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Research Article

Triple-Band and Wide-Angle Polarization-Insensitive Metamaterial Absorber

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Abstract

In this study, a metamaterial (MM)-based microwave absorber working at three microwave bandwidths is designed. The design works with 90% absorption in 3 different microwave bands, namely C band between 5.4 and 7.75 GHz, X band between 8.3 and 9.65 GHz and Ku band between 13.65 and 15 GHz respectively. The polarization of the wave incoming to the designed metamaterial absorber is changed, and the percent absorption is obtained exactly the same for TE and TM. In this respect, it is polarization insensitive absorber, and strong absorption results have been obtained at various oblique incidence (10°, 20° and 30°) for absorption performance. For the analysis of the microwave absorber, the electrical permittivity and magnetic permeability of the proposed metamaterial absorber is obtained in resonance. In addition, for impedance analysis, the normalized impedance of the proposed metamaterial absorber is obtained. In the frequency ranges where absorption is provided, it is observed that the normalized impedance of the absorber is almost similar the normalized impedance of the air. In addition, the surface currents of the proposed metamaterial absorber were obtained for the frequencies 5.67 GHz, 7.37 GHz, 8.76 GHz and 14.43 GHz where strong resonance frequencies were realized. The maximum percent absorption rates at strong resonance frequencies are compared with other reference studies. The transmission line equivalent circuit is given to understand the behavior of the metamaterial absorber. CST Microwave Studio (CST) is used as an electromagnetic simulation program.

Keywords: Metamaterial, absorber, triple-band, polarization-insensitive, wide-angle

Üçlü Bant Geniş Açılı Polarizasyon Hassasiyetsiz Metamalzeme Emici

Öz

Bu çalışmada üç mikrodalga bant genişliğinde çalışan metamalzeme tabanlı mikrodalga emici tasarımı yapılmıştır. Gerçekleştirilen tasarım sırası ile 5.4-7.75 GHz aralığında C bandında, 8.3 - 9.65 GHz aralığında X bandında ve 13.65 – 15 GHz aralığında Ku bandında olmak üzere 3 farklı mikrodalga bant aralığında %90 emilim ile çalışmaktadır. Tasarlanan metamalzeme emiciye gelen dalga polarizasyonu değiştirilmiş, metamalzeme geometrisi ile TE ve TM modları için yüzde emilimleri birebir aynı elde edilmiştir. Bu yönüyle polarizasyon hassasiyetsiz emici olup, emilim performansı için çeşitli açılarda (10°, 20° ve 30°) güçlü emilim sonuçları elde edilmiştir. Mikrodalga emicinin analizi için rezonans bölgesinde metamalzemenin elektriksel ve manyetik geçirgenlikleri elde edilmiştir. Ayrıca empedans analizi için metamalzemenin emici çalışma frekans aralığında normalize empedansı elde edilmiştir. Emilimin sağlandığı frekans aralıklarında emicinin normalize empedans değeri yaklaşık olarak havanın normalize empedansı ile aynı olarak elde edilmiştir. Ayrıca güçlü rezonans frekanslarının gerçekleştiği 5.67 GHz, 7.37 GHz, 8.76 GHz ve 14.43 GHz frekansları için metamalzeme emicinin yüzey akımları elde edilmiştir. Güçlü rezonans frekanslarda maksimum yüzde emilim oranları referans alınan diğer çalışmalarla karşılaştırılmıştır. Metamalzeme emicinin davranışının anlaşılması için transmisyon hattı eşdeğer devresi verilmiştir. Elektromanyetik simülasyon programı olarak CST Microwave Studio kullanılmıştır.

