

# Multi-functional Multi-band Metasurface for Linear and Circular Polarization in Reflection Mode

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## Abstract

A new metasurface design is presented in multi and broad frequency bands. Metasurface has been designed on Roger 5880 substrate with a thickness of 1.575 mm. The top of the designed metasurface consists of two diagonal mirror m-shaped unit cells. The background plane covers the whole metasurface. Numerical results demonstrate the metasurface's capability for both linear (12.48-13.62 GHz, 19.00-27.64 GHz, 39.45-41.72 GHz, 44.68-45.18 GHz, and 47.52-48.28 GHz) and circular (11.5-12.07 GHz, 30.01-37.77 GHz, 42.3-44.2 GHz, 45.45-47.1 GHz, 48.7-49.54 GHz) polarization conversion with over 90% efficiency. At the same time, the metasurface has good angular stability up to 45°.

**Keywords:** Metasurface, Unit cell, Polarization, Conversion, Reflection

## Yansıma Modunda Doğrusal ve Dairesel Polarizasyon için Çok Fonksiyonlu Çok Bantlı Metasurface

### Öz

Çoklu ve geniş frekans bantlarında yeni bir metasurface tasarımı sunulmaktadır. Metasurface, 1.575 mm kalınlığında Roger 5880 alttas malzeme üzerine tasarlanmıştır. Tasarlanan metayüzeyin üst kısmı iki adet capraz ayna görüntülü m-şekilli birim hücreden oluşmaktadır. Arka plan düzlemi metayüzeyin tamamını kaplar. Sayısal sonuçlar, metasurface'in hem doğrusal (12,48-13,62 GHz, 19,00-27,64 GHz, 39,45-41,72 GHz, 44,68-45,18 GHz ve 47,52-48,28 GHz) hem de dairesel (11,5-12,07 GHz, 30,01-37,77 GHz, 42,3) kapasitesini göstermektedir. -44,2 GHz, 45,45-47,1 GHz, 48,7-49,54 GHz) %90'ın üzerinde verimlilikle polarizasyon dönüşümü. Aynı zamanda metayüzey 45°'a kadar iyi bir açısal stabiliteye sahiptir.

**Anahtar Kelimeler:** Metasurface, Birim hücre, Polarizasyon, Donusum, Yansıma

## 1. Introduction

The polarization of electromagnetic waves is recognized as a crucial property. Recent studies (Cheng et al., 2014; Zhang et al., 2015) focus on this property. The adjustment of the polarization state of electromagnetic waves (EM) has garnered significant attention because of its promising applications in communication, beam steering, and polarization conversions. Conventional methods such as optical gratings and dichroic crystals start to decrease their importance because they offer big wavelengths big device sizes, and narrow bands (Chen et al., 2003; Masson & Gallot, 2006). These drawbacks have steered researchers toward exploring alternative methods.

Metamaterials are artificial materials, often called metasurfaces when they're in a planar form. Metasurfaces have gained attention because they are easy to print, cost-effective, thin, and cover a wide band. These qualities make them popular in various applications due to their ability to control the phase, amplitude, and polarization state of electromagnetic waves. Metasurfaces, especially in microwave (Khan & Tahir, 2017a, 2017b; Xu et al., 2018), and terahertz (Chen et al., 2022; Zang et al., 2021; Zheng et al., 2022). have shown their effectiveness in polarization control. Their primary use lies in polarization conversion.

Polarization conversion can take different forms, like linear-to-linear (LTL) (T. Q. H. Nguyen et al., 2021; Roy et al., 2022), or linear-to-circular (LTC) (Fahad et al., 2020; Li et al., 2021). These conversions can occur either in transmission (Ako et al., 2020; Li & Zhang, 2020) or reflection mode (Cildir et al., 2023; Guo et al., 2021). In polarization conversion, certain metasurface parameters, such as efficiency, bandwidth, and angular stability, are crucial. Researchers pay close attention to these aspects when studying metasurfaces..

