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Ultra-wideband cross-polarization conversion metamaterial unit cell stable to incident angles at C-band

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***Abstract*—This paper presents left-handed metamaterial (LHM) unit cell deployed for a wideband cross polarization conversion metasurface (CPCM); it's made up of double circular split ring resonator (DCSRR) designed on an FR4 dielectric substrate backed by a metallic ground plane. the response of the metasurface is stable regardless of the angle of the incident wave which makes it a potential candidate for many practical applications at the C-band. The structure exhibits an efficient cross-polarization conversion (CPC) for different angles normally and oblique incident electromagnetic (EM) wave. The proposed unit cell exhibits negative refractive index over 6 GHz to 8 GHz. The structure behaves as cross polarization conversion (CPC) metasurface over full width at half maxima (FWHM) bandwidth of 4.5 GHz ranging from 6 GHz to 10.5 GHz. The proposed CPC metasurface maintains bandwidth enhancement up to 45° incident angles under both transverse electric (TE) and transverse magnetic (TM) polarizations. The structure is ultra-thin ($\sim \lambda/5 \times \lambda/5 \times \lambda/17$ with $\lambda = 35.7$ mm).**

Keywords—Metasurface, LHM, polarization conversion, metamaterials, SRR, unit cell, PCR, PC.

I. INTRODUCTION

Metasurfaces, are two-dimensional artificial structure composed of subwavelength elements, that can achieve the flexible manipulation of phase, magnitude, and polarization of EM waves. An EM wave is made of linked oscillating electric (E) and magnetic (H) field vectors, which are perpendicular to each other; direction of E field is conventionally assume as polarization of EM wave. Polarization is one of the most basic properties of EM waves, and this area have drawn much attention of researchers and research community. Conventional methods and techniques used for controlling polarization of an EM wave are wave plate, birefringence crystal etc [1]. Nowadays to control and manipulate the polarization status of EM waves include anisotropic metamaterial [2], chiral metamaterial [3] and metasurfaces [4]. Metamaterials are engineered materials which have extravagant EM properties not found in natural materials. Metamaterials can be produced by physically structuring normal materials properly not by their chemical composition [5]. Metasurfaces are planar metamaterials made of 2-dimensional array of sub-wavelength resonant or non resonant unit cells [5]. Due to tiny and compact sizes, metasurfaces have high potential applications towards frequency selective surfaces (FSSs) [5].

To control and manipulate the polarization of EM waves over a wide bandwidth and small distances, different metasurface based designs have been proposed in the literature. The proposed metasurface in [6] converts an x-polarized wave into a y-polarized wave and vice versa over a broad frequency range of 5.3–10.8 GHz. The polarization conversion efficiency reaches 100% at three plasmon resonances at 5.3, 7.8, and 10.3 GHz, respectively. Moreover, all three resonance frequencies can be controlled through the side lengths of the split ring resonators (SRRs). The cross-polarization conversion efficiency of the proposed metasurface is independent of the angle of incidence and polarization of the incoming wave due to the subwavelength unit cell size that is 0.1k at 5 GHz and symmetric structure of the SRR in the xy plane. In [7] R. DUTTA proposed a planar metasurface based multi-band reflective polarization converter for both linear to-linear and linear-to-circular or circular to linear polarization transformation, the proposed structure can convert a y/x-polarised incident electromagnetic wave to an x/y-polarised reflected electromagnetic wave in four frequency bands with polarization conversion ratio (PCR) over 95%.

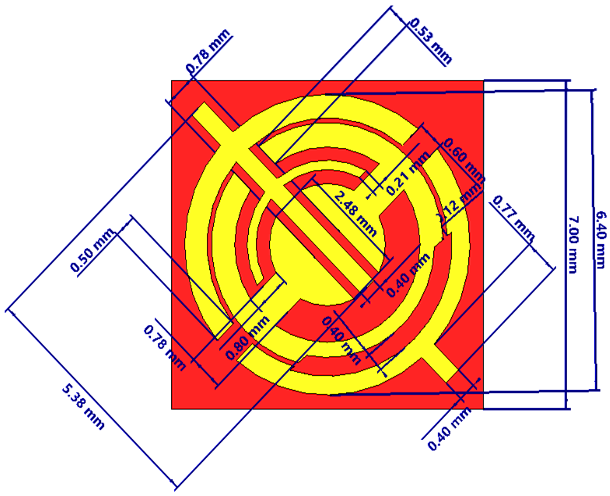
For LHM, we are focused in their response to electromagnetic fields. The most important application of LHM is to be used as a substrate or superstrate to improve the directivity and gain of antenna [9], [10], [11]. The other applications of LHMs are MTM-cloaking. The most attractive concept of LHM is the perfect lenses and near field imaging [12].

