Progress In Electromagnetics Research Letters, Vol. 97, 61–68, 2021

Design of Low Profile Multiband Reflective Polarization Converter for Both Linear and Circular Polarized Waves

Surya Durga Padmaja Bikkuri[1, *] and Sudhakar Alapati[2]

Abstract—This paper presents a multifunctional metasurface based reflective polarization converter, to convert the polarization of incident electromagnetic wave in three adjacent frequency bands. In the first band linear to circular polarization conversion and in the remaining two bands linear to orthogonal polarization conversion is achieved. The designed metasurface consists of two circular split rings and a star-shaped split resonator which is fabricated on a metal-backed dielectric substrate. From the simulation results, it is evident that the orthogonal linear polarization conversion band is observed at 9.2 GHz and 12.8 GHz with a polarization conversion ratio of more than 92%. Similarly, it is identified that the same metasurface converts the incident linear polarized wave to circularly polarized wave at 7.3 GHz. Furthermore, the proposed metasurface maintains the handedness of the circularly polarized incident wave at 9.2 & 12.8 GHz frequency upon reflection. The proposed multifunctional polarization converter has a simple planar geometry and low profile which can be used in many applications, such as reflector antennas, imaging systems, remote sensors, and radiometers.

1. INTRODUCTION

In recent times, artificial engineered surfaces, such as high impedance surface (HIS), frequency selective surface (FSS), and metasurface, have attained huge interest in the domain of electromagnetic engineering. Metasurface is one type of artificial sub-wavelength structure and consists of the periodic arrangement of dielectric and metal, which exhibits the distinctive characteristics that cannot be achieved through natural materials. This type of surface has the ability to manipulate the properties of the electromagnetic wave, such as the direction of propagation, phase, amplitude, and polarization [1, 2]. Besides these, engineered surfaces are also used for filtering [3, 4]. Due to these exotic properties, metasurface finds its way in several advanced application like absorber [5], cloak [6], polarization converter [7], etc.

Polarization Converter (PC) is a device or surface which can transform the polarization of an incident Electromagnetic (EM) wave. Traditionally, to convert the polarization of EM wave Faraday Effect and optical activity of crystals are used [8, 9]. However, these techniques suffer from narrow frequency response, bulkiness of the applied structure, and incident angle-dependent response. Due to these drawbacks, researchers have focused on the design of metasurface based PC, which can manipulate the polarization of incoming EM wave either in transmission mode [10] or in reflection mode [11]. A transmissive multilayer PC consists of metallic patches, rings, and Jerusalem cross and is reported [12]. However, this multilayer structure is relatively bulky and suffers from the fabrication error due to misalignment between layers. Besides this, multilayer and high profile transmissive type PC structures are affected by the less transmission efficiency due to the dielectric losses in the substrate. Due to

Received 26 February 2021, Accepted 31 March 2021, Scheduled 6 April 2021
* Corresponding author: Surya Durga Padmaja Bikkuri (padmaja1128@gmail.com).
[1] Department of Electronics and Communication Engineering, Acharya Nagarjuna University, Guntur, Andhra Pradesh, India. [2] Department of Electronics and Communication Engineering, R.V.R & J.C College of Engineering, Guntur, Andhra Pradesh, India.

this drawback, the reflection mode PC became more popular for controlling the polarization of EM wave [13].

In the reflective type of polarization converter, recently, several geometries have been reported in the literature [14–22]. A copper wire based 3D geometry is proposed in [14] to convert the polarization of the EM wave in a single frequency region. The non-planar geometry of the structure and narrow frequency of operation have extremely limited their practical applications. To provide a solution for bandwidth limitation, broadband polarization converter structures, such as double U-shaped structure [15], S shaped structure [16], and V shaped structure [17], are designed. Besides this wide band PC, for several advanced application, multi-band polarization converters also get attention [18, 19]. An extended double split ring based structure is reported [18] to convert the polarization of the incident EM wave in three frequency bands. An alternative design based on elliptical disk ring is reported by lin et al. [19] to manipulate the polarization state of incident EM wave. However, these polarization converters are only capable of transforming the polarization of the incident wave to its orthogonal polarization. For certain applications, we need to convert a linear polarized (LP) wave to circular polarization (CP) and vice versa. A handful of works are reported in literature to convert a linearly polarized wave to circularly polarized wave. A layer by layer structure [20] is developed to convert the wave from linear to circular polarization. Another anisotropic metamaterial based multilayer structure is reported [21] to perform circular polarization conversion. To overcome the drawback of a multi-layer structure [22], a planer metasurface is reported to convert the polarization of the reflected wave. However, none of the structures could convert the incident linearly polarized wave to orthogonal and circular polarization in different frequency bands.

