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Design and Analysis of a Compact Polarization-Independent Six-Band Metamaterial Absorber for Microwave Applications

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Abstract:
Metamaterials are artificially engineered structures that exhibit electromagnetic properties not normally found in natural materials, such as negative permittivity and permeability. These unique characteristics make metamaterials highly useful for electromagnetic wave absorption applications. In this paper, a compact six-band metamaterial absorber operating in the microwave frequency range is proposed and analyzed. The designed absorber consists of a symmetric metallic patch structure printed on a lossy FR-4 dielectric substrate, backed by a copper ground plane to eliminate transmission.The proposed unit cell supports six distinct resonance frequencies at 2.76 GHz, 6.25 GHz, 11.54 GHz, 13.28 GHz, 15.73 GHz, and 17.38 GHz, achieving absorption levels greater than 92% at all bands, with peak absorption exceeding 99%. Due to the symmetric geometry, the absorber exhibits polarization-independent behavior under normal incidence. Additionally, the structure demonstrates angular stability for incident angles up to 45° over a wide frequency range.The absorption mechanism is explained using normalized impedance matching, surface current distribution, and electric field analysis. The simulation results confirm that near-unity absorption occurs when the effective impedance of the metamaterial matches the free-space impedance. The entire design and performance evaluation are carried out using CST Microwave Studio 2018. Owing to its compact size, multi-band operation, polarization insensitivity, and high absorption efficiency, the proposed metamaterial absorber is suitable for applications such as electromagnetic interference shielding, radar cross-section reduction, sensors, and microwave communication systems.

Keywords: Metamaterial absorber, Six-band absorber, Polarization-independent absorber, Microwave absorption, Impedance matching, FR-4 substrate, Multi-band resonance, Electromagnetic wave absorption, CST Microwave Studio, Negative permittivity and permeability

1. Introduction

Metamaterials are the artificial materials which have the properties which are not generally present in the natural material. Material size should be smaller than the length of scale of external stimulus. It's a combination of two-dimensional periodic arrays of unit cells. These artificial structures have negative permittivity ε & permeability μ which is $\varepsilon < \varepsilon 0$ & $\mu < \mu 0$. These two parameters define the response of a material. The propagation of wave inside the any material depends on the sign of ε & μ.

Since it is convenient to describe the electromagnetic materials by the quadrant in the permittivity and permeability plane. The first quadrant where both ε & μ are positive is called Double Positive Medium. The second quadrant is called Epsilon Negative Medium since $\mu > 0$ & $\varepsilon < 0$. The third quadrant is called Double Negative Medium $\mu < 0$ & $\varepsilon < 0$ where the most of metamaterials lies and fourth quadrant ferrite material is present having μ < 0 & ε >0. The electromagnetic wave obeys the Left Hand Medium rule where the EM wave will be propagated in the opposite direction of wave propagation and this region contains metamaterial.

Metamaterials can be made by sub wavelength composites where all over permittivity and permeability are independent. By creation of such materials, we can have the new characteristic that is not available in nature. Metamaterials are utilized in many engineering applications like clocking, absorbers, polarization converters, electromagnetic interference shielding, super-lensing, radome etc. The metamaterial absorber unit cell consists of two metallic elements which is separated by a dielectric material.

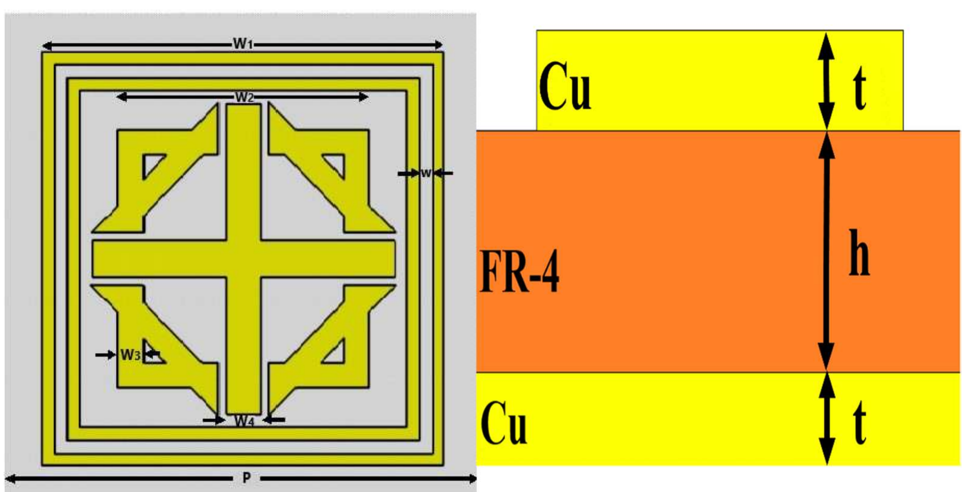
Metamaterial absorber can be design to get the absorption for single, dual, multiple, wide bands.