Anahtar Kelimeler: Metamalzeme, emici, üçlü bant, polarizasyon hassasiyetsiz, geniş açı

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1. Introduction

Although many materials are used to provide invisibility against the radar, many studies have been carried out using metamaterials in recent years. In 1967 and 1968, the Russian scientist Veselego examined the negative refractive index mathematically, and these studies indicate that the behavior of these materials constituted the milestone of left-handed metamaterials (Veselago, 1968). Veselego reported that negative refractive index materials not found in nature occur only when the electrical and magnetic permeabilities are simultaneously negative. With the studies of Pendry in 1998 and 1999, materials with negative permittivity and permeability were obtained respectively (Pendry et al., 1998; Pendry et al., 1999). By combining these materials, the first left-handed metamaterial production was carried out by Smith (Smith et al., 2000). The strong resonance properties of metamaterials allow it to be used in applications such as antenna, solar panel, optics, sensor, invisibility cloak and radar absorbers. (Pendry, 2000; Schurig et al., 2006; Wang et al., 2012; Ziolkowski and Erentok, 2006; Shalaev, 2007; Watts et al., 2012). There are numerous absorber applications for across civil and defense sectors. The reduction in the radar cross section (RCS) is very important for military aplications (Fallahi et al., 2010), Microwave absorbing materials are used to reduce the RSC of military devices such as aircraft, ships, helicopters and tanks (Özden et al., 2016). Metamaterial absorbers are preferred because they are superior to other absorbers in angular and polarization stability characteristics.(Ghosh et al., 2019) First, the metamaterial based microwave absorbers used by Landy and friends were later applied for many microwave bandwidths (Landy et al., 2008). These studies vary according to polarization sensitivity of the transmitted waves (for TE and TM mode), its performance according to the oblique incidence, the band or bands it operates on, and the thickness of the metamaterial absorber according to the wavelength (Huang and Chen, 2011; Tao et al., 2008; Wang et al., 2016; Wang et al., 2020). In addition, impedance matching has been made on metamaterial surfaces with lumped parameter (R-L-C) elements or by adding thin films and absorption is provided for wide band gaps (Zhi Cheng et al., 2012; Liu et al., 2012). In some studies, more than one metamaterial was connected consecutively as multilayer metamaterial absorber to obtain a wide band gap (Huang et al., 2009; Liu et al., 2020; Xiong 2013). In addition, studies have been conducted in which the metamaterial absorber works simultaneously in more than one band gap. Many metamaterial based absorbers with different geometries have been designed working in dual, triple, quad and even penta bands (Luo and Cheng, 2018; Shen et al.; 2011; Agarwal et al., 2016; Mao et al., 2014). In these studies, a single metamaterial structure or multiple layer metamaterial absorbers were used. These studies have been diversified according to their thickness, polarization insensitivity, simple production and performance in normal or oblique incidence.

Triple band metamaterial absorbers attract attention because they are used in triple band simultaneously. While the first triple band studies were performed for the C and X band (Shen et al., 2011), especially for the C, X and Ku bands, polarization was diversified as polarization insensitivity and wide-angle (Kaur, M., and Singh, 2020). In addition, thickness and strong resonance region comparisons for these bands have been added in further studies (Ni et al, 2013; Ji et al, 2019).

In this study, it is aimed to design triple band metamaterial absorber working in C, X and Ku bands by using only one layer metamaterial absorber. There are two main advantage of the proposed metamaterial absorber according to reference studies. First, this study works has a high absorption in resonance frequency. Second, this study showed the high absorption with smaller SRR structures.

