Bandwidth and Gain Improvement of a Circularly Polarized Metamaterial-Based Antenna Employing Square Ring-Shaped Defected Ground Structure

Shil, Anaynna
Chittagong University of Engineering and Technology (CUET)

Tabassum, Samia
Chittagong University of Engineering and Technology (CUET)

Jahan, Nusrat
Chittagong University of Engineering and Technology (CUET)

https://doi.org/10.5109/4102462

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 6, pp.46-51, 2020-10-22. Interdisciplinary Graduate School of Engineering Sciences, Kyushu University
バージョン：

Bandwidth and Gain Improvement of a Circularly Polarized Metamaterial-Based Antenna Employing Square Ring-Shaped Defected Ground Structure

Anaynna Shil, Samia Tabassum, Nusrat Jahan
Chittagong University of Engineering and Technology (CUET), Chittagong, Bangladesh
Corresponding author email: anaynnashil1@gmail.com

ABSTRACT: *In this work, a wideband compact and low-profile metamaterial-based antenna has been developed. The antenna bandwidth is improved by employing square ring-shaped defect in the ground plane. The circularly polarized (CP) antenna has been realized by two pairs of radiators and CP characteristics has been obtained by placing two radiators for X-polarized wave and two radiators for Y-polarized wave. Each radiator is designed with epsilon negative transmission line (ENG-TL) to generate zeroth order resonance (ZOR). Simulated results show that the antenna achieves a gain of 4.98 dBiC, which is improved by 0.62 dBiC compared to the structure without square ring-shaped defected ground structure. Also, the operating bandwidth of our proposed antenna improves to 698.6 MHz.*

Keywords: Metamaterial; Circularly polarized; Defected ground structure.

1. INTRODUCTION

The increasing demand of high data-rate wireless communication motivates us to design compact size antenna, which is a major component of wireless transceiver. Previously, Metamaterial (MTM) based antenna has been proposed by several researchers for the size reduction as it offers low profile characteristics using composite right-left handed (CRLH) structures [1]. A compact zeroth-order resonating wideband antenna based on CRLH transmission line with dual-band characteristics has been presented [2].

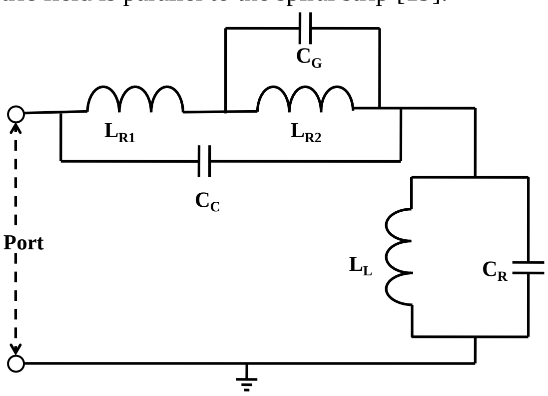
Circularly polarized (CP) structures have been used immensely because of the insensitivity of transmitter and receiver orientation. Various CP antennas have been proposed which provide various advantages. Omni-directional CP antenna utilizing zeroth order resonance has been designed to improve the axial ratio [3]. Coplanar waveguide fed dual band linear and circularly polarized antenna with composite split ring resonator has been designed [4]. Dual band circularly polarized antenna with (2×2) triangle mushroom antenna has been designed [5]. Low profile circularly polarized antenna based on fractal metasurface and fractal resonator has been designed [6]. A metamaterial based CP antenna [7] employing epsilon negative transmission line (ENG-TL) has been designed with single feed to improve the bandwidth. A broadband antenna has been proposed in [8] and by adding a circular patch at the corner of the rectangular patch and ellipse, linear polarization was converted to circular polarization. A new technique is used to design CP electrically small antenna using a chiral MTMs based on modal approach characteristic mode analysis (CMA) [9]. To realize circular polarization in a slot antenna, some slots has been attached on the top metal layer and a floating metal layer is attached to the bottom of the antenna [10]. In [11], a single patch single feed tri band antenna has been designed to realize different senses of circular polarization in different bands by tuning stubs and slots. But the above proposed antennas cannot be used in different applications where wide bandwidth, high gain and compact size are required.