Getting motivation from the above requirement, in our paper a single layer anisotropic metasurface to achieve different types of polarization conversion, such as LP-LP and LP-CP, in different frequency bands is designed. Here, the incident linearly polarized wave is converted to circularly polarized wave in 7.3 GHz frequency band, while it is transformed linear to its orthogonal polarization at 9.2 GHz and 12.8 GHz frequency band. Additionally for circularly polarized wave incidence at these particular frequency bands, reflected wave maintains its polarization. Thus, the proposed PC can act as a meta-mirror for CP incident wave. For the validation of simulated result, the structure is fabricated, and measurement is carried out. A good agreement is observed between the measured and simulated results which confirms the practicability of the structure.

2. THEORETICAL ANALYSIS

Generally, when an EM wave incidents on any surface, reflection, transmission, and absorption are the three fundamental phenomenons which are observed. During the process of reflection from a metasurface, the wave is reflected into two components. One of the components has the same polarization of the incident wave called co polarized reflection, and the other has orthogonal polarization of incident wave named as cross polarization reflection. The relation between the electric field of incident wave $E^i = \begin{bmatrix} E_x^i & E_y^i \end{bmatrix}^T$ and the reflected wave $E^r = \begin{bmatrix} E_x^r & E_y^r \end{bmatrix}^T$ can be expressed as

$$\begin{bmatrix} E_x^r \\ E_y^r \end{bmatrix} = [R] \begin{bmatrix} E_x^i \\ E_y^i \end{bmatrix} \tag{1}$$

where $[R]$ is the reflection coefficient matrix and defined as

$$[R] = \begin{bmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{bmatrix} \tag{2}$$

where R_{xx} and R_{yy} are the co-polarized reflection coefficients, and R_{xy} and R_{yx} are cross-polarized reflection coefficients. It can be stated that for an ideal PC

$$R_{xx} \approx R_{yy} \approx 0 \quad R_{xy} \approx R_{yx} \approx 1. \tag{3}$$

To measure the polarization conversion ability of a metasurface, Polarization Conversion Ratio (PCR) is defined for both x and y polarized wave incidences.

$$\text{PCR} = \frac{|R_{yx}|^2}{|R_{yx}|^2 + |R_{xx}|^2} \tag{4}$$

For understanding the polarization of the reflected wave, besides the PCR it is required to compute relative phase exhibited by the structure. The relative phase is defined as

$$\Delta\varphi = \varphi_{yx} - \varphi_{xx} \tag{5}$$

where $\varphi_{xx} = \arg(R_{xx})$ and $\varphi_{xy} = \arg(R_{xy})$. For orthogonal polarization conversion, the PCR should be nearly equal to 1, and the relative phase should be $n\pi$ when $n = 0, \pm1, \pm2, \ldots$. Similarly for linear to circular polarization conversion, the PCR should be 0.5, and the relative phase should be $n\pi/2$ where n is an odd multiple [23].

Besides this, if the wave which incidents on the metasurface is circularly polarized, then reflection magnitude and phase differ from that of linearly polarized wave. The transformed reflection coefficients in rectangular coordinates of a circularly polarized wave are represented as described in [23].

$$R_{\mathrm{CP}} = \begin{bmatrix} R_{rr} & R_{rl} \\ R_{lr} & R_{ll} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} R_{xx} - R_{yy} - i(R_{xy} + R_{yx}) & R_{xx} + R_{yy} + i(R_{xy} - R_{yx}) \\ R_{xx} + R_{yy} - i(R_{xy} - R_{yx}) & R_{xx} - R_{yy} + i(R_{xy} + R_{yx}) \end{bmatrix} \tag{6}$$

