

# A Multifunctional Reflective Terahertz Metasurface Enabling Broadband Polarization Conversion and Spin-Handedness Manipulation

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## Research Article

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# A Multifunctional Reflective Terahertz Metasurface Enabling Broadband Polarization Conversion and Spin-Handedness Manipulation

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## Abstract

A compact multifunctional reflective terahertz (THz) metasurface is proposed for broadband polarization manipulation. The one-layer anisotropic metasurface enables simultaneous linear-to-linear (LP-LP) and linear-to-circular (LP-CP) polarization conversion without additional structural complexity. The design proposed includes an asymmetrical split-square resonator, a diagonal metallic strip, and a metallic ground plane. It performs LP-LP polarization conversion with a polarization conversion ratio (PCR) exceeding 97% over the frequency ranges 1.45-1.75 THz and 3.10-3.75 THz. The axial-ratio fractional bandwidths are 14.81% and 49.07% for 3 dB, respectively, and the broadband LP-CP conversion is achieved in the frequency ranges of 1.25-1.45 THz and 1.83-3.02 THz. The high-quality circular polarization arises from nearly equal reflected amplitudes of the orthogonal fields and  $\pm 90^\circ$  phase difference, and the ellipticity analysis confirms the formation of LHCP and RHCP across multiple frequency bands. The proposed passive metasurface offers a compact and flexible platform for THz communication, imaging, sensing, stealth, and polarization-control applications.

**Keywords** Metasurface (MS) · Broadband · Fractional Bandwidth (FBW) · Cross-polarization conversion · Polarization extinction ratio (PER)

## 1. Introduction

The terahertz frequency range is the mid-frequency band (1–10 THz) of the electromagnetic (EM) spectrum, between microwave and infrared frequencies, with wavelengths ranging from 0.05 to 2.9 mm [1]. According to current studies, several potential uses in the THz range include time-domain spectroscopy for measuring complex dielectric constants of materials [3], cancer detection [4], the design of high-resolution sensors [2], and the enhancement of wireless communication signals and data transfer rates. Many electromagnetic devices are being developed to achieve the aforementioned goals of controlling the degree of polarization, magnitude, and phase of Terahertz waves. The most crucial elements in design are THz amplification and wave-polarization modulation [5–10]. Chirality or resilience is useful in many optical applications, such as drug detection [12], biomolecule sensing [11], and 6G wireless communication [13]. As mentioned above, the polarization states of THz waves can be easily changed by polarization converters. Polarization converters are utilized in microwave and terahertz communications [14], such as fiber optics, liquid crystal displays,