Jong-Im Park et al. first proposed the defective ground structure (DGS) in 1999 and the author proposed and applied it to microwave devices such as antennas and filters [12]. DGS changes the distributed capacitance and distributed inductance of the transmission line and changes the effective dielectric constant of the medium by etching different shapes and periodic planar structures on the metal ground plane of the transmission line, which changes the distribution of ground current and transmission characteristics of transmission lines. DGSs are used for different applications like filter implementations, circuit miniaturization and optimizing antenna performance. The performance of cylindrical conformal broadband array antenna without DGS and with DGS structure is compared in [13]. Here, rectangular DGS has been used to enhance the working bandwidth of the antenna, reduce the return loss and reduce the loss of gain. Asymmetric single S-shaped DGS is etched on the ground plane of the microstrip line for dual band band-pass filter performance [14]. Compact dual feed circularly polarized antenna has been designed in [15] and dual circular polarization is achieved by simply adding U shaped ground slot radiator on the bottom side along with asymmetrical patch feed lines on the top of the FR-4 substrate. Dumbbell shaped DGS has been used as a unit cell in an organized order in both horizontal and vertical directions for construction of 2D DGS [16]. Here, variation of resonance frequency has been obtained by increasing number of unit cell and placing them in different configurations. Dual T-shaped slits are inserted on either side of the radiating rectangular patch which provides dual band with better impedance characteristics [17]. Here, a zigzag shaped slit is introduced due to which the antenna resonates at an additional third band and the ground plane loaded with circular shaped dumbbell makes the resonant frequencies to shift at all the three bands to the left. A single resonant antenna has been converted to multi resonant antenna by inserting fractal defect in the ground plane [18].

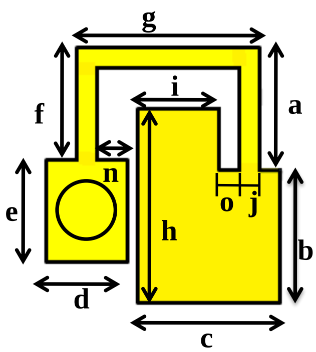
In this work, we propose a CP antenna implementing with defected ground structure to increase the antenna gain and bandwidth. Square ring-shaped defect has been implemented in the ground plane for each of the radiators of the antenna. The circuit and electromagnetic (EM) simulations throughout the manuscript have been done using Advanced Design System (ADS) and Computer Simulation Technology (CST) design studio, respectively.

2. PROPOSED ANTENNA DESIGN

Our proposed antenna is comprised of four unit cells interconnected to each other. The equivalent circuit of the proposed antenna unit cell is shown in Fig. 1(a). The equivalent circuit is realized by using two rectangular patches and a spiral strip to connect the patches, as shown in Fig. 1(b) [7]. Spiral strip is used for obtaining negative value of epsilon [19]. These metal spiral strip exhibit high-pass behavior for an incoming plane wave, whose electric field is parallel to the spiral strip [19].



(a)



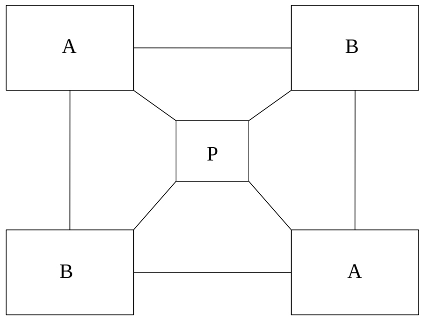
(b)

Fig. 1. Proposed antenna's unit cell (a) Equivalent circuit (b) Top view of patch realization.