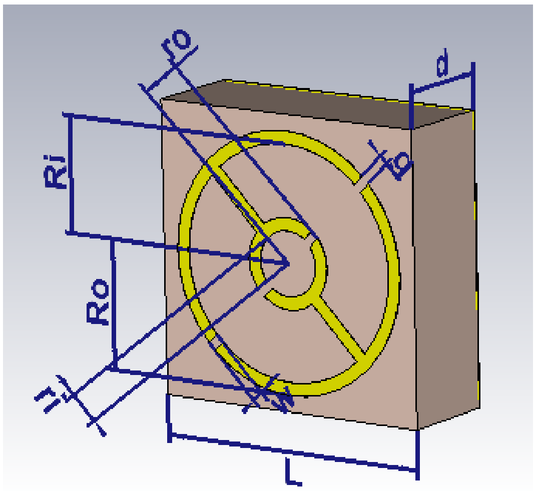


Figure 1. Proposed triple band metamaterial absorber

2. Material and Method

The proposed triple band metamaterial absorber design illustrates with length L in figure 1. Metamaterial absorber consist substrate layer is selected a dielectric FR-4, top layer and the bottom layer is selected to be copper plate. The conductivity of the copper is 5.8×10^{8} S/m. Besides, relative permittivity, relative permeability and loss tangent of the FR-4 material are, respectively, $\varepsilon_r = 4.4$, $\mu_r = 1$ and $\delta = 0.025$. The geometrical parameters of the SRR are L = 9 mm, ri = 1mm, ro=1.4 mm, Ri = 3.6mm, Ro = 4mm, g = 0.3mm, w = 0.4mm and d = 3.2mm. The copper thickness used is 35 μm.

Scattering parameters (S-parameters) are commonly used to examine electromagnetic response (reflection and transmission properties) at microwave frequencies. Using S-parameters, the absorption function $(A(\omega))$ of metamaterial absorber can be obtained as follows

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

Here, S_{11} and S_{21} are the reflection and transmission S-parameters, and | * | indicates the magnitude of the complex number. Metal-termination at the back of the proposed metamaterial absorber makes S_{21} zero, assuming that the thickness of this termination is substantially greater than the skin depth. Therefore, absorption function $A(\omega)$ becomes as follows

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

The constitutive parameters (ε, μ) give information about the potential of the material such as magnetization, and loss (ohmic, dielectric and magnetic) behavior. Retrieved of electromagnetic properties using S-parameters is a commonly used method (Ozturk et al., 2020). The effective constitutive parameters for the proposed metamaterial absorber as a function of the S-parameters are obtained as follows (Bhattacharyya, S., and Vaibhav Srivastava, K)

$$\varepsilon_{eff} = 1 + \frac{2jS_{11} - 1}{k_0 d S_{11} + 1}; \qquad (3)$$

$$\mu_{eff} = 1 + \frac{2jS_{11} + 1}{k_0 d S_{11} - 1}; \qquad (4)$$

Here ε_{eff} and μ_{eff} are effective permeability and permeability of the medium (MM absorber), respectively, and d is the MM absorber thickness. Figure 2.b shows how S11 parameters change with d thickness. According to Figure 2.b, absorption gradually decreases as the thickness d is decreased. When d = 3.2 is selected in the intended metamaterial absorber, optimum (-10 dB) absorption with the smallest d thickness is achieved. It is obvious that the effective refractive index $\left(n_{eff} = \sqrt{\mu_{eff}\varepsilon_{eff}}\right)$ effects the amplitude and phase of the propagation factor $e^{-jk_0 n_{eff} d}$ within a metamaterial absorber.

One of the most important factors for materials to be used as absorber is their normalized impedance. When electromagnetic wave come from air to metamaterial absorber, reflected waves will naturally occur if the normalized impedance of metamaterial absorber is different than normalized impedance of air. In order to behave metamaterial as an absorber, as can be inferred from equation (2), its characteristic impedance must match normalized impedance of air.

The normalized impedance of the metamaterial absorber as a function of the scattering parameter is as follows.

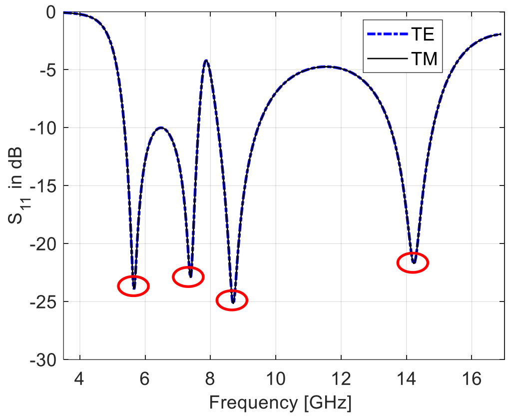
$$\begin{aligned} \bar{z} &= \sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}}; \quad S_{21} \to 0 \\ \bar{z} &= \frac{1+S_{11}}{1-S_{11}} \end{aligned} \qquad (5)$$