In the reflection mode, there have been studies (Chen et al., 2015; Lin et al., 2016; Moghadam et al., 2018) introducing metasurface-based designs for polarization conversion, achieving reported conversion efficiencies surpassing 90%. Some researchers aimed for broader bands in linear-to-linear (LTL) conversion (Shukoor et al., 2022; Yang et al., 2021) . Others focused on multifunctional designs that include LTL conversion, linear-to-circular (LTC) conversion, and angular stability (Dutta et al., 2021; Tutar & Ozturk, 2022; Wahidi et al., 2020). However, even when some studies present LTC conversion, they face challenges in achieving broadband metasurfaces (Ahmed et al., 2023; Khan et al., 2019; T. K. T. Nguyen et al., 2021).

This paper introduces a new multifunctional metasurface design that operates across multiple frequency bands with broadband circular-to-linear (CTL) conversion. The designed metasurface demonstrates linear-to-linear (LTL) conversion with an efficiency exceeding 90% in frequency bands spanning 12.48-13.62 GHz, 19.00-27.64 GHz, 39.45-41.72 GHz, 44.68-45.18 GHz, and 47.52-48.28 GHz. Additionally, the metasurface achieves linear-to-circular (LTC) polarization conversion within frequency bands of 11.5-12.07 GHz, 30.01-37.77 GHz, 42.3-44.2 GHz, 45.45-47.1 GHz, and 48.7-49.54 GHz. The design also exhibits angular stability up to 45 degrees. The study covers the metasurface design, its theory and working mechanism, simulation results and discussions, and concludes with findings.

## 2. Material and Method

### 2.1. Metasurface Design

Fig. 1 depicts the designed metasurface along with the direction of the incident and reflected waves. For this design, Roger 5880 substrate with a thickness of 1.575 mm and a loss tangent of 0.009 was utilized. As shown in Fig. 1, the top of the metasurface comprises unit cells, and the back features a metallic ground plane. The unit cells are formed by two diagonal mirror m-shaped structures, with dimensions  $h$ : 1.575,  $s$ : 5,  $l$ : 4.4,  $w$ : 2.4, and  $g$ : 0.26.

As illustrated in Fig. 1, when a y-polarized wave impinges, it reflects as a y-polarized wave. Conversely, a y-polarized incident wave can be reflected as an x-polarized wave. Similarly, it is possible to reflect an x-polarized incident wave as a y-polarized wave.

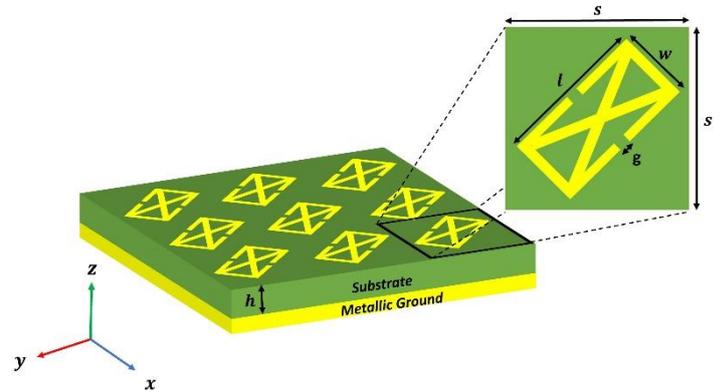


Fig. 1. Schematic view of the designed metasurface

To symbolize the incident waves and the reflected waves, the incident y- and x-polarized waves can be represented as  $E_{yi}$ , and  $E_{xi}$ , respectively. The reflected y- and x-polarized waves can be denoted  $E_{yr}$  and  $E_{xr}$ , respectively.

The relationship between the incident and reflected waves can be formulated using the following equations:  $R_{yy} = |E_{yr}/E_{yi}|$ ,  $R_{xy} = |E_{xr}/E_{yi}|$ ,  $R_{xx} = |E_{xr}/E_{xi}|$ , and  $R_{yx} = |E_{yr}/E_{xi}|$ .

Here,  $R_{yy}$ , and  $R_{xx}$  stand for co-coefficients of y- and x- polarized waves, respectively.  $R_{xy}$ , and  $R_{yx}$  stand for cross-coefficients of y- and x- polarized waves, respectively.