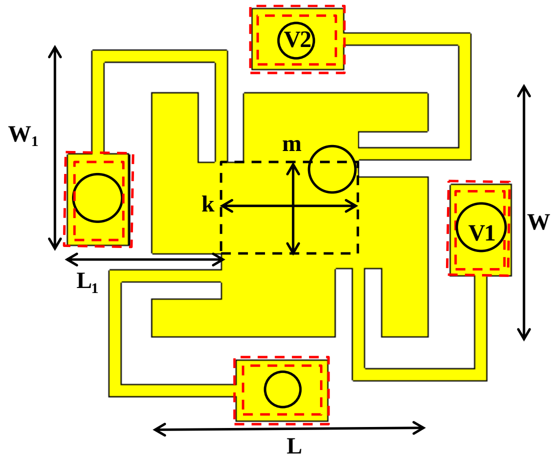
The series inductance L_{R1} is realized by the rectangular patch of area $h \times c$. The interconnected spiral strip of area $(a + g + f) \times j$ and rectangular patch of area $e \times d$ are contributing to the other series inductance L_{R2}. Coupling capacitor (C_C) is realized by the capacitive coupling between the patch and spiral strip. The shunt inductance (L_L) is realized by the shorted via between the smaller patch and ground plane. The shunt capacitor (C_R) is due to the capacitive coupling between the top radiator and ground plane. The capacitor (C_G) in parallel with the inductance (L_{R2}) is realized by the defects in the ground plane. This new parallel circuit ($C_G||L_{R2}$) in the equivalent circuit of CP antenna is contributing to the improvement of the antenna bandwidth and gain. The zeroth order resonance (ZOR) is managed by the shunt elements and ZOR frequency for single radiator can be calculated by the equation (1).

$$f_{ZOR} = 1/2\pi[(L_L C_R)]^{0.5} \qquad (1)$$

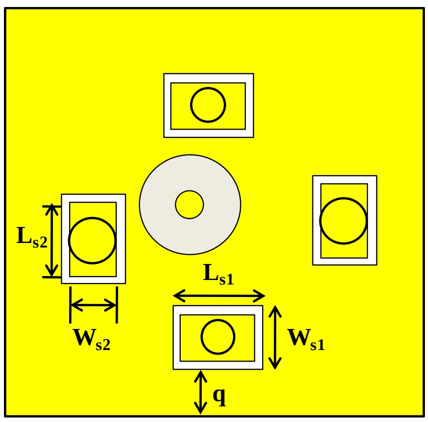
The optimized dimensions of the unit cell parameters are shown in Table 1. The orientation of the radiators is shown in Fig. 2(a), where cells A and B are interconnected through a port (P), which possesses an area of $k \times m$. For measurement of the proposed design, a coaxial cable is inserted in the top metal layer through ground plane and positioned in port (P), which is pointed in Fig. 2(b). The total size of the antenna is (20 mm × 20 mm × 2.4 mm) and antenna radiating element size is (13.3 mm × 12.3 mm) at 5.95 GHz. The parallel capacitance (C_G) in the equivalent circuit is realized by square ring-shaped defects in the ground plane, which is shown in white colour in Fig. 2(c). The circular shaped white colour element shows the port entry



(a)



(b)



(c)

Fig. 2. (a) Block diagram (b) Front view and (c) Back view of the proposed antenna.

point. Coaxial feeding technique is used. Here, Coaxial feed point is at (X, Y) = (1.5 mm, 1.5 mm) with an inner and outer diameter of 1.5 mm and 5 mm. Feed point is placed diagonally for obtaining CP radiation characteristics [20]. The optimized dimensions of parameters of the proposed antenna and square ring-shaped defected ground structure are listed in Table 2 and Table 3, respectively.