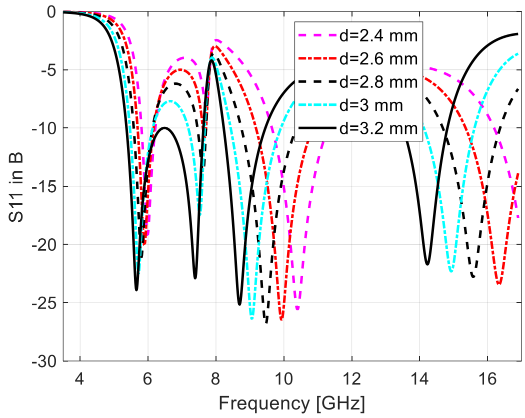
Here $\bar{z}$ is the normalized impedance of the metamaterial absorber.

3. Numerical Results and Discussion

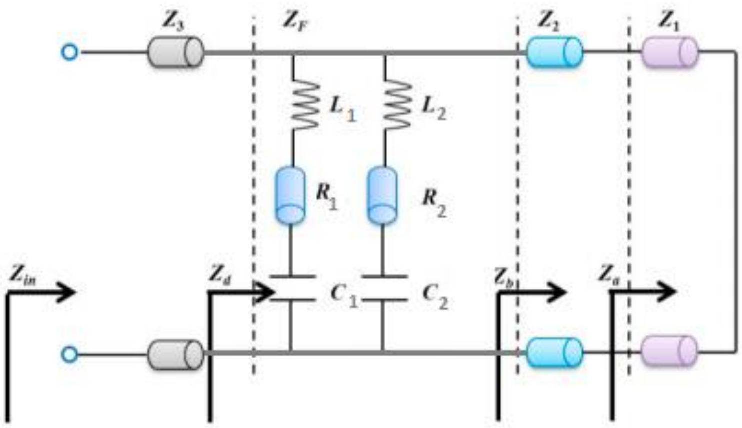
In the simulation, it is aimed that infinite metamaterials are thought to be formed side by side. For this purpose, unit cell boundary conditions are selected in Floquet mode. For the metal termination in the direction of the wave, the tangential component of the electric field is selected as zero and boundary conditions is applied. The simulation results obtained for range from 3 to 17 GHz are given in fig 2.a. According to the absorption results under the normal incidence in the frequency domain with CST, the S_{11} parameters in dB were obtained for TE and TM as shown in figure 2.a.

For a deep analysis of the metamaterial absorber, the equivalent circuit of the metamaterial absorber is constructed in figure 2.c using transmission line theory. In the equivalent circuit, the bottom part of the metamaterial absorber, the distance *d* of dielectric substrate and the air are modeled by Z_1, Z_2 and Z_3 respectively. The metamaterial surface is modeled just like Xu et al. and Jain et al. by connecting the serial RLC circuit in parallel (Xu et al. 2021; Jain et al.,2020). Here R, L and C (separately for 2 parts in one SRR surface) are the surface resistance, the inductance of the SRR structure and the capacitance due to adjacent unit cells respectively.





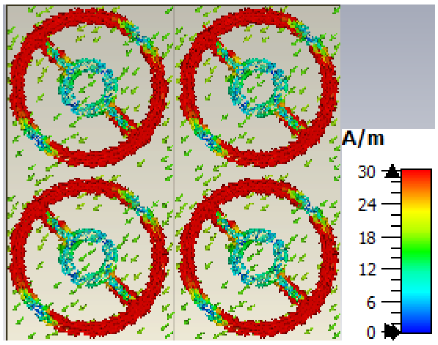
(a) **(b)**

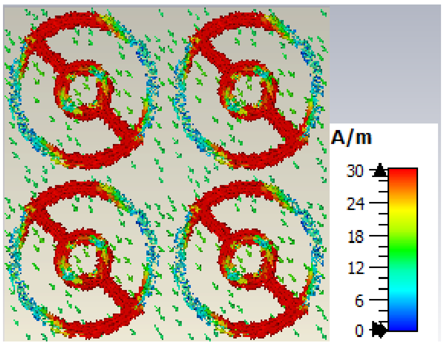


(c)