and nanophotonic sensor devices. Conversion between LP-LP and LP-CP is possible using reflective and transmissive polarization converters [15–27]. Standard polarization rotators, characterized by a high-profile design, narrow bandwidth [28], and reflection losses [29], rely on several principles, including the Faraday effect, anisotropy, optical gratings, and birefringent crystals. With the help of metastructures, or metasurfaces, featuring small profiles and lightweight materials, all the challenges associated with traditional techniques can be overcome [30]. There are currently several metasurface-based polarization converters that can alter the state of electromagnetic waves. For example, [31] developed a wideband reflective PC based on a split-ring metallic metasurface, achieving a PCR exceeding 89% over 0.61–1.42 THz. However, [32] have studied several cases of a broadband, transmissive LP-CP converter with diagonal symmetry. A wideband reflection element, which manipulates the size parameter for the purpose of converting an LP polarized wave to a CP wave, is discussed in [33]. [34] proposed an ultrahigh conversion efficiency CPC operating between 0.99 and 1.65 THz. Another split-ring reflecting cross-polarizer that achieved at least 80% PCR over 0.49–1.88 THz was proposed by Xu et al. [35]. Additionally, [36] proposed a metasurface based on a dual-polarization fractal in the THz region, achieving low PCR. [37] suggested a multi-band PC for dual-band CPC and single-band LP-CP conversion. [38] suggested a distinct metasurface for THz applications based on the meta-atom cluster. Also, [39] shows a graphene/gold bilayer-structured electrically programmable terahertz metasurface. Even after years of research, the major challenge of using metasurfaces for electromagnetic waves is that multiband converters have low relative bandwidth, and most polarization converters are limited to a single function. Multiple inputs, outputs, and frequencies of terahertz antennas [40, 41] are necessary. One of the most important issues in MIMO antennas is mutual coupling. Current studies show that coupling can be greatly reduced in multiband MIMO antennas with polarization converters incorporated into metasurfaces. Hence, multiband polarization converters are needed for terahertz applications. However, new application systems demand integrated multipurpose devices. By replacing multiple devices with a single universal device, the proposed devices reduce the system's performance. To simultaneously enhance bandwidth, polarization manipulation, and integration, multifunctional, reconfigurable THz metasurfaces have attracted increasing attention recently. A graphene-based multifunctional THz metasurface with angle-independent and polarization-insensitive characteristics was introduced in [42], demonstrating graphene's potential for dynamic electromagnetic regulation. However, such an idea requires electrical tuning via graphene doping, which increases both the cost and the fabrication complexity. In [43], a broadband, multifunctional polarization converter based on a hybrid graphene-VO<sub>2</sub> metasurface that can switch between LP-LP and LP-CP polarization states was demonstrated. Such a structure relies on phase-change materials and external control mechanisms, despite achieving this level of tunability. In a similar vein, a reconfigurable chiral THz metasurface using graphene and VO<sub>2</sub> for polarization conversion was developed by Xu and Cui in [45], whereas [44] demonstrated a VO<sub>2</sub>-based broadband THz metasurface for wavefront manipulation due to a thermally induced phase transition. Another development is [46], which introduced a dual-functional temperature-controlled THz metasurface capable of polarization conversion and absorption. The proposed metasurface implements LP-to-LP conversion at two frequencies, broadband LP-to-CP conversion, and spin-handedness control, all achieved with a fully passive single-layer structure, unlike recently fabricated THz metasurfaces that employ graphene and VO<sub>2</sub> and require an external voltage for multifunctional polarization manipulation. Since the proposed structure doesn't employ any of the above materials, it remains relatively simpler, free of complex biasing networks, additional power requirements, and fabrication problems associated with active

materials. Moreover, due to the single-layer architecture, manufacturing is easier, more robust, and cost-effective. Therefore, although the proposed technique is not as efficient as other polarization-conversion techniques, it offers a potential replacement for previously published active metasurfaces.

Table 1. Recently reported THz metasurfaces based on graphene and VO<sub>2</sub> are compared with the proposed passive metasurface.

| Feature                | Graphene Metasurface | VO <sub>2</sub> Metasurface | Proposed Work |
|------------------------|----------------------|-----------------------------|---------------|
| Active material        | Yes                  | Yes                         | No            |
| External bias          | Yes                  | Yes                         | No            |
| Thermal control        | No                   | Yes                         | No            |
| Single-layer           | No                   | No                          | Yes           |
| Fabrication complexity | High                 | High                        | Low           |
| Power consumption      | Yes                  | Yes                         | No            |
| LP-LP & LP-CP          | Yes (switchable)     | Yes                         | Yes           |

**This section is an overview of this work's key contributions and performance highlights:**

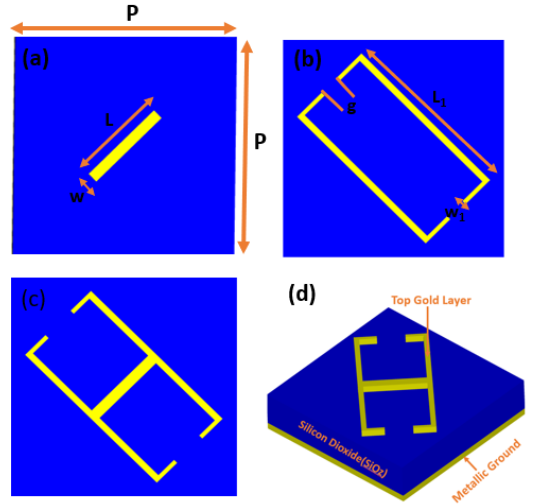
- A small single-layer reflecting metasurface for terahertz waves based on an asymmetrically split square resonator loaded with a metal strip placed diagonally is proposed in order to attain the functionality of polarization manipulation in the absence of multilayers and active elements.
- The proposed metasurface is compact, low-profile, and easy to fabricate, and is realized on a 10- $\mu$ m-thick SiO<sub>2</sub> dielectric substrate supported by a continuous metallic ground plane.
- The proposed metasurface simultaneously offers cross-polarization conversion from LP to LP and polarization conversion from LP to CP within a single unit cell, while conventional THz polarization converters perform only one polarization conversion operation.
- High efficiency LP-to-LP polarization conversion is realized in the frequency bands of 1.45–1.75 THz and 3.10–3.75 THz with the PCR over 90% and close to unity near the resonance frequencies.
- The efficiency of the circular polarization generation is validated by achieving the broadband LP-to-CP polarization conversion from 1.25 to 1.45 THz and 1.83 to 3.02 THz with an axial ratio less than 3 dB.
- Spin-handedness manipulation is made possible by the suggested metasurface, which produces LHCP within 1.25–1.45 THz and RHCP over 1.75–3.55 THz. The ellipticity angle approaches  $\pm 45^\circ$ , indicating nearly ideal circular polarization.
- Polarization extinction ratio (PER), amplitude balance, and about  $\pm 90^\circ$  out-of-phase reflection are employed to prove stable polarization-dependent behavior.

