Frequency-Tunable Corrugated Metasurface for Linear-to-Circular and Circular-to-Linear Polarization Conversion

Nandhitha Pauly, Gopikrishna M *
Research Facility in Applied Electromagnetics, Dept.of Physics, Govt.Victoria College, Palakkad,678001, Kerala, India
Corresponding Author: gopikrishna@gvc.ac.in

Abstract

This work introduces a dual-band polarization-converting metasurface capable of cross-polarization conversion, as well as transforming between linear and circular polarizations. While the structure exhibits responses at two frequencies, notably at 2.032 GHz and 3.96 GHz, the primary focus of the polarization conversion is at 3.96 GHz. The novelty of this study lies in the metasurface structure, where adjacent corrugated elements maintain a periodic relationship. This design also enables frequency tunability, allowing for shifts in both frequency and polarization characteristics. The capability of achieving multiple functionalities with a single compact structure positions the proposed design as a promising candidate for integration into critical microwave applications.

1.Introduction

Polarization is a critical characteristic of electromagnetic (EM) waves, defining how the electric field oscillates at a fixed point in space. Due to its foundational importance in numerous polarization-sensitive applications and devices such as polarization beam splitters, wave plates, and antennas, researchers have consistently pursued the development of methods and technologies to manage and influence EM wave polarization. Traditional approaches rely on the Faraday Effect and the optical activity of crystals for polarization manipulation. However, these methods are hampered by drawbacks such as bulky size, limited bandwidth, and sensitivity to incident angles, rendering them unsuitable for many practical applications. To circumvent these limitations, engineered structures known as metasurfaces offer a promising solution. These surfaces enable precise control over the electric and magnetic responses by designing subwavelength unit cells strategically. Numerous designs of anisotropic metasurfaces facilitating cross-polarization conversion (from x-to-y or y-to-x polarization) in reflection mode have been documented in the literature [1-4]. While the designs mentioned earlier achieve polarization conversion, they are limited to either cross-polarization conversion (CPC) or linear-to-circular polarization (LP-to-CP) conversion. There has been a longstanding interest in developing a single structure capable of achieving both functionalities simultaneously. Such a multifunctional device not only enables the miniaturization of systems by replacing multiple components with a single versatile component but also reduces overall system complexity and cost [5-6].

In this study, we introduce a multifunctional metasurface capable of several operations: linear cross-polarization conversion, conversion between linear and circular polarizations (both ways), and frequency tuning within the 0-12 GHz range. These diverse functionalities are enabled by novel corrugated structures. In contrast to previous work on polarization converting metasurfaces, we adopted a novel approach for designing the current metasurface. This involved establishing a periodic relationship between the lengths of adjacent arms. This design choice was crucial as it introduced specific periodic characteristics to the structure. By varying the lengths of these adjacent arms in a systematic manner, we were able to impart the metasurface with diverse and controlled periodic properties.This approach not only enhanced the functionality of the metasurface but also allowed us to tailor its performance to meet specific application requirements more effectively. It is rare in literature to find examples where a single compact structure achieves exceptional properties.

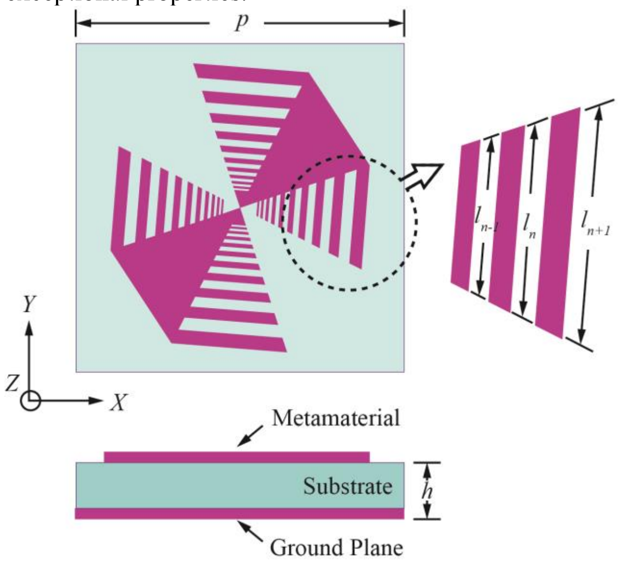


Figure 1. Schematic depiction of the proposed multifunctional metasurface (LP-CP)

