Wide band polarization insensitive metamaterial absorber using lumped resistors

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Received: 7 January 2020 / Accepted: 17 April 2020 / Published online: 11 May 2020
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Abstract

This paper presents a wideband polarization-insensitive Metamaterial Absorber (MA). The proposed structure consists of square-shaped with four lumped resistors connected to it in such a way that structure behaves as polarization-insensitive. The absorptivity obtained from a structure is in the gigahertz region ranging from 4.68 to 13.00 GHz. The absorption mechanism is explained by three different methods and the structure is analyzed under normal incident (for ϕ variation) and oblique incident (for TE and TM variation). The structure is fabricated on the FR₄ substrate and tested inside the Anechoic Chamber. The measured and simulated result is compared and found that they are almost similar to each other. The proposed absorber finds applications in Radar Absorbing Materials (RAM), Communications Antennas, Anechoic Chamber, Satellite Technology, Etc.

Keywords Metamaterial absorber · FWHM · Polarization insensitive · Normal incident · Oblique incident

1 Introduction

Metamaterials are artificial engineered structures having Electromagnetic (EM) properties generally not similar with respect to naturally occurring materials; therefore, these materials are termed as manmade materials or artificial materials or Left Handed Materials (LHM) [1]. The properties possess by these materials are used for various applications such as Cloaking Devices [2], Metamaterial Absorber [3], Super lens [4], Nonlinear Metamaterial [5], Subwavelength wave guides [6], Antennas [7], Filters [8], etc. From the applications outlined interest in metamaterials has grown from the past few decades.

Before metamaterials were introduced most researchers focus on absorptive materials found in nature termed as EM absorbers or Conventional absorbers or Traditional absorbers [9] and these EM absorbers can be categorized

as resonant absorbers (narrowband) [10] and broadband absorbers [11]. Salisbury screen [12], Jauman absorber [13], Dallenbar layer [14], cross grating absorber [15] and Circuit analogue absorber [16] are some examples of the resonant absorber. But in these types of absorbers incident waves are absorbed only for one particular frequency and they are made up of multilayers. To overcome these limitations pyramidal absorbers [17], ferrite tiles [18] and engineered Frequency Selective Surfaces (FSS) [19], which are examples of broadband absorbers come into the picture but they have a large thickness, fragile and fabrication complexity.

To overcome the limitations faced by an EM absorber, MA was introduced. They are thin, light in weight and easy to fabricate. The first MA was introduced by Landy et al [8], after that many MA have been proposed and demonstrated with narrow-band [20], dual-band [21],

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multi-band [22] and wideband absorption [23]. Though many absorbers proposed to increase the bandwidth by combining two or more different resonant structures to form a new structure, but overall dimension of the structure becomes too large, so to overcome this multilayer absorber is proposed but in this case thickness of the structure increases [24, 25]. To overcome all the above-mentioned limitations absorber with lumped resistors is proposed in this paper.

In this paper, a wideband square-shaped MA with lumped resistors in the gigahertz region is proposed. The structure is made up of copper as a conducting material and FR₄ as a dielectric medium. The overall dimension of MA is 14 mm × 14 mm. The suggested structure is fabricated on the FR₄ substrate. The designed offers -8 dB bandwidth of 8.32 GHz ranging from 4.68 to 13.00 GHz and Full Width Half Maxima (FWHM) bandwidth of 9.44 GHz ranging from 4.06 to 13.50 GHz. It has two peaks of absorption at 5.25 GHz and 12.50 GHz with absorptivity of 91.56 and 90.48% respectively. The absorption mechanism is explained by calculating effective parameters, proper impedance matching and by plotting surface current density. The proposed MA is analyzed under normal incident and oblique incident of a wave for different angles. The simulation is carried out using ANSYS HFSSv 19.1 and the testing is done inside the Anechoic-Chamber. The measured result obtain is almost similar to the simulated results.

2 Structure detail of unit cell

The unit cell structure proposed in this paper is a square-shaped MA with four lumped resistors connected to it, due to this overall structure act as a polarization-insensitive structure. The unit cell structure consists of three layers in which the top and the bottom layer is made up of copper (conductivity $\sigma = 5.8 \times 10^7$ S/m with thickness = 0.035mm) acting as a conducting medium separated by a dielectric medium made up of FR₄ ($\epsilon_r = 4.4$, loss-tangent $\tan \delta = 0.02$) substrate. The three-layer structure of the proposed MA is shown in Fig. 1. The overall dimension of a unit cell is 14mm × 14mm having a thickness of 3.2 mm as shown in Fig. 2. It also shows the direction of field vectors in which E represents the electric field; H represents the magnetic field and K represents the direction of incident wave. The absorption on the structure depends on equation mentioned in 1.

