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# Advanced Metasurface Engineering for Broadband Applications of Enhanced Angle-Insensitive Conversion: The Cross-Polarization

**Saif Y. Jarallah [1]**
**Abdullah H. Mohammed [1]**
**Hiam M. Ahmed [2]**

[1] Department of Physics, College of Education for Pure Sciences, Kirkuk University, Kirkuk, IRAQ
[2] Department of Physics, College of Education for Women, Kirkuk University, Kirkuk, IRAQ


A novel reflective metasurface designed for cross-polarization conversion (CPC) in the microwave frequency range is presented in this work. A split-ring resonator with a circular metallic outer ring and an embedded inner square ring is incorporated into each of the unit cells that make up the suggested layout. This structural configuration enables the transformation of both linearly and circularly polarized waves into their orthogonal counterparts upon reflection. A significant advancement in our design is the incorporation of four distinct plasmonic resonances, which play a crucial role in achieving an efficient and wideband CPC effect. As a result, the proposed metasurface achieves a fractional bandwidth of 72% with a -3 dB conversion efficiency, spanning frequencies from 1 GHz to 15 GHz. The proposed metasurface demonstrates the promising possibility of a large group of practical applications in polarization control devices, representing a significant advancement in microwave engineering and metamaterials.

**Keywords:** Metasurface; Cross-polarization; Improved broadband
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## 1. Introduction

The metasurface is an ultra-thin, two-dimensional structure that significantly influences the propagation of radio waves, especially when they interact with satellites at complex angles. Typically, signals received by satellites may not arrive in a direct line, which can lead to various complications. The metasurface addresses this issue by effectively manipulating the incoming signals, ensuring they remain robust and clear, even when arriving at unconventional angles, Additionally, the metasurface possesses a significant capability to modify the "polarization" of signals. Polarization pertains to the orientation of the signal waves during transmission. By enabling transitions between linear polarization (where waves propagate in a straight trajectory) and circular polarization (where waves rotate as they propagate), the metasurface enhances the resilience of signals against interference and attenuation. This characteristic is particularly vital for maintaining stable and reliable communication under real-world conditions, such as adverse weather or the presence of competing signals [1]. Polarization represents a significant characteristic of electromagnetic waves, which can be effectively manipulated using specially engineered two-dimensional periodic flat surfaces referred to as transformational surfaces. These surfaces facilitate the control of polarization across a diverse array of applications, including reflection arrays, devices sensitive to polarization, and the reduction of radar cross-sections [2-5]. Conventional techniques, for example, the Faraday's effect and the optical activity exhibited by crystals, have been employed to manage electromagnetic wave polarization. Nonetheless, these methods are often impractical due to their limited frequency responses, substantial structural requirements, and dependence on incident angles. Consequently, these approaches are not suitable for the production of compact flat devices for polarization control. Recent studies have introduced a variety of designs for transformational surfaces aimed at polarization conversion. Notable structures include bidirectional arrows [6-8]. V-shaped patches, L-shaped inverted resonators positioned diagonally, and square-shaped areas are parallel to the diameter of the designed shape, as they are designed to perform polarization conversion with excellent efficiency. [9]. Additionally, wideband polarization transformation utilizing split-ring resonators (SRRs) has been realized through multilayer configurations. However, such multilayer designs typically do not conform to the requirements of contemporary planar polarization control devices [10]. The advantages of circular polarization are especially significant, as antennas utilizing circular polarization play a vital role in communication systems, such as those found in satellites and rockets, which have faced challenges associated with the limited bandwidth of thin film antennas [11]. The applied external electric field has a significant impact on the behavior of charges and dipoles, as polarization mechanisms adjust based on the field's intensity and direction [12]. We suggest a novel wideband polarization converter in this work incorporating a circular split-ring resonator with a central square ring, fabricated on an FR4 dielectric substrate. The upper-layer structure of the design enables polarization conversion under normal incidence using a single layer, ensuring stable performance for waves that are both x- and y-polarized.