This paper aims to develop an electrically thin metasurface capable of broadening polarization conversion in the C-band frequency range. The design ensures high conversion efficiency, which remains consistent regardless of the incident wave's polarization. Additionally, the metasurface model exhibits stability against variations in the angle of incidence. Furthermore, assessments were conducted to verify the negativity of permittivity (ε) and permeability (μ), as well as the refractive index (η).

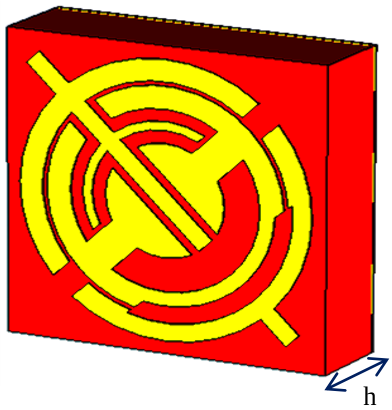
II. DESIGN OF THE STRUCTURE

The unit cell of the ultra-wideband metasurface is made of two circular shaped SRRs backed by copper plane, the outer SRR is double splitted, while the inner one is divided to accommodate the diagonal stripline between two inverted parallel microstrip radial stubs armatures as depicted in Fig.

1 (a). The DCSRR pattern is printed on a dielectric substrate. The dielectric is FR4 with thickness of h=2 mm, with dielectric constant of $\varepsilon_r = 4.3$ and 0.025 loss tangent. The proposed meta-material unit cell has a compact dimension of $7 \times 7 \times 2\ mm^3$. The optimized physical dimensions are depicted in Fig.1 (a)-(b).



(a)



(b)

Fig. 1. (a) top view of the unit cell, (b) perspective view of the unit cell,

III. SIMULATED RESULTS

The proposed structure is simulated using periodic boundary conditions and two EM solvers, the first one is based on finite elements and the second one uses finite integration technique. The whole structure was simulated taken into account the optimized dimensions. Where the floquet port is used as a plane wave source illuminating in the -Z-direction with an x-polarized electric field and periodic boundary conditions are applied along the X- and Y-directions to mimic an infinite periodic array for the S-parameter. Due to the complete copper backing of FR4 dielectric substrate, no incident electromagnetic wave gets transmitted (the bottom is a perfect electric conductor). If the co-polarized reflection from the structure is minimized, under that condition the cross-polarization reflection level can be enhanced.

To better interpret of this DCSRR unit cell, the co- and cross-polarization reflection coefficients of the infinite periodic unit cell are plotted in Fig. 2.(b)-(c) for normal incident wave where $|R_{xx}| = \frac{|E_{xr}|}{|E_{xi}|}$ and $|R_{yx}| = \frac{|E_{yr}|}{|E_{xi}|}$ represent the co- and cross polarization reflection coefficients for x-polarized incidence wave, respectively. In similar manner, $|R_{yy}| = \frac{|E_{yr}|}{|E_{yi}|}$ and $|R_{xy}| = \frac{|E_{xr}|}{|E_{yi}|}$ are co- and cross polarization reflection coefficients for y-polarized incidence wave, respectively. The polarization conversion ratio (PCR) used to describe the polarization conversion capability of the metasurface, which can be mathematically calculated using (1) [8]:

$$\mathrm{PCR} = \frac{|R_{yx}|^2}{|R_{yx}|^2 + |R_{xx}|^2} = \frac{|R_{xy}|^2}{|R_{xy}|^2 + |R_{yy}|^2} \qquad (1)$$

The criteria for the functionality of cross-polarization conversion (PCR > 90%), the co-components (R_{xx} and R_{yy}) should be less than -10 dB, and cross-components (R_{xy} and R_{yx}) must be closer to 0 dB.