To design this antenna, FR-4 substrate is chosen with a dielectric constant (ε_r) and loss tangent (δ) given in Table 3. The thickness of substrate is h_1 (2.4 mm). Copper is used for the design of ground and patch and thickness of copper is, h_2 = 0.02 mm. Equivalent circuit parameters (L_{R1}, L_{R2}, C_C, L_L, C_R) for unit cell A and B have been calculated using equations (2), (3) and (4).

$$L = 0.2 \times l \times [ln(\frac{2l}{W+H}) + 0.5 + 0.2235\frac{(W+H)}{l}]nH \quad (2)$$

$$C = \frac{\varepsilon A}{d} \quad (3)$$

$$L_L = \frac{\mu_0}{2\pi}[h_1 ln(\frac{h_1+\sqrt{r^2+h_1^2}}{r}) + \frac{3}{2}(r - \sqrt{r^2+h_1^2})] \quad (4)$$

Here, l = Length of the strip
W= Width of the strip
H = Distance between the strip and the ground plane
A = Area of plates
d= Distance between plates
h_1= Thickness of substrate and
r= radius of the via

Capacitance and inductance introduced because of the square ring shaped DGS can be calculated using equations (5) and (6) from [21]. The calculated equivalent circuit parameters for two unit cells are listed in Table 4.

$$L_{DGS} = y(L_{s1}+W_{s1})(0.0234 \times \{\log(\frac{2L_{s1}W_{s1}}{h_2+q}y) - \frac{L_{s1}}{L_{s1}+W_{s1}} \times \log[(L_{s1} + \sqrt{{L_{s1}}^2+{W_{s1}}^2})y] - \frac{W_{s1}}{L_{s1}+W_{s1}} \times \log[(W_{s1} + \sqrt{{L_{s1}}^2+{W_{s1}}^2})y]\} + 0.01\{2\left(\frac{\sqrt{{L_{s1}}^2+{W_{s1}}^2}}{L_{s1}+W_{s1}}\right) - 0.5 + 0.447(\frac{h_2+q}{L_{s1}+W_{s1}})\})\text{uH} \quad (5)$$

y =39.37

$$C_{DGS} = \frac{2W_{s2}}{\pi}\varepsilon_0\varepsilon_{reff}\cosh^{-1}(\frac{2(L_{s1}-L_{s2})}{W_{s1}-W_{s2}})mF \quad (6)$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2}, R_{DGS} = R_{dc} + R_{ac}\Omega$$

$$R_{dc} = \frac{2(L_{s1}+W_{s1})}{\sigma q h_2}$$

$$R_{ac} = \frac{(L_{s1}+W_{s1})}{q+h_2}\sqrt{\frac{\pi f \mu}{\sigma}}$$

There are two types of polarized waves- (i) X-polarized waves and (ii) Y-polarized waves. Unit cell A and B generate the X and Y polarized waves respectively and this eventually contributes to the CP waves. Unit cells A are orthogonally placed to unit cells B. Resonance frequency of orthogonally placed unit cells can be controlled by controlling the radius of shorted vias (V1) and (V2).

Table 1. Optimized dimension of the proposed antenna unit cell

Parameters	Unit cell A (mm)	Unit cell B (mm)
a	3.65	3.65
b	2.75	3.75
c	3	2.8
d	2	2
e	3	3
f	3.4	4.15
g	3.85	3.6
h	5.25	6
i	1.5	1.25
j	0.4	0.4
n	0.8	0.8
o	0.55	0.55

Table 2. Optimized dimensions of the square-ring shaped defected ground structure

Parameters	Unit cell A(mm)	Unit cell B(mm)
L_{s1}	3	3
L_{s2}	2.7	2.7
W_{s1}	2	2
W_{s2}	1.7	1.7
q	3.35	3.85

Table 3. Optimized dimensions of the proposed CP antenna

Parameters	Value (mm)
W	8
L	9
W_1	6.4
L_1	4.55
k	4.5
m	3
ε_r	4.4
δ	0.02
$V1$	0.83
$V2$	0.6

Table 4. Equivalent circuit parameters of the two unit cells

Parameters	Unit cell A	Unit cell B
L_{R1}	2.37 nH	3.23 nH
L_{R2}	1.324 uH	1.164 uH
L_L	0.344 nH	0.442 nH
C_c	0.32 pF	0.342 pF
C_R	0.097 pF	0.097 pF
C_G	0.034 pF	0.034 pF