## 2. Experimental Part

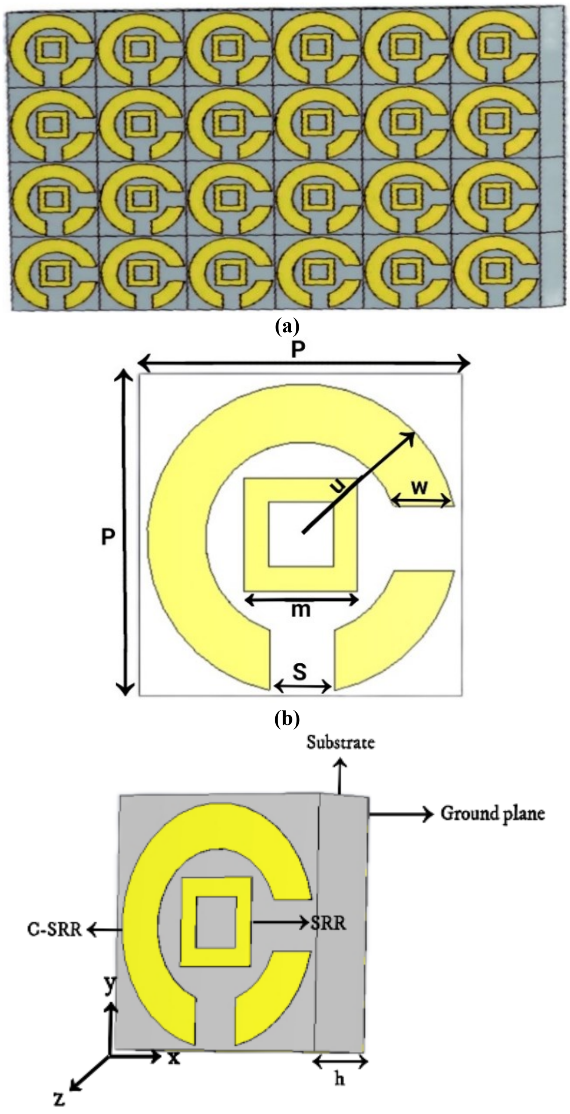
The structural design of the proposed metasurface is illustrated in Fig. (1a), providing a detailed schematic representation. The split-ring configuration features two orthogonal gaps of equal width, which define its unique characteristics. Furthermore, a ground plane has been incorporated at the base of the pillar, as shown in Fig. (1b). The FR-4 substrate on which the metasurface is constructed has a loss tangent of 0.02 and a relative permittivity of 4.30. The inner square, the ground plane, and the circular split-ring resonator are among the structural elements made of 0.03 mm thick copper.

FR4 is a commonly used and cost-effective substrate with stable dielectric properties for many microwave and RF applications. Its relatively low loss tangent is beneficial for maintaining signal integrity. Using copper for the resonator elements ensures high conductivity, which is crucial for efficient electromagnetic wave manipulation.

## 3. Results and Discussion

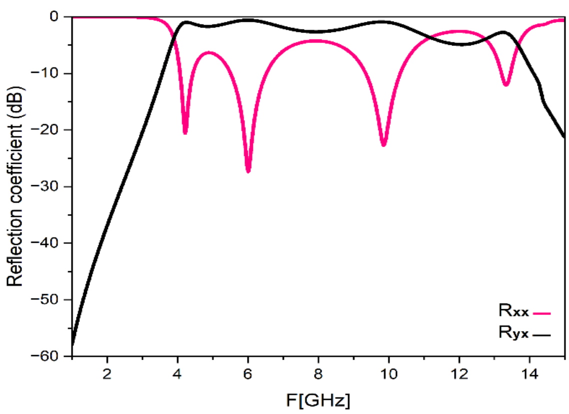
The designed metasurface functions in a vertical polarization mode. In its reflective setup, It changes a wave that is x-polarized into one that is y-polarized, and vice versa. Furthermore, it exchanges circularly polarised waves from the right to the left, and vice versa. The metasurface's unit cell, as seen in Fig. (1), was created using CST-Microwave Studio software, adhering to the specified design parameters. The physical dimensions, detailed in Fig. (1a,b), are as follows: u = 4.75 mm, S = 1 mm, m = 3.5 mm, h = 3.5 mm, P = 10 mm, and W = 1.5 mm.

The simulation results from the CST software are shown in Fig. (2a,b), the designed metasurface exhibits different characteristics, where the performance is symmetric along the x and y directions. These distinct characteristics lead to efficient cross-polarization conversion of both linear and circular waves. The symbols ($R_{xx}$ and $R_{yy}$) represent the reflection coefficients for co-polarization at the wave incidence and its interaction with the metasurface. Additionally, as observed in Fig. (2a,b), the polarization coefficients ($R_{xx}$ and $R_{yy}$) are notably low, whereas the cross-polarization reflection coefficients ($R_{yx}$ and $R_{xy}$), associated with cross-polarization reflection, surpass the -3 dB limit. This leads to a polarization conversion efficiency of 72% over the frequency range spanning from 4 to 14 GHz.