- The proposed meta-surface is a viable solution for terahertz communication devices, imaging, sensing, stealth techniques, and advanced polarization manipulation tasks because of its multi-functional behavior, compact structure, large operational bandwidth, high polarization conversion efficiency, and simple fabrication process.

## 2. Unit Cell Configuration

The proposed meta-atom configuration of the metasurface (MS) is shown in Fig. 1. On the top layer, a gold resonator structure consists of two metallic strips arranged diagonally in a square-ring shape (Fig. 1(c)). The proposed metasurface structure consists of three layers. The middle layer consists of a dielectric substrate  $\text{SiO}_2$  with dielectric constant  $\epsilon_r=3.5$ , loss tangent  $\tan\delta=0.001$ , and substrate thickness  $h=10\mu\text{m}$ . The patterned gold resonator is the top layer. The bottom layer,  $2\mu\text{m}$  thick, serves as a continuous gold ground plane. The proposed unit cell is analyzed in CST Studio Suite using optimized geometric parameters:  $P=51\mu\text{m}$ ,  $L_1=42\mu\text{m}$ ,  $g=8\mu\text{m}$ ,  $W_1=22\mu\text{m}$ ,  $L=21\mu\text{m}$ , and  $w=2.5\mu\text{m}$ . Electromagnetic simulation can be performed to analyze the proposed metasurface using Floquet ports along the z-axis and unit-cell boundaries along the x- and y-axes.

**Fig. 1.** Geometric scheme of MTS. SSR-shaped MTS (a), and diagonal line MTS (b). (c) The suggested unit cell. (d) View of the substrate property.



## 3. Numerical Results and Discussion

The evolution process and polarization conversion characteristics of the proposed metasurface in the THz region were analysed using CST Microwave Studio; Fig. 2 shows the phase responses and reflection coefficients corresponding to the various stages of the proposed metasurface structure's evolution; the co-polarized ( $R_{xx}$ ) and cross-polarized ( $R_{yx}$ ) reflection coefficients are examined to understand the transition from linear polarization (LP) behavior to circular polarization (CP).