3. SIMULATED RESULTS

The simulated Scattered (|S|) parameter (S_{11}) of our proposed CP antenna is shown in Fig.3. The operating bandwidth of the antenna is 698.6 MHz (5.6256-6.3242) GHz. Bandwidth of the proposed antenna is 1.07 times compared to [7]. The fractional bandwidth (FBW) of the antenna is calculated using equation (7).

$$FBW = \frac{f_{max} - f_{min}}{f_C} \times 100\% \qquad (7)$$

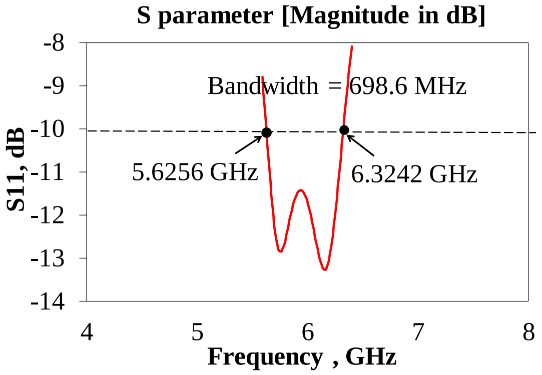


Fig. 3. Simulated result for the proposed antenna, input reflection coefficient ($|S_{11}|$).

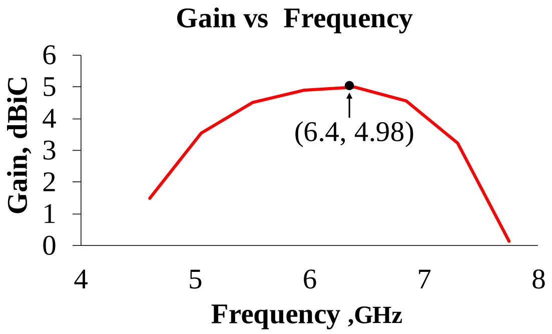


Fig. 4. Simulated gain of the proposed antenna.

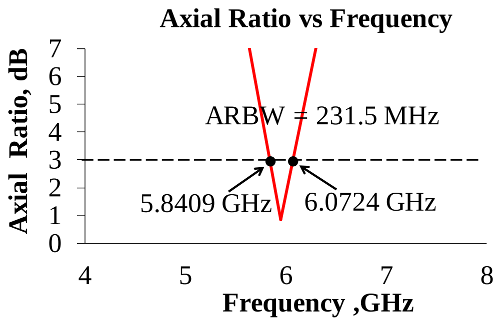


Fig. 5. Simulated result for the proposed antenna, ARBW.

Here, f_c is the centre frequency of the antenna. The FBW of the proposed antenna is 11.69%. The simulated gain of the proposed antenna is plotted in Fig.4. The introduction of the square ring-shaped defects improve the antenna gain to 4.98 dBiC at 6.4 GHz which is almost 0.62 dBiC higher than the structure without the defects in the ground plane [7]. Simulated result of axial ratio of the proposed antenna is shown in Fig.5. Axial Ratio Bandwidth (ARBW) of the antenna is 231.5 MHz (5.8409-6.0724) GHz which is improved by 101.5 MHz compared to the antenna in [7]. VSWR (Voltage Standing Wave Ratio) curve is shown in Fig. 6. The VSWR value of this proposed antenna is less than 2 throughout the operating band (5.6256-6.3242) GHz, so it is considered suitable for most antenna applications. The simulated radiation efficiency is plotted in Fig. 7 and it is greater than 76% throughout the entire operating band. Fig.8 (a) and Fig.8 (b) depict the simulated radiation patterns at XZ and YZ plane, respectively. Good left-handed circular polarization has been observed at 5.95 GHz.

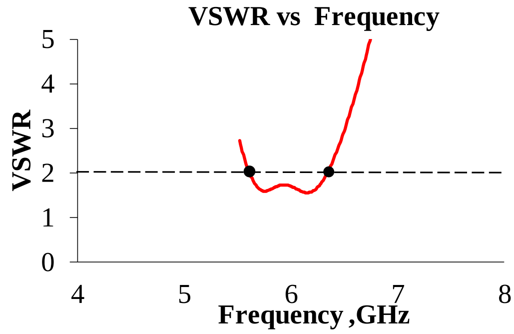


Fig. 6. VSWR vs Frequency curve.