(c)

**Fig. (1) (a) A detailed outline drawing of the proposed metasurface, (b) Cell unit in the upper layer, and (c) A cell in three dimensions**



(a)

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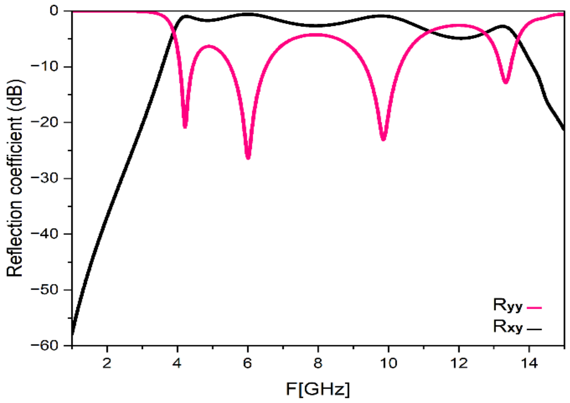
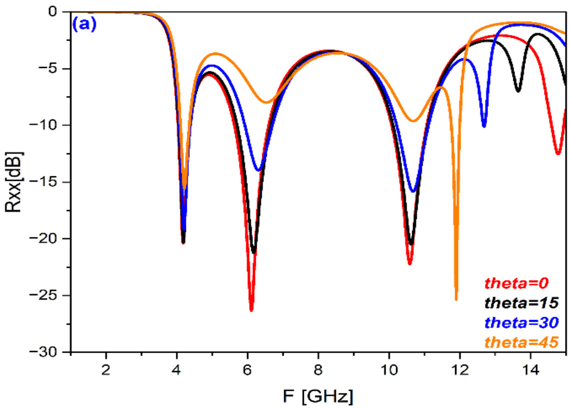


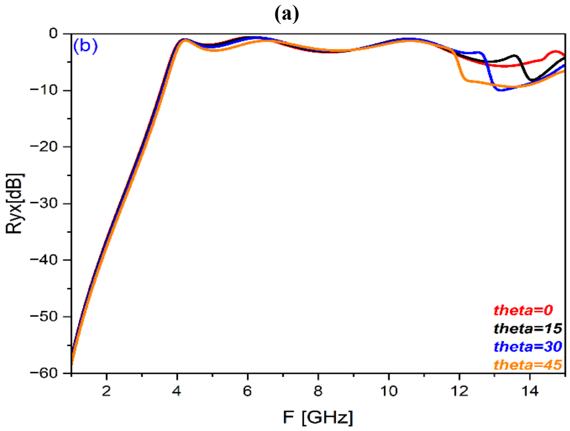

**(b)**

**Fig. (2) (a) Reflection coefficient of a wave in the x-direction and a right-handed circularly polarized wave in the normal incidence, and (b) Reflection coefficient of a wave in the y-direction and also in the right-handed circularly polarized wave in the normal incidence**

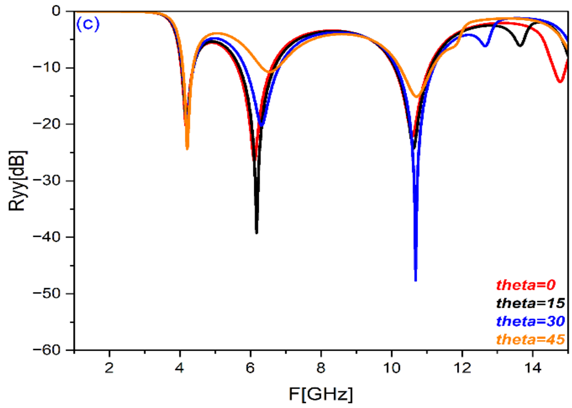
When the incident electromagnetic field is orientated along the x-axis, the reflection coefficient curves for co-polarized and cross-polarized waves are shown in figures (3a) and (3b). It is clear from Fig. (3a) that the common polarization's reflection coefficient is still relatively stable despite variations in the incidence angle. Notably, at a frequency of 13.3 GHz, a slight impact on the surface performance due to the incidence angle was observed, resulting in minor deviation.



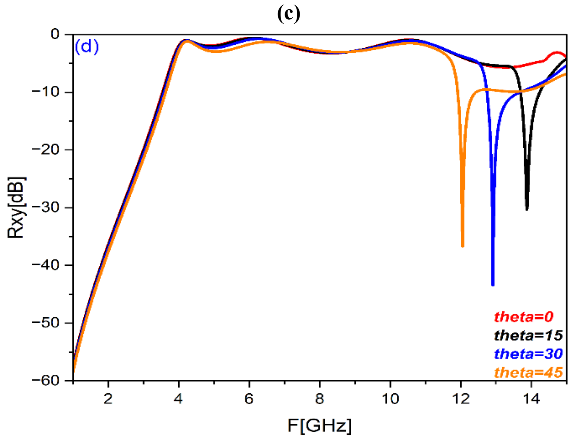

**(a)**




**(b)**




**(c)**




**(d)**

**Fig. (3) (a) Co-polarization reflection transactions, (b) Cross-polarization reflection transaction where x-polarization is the incident field, (c) Co-polarization reflection coefficient, and (d) Cross-polarization When the field of incident y-polarization**