2. Literature Review

In this paper, we introduced a new compact six-band metamaterial absorber which supports six distinct resonance frequencies which are independent of polarization effect of EM wave. The proposed structure having the FR-4 dielectric and copper is used as a patch also it is used as a ground metallic base for elimination of transmission of wave through the absorber. The proposed structure also has the angular stable for a band of frequency. The absorption mechanism of the structure is explained by the normalized impedance, surface currents and electric field distribution. The simulation results of proposed metamaterial absorber are investigated by using Computer Simulation Technology (CST) Microwave Studio version 2018.

3. Case and Methodology

Figure 1 shows that the unit cell of the proposed structureconsists of a patch which is grown on a FR-4 material. The bottom metallic layer is made of copper material which has the thickness (t) of 0.035mm and the conductivity (σ) of 5.8×107S/m. The main function of metallic bottom layer is to eliminate the transmission of EM wave through the absorber. This metallic layer leads to zero transmission of EM wave. In between the two metallic layer's the dielectric layer is used which is a commercially available lossyFR-4 (flame retardant) dielectric material having the thickness of h=2 mm with 0.025 loss tangent and its dielectric constant is 4.3. The total size of unit cell of the proposed metamaterial absorber is 19mm × 19mm × 1.6mm. The other design parameters are W=0.5mm, W1=3mm, W_2=10mm, W_3=1mm, W_4=1.6mm, with the periodicity of P=19 mm.



(a) (b)

Figure 1.(a) Unit cell design of six-band absorber (b) the cross sectional view of absorber

To understand the performance of the proposed metamaterial absorber the reflection coefficient(s_{11}) and transmission coefficient (s_{21}) are examined. The absorptivity of the metamaterial structure can be calculated by the mathematical expression:

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

Since the metal ground plate stops the incident wave from transmission that results to zero transmission coefficient ($s_{21} = 0$).

The reflection coefficient under the normal incident wave can be calculated by using the mathematical expression (2):

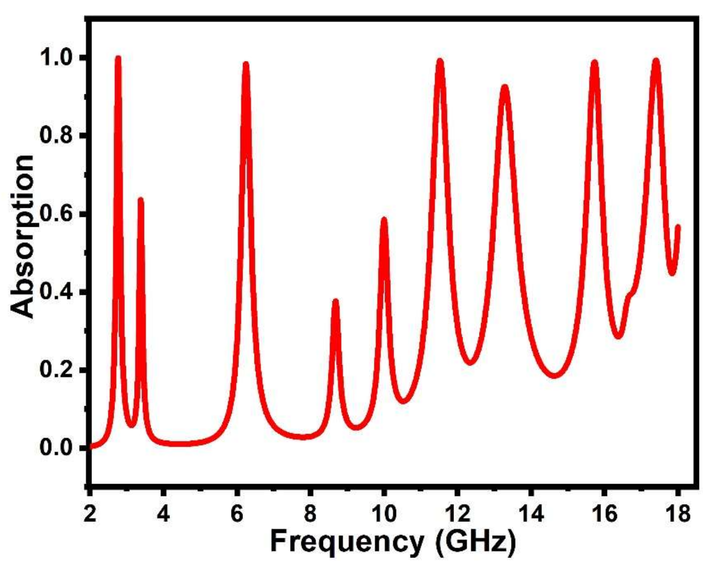
$$\Gamma(\omega) = \frac{(Z(\omega) - Z0)}{(Z(\omega) + Z0)} \quad (2)$$

Where Z (ω) is the input impedance of the absorber and Z_0 is the free space impedance which should be equal to 120 π or 377 Ω. To get the full absorption the impedance matching condition between the impedance of metamaterial Z (ω) and free space impedance Z_0should be full fill that will also leads to zero reflection, i.e., full absorption.

