Left-handed Circular-Shaped Compact Metamaterial for X- and Ku-Band applications

Tayaallen Ramachandran¹, Mohammad Rashed Iqbal Faruque¹, and Mohammad Tariqul Islam²

¹Space Science Center (ANGKASA), Universiti Kebangsaan Malaysia, 43600 UKM, Bangi, Selangor, Malaysia
²Dept. of Electrical, Electronic & Systems Engineering, Universiti Kebangsaan Malaysia, 43600 UKM, Bangi, Selangor, Malaysia

rashed@ukm.edu.my

Abstract. The purpose of this paper is to propose a new circular-shaped metamaterial (CM) design for X- and Ku-band applications. The discovery of exotic characteristics in metamaterial encourages to carry out this research study. The proposed design is numerically simulated by utilising Computer Simulation Technology (CST) software. The CM structure consists of few circular rings that designed on 8 × 8 mm² and 1.6 mm thick of FR-4 dielectric substrate material. The Finite Integration Technique (FIT) used to perform the simulation in CST. Frequency range of 4 to 18 GHz is adopted and the CM design manifest resonance frequencies at 8.19 GHz, 11.32 GHz (X-band) and 16.39 GHz (Ku-band). These resonance frequencies possess an acceptable magnitude values for instance, -30.70 dB, -22.59 dB, and -20.13 dB respectively. In additional, the proposed CM design exhibits left-handed characteristic at both resonance frequencies. Therefore, CM with unique behaviour can be applied for many current application fields such as satellite communication, wireless computer networks, weather monitoring, and etc.

1. Introduction

In recent years, metamaterial emerges as a popular term with scientists since it possesses unique electromagnetic properties. Generally, metamaterial defined as artificial material that has exotic properties and not available in natural or conventional material. Since, the discovery of this unconventional material, there are many application fields that utilise metamaterial to enhance the performance. Since the metamaterial exhibit some extraordinary electromagnetic properties, hence apply for many research fields such as SAR reduction, seismic metamaterial, energy harvesting, and sensors [1] – [6].

In 2019 [7], Tamim et. al. proposed horizontally inverse double L-shaped split ring resonator metamaterial for C-, X-, and Ku-band applications. Tamim designed metamaterial on Rogers RT5880 substrate material with a dimension of 10 × 10 mm² and thickness of 0.035 mm. Meanwhile, Mishra et. al. [8] investigated rectangular split ring resonator based on gradient refractive index metamaterial for similar frequency bands mentioned in reference above. The metamaterial structure was arranged on 30 × 10 array cells with unit cell dimension of 40 × 40 mm². Ozden et. al. in 2016 [9] designed and simulated metamaterial broadband absorber for X-band. 6.67 × 6.67 mm² FR-4 dielectric substrate
material was utilised with thickness of 0.75 mm and the metamaterial designed on it with thickness of 0.017 mm.

Ramachandran et. al. [10] proposed left-handed circular split ring resonator metamaterial for C- and Ku-band applications. FR-4 substrate material with thickness of 1.6 mm and dimension of $8 \times 8$ mm$^2$ was adopted in this research study. While, for array arrangement, $9 \times 9$-unit cells with total dimension of $72 \times 72$ mm$^2$ was selected. The numerical simulation was carried out by utilising CST software. In 2019 [11], Pham et. al. numerically and experimentally reviewed metallic disks isotropic metamaterial absorber for Ku-Band application. Pham observations manifested new way to obtain dual- and multi-band isotropic metamaterial absorber. Sen et. al. [12], investigated a broadband perfect metamaterial absorber on thin substrate material for X- and Ku-band applications. The FR-4 material with a dimension of $9 \times 9$ mm$^2$ and thickness of 2.7 mm were adopted in this study.