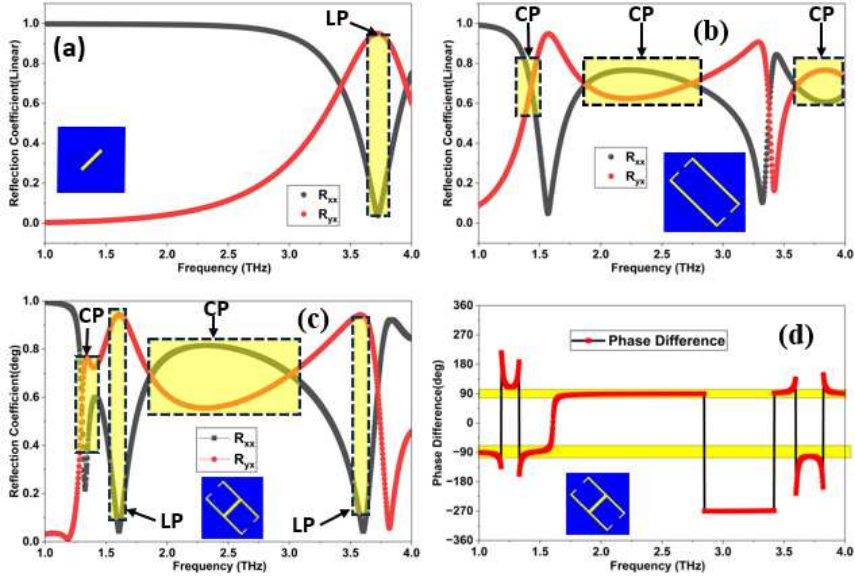


**Fig. 2** Evolution of MTS (a) a diagonal line, (b) asymmetric SRR (c) proposed design (d) phase difference

Fig. 2(a) shows the reflection response of the primary configuration of the metasurface in the evolution process. It can be seen that, over most of the operating frequency range, the co-polarized reflection coefficient  $R_{xx}$  remains close to unity, while the cross-polarized reflection coefficient  $R_{yx}$  remains relatively weak, except in the region around 3.5-3.8 THz, where  $R_{yx}$  increases dramatically. The light-yellow-shaded area labeled LP indicates that effective linear polarization conversion is achieved in this region. The original structure is characterized by the dominance of linear Reflection features with limited polarization conversion, as evidenced by the predominance of the co-polarized component over the cross-polarized component across most frequency ranges. Fig. 2(b) shows that polarization conversion is significantly improved by introducing geometric alterations during metasurface evolution. At this stage,  $|R_{xx}|=|R_{yx}|$  across many operational frequency bands, such as 1.25-1.55 THz, 2.0-3.0 THz, and 3.75-4.0 THz. The light-yellow-shaded regions correspond to the fabricated metasurface structure in the circular-polarization (CP) conversion state. The improved anisotropic response of the modified resonator shape results in the reflected wave beginning to exhibit circular polarization, as evidenced by the equal magnitudes of the orthogonal reflected components. The final stage of the proposed metasurface's evolution is also shown in Fig. 2(c), which compares the reflection coefficients of co- and cross-polarized waves over the entire THz operating range. LP and CP both have multiple distinct operating bands. The limited frequency regions of 1.45-1.75 THz and 3.10-3.75 THz characterize the LP conversion states, while the broad operating regions of approximately 1.83-3.02 THz and 1.25-1.45 THz describe the ultra-wideband CP conversion. By varying the metasurface geometry, the electromagnetic coupling between the orthogonal current components is increased, resulting in a broader CP bandwidth and improved polarization conversion performance. To further verify the LP-to-CP conversion mechanism during metasurface evolution, the phase difference between the orthogonal reflected components is shown in Fig.

2(d). The condition for a linearly polarized incident wave to be converted into a circularly polarized reflected wave is that the relative phase difference between  $R_{xx}$  and  $R_{yx}$  is about  $\pm 90$  degrees, and  $|R_{xx}| = |R_{yx}|$

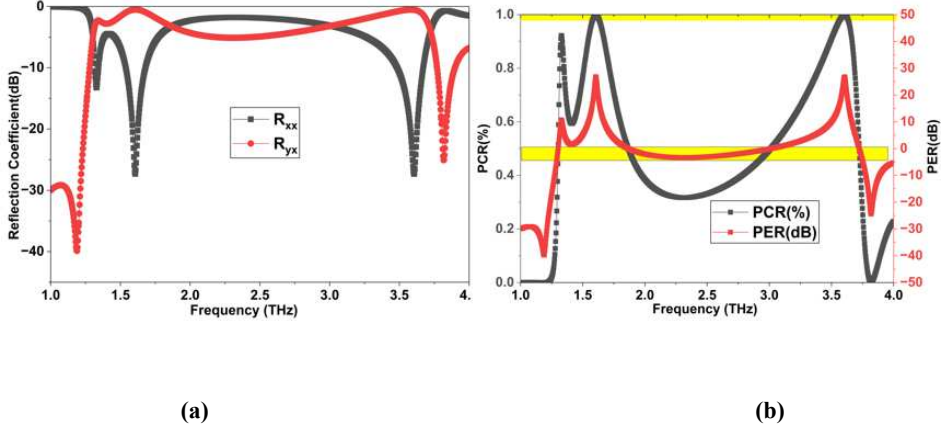


Fig 3. (a) Simulation results (rRHCP-y and rLHCP-y) and (b) PCR and PER (dB)

