declarations

Ethical Approval :- Not Applicable

Competing interests:- On behalf of all the authors, the corresponding author states that there is no competing interest.

Authors' contributions:-Anushree Prakash: Writing–original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. Neelam Singh: Writing–review & editing, Writing–original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Conceptualization. Kunal Singh: Writing–review & editing, Visualization, Validation.

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