The subscripts 'r' and 'l' represent right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP), respectively. The individual coefficients, i.e., R_{rl} indicates the reflection coefficient when the incident wave is LHCP, and the reflected wave is RHCP; R_{lr} indicates the reflection coefficient when the incident wave is RHCP, and the reflected wave is LHCP. Similarly R_{rr} and R_{ll} indicate the reflection coefficients when both the incident and reflected waves are RHCP or LHCP, respectively. Certain metasurfaces exhibit this type of behavior where $R_{rr} = 1$ or $R_{ll} = 1$ [24] indicates that the polarization is maintained by the designed metasurface. This polarization maintaining ability is defined as polarization maintaining ratio (PMR) for a wave which incidents on a metasurface surface with circular polarization.

$$\mathrm{PMR} = \frac{|R_{rr}|^2}{|R_{lr}|^2 + |R_{rr}|^2} \tag{7}$$

From the above analysis it can be stated that the PMR for circularly polarized wave incidence is the same as PCR in orthogonal polarization conversion bands.

3. DESIGN METHODOLOGY

In the following section, the geometry of our proposed unit cell is discussed. The artistic rendering of the proposed metasurface with incident and reflected EM wave is shown in Fig. 1(a). If the polarization of the incident electromagnetic wave over the metasurface is along the x direction, the reflected wave at certain frequency band is in circular polarization in nature, and in other frequency bands it is polarized along y direction. Thus, this single metasurface can be used to convert linearly polarized wave to its orthogonal polarization and circular polarization in different frequency regions. The unit cell of the proposed metasurface is shown in Fig. 1(b). The unit cell is composed of a two concentric circular split ring structure and a star with slit. This metallic texture is fabricated over the top layer of the dielectric substrate. The bottom side of the substrate is backed by a conducting ground plane to restrict the transmission of electromagnetic wave. The substrate has a dielectric constant of 4.4 and loss tangent of 0.02 with a thickness of 1.6 mm. The electric conductivity of the copper layer is set to $\sigma = 5.8 \times 10^7$ S/m. The optimized geometrical parameters of the structure are $a = 11$ mm, $r_1 = 5.5$ mm, $r_2 = 4.5$ mm, $s = 0.5$ mm, and $g = 0.5$ mm.

For analyzing the electromagnetic property of the designed metasurface, the unit cell is simulated in the ANSYS HFSS with the periodic boundary conditions along the x and y directions as shown in Fig. 1(c). To get a clear understanding of our proposed geometry, a step by step evolution procedure is also exhibited in Fig. 1(d). The outer split ring and inner split ring of the structure are termed as MS_1 and MS_2, respectively, whereas the star-shaped structure is named as MS_3 in Fig. 1(d). The co-polarized and cross-polarized reflection coefficients of each of the metasurface, i.e., MS_1, MS_2, and MS_3, are shown Fig. 2(a). It is observed that MS_1 provides orthogonal polarization conversion at frequency 8.88 GHz. Similarly MS_2 and MS_3 provide orthogonal polarization conversion in 10.98 GHz, 6.35 GHz and 12.9 GHz, 7.7 GHz frequency bands, respectively. Thus, it is expected that merging of all the three metasurfaces provides multiband polarization converter. In Fig. 2(b), the plot of co- and cross-polarization reflection coefficients of the final structure are depicted. Polarization conversion ratio and