2. Structure and Design

A schematic view of the proposed polarization converting metasurface (LP-CP) is shown in Fig.1. To investigate the polarization conversion properties of the proposed metasurface, numerical simulations were conducted using CST. The physical dimensions of the meta-atom optimized through extensive parametric analysis are P = 15mm. The material on the top and bottom is copper with the conductivity of 5.8×10^7 S/m, and the dielectric spacer is Rogers with the dielectric constant of 9.8 and the tangent loss of 0.0012. The proposed polarization converting metasurface (PCM) features a periodic structure where the ratio between the lengths of adjacent arms remains constant i.e.

$$l_n/l_{n-1} = l_{n+1}/l_n = k = 1.23 \quad (1)$$

Boundary conditions were applied to the unit cell along the x and y directions, and Floquet ports were assigned along the +z axis. The continuous backplane made of copper results in zero transmission, hence only the reflection properties were investigated and analyzed using CST Microwave Studio. Electromagnetic waves with varying polarizations were incident from above across a frequency span ranging from 0 to 5 GHz.

3.Results and Discussion

Fig. 2(a) illustrates the magnitude of co- and cross-polarized reflection coefficients when the incident wave is x-polarized ($E_i = xE_o e^{ikz}$) and normally strikes the metasurface, it clearly shows that the magnitude of the cross-polarized reflection coefficient |Ryx| exceeds 0.9 at

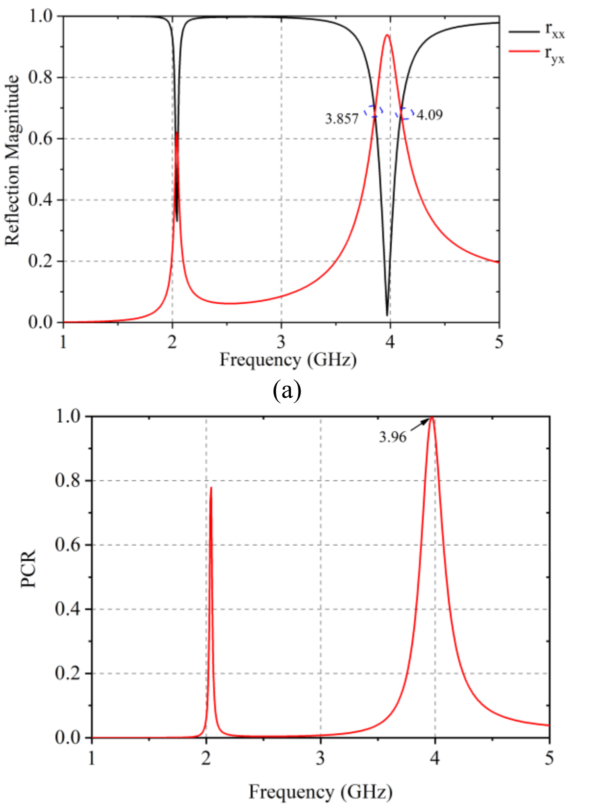


Figure 2. (a) Co and cross-polarized reflection coefficients at 3.96 GHz (b) PCR

3.96 GHz. Notably, strong plasmonic resonances occur at 3.96 GHz, where the metasurface rotates the plane of polarization by 90°, resulting in Ryx = 1 and Rxx = 0. Consequently, only y-polarized waves are reflected when illuminated with x-polarization.

