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Dual-Band, Polarization Insensitive, and Flexible EM Wave Absorber with High Angular Stability and Low Cross Reflection Level

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Abstract

This paper presents a dual-band polarization-insensitive, highly angular stable and flexible EM wave absorber with low cross-polarization reflection. The proposed unit cell has two resonators C and D which offers absorptions at two distinct frequencies at 8.7 and 11.5 GHz frequency in the X band. This FSS unit cell structure has four-fold symmetry make it polarization-insensitive. The absorbance mechanism of the proposed structure is explained with the help of electric and magnetic coupling along with effective impedance plot. The simulation results reveal that for both bands, the proposed absorber is polarization insensitive and angular stable up to 60^0. Along with this study, reflection due to cross-polarization is also analyzed and included in the absorbance equation, confirming that the proposed design is an absorber, not a polarization converter. Finally, the absorber prototype is fabricated and tested under different conditions, and the measurement results perfectly match the simulation result, which verified that it is working.

1. Introduction

Recently, frequency selective surfaces (FSSs) or metasurfaces structures are getting attention in the RF and antenna research community due to their exotic electromagnetic properties and wide range of applications. EM wave absorption is one of the most brilliant frequency selective surface or metasurface structure applications. EM wave absorber or Radar absorbing structure can be used for various applications such as: side lobe level reduction of antennas [1], EM compatibility and interference reduction [2], RCS reduction of missiles [1], bolometer design [3], portable RF imaging system [2], etc. Metamaterial or FSS based absorbers are preferred compared to the conventional absorber due to their compact nature, and the typical size of these types of absorbers is λ/15 to λ/10 [4]. Landy *et al.* proposed the first metamaterial absorber to absorb EM wave 10.2 GHz frequency. However, it has limitations in polarization sensitivity means, this absorber work as an absorber only for transverse electric (TE) polarized EM waves. There is no absorbance for TM polarized EM wave, which limits the practical applicability. This structure was a polarization-sensitive due absence of four-fold symmetry. After that, various single band, multi-band, and wide-band polarization-insensitive absorbers were presented [5-7]. The paper presented in [8], offers a dual-band response, but its angular stability is limited only up to 45°. Similarly, the work presented [9] offered the triple-band response, but angular stability is limited only up to 45°. The work presented in [10] and [11] discussed a wide absorption bandwidth. These absorbers use the resonator arranged on one diagonal side of the unit cell. However, the limitations of these structures are the reflection study due to cross-polarization is not explored and not included in absorbance equation. Due to this, it is challenging to comment on the structures, whether they are a polarization converters or absorbers. Most of the absorbers presented above are non-flexible, limiting their practical application for RCS reduction of cylindrical surfaces.

In this work, a dual-band polarization-insensitive flexible EM wave absorber is presented, designed using silicon rubber and a thin FR-4 substrate. The proposed structure offers a dual-band response at two different frequencies in the X band with angular stability of 60° in both TE and TM polarization cases. This structure also offers a low cross reflection level of -40 dB at both the resonance frequencies, verifying that the proposed structure is an absorber, not a polarization converter. The simulation result of the proposed structure is also verified by its approximate equivalent circuit model. Finally, the device is fabricated, and measurement results show that the proposed FSS absorbs EM waves at 8.7 and 11.5 GHz frequencies with absorption bandwidth of 180 and 320 MHz, respectively.

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2. Proposed unit cell with its equivalent circuit

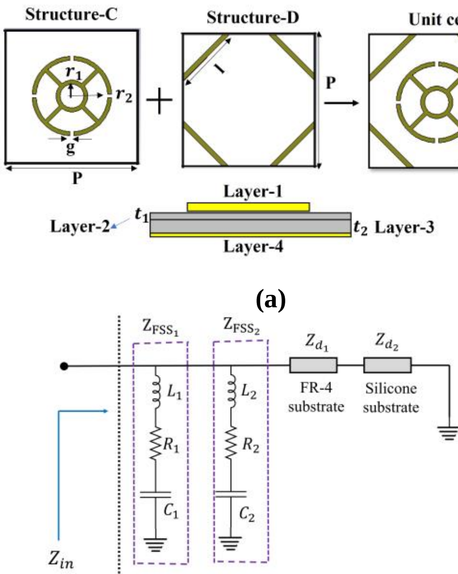
The proposed structure has four layers. The first layer is the FSS pattern printed on the 0.2 mm thin FR-4 substrate (named as a second layer) with the dielectric constant of 4.4 and loss tangent of 0.025. The third layer is 1 mm thick silicon rubber with a dielectric constant of 3.2 and a loss tangent of 0.056. The second- and third-layer combination makes the structure conformal/flexible. The silicon substrate's fourth layer or bottom side is a complete copper. This proposed unit cell has two resonator structures named resonators C and D. It can be understood from the absorbance equation given in Eq. N-1 that any design structure will absorb the EM waves only if transmission through and reflection from the structure would be minimum at the frequency of interest.