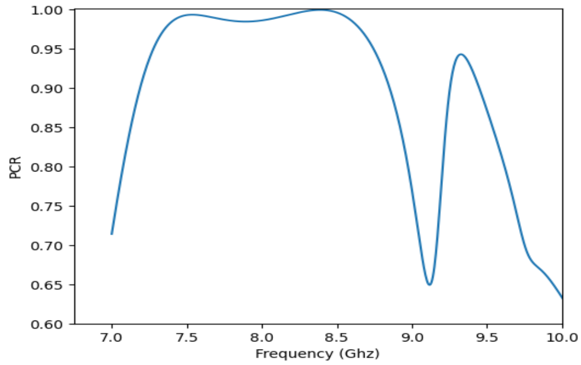
Since the incident wave completely reflects from the perfect electric conductor (PEC) bottom layer of the proposed structure, the denominator of (1) is $|R_{yx}|^2 + |R_{xx}|^2 = |R_{xy}|^2 + |R_{yy}|^2 = 1$ which means $\mathrm{PCR} = |R_{yx}|^2 = |R_{xy}|^2$. For simplicity, the unit cell is considered lossless, also. This means that the unit cell has good polarization conversion efficiency when $R^2{}_{xy}$ (or $R^2{}_{yx}$) has high value.

A. *Polarization Conversion under Normal Incidence*

The proposed unit cell can achieve polarization conversion of the incident wave to its cross-polarized one, with polarization conversion ratio (PCR) > 95 %. PCR of the designed DCSRR metasurface for normally incident EM waves is depicted in Fig.2. (a) At bandwidth of 7.5 GHz to 8.5 GHz, 99%-100% polarization conversion has been attained. Also, an excellent polarization conversion ratio is achieved, from 7.3 GHz to 8.7 GHz with PCR > 95% , the incident electromagnetic wave with x-polarization is completely converted into a y-polarized reflected wave and vice versa.

Based on extensive studies carried out on split ring resonators (SRR) in the literature, a comprehensive parametric and structural analysis of several DCSRR designs was performed and finally reached an optimized design that is shown in Fig.1. The enhancement of bandwidth resulted from the optimization of two primary archial slots. Additionally, the diagonal stripline was enlarged to fit snugly between the two stubs. This adjustment effectively reduced the co-polarization coefficients at resonant frequencies (7.55 GHz and 8.39 GHz) compared to previous configuration due to the minimized gap.

The simulated co-and cross-polarized reflection coefficients for normal incidence when the incident field is x-polarized are shown in Fig. 2(b)&(c). It is clear that the response is proximately the same for both solvers. We noticed that the co-polarized reflection coefficient is small than -10 dB, while the cross-polarized reflection coefficient is more than -3dB in the frequency band of 7.2 GHz−9.5 GHz. Notice that there are approximately same results for x-and y-polarized incidences due to the unit cell symmetry.



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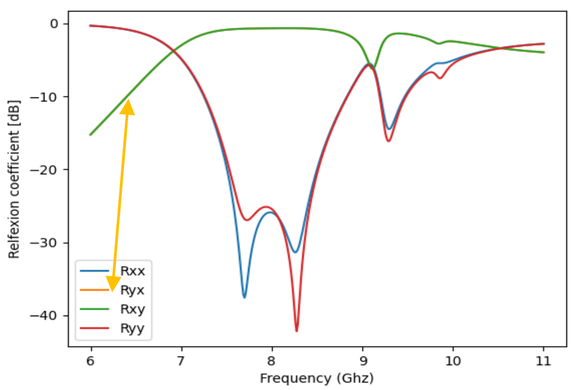

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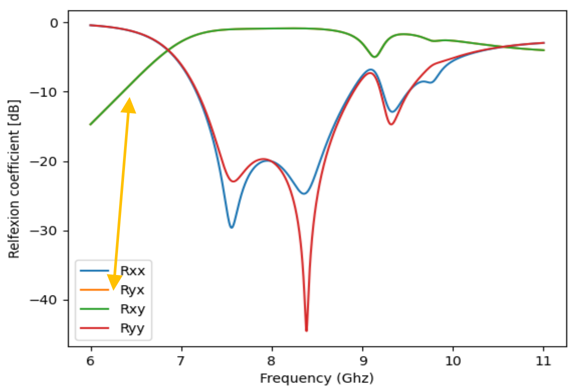
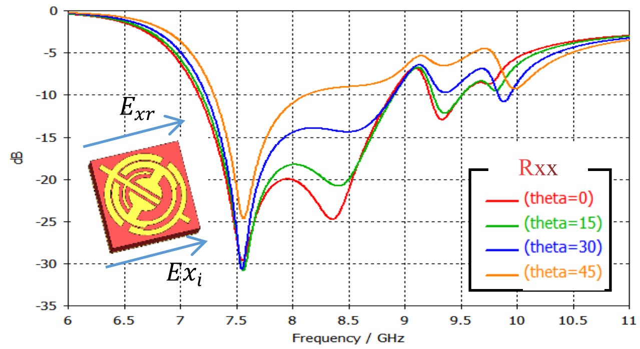