In 2019 [13], Almutairi et. al. designed and investigated a complementary slit ring resonator metamaterial for C-band microwave applications. For this research study, also FR-4 dielectric substrate material was used with dimension of $5.50 \times 5.50$ mm$^2$ and thickness of 1.6 mm. Mehedi et. al. [14] in 2018, suggested improved square-Z-shaped double negative metamaterial for C- and X-band applications. Unit cell dimension of $10 \times 10$ mm$^2$ and array arrangement of $200 \times 150$ mm$^2$ was designed and investigated in this paper. Although many previous research studies successfully carried out to apply for the proposed applications but have few drawbacks because of fast growing technology. The main constraints are the size miniaturization and operating frequency bands. The previously stated reference either operates in single band or has larger unit and array cells. Hence, a new left-handed circular-shaped metamaterial for dual-band application is proposed in this paper.

2. Metamaterial cell design and simulation geometry

Figure 1 (a) to (c) illustrate the dimension details and the perspective view of the CM structure. The introduced CM metamaterial consists of main five circular rings. The metamaterial structure is placed on the FR-4 substrate material with thickness of 0.035 mm. Meanwhile, the dimension of FR-4 is $8 \times 8$ mm$^2$ and thickness of 1.6 mm as shown in Figure 1 (b). The first ring has an outer radius of 1.2 mm and inner radius of 0.7 mm. The following circular ring with thickness of 0.25 mm was plotted using outer circular ring radius of 1.735 mm. For third circular ring, at 2.5 mm outer radius, a 0.5 mm thick circular ring was placed. A 0.4 mm thick rectangular bar with 5.5 mm long was positioned at the center of the design. This bar then rotated for 45-degree and 315-degree angle and subtracted the first and third rings. The remaining of the first and third rings was manually deleted until obtained shape like in Figure 1 (a). At an outer radius of 2.375 and 3.025 mm the circular rings with thickness of 0.25 mm was designed. Meanwhile, the final circular ring was positioned at the outer radius of 3.8 mm with thickness of 0.5 mm. A rectangular bar of 0.4 mm thick and 7.5 mm long from center of the CM structure was placed vertically to connect all the circular rings. The dielectric constant ($\varepsilon$) and tangent loss ($\mu$) of FR-4 is 4.3 and 0.025 respectively. The Figure 1 (c) represents the general perspective view of proposed CM design. Apart from that, the dimension details of the CM structure were listed in Table 1.

| Specifications                  | Dimensions, mm |
|--------------------------------|----------------|
| 1st Circular Ring Thickness, $r_{t1}$ | 0.5            |
| 2nd Circular Ring Thickness, $r_{t2}$  | 0.25           |
| 3rd Small Circular Ring Thickness, $r_{t3}$ | 0.25          |
| 3rd Big Circular Ring Thickness, $r_{t4}$    | 0.5            |
| 4th Circular Ring Thickness, $r_{t5}$       | 0.25           |
| 5th Circular Ring Thickness, $r_{t6}$       | 0.5            |
| Rectangular Bar, $r_{b1}$                   | 0.4            |
| Length of substrate material, $a$           | 8.00           |
| Length of substrate material, $b$           | 8.00           |
Thickness of substrate material, $c$  
Annealed copper thickness, $d$  

$$
\begin{align*}
\text{Thickness of substrate material, } c &= 1.60 \\
\text{Annealed copper thickness, } d &= 0.035
\end{align*}
$$

**Figure 1.** The CM structure sketch in CST software; (a) From top angle view, (b) From side angle view, (c) Perspective view of CM structure
3. CST Simulation Techniques and Methods

By utilising frequency-domain solver, the proposed single unit cell and array CM structure were successfully simulated employing FIT techniques in CST software. Two waveguide ports were positioned front and back of CM design which is at positive and negative z-axis as shown in Figure 2 (a) and (b). Meanwhile, the y-axis specified as perfect magnetic conductor (PMC) and x-axis as perfect electric conductor (PEC). A selective frequency range was utilised in this simulation which is from 4 to 18 GHz. As a result, the scattering parameters, for instance reflection (S11) and transmission coefficient (S21) were obtained. Furthermore, the effective medium parameters were calculated using the obtained S11 and S21 data. The well-known Robust method was utilised in the calculation of the effective medium parameters such as permittivity, permeability and refractive index [15] – [17].