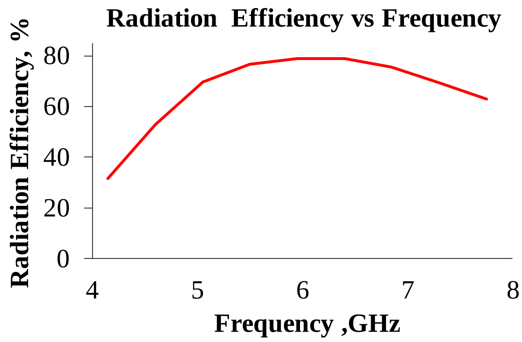


Fig. 7. Simulated radiation efficiency.

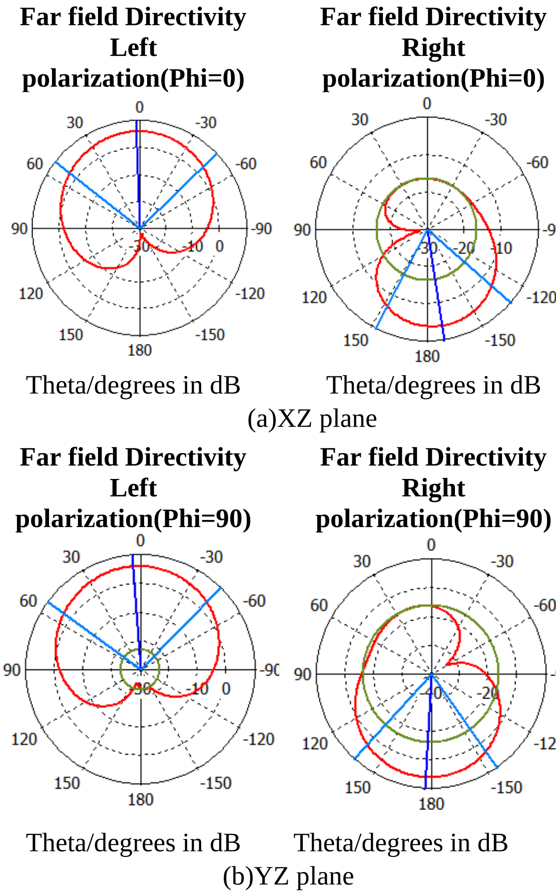


Fig. 8. Simulated radiation pattern at 5.95GHz.

The performance of the proposed defected ground based antenna is compared to the antenna without defected ground is shown in Table 5. Our proposed antenna is compared with other recently published works in Table 6 in terms of its size, BW, ARBW and gain. Our proposed antenna not only occupies smaller area but also shows improved gain in comparison to the other recently published state-of-arts.

4. CONCLUSION

An antenna has been presented with modified ground structure to increase the bandwidth. Simulated results show an impedance bandwidth of 11.69%, a gain of 4.98 dBiC at 6.4 GHz and radiation efficiency of greater than 76%. The proposed antenna is in compact size and low profile with high gain which can be easily incorporated with other devices working at the same frequency band for particular application. The proposed antenna is working from 5.6256 to 6.3242 GHz which is applicable for WLAN band of 5.9 GHz, Wi-Fi devices, weather radar systems, wireless applications and surveillance.

Table 5. Performance comparison of the CP antenna with and without DGS

Parameters	With DGS	Without DGS
Overall size(mm)	20×20×2.4	20×20×2.4
BW(MHz)	698.6	650
Gain(dBiC)	4.98	4.36
ARBW(MHz)	231.5	130
Radiation Efficiency (%)	>76	>72