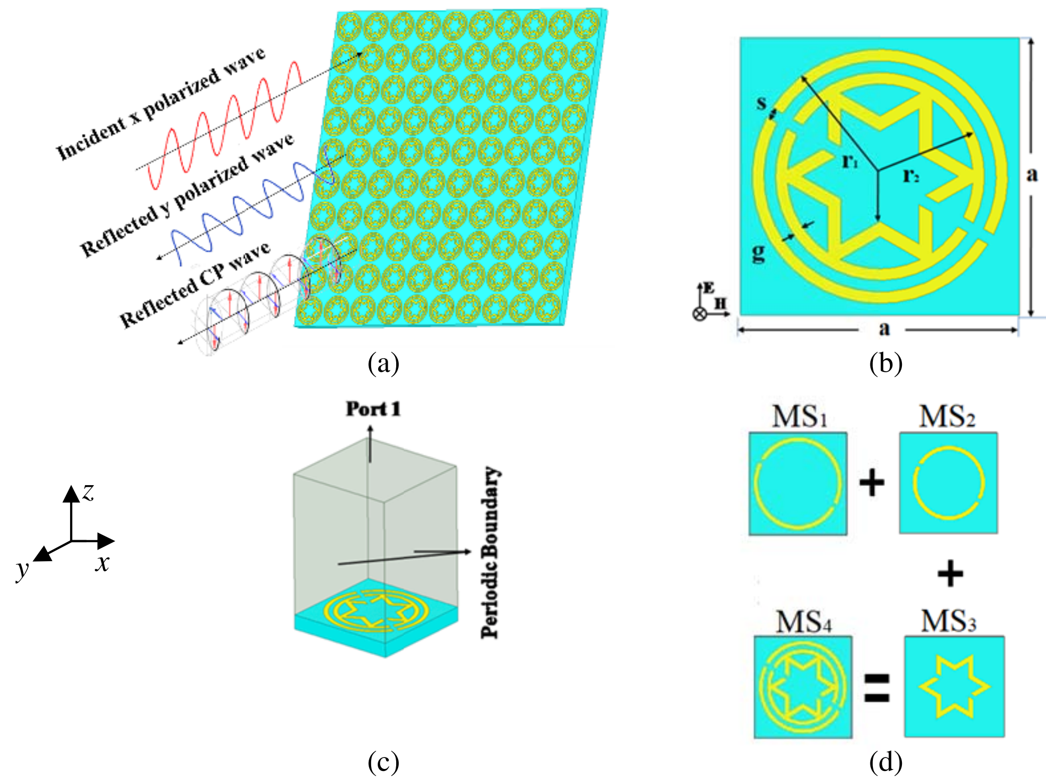


Figure 1. The proposed metasurface. (a) Artistic rendering of metasurface with incident EM wave 10×10 metasurface. (b) Unit cell of the structure. (c) Simulation setup. (d) Step by step evolution of unit cell.

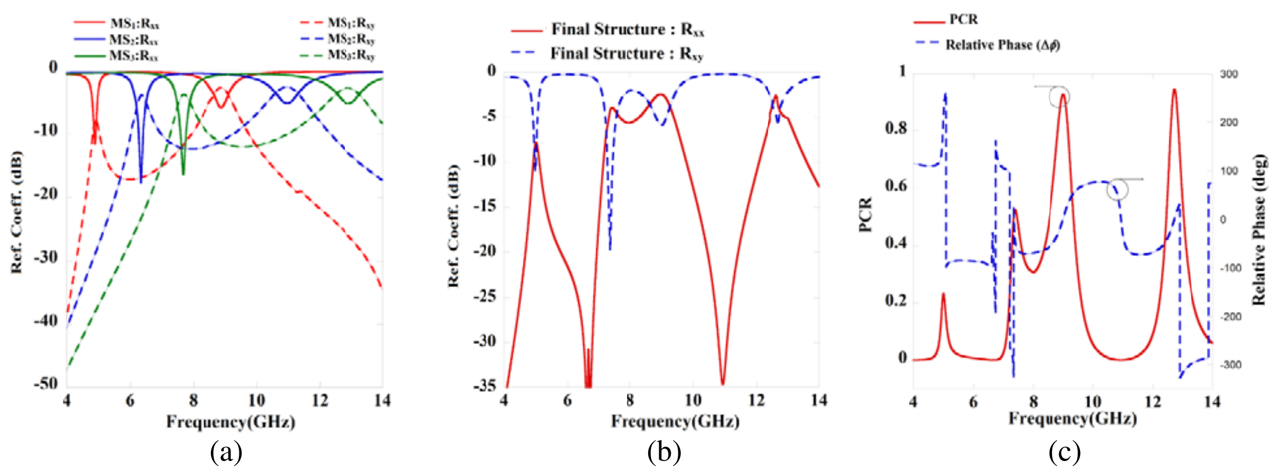


Figure 2. Characteristics of the PCR structure. (a) Co & Cross polarization reflection of the metasurfaces MS_1, MS_2, and MS_3. (b) Co & Cross polarization reflection of final structure. (c) PCR and relative phase of the final structure.

relative phase of the designed metasurface in three adjacent bands are shown in Fig. 2(c). As expected, the PCR at 9.2 GHz and 12.8 GHz frequencies is more than 90%. Moreover, it is observed that at these two frequency bands the relative phase ($\Delta\varphi$) of the metasurface is around 0°. Thus, at these two frequency bands the proposed metasurface has the capability to convert the polarization of the incident wave to its orthogonal polarization. In addition, one more frequency band with PCR of 50% at 7.3 GHz is noticed. At this particular frequency band, the relative phase of the metasurface is 90° as shown in Fig. 2(c). This phenomenon indicates that at 7.3 GHz frequency band LP wave is converted to CP wave. Therefore, from the above discussion it can concluded that the designed metasurface succeeded in achieving both linear to orthogonal and linear to circular polarization conversions at different frequency regions.