(c)

Fig. 2.(a) PCR, (b) solver one and (c) solver two simulated Co-polarized and cross polarized reflection coefficients when the incident field is x-polarized and y-polarized.

B. *Polarization Conversion under different angles of Incidence.*

In most of the practical scenarios, especially in the microwave frequency regime, EM waves may have arbitrary incidence angles. Therefore, it is of practical benefit for the metasurface to have stable response to the incidence angle. Therefore, we numerically investigate the oblique incidence response of the metasurface for both transverse electric (TE) polarization (the electric field of the incident wave is in the yz-plane) and transverse magnetic (TM) polarization (the electric field of the incident wave is in the xz-plane), in the frequency range of 7.2GHz–9.5GHz. It can be seen from Figs. 3(a) and 3. (b) that, for both TM and TE polarizations, the magnitude of co- and cross-polarized reflection coefficients, respectively, for different angles of incidence when the incident wave is x-polarized remains stable against the oblique incidence angle up to 45° in the frequency band mentioned above. The co- and cross-polarized reflection coefficients when the incident wave is y-polarized for different angles of incidence are shown in Figs. 3(c) and 3.(d), respectively. As can be seen from Fig. 3(d), the proposed design achieves a stable cross-polarized reflection coefficient also for y-polarized incident waves.



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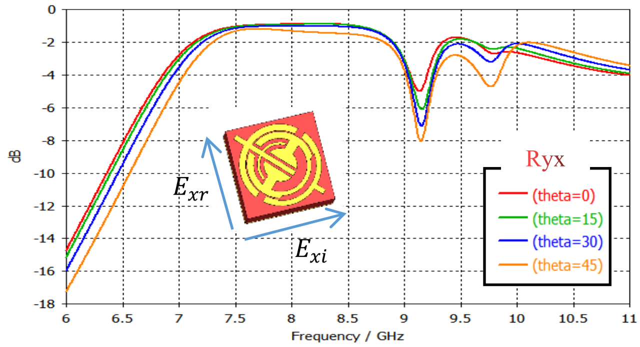

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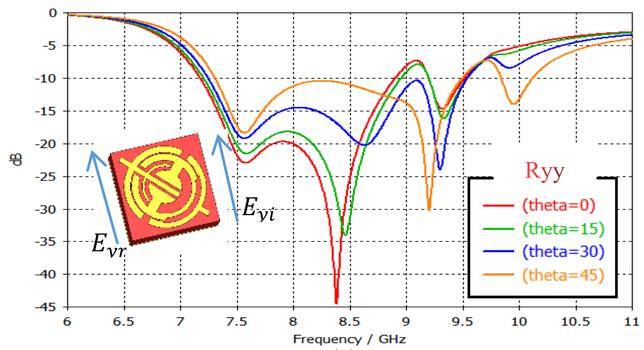

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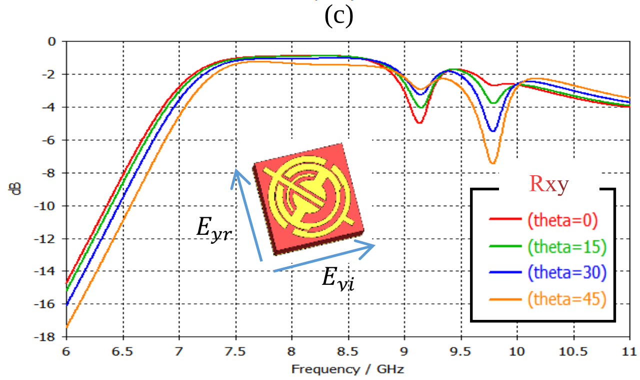

(d)

Fig. 3. (a) Co-polarized and (b) cross polarized reflection coefficients for x-polarized incident wave. (c) Co polarized and (d) cross-polarized reflection coefficient for the y-polarized incident wave.