4. Results and Discussion

The reflection coefficient (S11) and transmission coefficient (S21) of the unit cell and array, permittivity, permeability and refractive index are illustrated in Figure 3 (a) to (e). The Figure 3 (a) indicates that, three resonance frequencies are manifest in this research study in particular at 8.19, 11.32, and 16.39 GHz with a satisfied magnitude value of -30.70, -22.59 and -20.13 dB respectively. The both resonance frequencies exhibit negative permittivity values. At X-band, ranges from 8.63 to 9.64 GHz and 11.73 to 11.99 GHz the metamaterial manifest negative permittivity behaviour as shown in Figure 3 (b). The highest permittivity value occurred at 8.80 GHz with an amplitude value of -22.33 dB. Furthermore, at Ku-band, the proposed CM design demonstrated negative behaviour from 12.02 to 12.78 GHz with amplitude values from -5.81 to 0.01 dB. Meanwhile, since the permeability value manifest less zero for whole selective frequency range, hence both X- and Ku-band have longest negative permeability behaviour. At X-band, the metamaterial exhibit two peak values for instance, -2.32 and -1.91 dB at 8.17 and 11.29 GHz. Simultaneously, at 16.35 GHz, the CM has a peak value of -1.94 dB. Apart from these behaviours, the CM design also manifests left-handed characteristic at all resonance frequencies. From frequency ranges of 8.63 to 9.64 GHz and 11.73 to 11.99 GHz, the metamaterial has left-handed behaviour. At the first left-handed behaviour, the metamaterial possesses permittivity, permeability and refractive index amplitude values of -3.67 to -0.06 dB, -0.87 to -0.59 dB.
and -7.48 to -1.13 respectively. While the second frequency range has amplitude values of -0.97 to -5.94 dB, -0.95 to -0.94 dB and -4.62 to -3.47 respectively. Furthermore, at Ku-band, the range is from 12.02 to 12.78 GHz with amplitude values of -5.81 to -0.01 dB, -0.94 to -0.57 dB and -3.40 to -1.09 respectively. The Figure 3 (e) illustrates, reflection and transmission coefficient results of array arrangement of CM design. There is a slight difference in resonance frequencies and has almost similar results with unit cell simulation. Approximately, less than 1.5% difference occurred in the array cell simulation which is in an acceptable manner.

**Figure 3.** Simulated results of CM design; (a) Transmission and reflection coefficient, (b) Electric permittivity, (c) Magnetic permeability, (d) Refractive index, (e) Transmission and reflection coefficient of array cell.
The electric field distribution is shown in Figure 4 (a) to (c) at the resonance frequencies. The observation clearly indicates that, all have own electric field distribution at every resonance frequency. At 8.19 GHz, the CM design exhibit field distribution at left side of 5th ring and right side of 2nd to 4th rings. Besides that, it also appears electric field distribution on dielectric substrate material. Moreover, at 16.39 GHz, the CM design manifests the lowest field distribution to in another two resonance frequencies. The electric field focused on the center of the design and faded when reach the 5th ring. Meanwhile, at 11.32 GHz, the CM design has field distribution almost all over the design. Basically, the dielectric substrate material has no free electrons, but because of CM metal design on it, causes electron oscillation exits at metal itself and substrate material interface are delocalised. The electric field occurred in the substrate material because of this particular reason.

**Figure 4.** Electric field distribution at; (a) 8.19 GHz, (b) 11.32 GHz, (c) 16.39 GHz
5. Conclusion
A new compact, left-handed metamaterial for X- and Ku-band frequencies investigation is presented in this conference paper. The numerical simulation successfully completed by utilising FIT in CST software. Besides unit cell design, the 2 × 2 array arrangement structure also proposed in this paper. A significant left-handed characteristic that manifested from the introduced metamaterial design contribute wide range of application field. X- and Ku-band frequencies can apply in satellite broadcast service, air traffic control, vehicle speed detection for law enforcement and vessel traffic control.

Acknowledgements:
This work was supported by Fundamental Research Grant Scheme (FRGS), MOE, Malaysia, Code: FRGS/1/2018/TK04/UKM/02/13.