When we divide the metamaterial impedance with the free space impedance that is called a normalized impedance which should be unity at the case of full absorption. If the normalized impedance not equals to unity that leads to be less absorption so it is very necessary to make the proper impedance matching for full absorption. The impedance of metamaterial Z (ω) is depended on the relative permittivity ε and relative permeability μ.

4. Results and discussion

Figure 2 shows the absorption plot of the Six- band metamaterial absorber. The six discrete resonance peaks can be shown from low to high frequency which is located at 2.76GHz,6.25GHz,11.54GHz, 13.28GHz, 15.73GHz, and 17.38GHz with the absorption percentage of 99.5%,98%,98.85%,92.5%,98.8%,99.2%, respectively.



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The most important condition for the wave absorption is the impedance matching that means the impedance of the metamaterial absorber should match with the impedance of the free space which is 377 ohm.Figure 3 shows the normalized impedance of the absorber. If impedance of both the medium is not matched then it will create an impedance mismatching which leads to less absorption. Here impedance is almost perfectly matching at the frequency's 2.76GHz,6.25GHz, 11.54GHz, 13.28GHz, 15.73GHz, and 17.38GHzafter that the other freq. impedance is near to the free space so we get little less absorption. In the B.W. (8 to 10 GHz) Normalized impedance is so high that gives almost no absorption in this B.W.

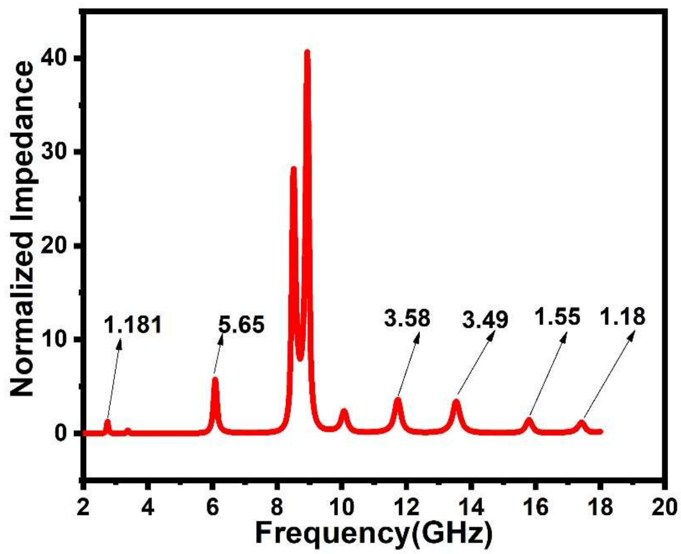


Figure 3. Normalized impedance of the proposed metamaterial absorber.

The unity absorption are the results from the coupling of magnetic and electric resonances. The proposed structure is insensitive to polarization state of the incident light wave due to a symmetric structure. Figure 4 shows that the proposed absorber geometry is independent of the polarization effect that which fulfil the one of the important conditions of the absorber.

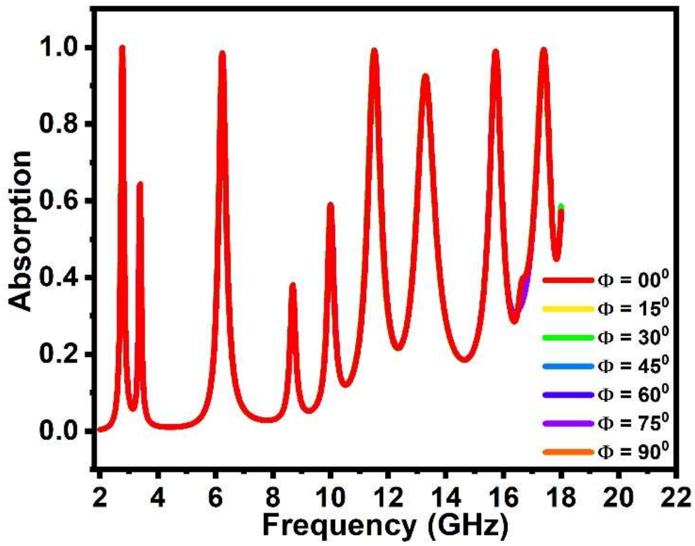


Figure 4. Response of metamaterial absorber on diifernt angle of polarization of incident wave.