The effectiveness of an electromagnetic structure's cross-polarization conversion capability is more accurately represented by the polarization conversion ratio (PCR). This ratio is defined as the fraction of power reflected in the cross-polarized component relative to the total reflected power, expressed mathematically as:

$$\text{PCR} = \frac{|r_{yx}|^2}{|r_{yx}|^2 + |r_{xx}|^2} \qquad (2)$$

Fig. 2(b) shows that the PCR approaches 100% at 3.97 GHz, thus only y-polarized wave is reflected for x polarized illumination. Upon observation, it is noted that at two frequencies adjacent to 3.97 GHz, the magnitude of both R_{xx} and R_{xy} are equal, and their phase difference is approximately ±90°. This indicates that the incident x-polarized wave not only converts to y-polarization but also generates circular polarization at these additional frequencies. Fig.3 (a) & (b) illustrates the magnitude and phase difference between the co- and cross-polarized reflection coefficients.

Both the amplitudes and the phase difference of the reflected fields are crucial factors considered in the evaluation of the axial ratio (AR), defined as [7]

$$\text{AR} = \left\{ \frac{|Rxx|^2 + |Rxy|^2 + \left(|Rxx|^4 + |Rxy|^4 + 2|Rxx|^2\,|Rxy|^2 \cos(2\Delta\varphi)\right)^{1/2}}{|Rxx|^2 + |Rxy|^2 - \left(|Rxx|^4 + |Rxy|^4 + 2|Rxx|^2|Rxy|^2 \cos(2\Delta\varphi)\right)^{1/2}} \right\}^{\frac{1}{2}} \qquad (3)$$

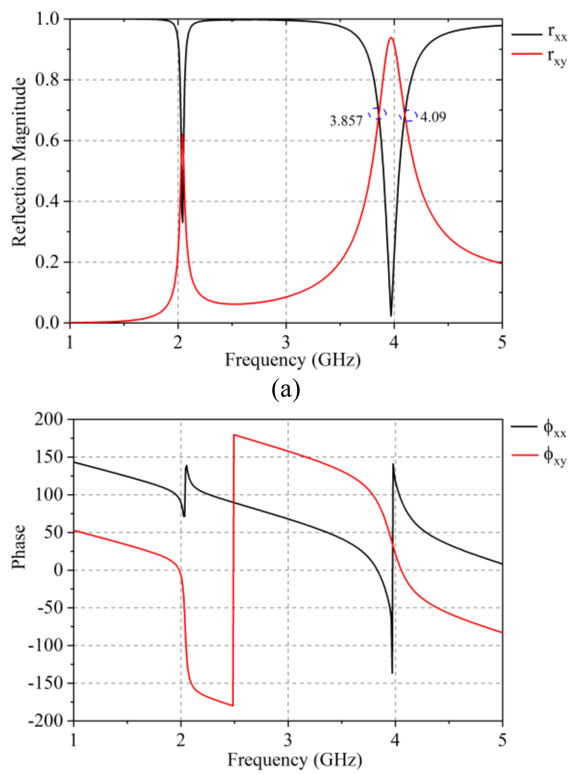


Figure 3. Co- and cross-polarized reflection coefficients for x-polarized illumination (a) magnitude (b) phase

The axial ratio represents circular polarization if it is less than or equal to 3dB, i.e. AR $\leq$ 3 dB. The axial ratio obtained using Eq. (3) is presented in Fig.4. It is clear from Fig.4 that the criterion for circular polarization is satisfied for the frequency 3.857 and 4.09 GHz as the axial ratio was found to be less than 3 dB.

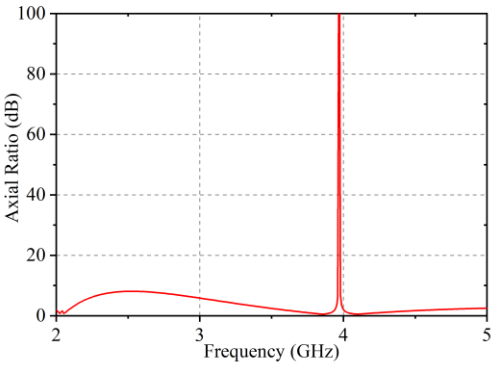


Figure 4. Axial ratio of the proposed absorber at 3.857 and 4.09 GHz.