$$A(\omega)\% = \left[1 - |S_{11}(\omega)|^2 - |S_{21}(\omega)|^2\right] \times 100 \quad (1)$$

and further S_{11} can be resolve in two components, and that is cross (r_{xy}) and co (r_{xx} -for x polarized EM waves) coefficient component and given as follow

$$|S_{11}(\omega)|^2 = |r_{xx}(\omega)|^2 + |r_{xy}(\omega)|^2 \quad (2)$$

Here, the bottom side of the absorber is complete metal (shown in Fig.1 (a)). Therefore, it blocks the EM wave passing through it and zero transmission (S_{21}). However, the reflection can be minimized using a combination of resonators C/D and a short circuit transmission line (combination of layer-2,3 and 4). The front and side view of the proposed unit cell with its equivalent circuit and dimensions is given in Fig.1 (a) and (b), respectively.



(b)

Figure 1. (a) Front and side view of proposed unit cell and (b) its equivalent circuit (dimensions of unit cell: P = 10, r_1 = 0.6, r_2 = 2.6, g = 0.3, t_1 = 0.2, t_2 =1 and, l = 4.3; all dimension in millimeter)

Here, L_1, C_1, R_1 and L_2, C_2, R_2 are the inductances, capacitances, resistances offered by the resonator-C and D, respectively. The values inductances and capacitances of resonators-C and D can be calculated with the help of the method discussed in [7], [10],[12]. The calculated value of L_1, R_1 L_2, R_2, C_1 and C_2 are 2.95 nH, 53.6 fF, 5Ω, 6.59 nH, 35.17 fF and 2Ω, respectively, which later fit in the model given above in Fig.1 (b) and simulated using Advance design (ADS) software and compared with the full-wave simulated and measurement result. The input impedance seen by the wave can be given as

$$Z_{in} = Z_{FSS_1} \,||\, Z_{FSS_2} \,||\, Z_d \quad (3)$$

Here, Z_{FSS1}, Z_{FSS2} are impedance offered by resonator-C, D and can be calculated using Eq. N-4 and 5. Whereas, Z_d (cascade of Z_{d1} and Z_{d2}) is the impedance offered by combination of layer 2, 3 and 4 respectively can be calculated using the method given [13].

$$Z_{FSS_1} = R_1 + j\omega L_1 + \frac{1}{j\omega C_1} \quad (4)$$

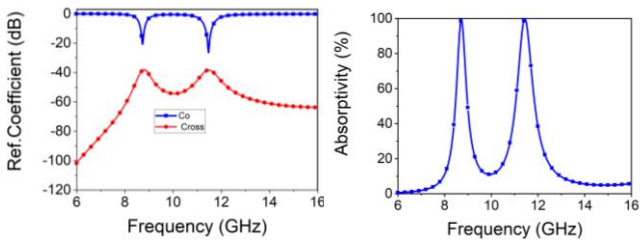
$$Z_{FSS_2} = R_2 + j\omega L_2 + \frac{1}{j\omega C_2} \quad (5)$$

It can be seen from Fig.1 (b) that reflection from the air-absorbance interface would be minimum at the frequencies where Z_{in} become equal to free space impedance (Z_0) which bring maximum absorbance at those frequencies.

3. Simulation results and absorbance mechanisms

Here, the design and simulation of the proposed unit cell is done with the help of the frequency domain solver of CST microwave studio software by taking the unit cell boundary condition in X and Y direction and free space boundary condition in +Z direction. A reflection study due to cross and co-polarized components is required to differentiate the polarization converter and absorber. The design structure would work as an absorber only if reflection due to co and cross components is zero. However, if co reflection coefficient is zero and cross reflection is 1. The proposed structure would work as a polarization converter. The simulated reflection coefficient with absorbance for the normal angle of incidence is presented in Fig.2. It can be observed from Fig.2 (a) that the proposed structure has a low reflection coefficient due to co and cross components at both 8.7 and 11.5 GHz frequencies. Therefore, the proposed structure works as an absorber, not a polarization converter.

Further, the absorbance of the designed absorber is calculated using Eq. N-1 and 2. It can be observed from the absorbance shown in Fig. 2 (b) that proposed FSS offered absorbance at 8.7 and 11.5 GHz frequencies with absorbance bandwidth of 180 and 320 MHz, respectively.