C. Left-handed metamaterial characteristics.

The effective parameters of this proposed DCSRR metamaterial structure such as complex permittivity and complex permeability are extracted using a transfer matrix method [13]. We can retrieve values for the complex refractive index n and wave impedance z using below equations:

$$z = \pm\sqrt{\frac{(1+S_{11})^2+S_{21}{}^2}{(1-S_{11})^2+S_{21}{}^2}} \qquad (2)$$

$$n = \frac{1}{kh}\cos^{-1}\left[\frac{1}{2S_{21}}\left(1-S_{11}{}^2+S_{21}{}^2\right)\right] \qquad (3)$$

$$\varepsilon = {}^{n}/_{z} \quad \text{and} \quad \mu = nz \qquad (4)$$

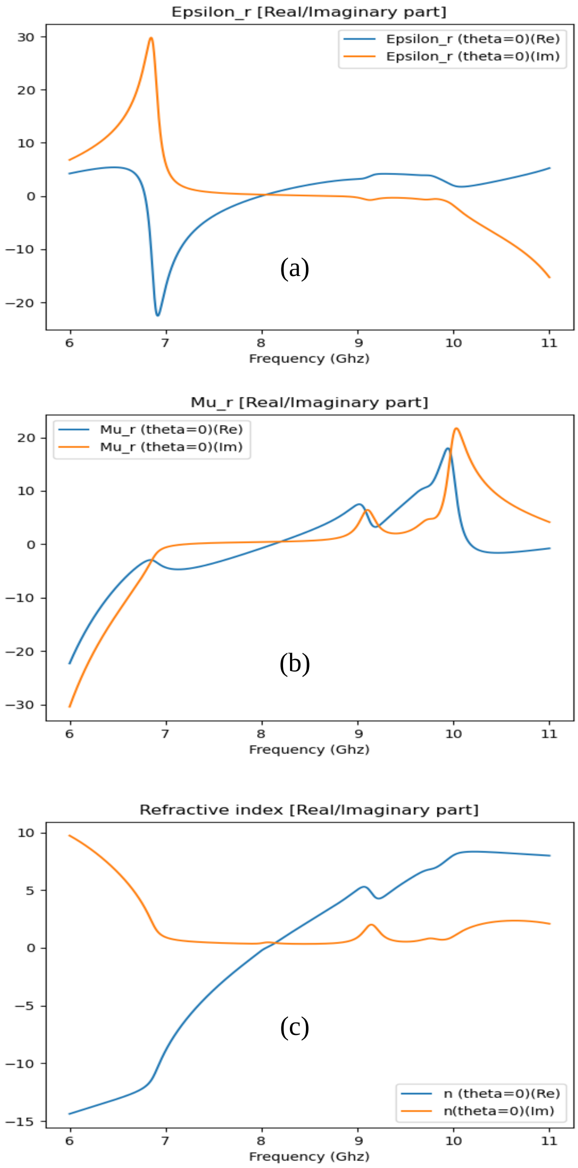

Fig. 4. (a) permittivity, (b) permeability, and (c) refractive index of the unit cell structure.

Where z is the effective impedance, k is the wave vector, μ is effective permeability, ε is effective permittivity, h is the thickness of substrate, and n is the refractive index. S_{21} and S_{11} represent the transmission and reflection coefficients of the simulated unit cell structure. This unit cell is a left-handed metamaterial (LHM) since resulting in negative permeability (μ) and permittivity (ε) with a stable negative refractive index. The negative permeability (μ) of the reported unit cell is from 6 GHz to 8.12 GHz and from 10.17 GHz to 11 GHz. The negative permittivity (ε) of the unit cell is from 6.78 GHz to 8 GHz as shown in Fig.4. (a),(b). The negative refractive index will appear if the permittivity and permeability of a unit cell remain negative simultaneously. Fig.4.(c) demonstrates the effective refractive index (n) from 6 GHz to 8 GHz, which represents the proposed unit cell as having negative metamaterial characteristics.