#### 2.1.1. Metasurface Theory

In Fig. 2, the designed unit cell and the incident and reflected polarized waves are depicted in the anisotropic ( $uv$ -) coordinate system. It is evident from Figure 2 that the unit cell exhibits symmetry along the  $u$ - and  $v$ - axes. The incident ( $\mathbf{E}_i$ ) and reflected ( $\mathbf{E}_r$ ) polarized waves are formulated in Equ.1 and 2. Vector symbols are represented with arrows or bold fonts.

$$\mathbf{E}_i = \vec{y}E_i = \vec{u}E_{iu}e^{j\varphi_{iu}} + \vec{v}E_{iv}e^{j\varphi_{iv}} \quad (1)$$

$$\mathbf{E}_r = \vec{u}E_{ru}e^{j\varphi_{ru}} + \vec{v}E_{rv}e^{j\varphi_{rv}} \quad (2)$$

Here,  $E_{iu}$ , and  $E_{iv}$ , represent u-, and v- polarized incident waves, while  $E_{ru}$ , and  $E_{rv}$  represent u-, and v- polarized reflected waves. The symbol  $\varphi$  denotes the phase of these polarized waves.

Upon analyzing Equ. 1 and 2, it is expected that  $|R_{uu}|$  and  $|R_{vv}|$  are approximately equal to 0 dB

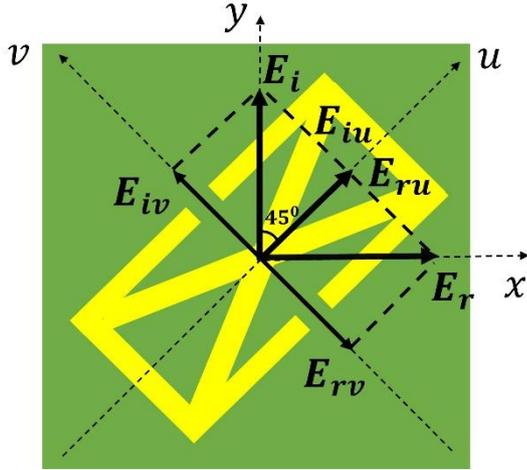


Fig. 2. The designed unit cell in the anisotropic coordinate system

To obtain LTC conversion, Equ. 3 and 4 must be provided. So, the magnitude of the co- and cross-coefficients must be equal to each other and also, their phase difference must be equal to  $\pm 90$  degrees or its multiple.

$$|R_{yy}| = |R_{xy}| \quad (3)$$

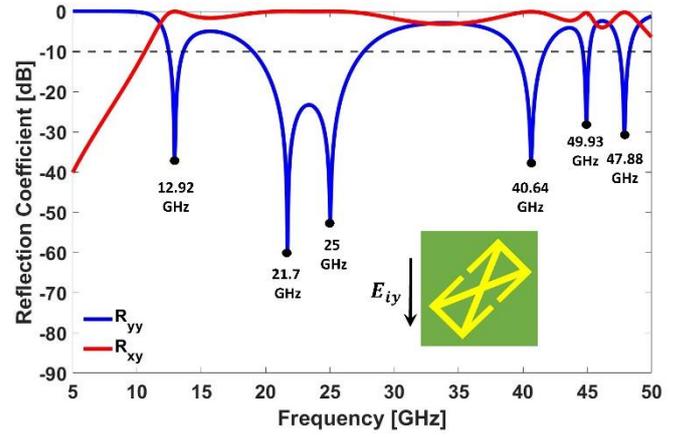
$$\Delta\varphi_{xy} = \varphi_{xx} - \varphi_{yx} = \pm\pi/2 \quad (4)$$