For the regions marked in Fig. 3, the phase differences are approximately  $+90^\circ$ ,  $-90^\circ$ , and  $\pm 270^\circ$ , demonstrating good LP-to-CP conversion in the improved metasurface structure. The reflection coefficients of the designed metasurface for the RHCP and LHCP are presented as equations 1:

$$r_{RHCP} = \frac{1}{\sqrt{2}}(R_{yx} + iR_{xx}), r_{LHCP} = \frac{1}{\sqrt{2}}(R_{yx} - iR_{xx}) \quad (1)$$

PCR and PER, which can be obtained by equations (2) and (3)

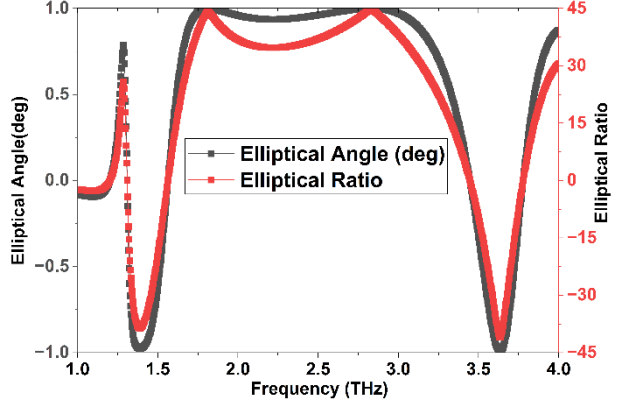
$$PCR = \frac{|r_{RHCP}|^2}{|r_{RHCP}|^2 + |r_{LHCP}|^2} \quad (2)$$

And

$$PER = 20 \log \left| \frac{r_{RHCP}}{r_{LHCP}} \right| \quad (3)$$

correspondingly. In addition, the reflected wave could be considered to have circular polarization as long as its axial ratio (AR) remains below 3 dB. Consequently, the obtained data demonstrate that the proposed metasurface develops stable multi-band performance in the THz spectrum and increases the efficiency of linear-to-circular polarization conversion

**Fig.4** shows a calculated ellipticity (angle) and elliptical Ratio



$$R = \frac{r_{xy}}{r_{yy}} \quad (4)$$

$$\chi = \frac{1}{2} \arcsin((2R \sin(\Delta\phi_{yx})) / (1 + R^2)) \quad (5)$$

$$AR = |1/\tan(\chi)| \quad (6)$$

Fig. 5 shows the theoretical polarization conversion characteristics and the simulated axial ratio (AR) for the proposed reflective metasurface in the THz frequency range. These parameters demonstrate the circular polarization purity of the reflected wave and the LP-to-CP conversion efficiency. Fig. 5(a) presents the simulated axial ratio in the normal incidence regime. When the AR is less than 3 dB, the reflected wave is considered circularly polarized. The axial ratio plays an important role in achieving circular polarization conversion. In Figure 5 (b). Below, there are various operational zones where the AR is below the 3 dB limit. An extended ultra-wideband RHCP operation zone can be achieved from around 1.83 to 3.02 THz, while a narrow LHCP conversion zone is obtained at approximately 1.25- 1.45 THz. In Fig. 4(b), the orthogonal reflection coefficient ratio ( $r_{yx}/r_{yy}$ ) represents the best polarization conversion capability of the proposed metasurface. The magnitudes of the co- and cross-polarized reflected components should be equal for optimal circular polarization conversion, resulting in a ratio close to 1. In the highlighted yellow region shown in Fig. 5(b), the ratio  $r_{yx}/r_{yy}$  remains nearly constant at 1 across the frequency ranges around 1.8–3.0 and 3.7–3.9 THz. From these frequency regions, it is evident that the proposed metasurface achieves optimal circular-polarization conversion.