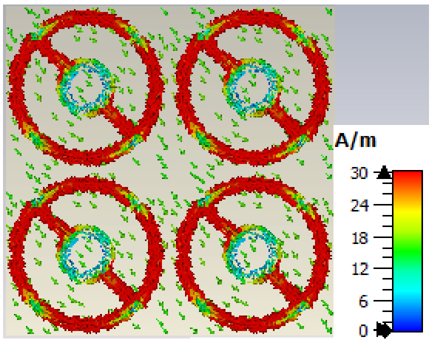
Figure 2. a) S_{11} parameters of the proposed metamaterial absorber in dB for TE and TM **b)** S11 in dB for different thickness d **c)** Calculated normalized equivalent input impedance of MMA.

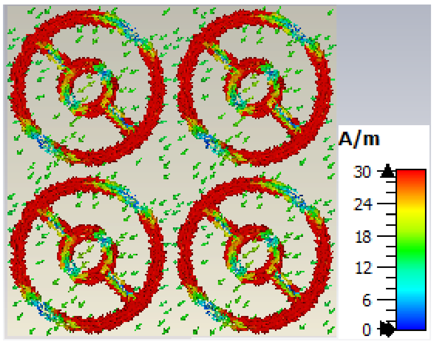
According to figure 2, strong resonances occur at 5.76 GHz, 7.32 GHz, 8.76 GHz and 14.43 GHz for TE and TM. The absorber provides %99.49 (-23,7 dB), %99.44 (-22,7 dB), %99.71 (-25.42 dB) and 99.29% (-21,5 dB) absorption at these frequencies, respectively. Surface currents at frequencies where strong absorption is provided for TE and TM at normal incidence are given in figure 3 to examine the types of resonances. Figure 3 shows that at the strongest absorption resonant frequency (8.76 GHz) more current is stored compared to the others resonant frequency (5.76 GHz, 7.32 GHz and 14.43 GHz) because of higher energy storage. At this frequency value, the capacitive and inductive effects of the resonator are almost matched.





(a) 5.76 GHz (b) 7.32 GHz





(c) 8.76 GHz (d) 14.43 GHz

Figure 3. Surface currents of the proposed metamaterial absorber in strong resonance frequency **a)** for 5.76 GHz **b)** for 7.32 GHz **c)** for 8.76 GHz **d)** for 14.43 GHz

Using equations (3) and (4) for the normal incidence, the effective constitutive parameters of the metamaterial absorber are obtained as in figure 4. Figure 4 shows real and imaginary parts of the retrieved effective permittivity and effective permeability.

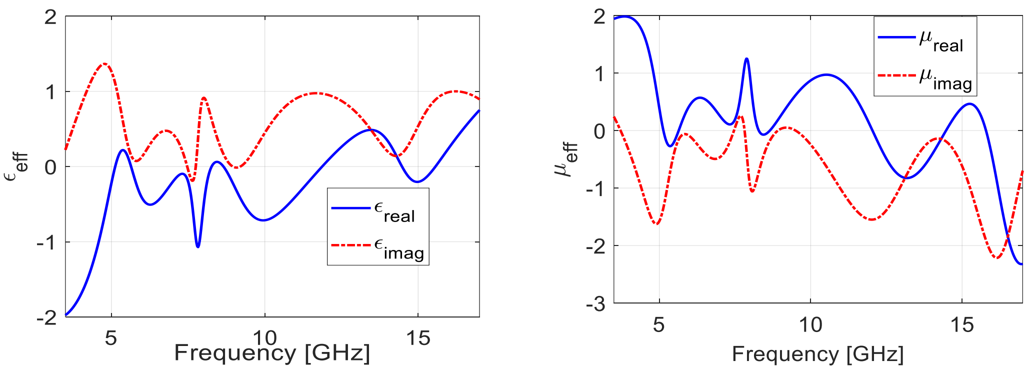


Figure 4. Effective permittivity and permeability of proposed metamaterial absorber for normal incidence in TE and TM.