A perfect absorber should be angular stable that means angle at which incident wave strikes over the absorber this also effects the absorption behavior of the absorber.

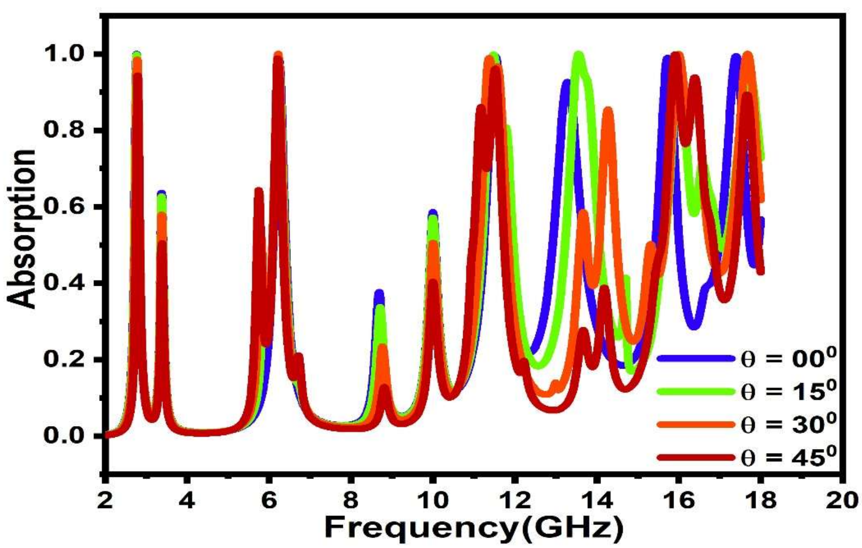
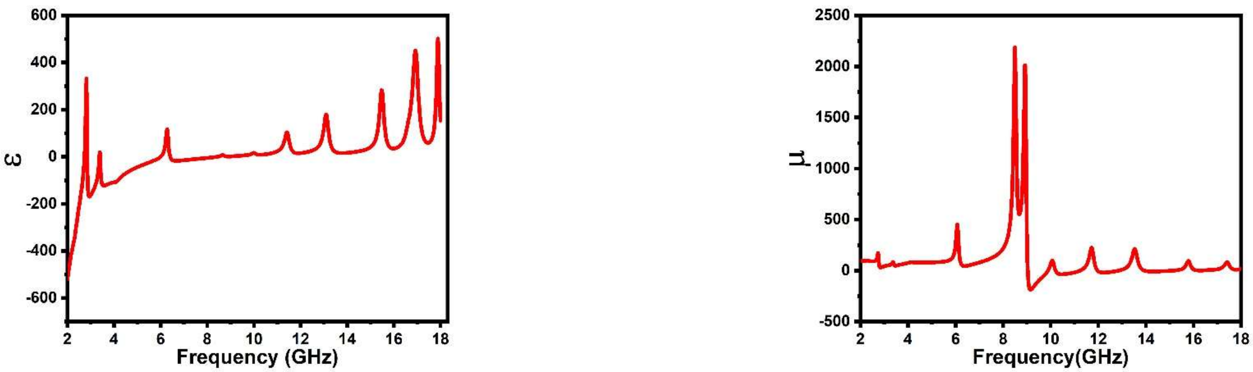


Figure 5. Response of metamaterial absorber on different angle of incident wave.

Figure 5 shows the proposed structure is angular stable up to the band width of 2 to 12 GHz at this we get almost similar response for the variation in angle theta from 0 to 45 degree beyond this the structure is less stable to angular incident of wave.

Since the metamaterials are the materials which generally not found in nature this is because of its permeability and permittivity of the material. Metamaterials have the negative value of permittivity and permeability as shown in Figure 6 some part of graph have negative value of ε & μ.



(a) (b)

Figure 6. (a) Variation of permittivity over the different frequency (b) variation of permeability over the different frequency.

Figure 7 shows the electric field and current density of the resonance frequency the 2.76GHz, 6.25GHz, 11.54GHz, 13.28GHz, 15.73GHz, 17.38GHz frequency is termed as F1, F2, F3, F4, F5 and F6.