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

Fig. 1 Three layer structure of proposed MA

Fig. 2 Front view of proposed MA

where, S_{11} and S_{21} represents reflected and transmitted power respectively.

As the bottom layer is made up of copper the incident wave cannot transmit through the structure due to this transmitted power becomes zero and absorption fully depends on reflected power as given by Eq. 2.

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

To achieve maximum absorption value of the reflected power should be minimum.

3 Analysis of simulation results

The commercial available FEM solver ANSYS HFSSv 19.1 is used to simulate the proposed square shaped with four lumped resistor MA. Master and Slave boundary which

Fig. 3 Simulated absorptivity of proposed MA structure

serves as a periodic boundaries condition is applied in E and H directions, whereas K direction is for an incident of electromagnetic waves on the top of proposed MA. Two waveguide port i.e., Floquet port is assigned in front and back of MA to obtained transmission and reflection.

Under normal incident of wave simulation result obtained is portrayed in Fig. 3. It is seen that -8 dB bandwidth is 8.32 GHz (from 4.68 to 13.00 GHz) and FWHM bandwidth of 9.44 GHz (from 4.06 to 13.50 GHz). It also has two absorption peak at 5.25 GHz and 12.50 GHz with absorptivity of 91.56 and 90.48% respectively, which confirms that the proposed MA can serve as a wideband MA.

4 Absorption phenomenon

The absorption mechanism of the proposed MA can be explained by the following mechanisms:- (1) Effective EM parameters. (2) Impedance Matching. (3) Surface current distribution.

4.1 Effective electromagnetic parameters

Effective EM parameters consist of effective permittivity (ϵ_{eff}) and effective permeability (μ_{eff}), which are evaluated first by calculating impedance (z) from Eq. 3 and reflective index (η) from Eq. 4 [26], by considering MA as a homogeneous medium.

$$Z = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \quad (3)$$

$$\eta = \frac{1}{kd} \cos^{-1} \left[\frac{1}{2S_{21}} (1 - S_{21}^2 - S_{11}^2) \right] \quad (4)$$

where, k = wave number, d = thickness of MA.

As the bottom layer is made up of copper the incident wave cannot transmit through the structure due to this S_{21} becomes zero which is an important parameter in calculating z and η . So, to the achieve value of S_{21} small portion is etched from all four corners of the bottom layer in such a manner that there will be no deviation in absorption frequencies.

Now from the value of z and η effective value of electromagnetic parameters are achieved by the relation given by Eqs. 5 and 6.

$$\epsilon_{eff} = \frac{\eta}{Z} \quad (5)$$

$$\mu_{eff} = \eta Z \quad (6)$$

The real and imaginary part of effective EM parameters are plotted in Figs. 4 and 5 respectively, and it is seen that parameters changes rapidly at peak absorption frequency which confirms the electric and magnetic resonance over

Fig. 4 Simulated effective value of ϵ_{eff}

Fig. 5 Simulated effective value of μ_{eff}

a wide range of frequency which confirms wideband of absorption.

4.2 Impedance matching

The wideband absorption mechanism is also achieved by proper impedance matching of the proposed MA. The proper impedance matching achieved is proved by calculating normalized input impedance ($Z(\omega)$) from Eqs. 7 and 8.

$$Z(\omega) = \sqrt{\frac{\mu_0 \mu_{eff}}{\epsilon_0 \epsilon_{eff}}} = \eta_0 \sqrt{\frac{\mu_{eff}}{\epsilon_{eff}}} \quad (7)$$

Fig. 6 Simulated value of impedance

$$\begin{aligned} \text{Normalized Impedance} &= \frac{Z(\omega)}{\eta_0} \\ &= \sqrt{\frac{\text{Re}(\mu_{eff}) - j\text{Im}(\mu_{eff})}{\text{Re}(\epsilon_{eff}) - j\text{Im}(\epsilon_{eff})}} \end{aligned} \quad (8)$$

Figure 6 shows the retrieved $Z(\omega)$ plot of proposed MA which consists of the real and imaginary part of $Z(\omega)$. From the plot it is seen that real and imaginary part become unity and zero over a wide range which confirms the presence of wideband absorption.

4.3 Surface current distribution

The absorption mechanism can also be analyzed by plotting surface current distribution at two different frequencies where maximum absorption is achieved as shown in Fig. 7. Conduction current and displacement current which act as a dominant current is formed on the top and bottom layer where both are antiparallel to each other. At the top surface, electrical excitation is created due to an incident electric field and similarly, magnetic excitation is created due to the incident magnetic field circulating as the current loop. Both the field are created simultaneously due to this high absorption is achieved.