For the further evaluation of the polarization conversion performance, axial ratio (AR) and ellipticity of the reflected wave are calculated.

$$\mathrm{AR} = \left(\frac{|R_{xx}|^2 + |R_{yx}|^2 + \sqrt{a}}{|R_{xx}|^2 + |R_{yx}|^2 - \sqrt{a}} \right)^{1/2} \tag{8}$$

where $a = |R_{xx}|^4 + |R_{yx}|^4 + 2|R_{xx}|^2|R_{yx}|^2 \cos(2\Delta\varphi_{xy})$. Particularly to identify the polarization of the wave reflected by the metasurface, AR is an ideal measure. If AR of the electromagnetic wave at particular frequency is less than 3 dB, the polarization of the wave is circular in nature. On the other hand, higher AR value indicates linear polarization. In Fig. 3(a), we plot the AR for our designed metasurface, and it is found that at 7.54 GHz, the AR is around 0 dB indicating CP wave. To understand the handedness of the reflected circularly polarized wave we need to plot the ellipticity. The ellipticity is defined as

$$e = \frac{2|R_{xx}||R_{yx}|\sin(\Delta\varphi)}{|R_{xx}|^2 + |R_{yx}|^2} \tag{9}$$

If the ellipticity is +1, polarization of the wave is right-hand circularly polarized (RHCP) whereas if the ellipticity is −1, the polarization is left-hand circular polarization (LHCP) [23]. The result of ellipticity of the proposed metasurface is presented in Fig. 3(b). It is observed that at 7.3 GHz the ellipticity is −1, so it indicates the reflected wave in LHCP in nature.

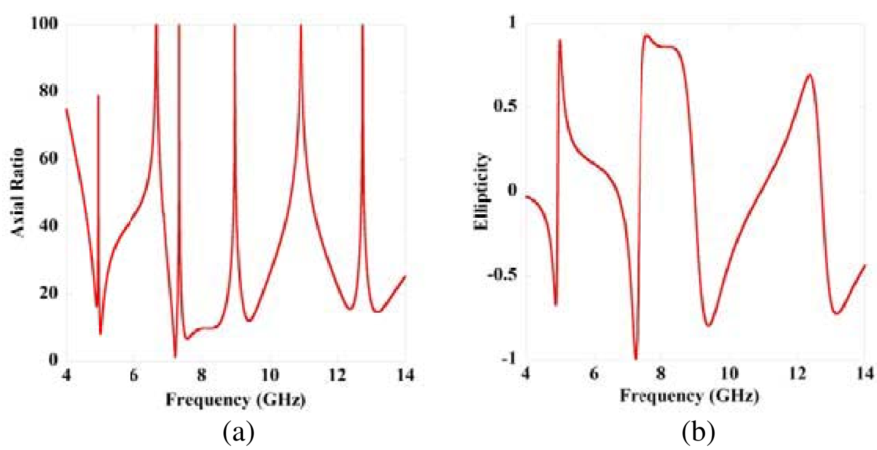
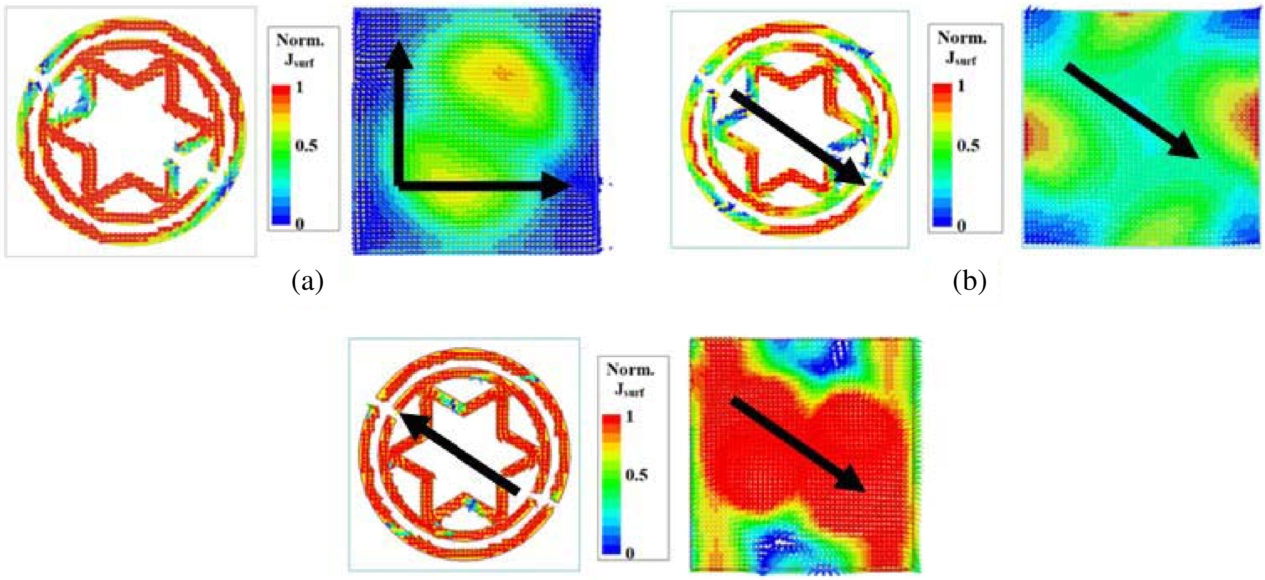