At frequencies of 5.76 GHz, 7.32 GHz, 8.76 GHz, and 14.43 GHz, the refractive index of the proposed metamaterial absorber is complex and consists of only the imaginary part. Therefore, propagation of electromagnetic wave in metamaterial will act as evanescent waves. In this case, damped waves will appear in the proposed metamaterial, absorbing or dissipating much of the electromagnetic wave. For the impedance matching analysis, figure 5 presents the effective impedance of the designed MM absorber versus frequency using equation (5) for the normal case in TE and TM.

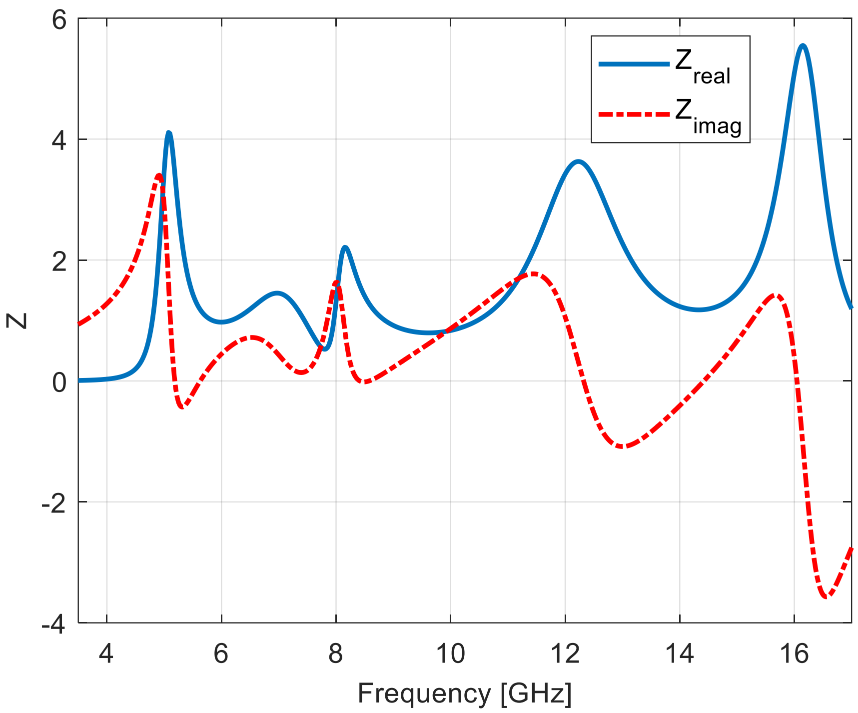


Figure 5. Normalized impedance of the proposed metamaterial for normal incidence in TE and TM

Figure 5 show that in the absorption frequency ranges (5.35–7.71 GHz, 8.27–9.55 GHz, and 13.7–15 GHz) the real part of the normalized impedance is approximately 1 but its imaginary part is 0. This value is normalized impedance value of the air. Therefore, it is very clear that impedance matching is provided for the frequency ranges 5.35–7.71 GHz, 8.27–9.55 GHz, and 13.7–15 GHz. Using equation (2), the percentage absorption plot of the proposed metamaterial absorber in TE and TM for the normal incidence is given in figure 6.