### 3. Simulation Results and Discussions

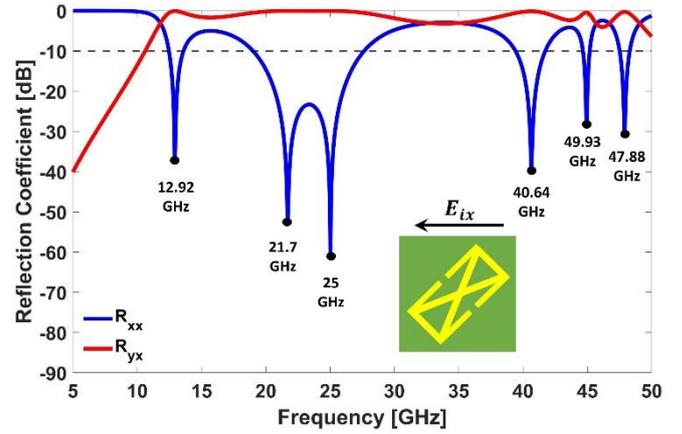
The reflection coefficient results for y-, and x-polarized waves are given in Fig. 3. The resonance frequency outcomes for y-, and x- polarized waves are observed to be identical. Additionally, it is seen that the magnitudes of reflection coefficients for the two polarized waves are almost identical due to the mirror symmetry in the anisotropic coordinate system.

For LTL conversion, co-polarized coefficients should be below -10 dB, while the cross-polarized coefficients should be close to 0 dB (Pozar, 2000). As analyzed in Fig.3, it is seen that the design has a lot of resonance frequencies and LTL conversion across multiple frequency bands.

For LTC conversion, as stated in Equ. 3, co- and cross-components should be almost equal to each other.



(a)



(b)

Fig. 3. Reflection coefficient simulation results for (a) y-polarized wave, (b) x-polarized wave

To gain a detailed understanding of LTL conversion, it is pertinent to analyze Fig. 4. In Fig. 4, the results of the polarization conversion ratio (PCR) are presented. PCR results show the efficiency of LTC conversion and can be calculated using Equ. 5.

$$PCR = \frac{|R_{xy}|^2}{|R_{xy}|^2 + |R_{yy}|^2} \quad (5)$$

As seen in Fig. 4 (a), it is understood that the metasurface converts incident wave as a linearly polarized wave within frequency bands of 12.48-13.62 GHz, 19.00-27.64 GHz, 39.45-41.72 GHz, 44.68-45.18 GHz, and 47.52-48.28 GHz over than 90 % efficiency.

Fig. 4 (b) shows the PCR angular stability of the metasurface. As the angles change, variations in the efficiency of the metasurface are observed. The designed metasurface is capable of performing Linear-to-Circular (LTC) conversion with a certain level of efficiency up to 45 degrees.

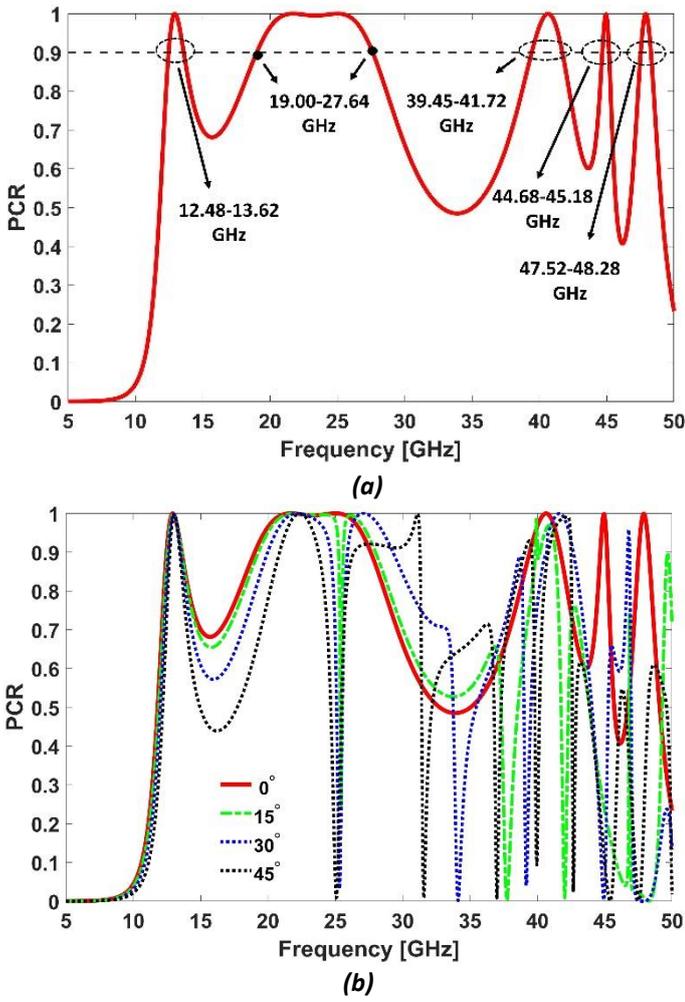


Fig. 3. PCR simulation results for: (a) normal incidence (0 degree), (b) different angles