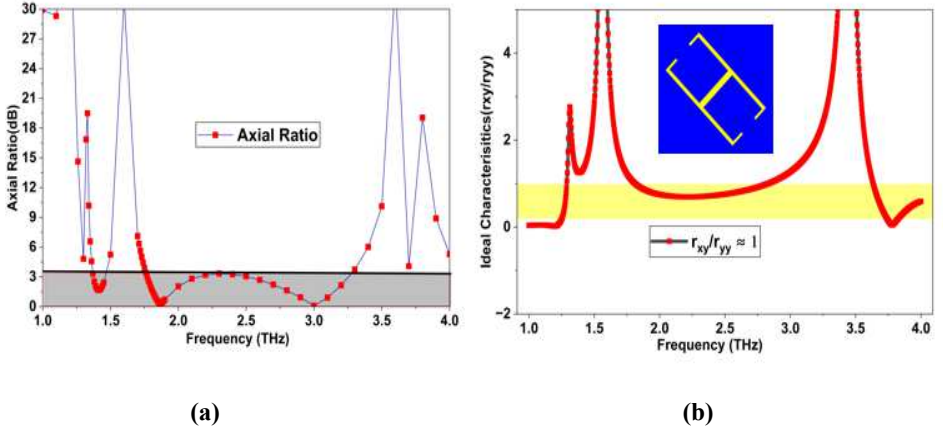


**Fig 5.** (a) Axial ratio and (b) Optimal properties

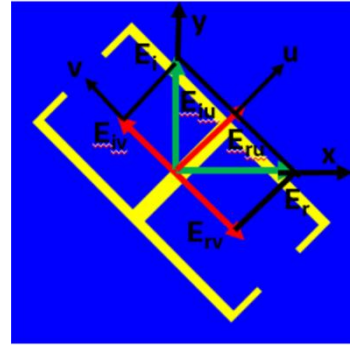
As shown in Fig. 4, the polarization conversion properties are further examined utilizing the elliptical angle and normalized ellipticity. The expression for the normalized ellipticity and elliptical angle is expressed by equations (7) or (8)

$$e = \frac{2R\sin(\Delta\phi_{yx})}{1+R^2} \quad (7)$$

$$\chi = 0.5\arcsin((2R\sin(\Delta\phi_{yx}))/((1 + R^2))) \quad (8)$$

where  $\Delta\phi_{yx}$  represents the relative phase shift between the orthogonal reflected modes, and  $R$  stands for their amplitude ratio. The normalized ellipticity and elliptical angle of the proposed metasurface as a function of the frequency have been presented in Fig. 4. The right-hand circular polarization (RHCP) mode and left-hand circular polarization (LHCP) mode are validated by the normalized ellipticity being close to +1 and -1, respectively, in the operating region of the CP mode. The normalized ellipticity remains around +1 over the broad frequency range of approximately 1.83–3.02 THz for the RHCP mode. But the normalized ellipticity tends to -1 around 1.25-1.45THz, 3.55–3.75 THz.

**Fig. 6** shows the decomposition of the wave into components along the  $u$ - and  $v$ -axis



Moreover, in the CP operation bands, the ellipticity angle remains approximately  $\pm 45^\circ$ . The presence of the RHCP is evidenced from the angle close to  $+45^\circ$ , whereas the presence of the LHCP results from the angle near  $-45^\circ$ . This demonstrates that the proposed metasurface can

perform multi-band LP-to-CP polarization transformation with an ultra-wideband CP response in the THz range, along with handedness switching and polarization purity. Fig. 6 shows the decomposition of the wave along the u- and v-axes to evaluate the operating principle of the proposed structure. Our intensive theoretical investigation resulted in a thorough physical architecture. The reflection matrix ( $R_{lin}$ ) for linearly polarized incident waves (LP) in the UV local frame is shown in equation (9):

$$R_{lin} = \begin{pmatrix} r_{uu} & 0 \\ 0 & r_{vv} \end{pmatrix} \quad (9)$$

In the coordinate system,  $R_{lin}$  is computed as follows:

$$R_{lin} = \begin{pmatrix} r_{xx} & r_{xy} \\ r_{yx} & r_{yy} \end{pmatrix} = \frac{1}{2} r_{uu} \begin{pmatrix} 1 + e^{-j\phi_{uv}} & 1 - e^{-j\phi_{uv}} \\ 1 - e^{-j\phi_{uv}} & 1 + e^{-j\phi_{uv}} \end{pmatrix} \quad (10)$$

The following equation can be determined by applying Eq. (10).