Table 6. Performance comparison table

Ref.	f_{ZOR} (GHz)	Overall antenna size (mm)	BW (%)	ARBW (%)	Gain (dBiC)
[7]	5.5	20×20×2.4	11.55	2.34	4.36
[22]	2.504	42×42×4.5	12.7	2.345	3.97
[23]	--	45×41×1.6	61.81	--	2.74
[24]	7.5	30×30×1.6	11.77	--	6.61
[25]	22	4.2×4.2×0.127	60.77	--	4.198
[26]	0.95	250×250×1.6	18.3	18.3	8.4
[27]	3.22	26.8×30.6×.508	26.77	13.95	1.65
[28]	1.575	45×45×3.18	1.91	0.38	2.2
This work	5.95	20×20×2.4	11.69	3.88	4.98

5. REFERENCES

[1] S. Painam and C. Bhuma, "Miniaturizing a Microstrip Antenna Using Metamaterials and Metasurfaces," *IEEE Antennas Propag. Mag.*, vol. 61, pp. 91–135.

[2] S. K. Sharma and R. K. Chaudhary, "A Compact Zeroth-order Resonating Wideband Antenna with Dual-band Characteristics," *IEEE Antennas and Wireless Propagation Letters*,vol. 14, pp. 1670–1672, 2015.

[3] B. Park and J. Lee, "Omnidirectional Circularly Polarized Antenna Utilizing Zeroth-Order Resonance of Epsilon Negative Transmission Line,"*IEEE Transactions on Antennas and Propagation*, vol. 59, no. 7, pp. 2717–2721, 2011.

[4] C. Zhou, G. Wang, Y. Wang, B. Zong, and J. Ma, "CPW-Fed Dual-Band Linearly and Circularly Polarized Antenna Employing Novel CompositeRight/Left-Handed Transmission-Line," *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 1073–1076, 2013.

[5] S. Ko, B. Park, and J. Lee, "Dual-Band Circularly Polarized Patch AntennaWith First Positive and Negative Modes," *IEEE Antennas and Wireless Propagation Letters*,vol. 12, pp. 1165–1168, 2013.

[6] T. Cai, G. Wang, X. Zhang, and J. Shi, "Low-profile Compact Circularly-Polarized Antenna Based on Fractal Metasurface and Fractal Resonator," *IEEE Antennas and Wireless Propagation Letters* ,vol. 14, pp.1072-1076, 2015.

[7] M.Ameen and R. K. Chaudhary, "Metamaterial-based circularly polarised antenna employing ENG-TL with enhanced bandwidth for WLAN applications," *Electron. Lett.*, vol. 54, no. 20, pp. 1152–1154, 2018.

[8] R. Xu, J. Y. Li, K. Wei, and G. W. Yang, "Broadband rotational symmetry circularly polarised antenna," *Electron. Lett.*, vol. 52, no. 6, pp. 414–416, 2016.

[9] N. Kari, D. Seetharamdoo, J. M. Laheurte, and F. Sarrazin, "Circularly Polarized Electrically Small Antenna Using Chiral Metamaterials and Based on Characteristic Modes Theory," *14th Eur. Conf. Antennas Propagation, EuCAP 2020*, 2020.

[10] T. Ijiguchi *et al.*, "Circularly Polarized One-Sided Directional Slot Antenna With Reflector Metal for 5.8-GHz DSRC Operations,"*IEEE Antennas and Wireless Propagation Letters*, vol. 13, pp. 778–781, 2014.

[11] Q. Tan and F.-C. Chen, "Tri-Band Circularly Polarized Antenna Using A Single Patch," *IEEE Antennas Wirel. Propag. Lett.*, vol. 1225, no. c, pp. 1–1, 2020.

[12] J. I. Park *et al.*, "Modeling of a photonic bandgap and its application for the low-pass filter design," *Asia-Pacific Microw. Conf. Proceedings, APMC*, vol. 2, pp. 331–334, 1999.

[13] Y. Liu, T. Wang, P. Zhong, and S. Wang, "Cylindrical conformal broadband array antenna based on defective ground structure," *Proc. 2019 IEEE 4th Adv. Inf. Technol. Electron. Autom. Control Conf. IAEAC 2019*, no. Iaeac, pp. 382–385, 2019.