Figure 3. (a) Axial ratio of the final structure. (b) Ellipticity of the final structure.

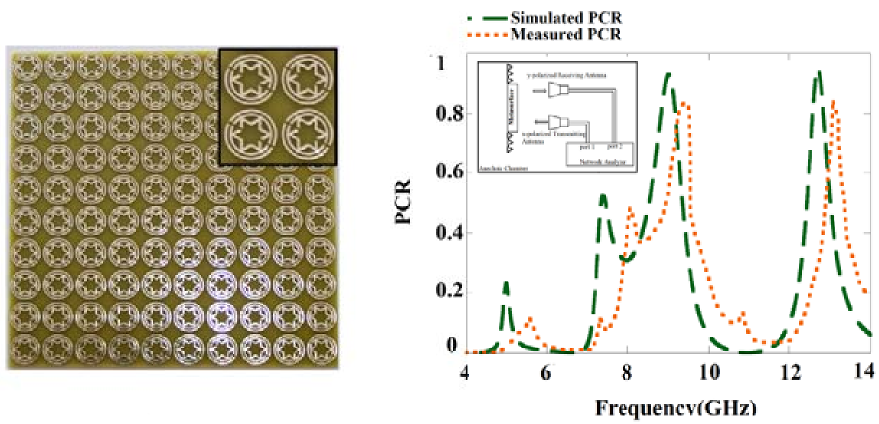
To clearly understand the mechanism of polarization conversion, it is required to analyze the surface current on the top and bottom layers of the metasurface at the desired frequency regions. The surface current distribution at 7.3 GHz frequency for both the planes is shown in Fig. 4(a). As mentioned earlier, at this frequency band, linearly polarized wave is converted to circularly polarized wave. In the surface current distribution plot, two orthogonal components of the surface currents are clearly observed which indicate the circular polarization behavior of the reflected wave [25]. In Figs. 4(b) and 4(c), surface current distribution for the orthogonal polarization conversion bands is also exhibited. The distributions of parallel and anti-parallel currents in the top and bottom planes indicate the occurrence of electric and magnetic resonances in the structure. From Figs. 4(b) and 4(c) we can conclude that at 9.3 GHz the structure behaves as an electric resonator, and at 12.8 GHz it behaves as a magnetic resonator.

To validate the methodology, we fabricate our prototype and measure the reflection coefficients inside an anechoic chamber. The 10 × 10 array of the fabricated prototype is depicted in Fig. 5(a) as



(a) (b) (c)

Figure 4. Surface current distribution at (a) 7.3 GHz, (b) 9.2 GHz, (c) 12.8 GHz.



(a) (b)

Figure 5. (a) Fabricated metasurface prototype. (b) Simulated and measured PCR. Inset: Schematic for measurement setup.

mentioned in [17], and two horn antennas and vector network analyzer (VNA) are used to measure the co-polarization and cross-polarization reflection coefficients. By these measured reflection coefficients, the PCR of our structure is computed. For comparison, the measured PCR along with the simulated results is shown in Fig. 5(b). The simulated results are verified by the experimental ones. The slight variation in the measured data is due to fabrication tolerance and finite size of the metasurface.