IV. CONCLUSION

The proposed metasurface exhibits cross-polarization conversion efficiency that remains consistent regardless of the angle of incidence or the polarization of the incoming wave. This is achieved through a sub-wavelength unit cell size of 0.2λ at 8.4 GHz and a symmetric structure of the SRR in the xy plane. The wide bandwidth for polarization conversion and its angular stability position the designed metasurface as a promising candidate for modern polarization-control devices.

REFERENCES

[1] Li C, Liu X, Liu G, et al. Experimental demonstration of illusion optics with “external cloaking” effects[J]. Applied Physics Letters, 2011, 99(8): 084104.

[2] M. I. Khan, F. A. Tahir and R. Saleem, "An angularly stable tri-band reflective cross-polarization conversion anisotropic metasurface," 2017 Progress in Electromagnetics Research Symposium - Fall (PIERS - FALL), Singapore, 2017, pp. 1735-1737, doi: 10.1109/PIERS-FALL.2017.8293416.

[3] M. Bakir et al., "Chiral Metamaterial Based Microfluidic Sensor," 2018 12th International Congress on Artificial Materials for Novel Wave Phenomena (Metamaterials), Espoo, Finland, 2018, pp. 43-45, doi: 10.1109/MetaMaterials.2018.8534061.

[4] S. Yang, S. Huang, Y. Yuan and Q. Wu, "A Chiral Metasurface for Vortex Wavefront Manipulation in Microwave Region," 2023 IEEE International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM), Harbin, China, 2023, pp. 156-158, doi:10.1109/iWEM58222.2023.10234847.

[5] Abdullah, B. Khan, S. Ullah and B. Kamal, "Design and Analysis of a Wide Band Cross-Polarization Converting Metasurface," 2019 International Conference on Communication Technologies (ComTech), Rawalpindi, Pakistan, 2019, pp. 9-12, doi: 10.1109/COMTECH.2019.8737795.

[6] Muhammad Ismail Khan, Qaisar Fraz, Farooq A. Tahir; Ultra-wideband cross polarization conversion metasurface insensitive to incidence angle. J. Appl. Phys. 28 January 2017; 121 (4): 045103. https://doi.org/10.1063/1.4974849.

[7] R. Dutta, J. Ghosh, Z. Yang and X. Zhang, "Multi-Band Multi-Functional Metasurface-Based Reflective Polarization Converter for Linear and Circular Polarizations," in IEEE Access, vol. 9, pp. 152738-152748, 2021, doi: 10.1109/ACCESS.2021.3128190.

[8] S. Bhattacharyya, "An ultra-thin wide-angle cross polarization conversion metasurface with enhanced bandwidth," 2017 International Symposium on Antennas and Propagation (ISAP), Phuket, Thailand, 2017, pp. 1-2, doi: 10.1109/ISANP.2017.8228886.

[9] H. Attia, L. Yousefi, M. M. Bait-Suwailam, M. S. Boybay and O. M. Ramahi, "Enhanced-Gain Microstrip Antenna Using Engineered Magnetic Superstrates," in IEEE Antennas and Wireless Propagation Letters, vol. 8, pp. 1198-1201, 2009, doi: 10.1109/LAWP.2009.2035149.

[10] D. Jin, B. Li and J. Hong, "Gain improvement of a microstrip patch antenna using metamaterial superstrate with the zero refractive

index," 2012 International Conference on Microwave and Millimeter Wave Technology (ICMMT), Shenzhen, China, 2012, pp. 1-3, doi: 10.1109/ICMMT.2012.6230150.

[11] B. Garg and P. K. Singhal, “DESIGN AND CHARACTERIZATION OF COMPACT MICROSTRIP PATCH ANTENNA USING ‘SPLIT RING’ SHAPED METAMATERIAL STRUCTURE,” International Journal of Electrical and Computer Engineering (IJECE), vol. 2, no. 5, Oct. 2012, doi: https://doi.org/10.11591/ijece.v2i5.788.

[12] M. Lapine and S. Tretyakov, "Contemporary notes on metamaterials", IET Microw. Antennas Propag., vol. 1, no. 1, pp. 3-11, Feb. 2007.

[13] D. R. Smith, D. C. Vier, T. Koschny, and C. M. Soukoulis, “Electromagnetic parameter retrieval from inhomogeneous metamaterials,” Phys. Rev. E, Stat. Phys. Plasmas Fluids Relat. Interdiscip. Top., vol. 71, pp. 036617-1–036617-11, Mar. 2005.