To further investigate the handedness of the reflected circular polarization we make use of Stokes' parameters which are defined as [8]:

$$\begin{aligned} S_0 &= |R_{xx}|^2 + |R_{xy}|^2 \\ S_1 &= |R_{xx}|^2 - |R_{xy}|^2 \\ S_2 &= 2\,|R_{xx}|\,|R_{xy}| \cos \Delta\varphi \\ S_3 &= 2\,|R_{xx}|\,|R_{xy}| \sin \Delta\varphi \end{aligned} \quad (4)$$

Normalized ellipticity is defined as e = S_3/S_0. It can be easily deduced from the Stokes' parameters that the normalized ellipticity is +1 for right handed circularly polarization (RHCP) and -1 for the left handed circular polarization (LHCP). By employing the equation above, it was determined that the ellipticity is -1 at a frequency of 3.857 and +1 at 4.09 GHz. This indicates that an incident x-polarized wave converts to Right Hand Circular Polarization (RHCP) at 3.857 GHz and to Left Hand Circular Polarization (LHCP) at 4.09 GHz. Notably, this property reveals that simultaneously, the incident linearly polarized wave is converted into a y-polarized wave, RHCP, and LHCP at three distinct frequencies.

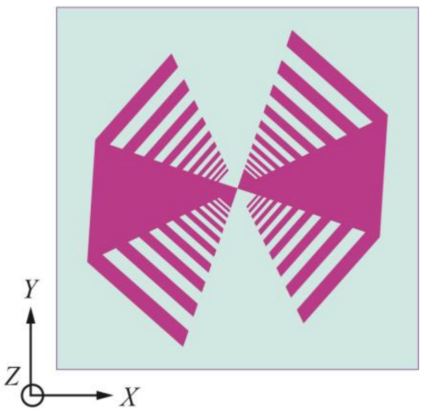
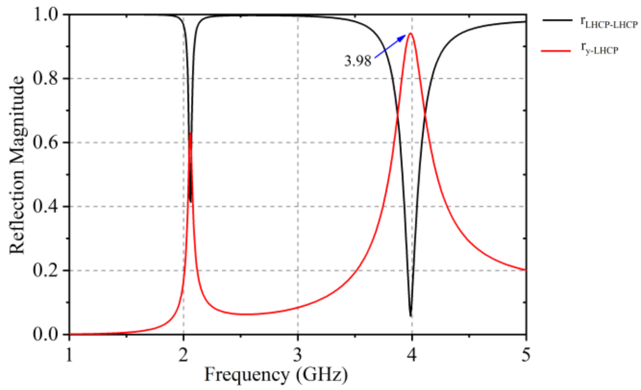
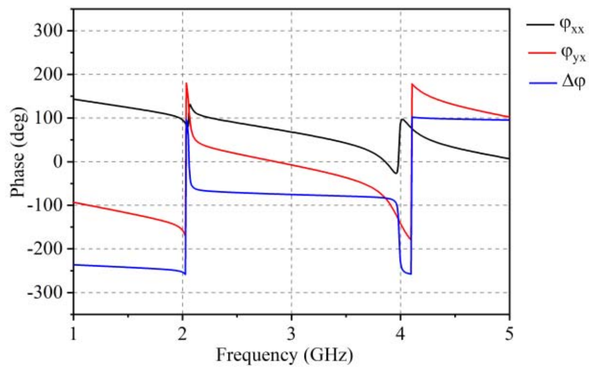


Figure 5. Schematic view of the proposed PCM (LHCP-LP)

Fig.5 depicts the schematic configuration of the PCM designed to convert left hand circular polarization (LHCP) to linear polarization along the y-axis (LPy). The conversion from LHCP to LPy occurs when the top resonator is rotated 19^0 degrees clockwise. Specifically, $R_{LHCP\text{-}LHCP} \approx 0$, $R_{LY\text{-}LHCP}$ reaches its maximum, and their phase difference measures -180^0. Fig.6 (a) &(b) shows the magnitude and phase difference between incident LHCP and reflected y-polarized wave.



(a)



(b)

Figure 6. Simulation results of CP-to-LP polarization converter under LHCP incidence (a)Magnitude (b) Phase.