References
[1] Wang et al., M.: Investigation of SAR Reduction Using Flexible Antenna with Metamaterial Structure in Wireless Body Area Network. *IEEE Trans. Antennas Propag.*, vol. 66, no. 6, pp. 3076–3086 (2018).
[2] Ramachandran, T., Faruque, M. R. I., Ahamed, E., and Abdullah, S.: Specific absorption rate reduction of multi split square ring metamaterial for L- and S-band application. *Results Phys.*, vol. 15, pp. 2–10 (2019).
[3] Brûlé, S., Enoch, S., and Guenneau, S.: Emergence of seismic metamaterials Current state and future perspectives. *Phys. Lett. A*, vol. 384, no. 1, pp. 1–11 (2020).
[4] Tan, T., Yan, Z., Zou, H., Ma, K., Liu, F., and Zhao, L.: Renewable energy harvesting and absorbing via multi-scale metamaterial systems for Internet of things. *Appl. Energy*, vol. 254, pp. 2–15 (2019).
[5] Wu, Y., Meng, Y., Yakupoglu, B., and Adams, M.: A metamaterial/liquid-core waveguide microfluidic optical sensor. *Sensors Actuators A. Phys.*, vol. 300, pp. 2–26 (2019).
[6] Ji et al., Y.: High-performance metamaterial sensors based on strong coupling between surface plasmon polaritons and magnetic plasmon resonances. *Results Phys.*, vol. 14, pp. 1–6 (2019).
[7] Tamim, A. M., Faruque, M. R. I., and Alam, M. J.: Split ring resonator loaded horizontally inverse double L-shaped metamaterial for C-, X- and K u-band Microwave applications. *Results Phys.*, vol. 12, pp. 2112–2122 (2019).
[8] Panjar, B., Sahu, S., Parashar, S. K. S., and Pathak, S. K.: A compact wideband and high gain GRIN metamaterial lens antenna system suitable for C, X, Ku band application,” *Opt. - Int. J. Light Electron Opt.*, vol. 165, pp. 266–274 (2018).
[9] Ozden, K., Mert, O., and Kocer, H.: Metamaterial based broadband RF absorber at X-band. *AEUE - Int. J. Electron. Commun.*, vol. 70, no. 8, pp. 1062–1070 (2016).
[10] Ramachandran, T., Faruque, M. R. I., and Ahamed, E.: Composite circular split ring resonator (CSRR) -based left-handed metamaterial for C- and Ku-band application. *Results Phys.*, vol. 14, pp. 1–11 (2019).
[11] Linh et al., P. T.: Dual-band isotropic metamaterial absorber based on near-field interaction in the Ku band. *Curr. Appl. Phys.*, vol. 20, no. 2, pp. 331–336 (2020).
[12] Sen, G., Islam, S. N., Banerjee, A., and Das, S.: Broadband Perfect Metamaterial Absorber on Thin Substrate for X-Band and Ku-Band Applications. *Prog. Electromagnetics Res. C*, vol. 73, pp. 9–16 (2017).
[13] Almutairi, A. F., Shahidul, M., and Islam, T.: A complementary split ring resonator based metamaterial with effective medium ratio for C-band microwave applications. *Results Phys.*,
vol. 15, pp. 1–10 (2019).

[14] Hasan, M. M., Faruque, M. R. I., and Islam, M. T.: Improved square-Z-shaped DNG metaatom for C- and X-band application. *Curr. Sci.*, vol. 114, no. 12, pp. 2518–2524 (2018).

[15] Chen, X., Grzegorczyk, T. M., Wu, B., Pacheco, J., and Kong, J. A.: Robust method to retrieve the constitutive effective parameters of metamaterials. *Phys. Rev. E*, vol. 70, pp. 1–7 (2004).

[16] Castané, A., Mercier, J., Félix, S., and Maurel, A.: Generalized method for retrieving effective parameters of anisotropic metamaterials. *Opt. Express*, vol. 22, no. 24, pp. 649–661 (2014).

[17] Smith, D. R., Vier, D. C., and Soukoulis, C. M.: Electromagnetic parameter retrieval from inhomogeneous metamaterials. *Phys. Rev. E*, vol. 71, no. 036617, pp. 1–11 (2005).