5 Examination under normal and oblique incident of waves

The proposed MA is first examined under normal incident of wave up to 90° which is shown in Fig. 8. The structure is then rotated from a horizontal polarization ($\phi = 0^\circ$) to a vertical polarization ($\phi = 90^\circ$), and the reflection coefficient is measured at every 15° increments. When the polarization angle is changed still the absorptivity remains the same which confirms that the structure proposed is polarization-insensitive. The structure is secondly examined under the oblique incident of a wave for TE and TM polarization and the result obtained after the simulation is plotted in Figs. 9 and 10 respectively. From the plot, it is concluded that absorptivity is still higher in both cases for a wide angle of incident. After 45° response gradually decreases in both the cases.

6 Experimental setup

The proposed square-shaped with four lumped resistors MA is fabricated on the FR₄ substrate with permittivity of 4.4 and dielectric loss of 0.02. The fabricated structure consists of 11×11 unit cell etched on FR₄ substrate as shown in Fig. 11.

To measure the performance of the proposed MA, the experimental setup is done inside the Anechoic Chamber

Fig. 7 Simulated surface current density at **a** Top surface and **b** Bottom surface of proposed MA

which is shown in Fig. 12. Two horn antennas are connected to Vector Network Analyzer (VNA) in such a way that one is acting as a transmitter of electromagnetic wave and another receives the reflected signal from the fabricated sample. The horn antennas are placed at 1 mm apart to avoid near field effect. The measured result obtained is compared with the simulated result as shown in Fig. 13.

Comparison of proposed MA and already reported MAs listed in Table 1. From the table, it is concluded that bandwidth of proposed MA is best among the entire listed MA and FWHM bandwidth is best in terms of percentage bandwidth

Fig. 8 Simulated absorptivity under different polarization angles. (0° to 90°)

Fig. 10 Simulated absorptivity for oblique incident under TM Polarization. (0° to 45°)

Fig. 9 Simulated absorptivity for oblique incident under TE Polarization. (0° to 45°)

7 Conclusion

In this paper, a wideband polarization-insensitive MA has been proposed. The structure consists of square-shaped with four lumped resistors. The -8 dB

Fig. 11 Fabricated Model of Proposed MA **a** 11×11 of proposed MA **b** Enlarge View

bandwidth achieved is 8.32 GHz (from 4.68 to 13.00 GHz) and FWHM bandwidth of 9.44 GHz (from 4.06 to 13.50 GHz). It has two peaks of absorption at 5.25 GHz and 12.50 GHz with absorptivity of 91.56 and 90.48 % respectively. The absorption mechanism is explained by calculating effective EM parameters, proper impedance matching and by plotting surface current density. The structure polarization-insensitive is proved by

Fig. 12 **a** Experimental setup for MA measurement **b** Set up inside Anechoic chamber **Fig. 13** Reflection coefficient of simulated and measured result

analyzing structure under normal incident for a different angle of ϕ from 0 to 90 at an increment of 15°. The structure is fabricated on the FR₄ and tested inside Anechoic Chamber with the help of two horn antennas and VNA. The result obtained is almost similar to the simulated result with a little bit of variations due to fabrication tolerance. The proposed MA works for different applications in the gigahertz region such as RAM, Communication Antennas, Anechoic Chambers, Electromagnetic Interference (EMI), Electromagnetic Compatibility (EMC), Stealth Technology, etc.

Table 1 Comparison of Proposed MA with already reported MA

References	f_0 (GHz)	Size of Unit Cell(mm × mm)	Thickness (mm)	FWHM Bandwidth (GHz)	Bandwidth (GHz)
[27]	8.25	$13.6 \times 13.6(0.37\lambda)$	1.6 (0.04 λ)	8.25 (101.76%)	5.9 (70.7%)
[28]	10.75	$12 \times 12(0.44\lambda)$	3.0 (0.11 λ)	9.1(84.6%)	7.5 (69.7%)
[29]	10.9	$12 \times 12(0.45\lambda)$	3.25 (0.11 λ)	11.4 (104.58%)	6.2 (56.8%)
[30]	11.45	$9.5 \times 9.5(0.36\lambda)$	3 (0.11 λ)	NA	6.3 (55.02%)
[31]	6	$12.5 \times 12.5(0.25\lambda)$	5 (0.10 λ)	4.4 (78.34%)	4 (66.67%)
[32]	8.78	$12 \times 12(0.35\lambda)$	2 (0.05 λ)	8.8 (100.22%)	7.6 (87%)
Proposed MA	8.84	$14 \times 14(0.42\lambda)$	1.6 (0.04 λ)	9.44 (104.78 %)	8.32 (94.11%)

Compliance with ethical standards

Conflict of interest All authors have declare that they have no conflict of interest.

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