A comprehensive comparison based on the polarization conversion performance between the proposed metasurface and other reported structures is presented in Table 1. It is evident that the present research provides both linear to orthogonal linear and linear to circular polarization conversion bands in different frequency regions. It should be noted that in [22] two different types of polarization conversion, i.e., LP-LP and LP-CP, are achieved. However, this structure is a multilayer structure with the overall thickness of 3 mm. Due to this high profile nature of this structure, it may not be suitable for different advance applications. In this work, with the help of simple planar and low profile geometry, two LP-LP conversion and one LP-CP conversion bands are achieved.

Table 1. Comparison of the proposed with the earlier reported works.

Ref	No of Bands		Operating Frequency		Thickness
	LP-LP	LP-CP	LP-LP (GHz)	LP-CP (GHz)	
[14]	1		2.65		2 mm
[26]	2		15 & 17		1.6 mm
[22]	1	2	17.4–18.9	9.1–16.5 & 20–25.4	3 mm
[27]	1		6.8–9.7		3.2 mm
Proposed Work	2	1	9.2, 12.8	7.3	1.6 mm

4. CONCLUSIONS

In this paper, a single layer reflection based polarization converter that converts linearly polarized wave to its orthogonal and circular polarization in different frequency bands is presented. By introducing a double circular split ring structure and a split star-shaped resonator, two linear to linear and one linear to circular polarization conversion bands are obtained. To verify this multifunctionality regarding the polarization conversion, a sample of the polarization converter is fabricated. Both the simulated and measured results in the microwave frequency show that the proposed metasurface can be used for manipulating the polarization of the electromagnetic wave at three desired frequency regions. Due to the simple and low profile characteristics, this multifunctional polarization converter can play its role in different applications like reflect arrays, RCS reduction, and microwave imaging.

REFERENCES

1. Caloz, C. and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*, John Wiley & Sons, 2005.
2. Alkurt, F. O., M. Karaaslan, M. Karaaslan, M. Furat, E. Unal, and O. Akgol, "Monopole antenna integrated cavity resonator for microwave imaging," *Optical Engineering*, Vol. 60, No. 1, 013106, 2021.
3. Nazeri, A., et al., "A reflection-only method for characterizing PEC-backed anisotropic materials using waveguide higher order modes," *International Journal of RF and Microwave Computer-Aided Engineering*, Vol. 30, No. 10, e.22340, 2020.
4. Mahmud, R. H., H. N. Awl, Y. I. Abdulkarim, M. Karaaslan, and M. J. Lancaster, "Filtering two-element waveguide antenna array based on solely resonators," *AEU-International Journal of Electronics and Communications*, Vol. 121, 153232, 2020.
5. Landy, N. I., S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "A perfect metamaterial absorber," *Physical Review Letters*, Vol. 100, No. 20, 1–6, 2008.
6. Ghosh, J. and D. Mitra, "Restoration of antenna performance in the vicinity of metallic cylinder in implantable scenario," *IET Microwaves, Antennas & Propagation*, Vol. 14, No. 12, 1440–1445, 2020.
7. Yang, D., H. Lin, and X. Huang, "Dual broadband metamaterial polarization converter in microwave regime," *Progress In Electromagnetics Research Letters*, Vol. 61, 71–76, 2016.
8. Hao, J., Y. Yuan, L. Ran, T. Jiang, J. A. Kong, C. T. Chan, and L. Zhou, "Manipulating electromagnetic wave polarizations by anisotropic metamaterials," *Physical Review Letters*, Vol. 99, 063908 1–4, 10, 2007.
9. Meissner, T. and F. J. Wentz, "Polarization rotation and the third Stokes parameter: The effects of spacecraft attitude and Faraday rotation," *IEEE Transactions on Geoscience and Remote Sensing*, Vol. 44, No. 3, 506–515, 2006.

