Design and analysis of compact perfect metamaterial absorber for X-band applications

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Abstract. A new tri-ring hexagonal with meandered line design structure based on simple outline is proposed for X-band application in microwave ranges. The finite-difference time-domain (FDTD) method-based CST simulator was approved to observe the perfect metamaterial absorbance (PMA) analysis. Analysis was completed by using three configurations of PMA such as 1 × 1 unit-cell structure; 1 × 2 unit-cell and 1 × 2 array unit-cell structures; 2 × 1 unit-cell and 2 × 1 array unit-cell structures. The structure revealed the resonance frequency within the X-band of the microwave spectra. At resonance frequencies, the absorbance’s peaks are 99.95% at 8.006 GHz and 99.61% at 11.525 GHz, correspondingly. X-band operating frequency has been obtained by all design configurations. The dimension of the offered structure is 10.50 mm × 10 mm that comprises all geometrical parameters to suitable the structure inside the area of substrate material. The results of the offered PMA exhibited X-band absorber response over the frequency ranges from 5 to 14 GHz. Hence, the offered structure enables numerous application areas, for instance, satellite communications, security, protection, stealth innovation and wireless computer networks.

1. Introduction
Negative refractive index metamaterials are engineered materials with negative permittivity and permeability simultaneously, which have exotic properties in terms of well-known phenomena like Snell’s law, and Doppler Effect etc. Due to the interesting properties, the scientific community has been concerned to the metamaterials for strange characteristics and extensive applications in energy harvesting, invisibility clocks, filtering, electromagnetic absorber [1] and perfect lenses, SAR reduction [2]. Kollatou et al. offered a polarization-insensitive metamaterial absorber (MA) which worked in the microwave spectra. They gained the maximum absorbance peak of 95.81% at 10.31 GHz [3]. In this article, authors achieved very low absorbance rate at resonance frequency of 10.31 GHz instead of small design structure. Landy et al. proposed the metamaterial design structure for absorbing electromagnetic wave with an absorbance of 96% [4]. On the other hand, the experimental result of the absorber was 88% at 11.50 GHz frequency. From this article, it was shown that they used cut wire in the back side of the design structure. For that reason, the transmission parameter of the incident electromagnetic wave was not fully zero. Moreover, they got the less absorbance from their design structure by numerically and experimentally because of cut wire of the back side of the unit
Mohammad et al. proposed a Jerusalem cross with meandered load absorber which has a dimension of 24×24 mm² exhibits more absorption like 95% [5]. Author proposed very large size of the design structure and achieved very low absorbance rate of 95%. Lin et al. suggested a design structure that has a dimension of 1.092 cm × 1.0 cm. It was appropriate in microwave spectra. The structure depicted the peaks of absorbance at different resonance frequencies such as 96.5% at 2.15 GHz, 96.8% at 2.28 GHz, and 99.6% at 2.38 GHz, correspondingly [6]. Authors obtained multi absorbance rate at multi resonance frequency, however, they got less absorbance rate at first two resonance frequencies. An ultra-broadband perfect absorber with 10×10 mm² dimensions depends on electric resonator proposed by Zhao et al. The absorption peak of 99.3% at 5.45 GHz, 97.1% at 15.46 GHz and 98.6% 19.48 GHz, simultaneously [7]. Authors also achieved lower absorbance rate at higher frequencies such as 15.46 GHz and 19.48 GHz, whereas the size of the design structure was little bit compact. A unity absorbance metamaterial was designed and fabricated by Dincer et al. [8]. They depicted a PMA, which have absorbance pinnacles of 99.99% and 99.92% at 5.48 GHz 0.865 THz, respectively. Nevertheless, the size of the design structure was 3.6 cm × 3.6 cm.

In this paper, the both side planar multi-ring hexagonal with meandered line-based metamaterial absorber depicts dual resonances X-bands with different structural analysis such as 1 × 1 unit-cell structure; 1 × 2 unit-cell and 1 × 2 array unit-cell structures; 2 × 1 unit-cell and 2 × 1 array unit-cell structures. In addition, the dimension of the offered structure is 10.5 mm × 10 mm × 1.6 mm, which is smaller than the proposed metamaterials structure in [8, 9, 10, 12]. Also, the plan structure offers high absorbance value 99.95% at 8.006 GHz and 99.61% at 11.525 GHz, correspondingly. It is perceived that the absorbance of the offered structure is superior to the proposed MA structure in [3, 4, 5, 6, 7, 9, 10, 11, 12]. To govern the absorbance properties, the CST studio simulator 2015 was utilized.