To validate LTC conversion, the axial ratio (AR) can be analyzed. AR helps us discover circular polarization conversion.

$$AR_{dB} = 10 \log \left| \frac{R_{xy}}{R_{xx}} \right| \quad (6)$$

Axial ratio simulation results are depicted in Fig. 4. According to Equ. 4, and 6, the axial ratio results falling between -3 and +3 dB can be considered thresholds for LTC conversion. Fig. 4 shows the frequency band regimes where LTC conversion occurs for a normal incidence wave (0 degrees).

Fig 4 (b) also demonstrates that the metasurface can make LTC conversion with different angles. The different angles in the axial ratio graph show that the metasurface exhibits angular stability up to 45 degrees. Hence, this metasurface has the capability to convert circular polarization across various frequencies for different angles.

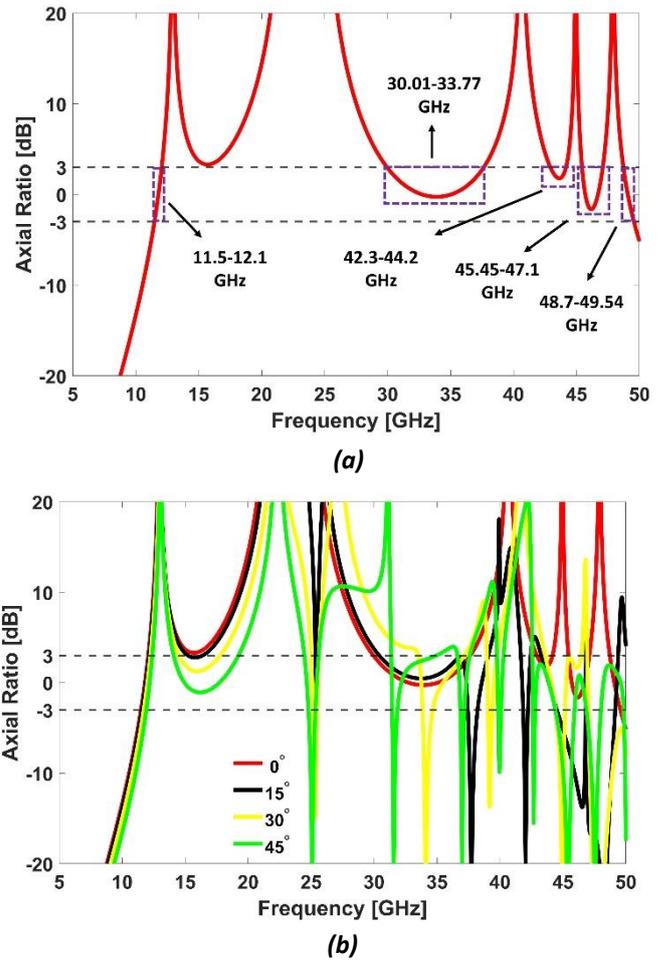


Fig. 4. Axial ratio simulation results for (a) normal incidence (0 degrees), and (b) different angles.

## 4. Conclusion

In this paper, a new multi-functional, multi-broadband metasurface design has been presented. The metasurface effectively converts linear x- and y-polarized waves to linear y- and x-polarized waves within frequency bands spanning 12.48-13.62 GHz, 19.00-27.64 GHz, 39.45-41.72 GHz, 44.68-45.18 GHz, and 47.52-48.28 GHz, achieving an efficiency exceeding 90%. This metasurface can also do LTC conversion in frequency bands of 11.5-12.07 GHz, 30.01-37.77 GHz, 42.3-44.2 GHz, 45.45-47.1 GHz, 48.7-49.54 GHz. Moreover, this design includes angular stability up to 45°. Future studies can focus on wider frequency bands for LTL and LTC conversion.

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