Similarly, figures (3c) and (3d) depict the design reflection coefficient at the incident electromagnetic field aligned with the y-axis polarization. It was found that the magnetic field reaches across S-SRR and C-SRR rings minimally affects cross-polarization results by disrupting the current flow within the unit cells of metallic. However, these fluctuations are acceptable within the constraints imposed by the current flow on the SRR during resonance. Ultimately, the cross-polarization component influenced by these interactions is affected by oblique incidence and response stability. The consistency of this interaction concerning precise structural geometry and ideal physical parameters determine changes in the incidence angle. However, attaining a high conversion rate of cross-polarization efficiency is anticipated when the surface exhibits significant resistance and maintains its stability across various incidence angles, mimicking the behavior of an ideal electric conductor. A thin substrate can enhance angular stability. In summary, the proposed surface, characterized by tunable properties, achieved a high polarization conversion ratio (PCR) when integrated with a surface of high impedance suitable for an ideal magnetic conductor.

The polarization conversion ratio is represented by the following equation [3]:

$$PCR = \frac{(Ryx)^2}{(Ryx)^2+(Rxx)^2} \qquad (1)$$

Figure (4) illustrates the polarization conversion ratio that metasurfaces achieve at normal incidence. From the figure and using Eq. (1), it is evident that the conversion ratio demonstrates high efficiency at specific frequencies: 4, 6, 9.8, and 13.3 GHz. At these points, an incident polarized electromagnetic wave along the x-axis is fully transformed into a reflected wave polarized along the y-axis, and vice versa. The wideband performance of the proposed structures can be attributed to plasma resonances occurring at these four frequencies. These resonances are primarily influenced by the dimensions of the complementary split-ring resonator (C-SRR) and the split-ring resonator (SRR). Specifically, the lower resonant frequencies of 4 GHz and 6 GHz can be adjusted by altering the size of the external C-SRR, while the higher resonant frequencies of 9.8 GHz and 13.3 GHz can be tuned by modifying the dimensions of the internal SRR.

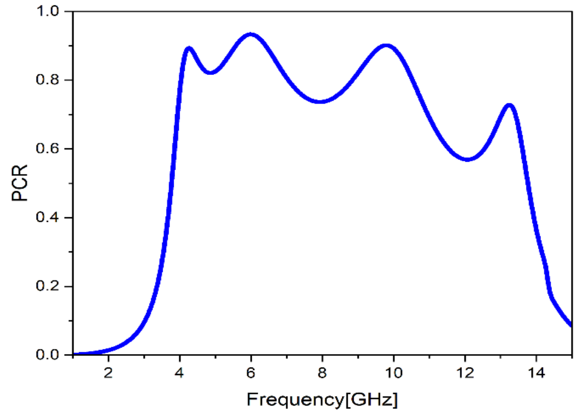



**Fig. (4) Ratio of polarization conversion**

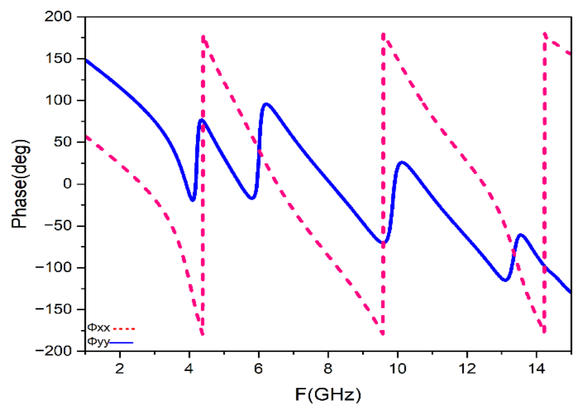



**Fig. (5) Phase for x and y polarized waves**

To explain the physical principles underlying the Circular Polarization Converter, the previous design is analyzed for both x and y polarizations, focusing on the reflection phase and magnitude coefficients. The results for these coefficients, corresponding to x and y-polarized waves, are illustrated in Fig. (5). From the figure, it can be observed that the phase difference between the reflected fields for x and y polarizations consistently measures 180 degrees across the 4–14 GHz operational frequency band. An x-polarized wave is reflected as a y-polarized wave, and vice versa, according to this 180-degree phase shift.

## 4. Conclusion

This work presents an advanced and innovative metasurface for conversion of the cross-polarization using circular and square split-ring resonators. The proposed design exhibits high polarization conversion efficiency over a broad bandwidth, demonstrating its capability to convert both circular and linear polarizations into their counterparts (i.e., reverse states). Most importantly, this design has proven its ability to achieve cross-polarization conversion with a fractional bandwidth of 72% in a frequency range from 1 GHz to 15 GHz when normal incidence, while remaining insensitive to the incidence angle at various values. Ultimately, this cross-polarization conversion enables a wide range of applications and devices for polarization control.

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