Another intriguing and innovative aspect of the proposed design is our capability to adjust the resonant frequency to 3.9 GHz by reducing the number of corrugated elements. This decreases the overall inductive and capacitive effects, thereby shifting the resonant frequency higher. This characteristic enables us not only to achieve frequency tuning but also to adjust different polarizations at varying frequencies. Fig.7 illustrates the frequency tuning outcomes of the metasurface, demonstrating that reducing the number of corrugated elements results in a shift towards higher frequencies.

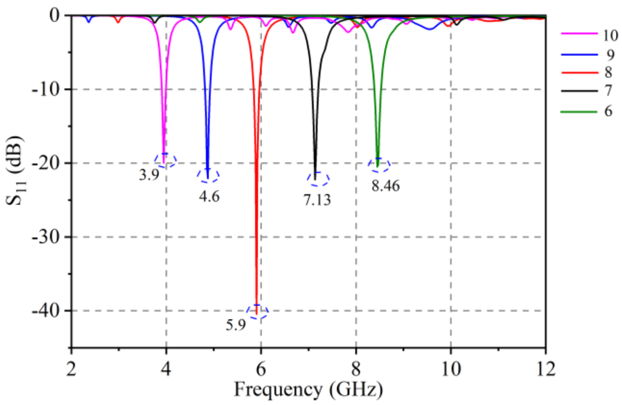


Figure 7. Simulation results showing frequency shift as number of arms decreases.

4. Conclusion

In summary, we have developed a metasurface for polarization conversion that achieves cross-polarization conversion at 3.96 GHz, linear-to-circular conversion at frequencies near 3.96 GHz (3.857 and 4.02 GHz), and circular-to-linear conversion at 3.96 GHz. This design is rooted in the periodic relationship between the lengths of adjacent arms within the structure. The multifunctionality of our design is enabled by this periodicity. By applying rotational effects to the metasurface, we can achieve exceptional properties that allow us to tune the polarization effects effectively.

5. Acknowledgements

The work presented in this paper is supported by the Science and Engineering Research Board (SERB), Department of Science and Technology (DST), India, under grant EEQ/2021/000931.

6. References

1. Feng, M., Wang, J., Ma, H., Mo, W., Ye, H. and Qu, S., 2013. Broadband polarization rotator based on multi-order plasmon resonances and high impedance surfaces. *Journal of Applied Physics*, *114*(7).
2. Chen, H.Y., Wang, J.F., Ma, H., Qu, S.B., Zhang, J.Q., Xu, Z. and Zhang, A.X., 2015. Broadband perfect polarization conversion metasurfaces. *Chinese Physics B*, *24*(1), p.014201.
3. Chen, H., Wang, J., Ma, H., Qu, S., Xu, Z., Zhang, A., Yan, M. and Li, Y., 2014. Ultra-wideband polarization conversion metasurfaces based on multiple plasmon resonances. *Journal of Applied Physics*, *115*(15).
4. Zhang, L., Zhou, P., Chen, H., Lu, H., Xie, J. and Deng, L., 2015. Broadband and wide-angle reflective polarization converter based on metasurface at microwave frequencies. *Applied Physics B*, *120*, pp.617-622.
5. Zhang, L., Zhou, P., Chen, H., Lu, H., Xie, J. and Deng, L., 2015. Adjustable wideband reflective converter based on cut-wire metasurface. *Journal of Optics*, *17*(10), p.105105.
6. Zheng, X.X., Xiao, Z.Y. and Ling, X.Y., 2016. Broadband and efficient reflective polarization converter based on a three-dimensional metamaterial. *Optical and Quantum Electronics*, *48*, pp.1-9.
7. Khan, M.I., Chen, Y., Hu, B., Ullah, N., Bukhari, S.H.R. and Iqbal, S., 2020. Multiband linear and circular polarization rotating metasurface based on multiple plasmonic resonances for C, X and K band applications. *Scientific reports*, *10*(1), p.17981.
8. Khan, M.I., Khalid, Z. and Tahir, F.A., 2019. Linear and circular-polarization conversion in X-band using anisotropic metasurface. *Scientific reports*, *9*(1), p.4552.