[14] D. Suhas and D. Kannadassan, "Single S-Shaped defected ground structure for dual-band band-stop and band-pass filter applications," *2019 IEEE MTT-S Int. Microw. RF Conf. IMARC 2019*, pp. 13–16, 2019.

[15] A. Gunjal and S.Kumar,"Gain Enhancement in U-Slotted Broadband Dual Circularly Polarized

Antenna for S-Band Radar Applications,”*2020 International Conference on Emerging Smart Computing and Informatics(ESCI),* vol. 4, pp. 124–128, 2020.

[16] C. Shekhar, A. Bhadauria, and M. Radhakrishna, “Application of 2D defected ground structures in microstrip lines,” *2013 IEEE Int. Conf. Electron. Comput. Commun. Technol. CONECCT 2013*, pp. 2–5, 2013.

[17] B. R. S. Reddy and D. Vakula, “Compact zigzag-shaped-slit microstrip antenna with circular defected ground structure for wireless applications,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 14, no. c, pp. 678–681, 2015.

[18] S. Sreepriya, N. George, and S. Amit, “A Multi-Resonant Microstrip Patch Antenna with Fractal Defected Ground Structure,” *1st Int. Conf. Adv. Technol. Intell. Control. Environ. Comput. Commun. Eng. ICATIECE 2019*, pp. 284–286, 2019.

[19] Wojciech Jan Krzysztofik and Thanh Nghia Cao,“Metamaterials in Application to Improve Antenna Parameters,”*Metamaterials and Metasurfaces*, Josep Canet-Ferrer, IntechOpen,pp. 67, November 5,2018.

[20] Balanis C. A.,“Antenna Theory: analysis and design” (John Wiley & Sons,USA,2007)

[21] N. Jahan, S. A. E. Ab Rahim, A. Barakat, T. Kaho, and R. K. Pokharel, “Design and Application of Virtual Inductance of Square-Shaped Defected Ground Structure in 0.18-μm CMOS Technology,” *IEEE J. Electron Devices Soc.*, vol. 5, no. 5, pp. 299–305, 2017

[22] S. Kotla, V. Shivani, M. Ashish, and S. Kumar, “Compact circularly polarized fractal patch antenna using defected ground structure,” *Proc. 2019 TEQIP - III Sponsored International Conference on Microwave Integrated Circuits, Photonics Wireless Networks (IMICPW),* Tiruchirappalli,India,pp. 29–33, 2019.

[23] R. Pandey, A. K. Shankhwar, and A. Singh, “Defected Ground Structured Wideband Antenna for RF Energy Harvesting,”*2020 4th International Conference on Trends in Electronics and Informatics(ICOEI),* pp. 288–291, 2020.

[24] R.K.Dash, P.Bikash Saha and D.Ghoshal, “Design of a Equally Spaced U shaped slotted Patch Antenna with Defected Ground Structure for Multiband Applications,” *2020 7th International Conference on Signal Processing and Integrated Networks (SPIN)*,pp. 267–272, 2020.

[25] S. K. Gupta and A. Bage, “A Compact, T-Slotted Wide Band Microstrip Antenna with Defected Ground Structure for Future 5G Communications,”*2020 URSI Regional Conference on Radio Science (URSI-RCRS),* no. 1, pp. 1–4, 2020.

[26] S.Konjunthes, W.Thaiwirot, and P.Akkaraekthalin, “A Wideband Circularly Polarized Stacked Patch Antenna With Truncated Corners Ground Plane for Universal UHF RFID Reader,”*2020 17th International Conference on Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*,pp. 84–87, 2020.

[27] K. E. Kedze, Y. Kim, and I. Park, “Compact Circularly Polarized E-Shaped Crossed-Dipole Antenna,”*2020 14th European Conference on Antennas and Propagation(EuCAP),* Copenhagen, Denmark,2020 pp. 2–5.

[28] K. Wei, J. Y. Li, L. Wang, R. Xu, and Z. J. Xing, “A New Technique to Design Circularly Polarized Microstrip Antenna by Fractal Defected Ground Structure,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 7, pp. 3721–3725, 2017.