10. Baena, J. D., A. P. Slobozhanyuk, J. D. Ortiz, and P. A. Belov, "Linear to circular polarization converters based on self-complementary metasurfaces," *IEEE 2014 8th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics*, 43–45, Denmark, Europe, August 2014.
11. Khan, M. I., Q. Fraz, and F. A. Tahir, "Ultra-wideband cross polarization conversion metasurface insensitive to incidence angle," *Journal of Applied Physics*, Vol. 121, No. 4, 045103, 2017.
12. Zhang, F., G. M. Yang, and Y. Q. Jin, "Microwave polarization converter with multilayer metasurface," *IEEE 14th European Conference on Antennas and Propagation (EuCAP)*, 1–4, March 2020.
13. Khan, B., B. Kamal, S. Ullah, I. Khan, J. A. Shah, and J. Chen, "Design and experimental analysis of dual-band polarization converting metasurface for microwave applications," *Scientific Reports*, Vol. 10, No. 1, 1–13, 2020.
14. Xu, P., S. Y. Wang, and W. Geyi, "A linear polarization converter with near unity efficiency in microwave regime," *Journal of Applied Physics*, Vol. 121, No. 14, 144502, 2017.
15. Mei, Z. L., X. M. Ma, C. Lu, and Y. D. Zhao, "High-efficiency and wide-bandwidth linear polarization converter based on double U-shaped metasurface," *AIP Advances*, Vol. 7, No. 12, 125323, 2017.
16. Zhang, J., L. Yang, L. Li, T. Zhang, H. Li, Q. Wang, Y. Hao, M. Lei, and K. Bi, "High-efficiency polarization conversion phase gradient metasurface for wideband anomalous reflection," *Journal of Applied Physics*, Vol. 122, No. 1, 014501, 2017.
17. Gao, X., X. Han, W. P. Cao, H. O. Li, H. F. Ma, and T. J. Cui, "Ultrawideband and high-efficiency linear polarization converter based on double V-shaped metasurface," *IEEE Transactions on Antennas and Propagation*, Vol. 63, No. 8, 3522–3530, 2015.
18. Khan, B., S. Ullah, and B. Kamal, "An extended split ring resonator type metasurface for microwave applications," *IEEE 2019 16th International Bhurban Conference on Applied Sciences and Technology (IBCAST)*, 1046–1049, Pakistan, Islamabad, January 2019.
19. Lin, B., B. Wang, W. Meng, X. Da, W. Li, Y. Fang, and Z. Zhu, "Dual-band high-efficiency polarization converter using an anisotropic metasurface," *Journal of Applied Physics*, Vol. 119, No. 18, 183103, 2016.
20. Liu, D. Y., L. F. Yao, X. M. Zhai, M. H. Li, and J. F. Dong, "Diode-like asymmetric transmission of circularly polarized waves," *Applied Physics A*, Vol. 116, No. 1, 9–13, 2014.
21. Cheng, Y., J. Fan, H. Luo, and F. Chen, "Dual-band and high-efficiency circular polarization convertor based on anisotropic metamaterial," *IEEE Access*, Vol. 8, 7615–7621, 2019.
22. Liu, X., J. Zhang, W. Li, R. Lu, L. Li, Z. Xu, and A. Zhang, "Three-band polarization converter based on reflective metasurface," *IEEE Antennas and Wireless Propagation Letters*, Vol. 16, 924–927, 2016.
23. Khan, M. I., Z. Khalid, S. A. K. Tanoli, F. A. Tahir, and B. Hu, "Multiband linear and circular polarization converting anisotropic metasurface for wide incidence angles," *Journal of Physics D: Applied Physics*, Vol. 53, No. 9, 095005, 2019.
24. Khan, M. I., Z. Khalid, and F. A. Tahir, "Linear and circular-polarization conversion in X-band using anisotropic metasurface," *Scientific Reports*, Vol. 9, No. 1, 1–11, 2019.
25. Zheng, Q., C. Guo, G. A. Vandenbosch, P. Yuan, and J. Ding, "Dual-broadband highly efficient reflective multi-polarisation converter based on multi-order plasmon resonant metasurface," *IET Microwaves, Antennas* & *Propagation*, Vol. 14, No. 9, 967–972, 2020.
26. Dutta, R., D. Mitra, and J. Ghosh, "Dual-band multifunctional metasurface for absorption and polarization conversion," *International Journal of RF and Microwave Computer-Aided Engineering*, Vol. 30, No. 7, 22200, 2020.
27. Noishiki, T., R. Kuse, and T. Fukusako, "Wideband metasurface polarization converter with double-square-shaped patch elements," *Progress In Electromagnetics Research C*, Vol. 105, 47–58, 2020.