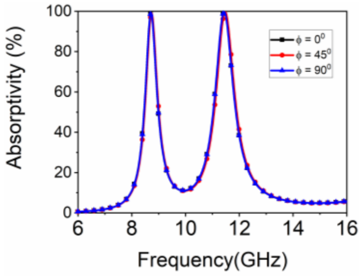


(a) (b)

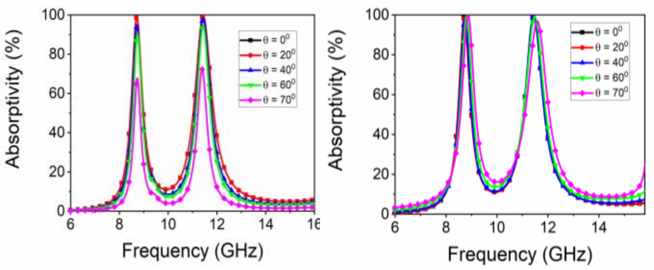
Figure 2. simulated (a) reflection coefficient and (b) absorbance

3.1 Angular stability and polarization insensitivity analysis

The literature survey shows that the absorber must be angular stable and polarization-insensitive for practical applications. Therefore, polarization insensitivity and angular stability analysis of the structure are important design parameters. To study the polarization insensitive nature of the structure, the absorbance is calculated for different angles of polarization (ϕ) and presented in Fig.3 (a), and it can be observed from Fig.3 (a) that the proposed structure offered the same response at 8.73 and 11.5 GHz frequencies for different value of ϕ. As a result, the proposed absorber can be concluded to be polarization insensitive. This structure shows polarization-insensitive nature due to the presence of four-fold symmetry. The absorbance is calculated for different angle of incident (θ) for TE and TM polarization and presented in Fig.3 (b) and (b) to evaluate the angular stability of the proposed design. Fig.3 (b) and (c) illustrate that the proposed structure offered absorbance of more than 80% of absorbance at 8.7 and 11.5 GHz frequencies for θ up to 60^0 in the TE and TM polarization case respectively. Therefore, one can conclude that the proposed structure is angular stable up to 60^0 for both the polarization.



(a)

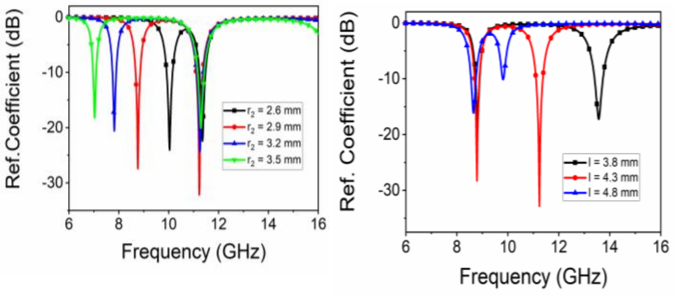


(b) **(c)**

Figure 3. Simulated absorptivity of unit cell for (a) different angle of polarization and different angle of incident in (b) TE polarization and (c) TM polarization

3.2 Effect of change of outer radius (r_2) and arm length (l) on reflection coefficient

The outer radius (r_2) and arm length (l) are two important parameters of the unit cell, which changes can bring changes in the resonance frequencies. To understand the effect of 'r_2' and 'l' on the resonance frequencies, the reflection coefficients are calculated for different values of 'r_2' and 'l' and presented in Fig. 4(a), (b), respectively. It can be observed from Fig.4 (a) that as r_2 changes from 2.5 mm to 3.5 mm in the interval of 0.3, the lower (band 1) resonance frequency shifts from the left side to the right side. There is no change in the resonance frequency of the upper band (11.5 GHz), which tells that the first band response is coming due to the resonator-C. However, the lower frequency shifted from the higher lower due to increment in inductance as the r_2 increases. Similarly, it can be observed from the Fig.4 (b) that as l changes from 3.8 to 4.8 mm in the interval of 0.5 mm, the resonance frequency of band-2 shifted from a higher side to a lower side, and there is no change in the resonance frequency of band-1 which exhibits the band-2 belongs to resonator-D. The inductance given by the arm length increases as the 'l' increases, and because of this increment, the resonance shifts from higher to lower as the 'l' increases.