The F1 resonance frequency is mostly due to the outer ring.F2 resonance frequency is due to the outer edges of plus geometry. F3 resonance frequency is due to the star shaped geometry. F4 resonance frequency is mostly due to the edges and outer ring.F5 resonance frequency is due to the combination of star geometry and inner ring. F6 resonance frequency is due to the combined effect of plus geometry, star geometry and inner ring all these contributing in F6 frequency absorption.

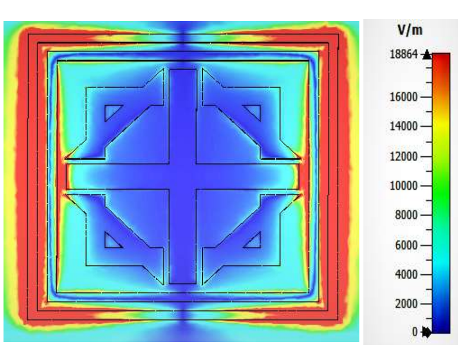


Figure 7. (F1)

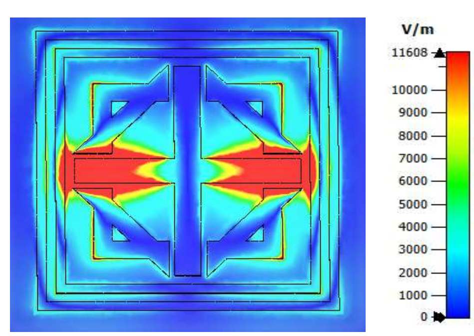


Figure 7. (F2)

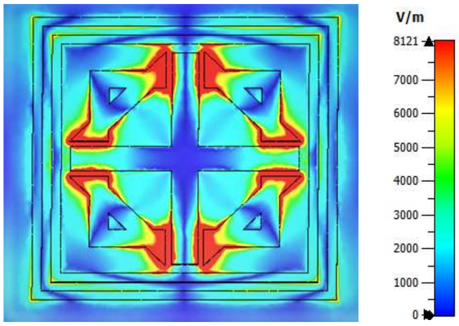


Figure 7. (F3)

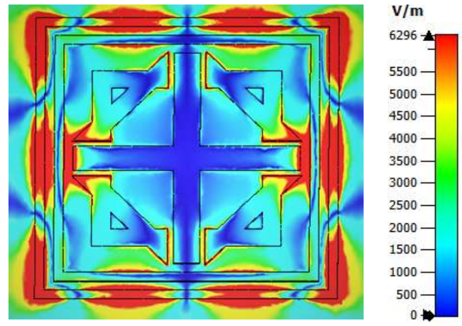


Figure 7. (F4)

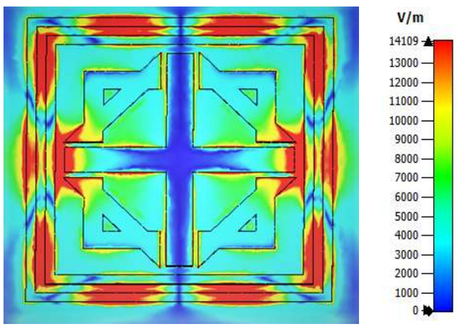


Figure 7. (F5)

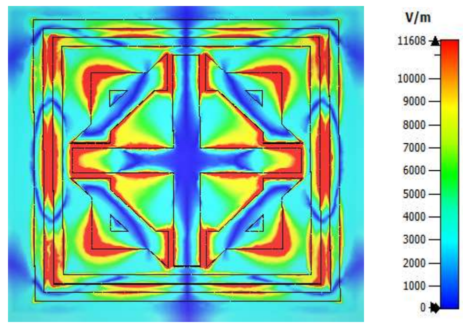


Figure 7. (F6)

Figure 7.Electric field distribution on different resonance peaks of the metamaterial absorber

5. Conclusion

In this paper, a compact six-band metamaterial absorber operating in the microwave frequency range is analyzed. The absorption mechanism is explained using normalized impedance matching, surface current distribution, and electric field analysis. The simulation results confirm that near-unity absorption occurs when the effective impedance of the metamaterial matches the free-space impedance.

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