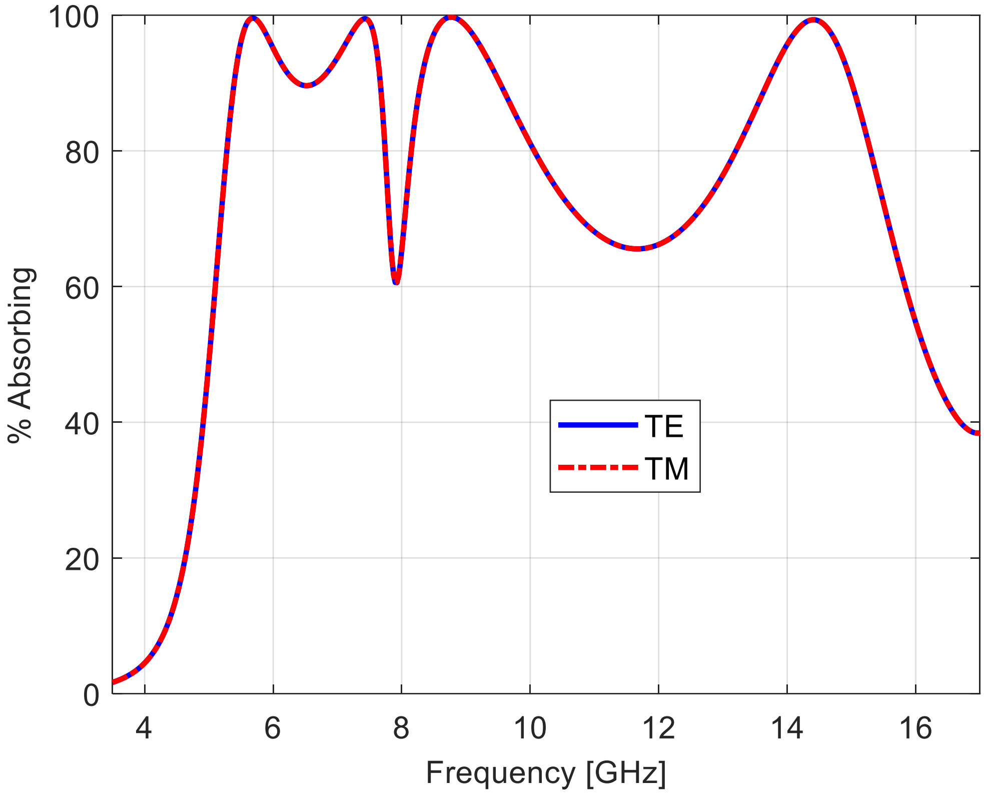


Figure 6. Percent Absorbing of proposed design for normal incidence in TE and TM

According to Figure 6, the proposed design provides over 90 percent absorption in the range from 5.35 to 7.71 GHz in C band, from 8.27 to 9.55 GHz in X band and from 13.7 to 15 GHz in K band for the normal incidence. It also provides 85 percent absorption in the 5.31–7.75 GHz, 8.18–9.8 GHz and 13.45–15.18 GHz range. The frequencies at which absorption is achieved in the C, X and Ku bands, respectively. Due to the symmetrical geometry of the absorber, the polarization of the wave sent to the absorber gave the same results for both TE and TM. Therefore, the proposed design works as polarization insensitive absorber.

Figure 7 shows the absorption performance of the absorber in TE and TM for oblique angle condition (10^o, 20^o and 30^o).