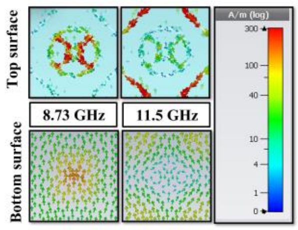


(a) **(b)**

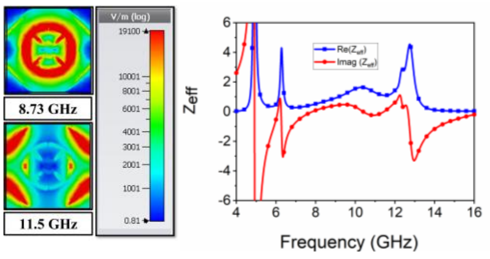
Figure 4. Effect of change (a) outer radius (r_2) of resonator-C and (b) arm length 'l' of resonator-D on the resonance frequencies

3.3 Absorbance mechanism-

The absorbance mechanism of the proposed structure can be explained with the help of electric/magnetic coupling and impedance matching conditions. To explain the E/H coupling and matching condition the E-field distribution, magnetic field distribution and Z_{eff} plot of the unit cell is presented in Fig. 5. It can be observed from Fig. 5(a) that the surface current distribution on the top and bottom side of the unit cell flows in the opposite direction, forming a close loop and exhibiting magnetic coupling. As shown in Fig.5 (a), the H-field is perpendicular to the close loop surface current. Hence, manipulate the effective permeability of the medium [3], which help to achieve the matching condition. It can be observed from Fig. 5(b) that the proposed unit cell offers maximum E-field at the top surface in the resonator-C and D at 8.73 and 11.5 GHz, respectively, which signifies the maximum E coupling in the unit cell at 8.73 and 11.5 GHz. This E-field coupling also manipulates the medium's effective permittivity [3], which would help achieve the impedance matching condition. It can be observed from Fig. 5 (c) that the real and imaginary parts of Z_{eff} (normalize input impedance (Z_{in}) with respect to free space impedance) at 8.7 and 11.5 GHz frequencies are one and zero, respectively. This satisfies the matching condition, which leads to zero reflection and maximum absorption.



(a)

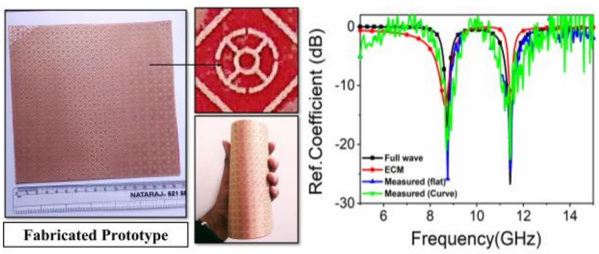


(b) **(c)**

Figure 5. (a) surface current of proposed unit cell on the top and bottom side at 8.7 and 11.5 GHz (b) E-field distribution of proposed unit cell on the top surface (c) Z_{eff} plot of unit cell

4. Fabrication and Measurement result

To verify the working of absorber, the absorber prototype with the dimension of 18 × 18 × 1.235 mm^3 is fabricated using a wet etching process and tested in the anechoic chamber using two horn antennas (work as a transmitter and receiver) and a vector network analyzer (VNA). The fabricated prototype with the comparison of simulated and measured results is shown in Fig. 6 (a) and (b), respectively. It can be observed from Fig. 6(b) that the simulated reflection coefficient (RC) due to full-wave simulation and ECM is well-matched with the measurement result that verifies the absorber's working. The proposed structure is flexible in nature, so it is essential to measure its reflection coefficient in the case of bending. Here, to measure the reflection in case of 140^0 of bend angle (ψ), the absorber is mounted on the cylindrical surface with a cylinder radius of 7 mm, and the measured RC is presented in Fig. 6 (b). It can be observed form Fig. 6(b) that the measured RC after bending the structure at $\psi = 140^0$ matches with the RC of the flat absorber. Therefore, one can conclude that the proposed absorber can also be used for RCS reduction of the cylindrical surface.



(a) **(b)**

Figure 6. (a) Fabricated prototype (b) comparison of simulated and measured result along with measured reflection for angle of bend for 140^0

5. Conclusion

In this work, a polarization-insensitive, high angular stable dual-band and flexible EM wave absorber were presented. The absorber has used two resonator structures- C and D, and the structure offered dual-band response at 8.7 and 11.5 GHz, respectively. The device is simulated for different angles of incident and polarization, which tells that the proposed absorber is polarization-insensitive and angular stable up to 60^0 for both frequency bands. The absorbance mechanism in the structure has been explained with the Electric coupling, magnetic coupling, and effective input impedance plot. Finally, the device is fabricated and tested for its reflection coefficient, verifying the absorber's working.

6. Acknowledgements

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