2. Design structure and numerical simulation

The suggested structure consists of tri-ring hexagonal with meandered line resonators which was employed to attain unconventional characteristics of metamaterials that were usually not found in nature. The offered metamaterial absorber structure and parameter specification are illustrated in Figure 1(a). Figure 1(b) indicates the numerical simulation setup of proposed structure. FR4 substrate material was utilized as a separator between the resonator and the ground plane. The resonators and ground plane are built by copper material thickness of 35µm. The conductivity of resonators and ground plane are $5.8 \times 10^7$ S/m. The loss tangent $\delta$ and standard relative permittivity are 0.025 and 4.3. The specifications of the structure are $W_s=10.5$ mm, $L_s=10$ mm, $W_1=0.4$ mm, $W_2=0.65$ mm, and $W_3=0.7$ mm.

![Figure 1](image-url) (a) The offered absorber structure (b) Simulation setup with boundary condition.
In this paper, the FDTD method based CST simulator was applied to observe this design structure. This method shows more accurate result comparing the other numerical tools like High Frequency Structure Simulator (HFSS), IE3D, etc. It can be used to analysis the design structure very easily. As a boundary condition, two waveguide ports are setup along the z-direction. On the other hand, along the y-direction and x-direction, the perfect magnetic conductor and perfect electric conductor were applied in numerical simulation. Frequency domain solver of CST simulator was applied to find out the transmittance and the reflectance in numerical simulation and frequency samples of 1001 were considered. The absorption of the unit-cell structure was governed by the following formula, $A(\omega) = 1 - R(\omega) - T(\omega)$, where $T(\omega)$, $R(\omega)$, and $A(\omega)$ are the transmittance, reflectance and absorbance, individually. Absorption be governed by on the scattering parameters, for example, $|S_{21}|^2 = T(\omega)$, and $|S_{11}|^2 = R(\omega)$. Because of ground plane, the transmittance of the structure is zero means $T(\omega) = 0$. Therefore, from the absorbance formula, it has to be realized that decreasing the reflectance parameters which has to expand the absorbance of the metamaterial absorber.

3. Results and discussion
The reflectance ($R(\omega)$) and absorbance ($A(\omega)$) of the PMA are demonstrated in Figure 2. The deep values of the reflectance at resonance frequencies are -33.334 dB at 8.006 GHz and -23.626 dB at 11.525 GHz, respectively. Then again, the pinnacle estimations of absorbance are 99.95% at 8.006 GHz and 99.61% at 11.525 GHz, individually. It is seen from Figure 2 that less value of reflectance creates more value of absorbance.

![Figure 2. Reflectance and absorbance of unit-cell structure.](image)
Figure 3 depicts the electric field of the resonator with two peaks such as 8.006 GHz and 11.525 GHz, where its expose high absorbance peak respectively. At 8.006 GHz, the distributions of electric field have concentrated on the areas of outer ring and inner ring of right side. It is also seen around the left side of the middle ring. On the other hand, at 11.525 GHz, the concentration of electric field present between the gap of upper and middle ring on the upper side. Hence, the high absorption peak is subjected due to the electric resonance of the regions.

3.1 Analysis of $1 \times 2$ unit-cell structure
The fundamental structure of $1 \times 2$ unit-cell is composed on the separate substrate materials. Two structures of the unit-cells are horizontally detached by 0.4 mm and 5-14 GHz frequency ranges are used in numerical simulation for analysis this design structure.

Figure 4. Reflectance and absorbance of $1 \times 2$ unit-cell structure.

The reflectance ($R(\omega)$) and absorbance ($A(\omega)$) of the PMA are presented in Figure 4. The negative peak values of the reflectance of resonance frequencies are -33.04 dB at 8.15 GHz and -22.41 dB at
11.44 GHz, separately. However, the absorbance’s pinnacle estimations 99.95% and 99.48%, at 8.15 GHz, 11.44 GHz, correspondingly. It is seen from Fig. 4 that the peak of absorbance increased of first resonance, on the other hand, second absorbance peak decreased due to joint of the two unit-cells separately in the 1 × 2 unit-cell horizontal form.

3.2 Analysis of 1 × 2 array unit-cell structure
The fundamental structure of 1 × 2 array unit-cell outlined on a similar substrate material. Two front side resonators are horizontally detached by 0.4 mm and 5-14 GHz frequency ranges are utilized in numerical simulation for analysis this design structure. Figure 5 indicates that the reflectance (\(R(\omega)\)) and absorbance (\(A(\omega)\)) of the design structure. The deep values of the reflectance of resonance frequencies are -24.68 dB at 8.17 GHz and -23.08 dB at 11.41 GHz, respectively. Nonetheless, the peak values of absorbance at 8.17 GHz be 99.66% and at 11.41 GHz be 99.51%, respectively. It is seen from Figure 5 that the peak of absorbance of first resonance is increased and shifted toward the upper frequency, though, second resonance is decreased toward lower frequencies with lower peak in order to joint of the two unit-cells same substrate and same ground plane in the 1 × 2 array unit-cell horizontal form.