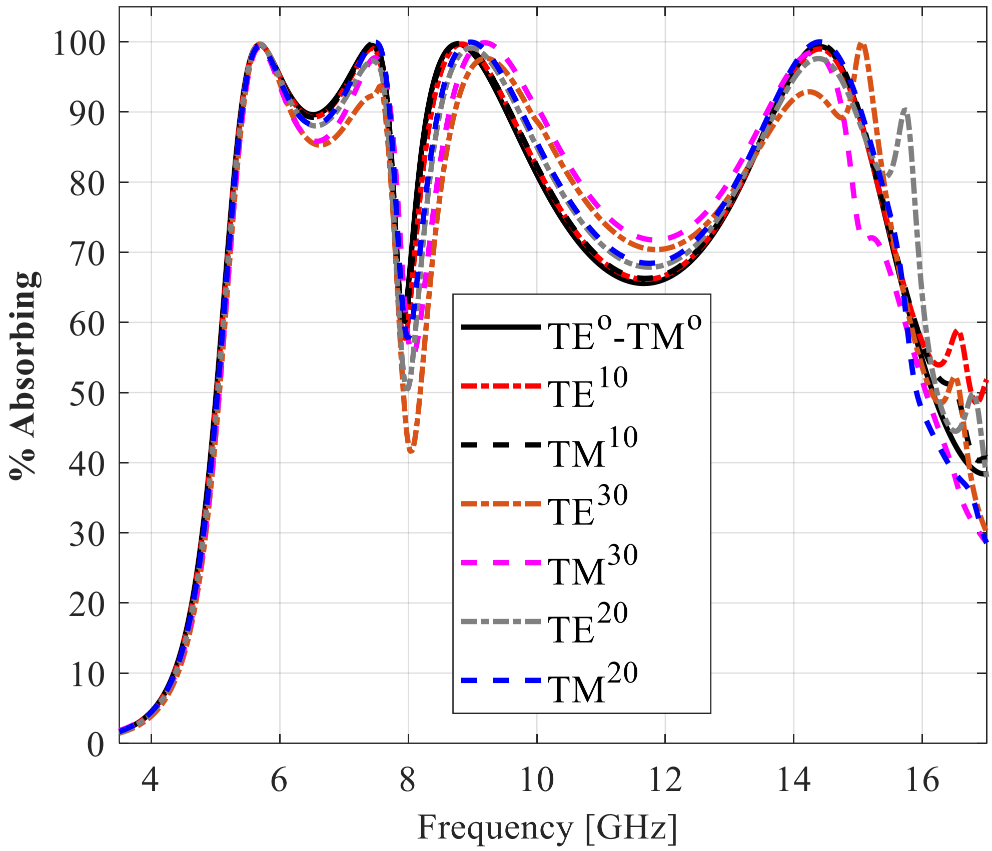


Figure 7. Percent Absorbing of proposed design for oblique incidence (10°, 20° and 30°) in TE and TM

Figure 7 shows the percent absorption performances for electromagnetic wave conditions coming to the proposed metamaterial absorber at various oblique incidences in TE and TM. As can be seen in Figure 7, percent absorption is above %85 in both TE and TM for 10, 20 and 30 degrees. In addition, it is noted that there is no significant change in absorption percentages for C, X and Ku bands at different angle values. In additional to, almost similar percent absorption performance was achieved in both TE and TM. In this case, the absorber performs polarization insensitivity even for oblique incidence up to 30 degrees.

In order to examine the performance of the designed metamaterial absorber, the maximum absorption values in absorbed bands for the strong resonance region also compare with similar reference articles in triple band. Table 1 is for comparison of this study with reference articles.

Table 1. Comparison of absorption rate of the proposed metamaterial absorber with those of MM absorbers in the literature

References	**Unit cell of MMAs (mm^2)**	**Resonance Frequency (GHz)**	**Absorption Rate**
Sharma et al.	9.3x9.3	5.8	%95
		9.52	%97
		11.97	%99
Asgharian et al.	10x10	4.06	%99
		6.73	%93
		9.22	%95
Ni et al.		9.86	%99.4
		12.24	%96.7
		15.34	%99.1
Huang et al.	25x25	6.51	%99
		7	%93
		7.61	%95
Agarwal et al.	20x20	3.50	%98
		4.70	%93
		6.60	%94
Ji et al.	14x14	3.70	%99.67
		6.57	%99.05
		17.61	%99.98
Proposed work	9x9	5.76	%99.49
		8.76	%99.71
		14.43	%99.30

According to Table 1, the absorption (not less than 99.30%) of the proposed metamaterial absorber at triple-bands are greater than the corresponding absorption of the referenced study.

4. Conclusion

In this study, a triple-band metamaterial absorber operating in C, X and Ku bands in TE and TM has been designed. The proposed absorber operates in the C band from 5.35 to 7.71 GHz, in the X band from 8.18 to 9.8 GHz and in the Ku band from 13.45 to 15.18 GHz. The absorption performance of the absorber for TE and TM is nearly the same and it works as a polarization insensitive absorber. In addition, the performance of the absorber at various oblique incidences has been analyzed and the absorption characteristic of the absorber is almost above 85% for 10, 20 and 30 degrees. In addition, highest absorption of the proposed metamaterial absorber are compared with other triple-band MM absorbers in the literature. It is observed from this comparison that for 3 bands (C, X, and Ku), absorption in proposed metamaterial absorber is more than the reference studies according to maximum absorption rates in strong resonances. In addition to, The intended metamaterial at the resonance frequencies showed higher absorption than the larger Ji et all and using SRR structure with a smaller unit cell (7x7 mm) than absorber Ji et at (14x14 mm) .

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