![Figure 5. Reflectance and absorbance of 1 × 2 array unit-cell structure.](image)

3.3 Analysis of 2 × 1 unit-cell structure
The basic structure of 2 × 1 unit-cell composed on the separate substrate materials. Two structures of unit-cell are vertically detached by 0.4 mm and 5-14 GHz frequency ranges are used in numerical simulation for analysis this design structure. The reflectance (\(R(\omega)\)) and absorbance (\(A(\omega)\)) of the PMA are display in Figure 6. The negative peak values of the reflectance of resonance frequencies are -20.50 dB at 8.13 GHz and -22.56 dB at 11.53 GHz, separately. However, the absorbance’s pinnacle estimations 99.11% and 99.47%, at 8.13 GHz, 11.53 GHz, correspondingly. It is seen from Fig. 6 that the peaks of absorbance of first and second resonances are decreased compared with fundamental structure due to joint of the two unit-cells separately in the 2 × 1 unit-cell vertical form.
3.4 Analysis of $2 \times 1$ array unit-cell structure

The basic structure of $2 \times 1$ array unit-cell is outlined on a vertically similar substrate and ground plane. Two structure unit-cells are vertically detached by 0.4 mm and 5-14 GHz frequency ranges are applied in numerical simulation to analysis this design structure. The reflectance ($R(\omega)$) and absorbance ($A(\omega)$) of the design structure are illustrated in Figure 7. The deep values of the reflectance of resonance frequencies are $-22.35$ dB at 8.13 GHz and $-26.42$ dB at 11.16 GHz, correspondingly. On the other hand, the absorbance’s pinnacle estimations are 99.42% and 99.76%, at 8.13 GHz, 11.42 GHz, correspondingly. It is observed from Figure 7 that the peak of absorbance increased both of the resonances and shifted toward the lower frequencies due to joint of the two unit-cells separately at same substrate and the ground plane in the $2 \times 1$ unit-cell vertical form.
The dimension (36×36 mm²) of square shape is suggested by Dincer et al. [8], whereas authors achieved 99.99% maximum absorbance peak in C-band application.

| Author name with reference | Structured shape | Covered band | Size (mm²) | Maxi% peak of absorbance (%) | Published year |
|----------------------------|-----------------|--------------|------------|-------------------------------|----------------|
| Dincer et al. [8]          | Square shape    | C-band       | 36 × 36    | 99.99                         | 2015           |
| Rana et al. [9]            | U-shape         | X-band       | 15 × 15    | 98.00                         | 2016           |
| Borah et al. [10]          | O-shape         | X-band       | 12 × 12    | 98.90                         | 2016           |
| Sen et al. [11]            | L-shape         | X-, Ku-band  | 9 × 9      | 95.00                         | 2017           |
| Mahmood et al. [12]        | Modified S-shape| X-band       | 16 × 16    | 90.00                         | 2017           |
| This paper                 | Hexagonal shape | X-band       | 10.5×10    | 99.95                         | ---            |

In addition, a U-shape multiband absorber designed by Rana et al. that had a dimension (15×15×mm²). Authors got the peak of absorbance (98%) with big design structure. Sen et al. suggested a compact design structure (9×9 mm²) compared with offered structure (10.5×10 mm²). However, offered metamaterial absorber gained high absorbance peaks (95.00%) that are shown in Table 1. A large size, design structure (12×12 mm²) was suggested by Borah et al. in this paper. The authors achieved less absorbance about 98.90% compared with offered PMA. Mahmood et al. recommended a big size (16×16 mm²) unit-cell structure, whereas they had to obtain less absorbance rate (90.00%) comparison with offered design structures. A new compact (10.5×10 mm²) multi-ring hexagonal with meandered line design structure analyzed and achieved a high absorbance rate (99.50%) in this study. The offered metamaterial absorber achieved high absorbance and compactness comparing stated references which are appropriate for the microwave spectra.

4. Conclusions
A new design of PMA was offered for mono-band, for example, X-band applications in the manuscript. The design unit-cell structure and different array structure were analyzed for absorbing purposes over a frequency range of 5-14 GHz. Seven structural designs such as 1 × 1 unit-cell structure; 1 × 2 unit-cell and 1 × 2 array unit-cell structures; 2 × 1 unit-cell and 2 × 1 array unit-cell structures are designed and analyzed to observe absorbance. The electric field distributions also analyzed to observe the behavior of offered structures. The CST electromagnetic simulator was utilized to find out the absorption for different structures. The offered PMA is proper for X-band applications. A comparative examination additionally was done based on the author name with reference, structure shape, covered band, size, maximum absorbance rate, and published year. It was observed that the maximum absorbance rate of 99.95% at 8.006 GHz was attained from the 1×1 unit-cell structure. Hence, the PMA was compact in dimension and high absorbance which were more appropriate in microwave bands.

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