$$\frac{r_{yy}}{r_{xy}} = \frac{r_{xx}}{r_{yx}} = \frac{1 + e^{-j\Delta\phi_{uv}}}{1 - e^{-j\Delta\phi_{uv}}} = \frac{e^{j\Delta\phi_{uv}/2} + e^{-j\Delta\phi_{uv}/2}}{e^{j\Delta\phi_{uv}/2} - e^{-j\Delta\phi_{uv}/2}} \quad (11)$$

With the condition  $-180^\circ < \Delta\phi_{uv} < 180^\circ$  satisfied, the value  $\Delta\phi_{uv}/2$  will fall within the range  $-90^\circ$  and  $90^\circ$ . As illustrated in Fig. 7 below,  $\Delta\phi_{uv} = 90^\circ$  is obtained between  $r_{yy}$  and  $r_{xy}$  with an incident x- and y-polarized wave, where  $0^\circ < \Delta\phi_{uv} < 90^\circ$ . However, from Fig. 7(b), it is observed that  $\Delta\phi_{uv}$  will equal  $90^\circ$  if  $90^\circ < \Delta\phi_{uv}/2 < 0^\circ$ . It is clear from the above discussion that the phase difference  $\Delta\phi_{uv}$  between  $r_{xx}$  and  $r_{xy}$  remain constant across the frequency range from 1 THz to 4 THz. Therefore, we find that the ratio of reflection coefficients for y and x polarization, i.e.,  $r_{yy}/r_{xy}$  or  $r_{xx}/r_{yx}$ , always stays the same, as shown in Equ (15). The polarization difference LP-CP can be explained simultaneously for the case in which the wave is polarized in the x direction. The incidence wave that is polarized in the x direction would equally be converted to an LHCP or RHCP reflected wave. In addition, Equ (11) can be used to explain the values of reflection coefficients as follows:

$$|r_{yy}| = \sqrt{(1 + \cos\Delta\phi_{uv})/2}, \quad |r_{xy}| = \sqrt{(1 - \cos\Delta\phi_{uv})/2} \quad (12)$$

Equation (12) shows that when  $\Delta\phi_{uv} = 0^\circ$ , both the incident and reflected waves are polarized in the same direction. In contrast to this situation, maximum cross polarization will occur when  $|r_{yy}| = |r_{xx}| = 0$  at  $\Delta\phi_{uv} = 180^\circ$ . On the other hand, the reflected wave polarizes elliptically when  $\Delta\phi_{uv} \neq 0^\circ$  and  $\pm 180^\circ$ , where the axial ratio may be written as:

$$AR = \sqrt{\frac{1 \pm \cos\Delta\phi_{uv}}{1 \mp \cos\Delta\phi_{uv}}} \quad (13)$$

Equation (13) states that the procedure of choosing the addition (+) and subtraction (−) symbols ensures that AR is never less than 1.0.

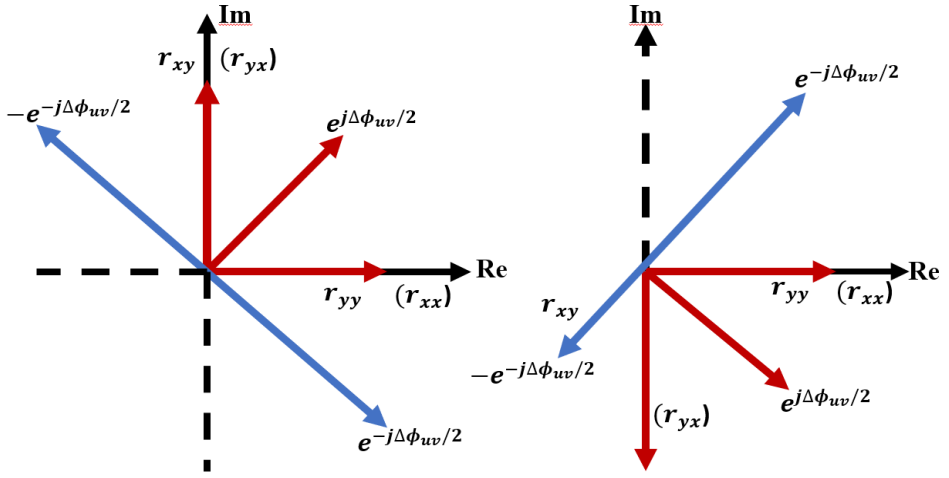


Fig. 7 shows a basic graphic representation under y- and x-polarized conditions, polarization reflection coefficients

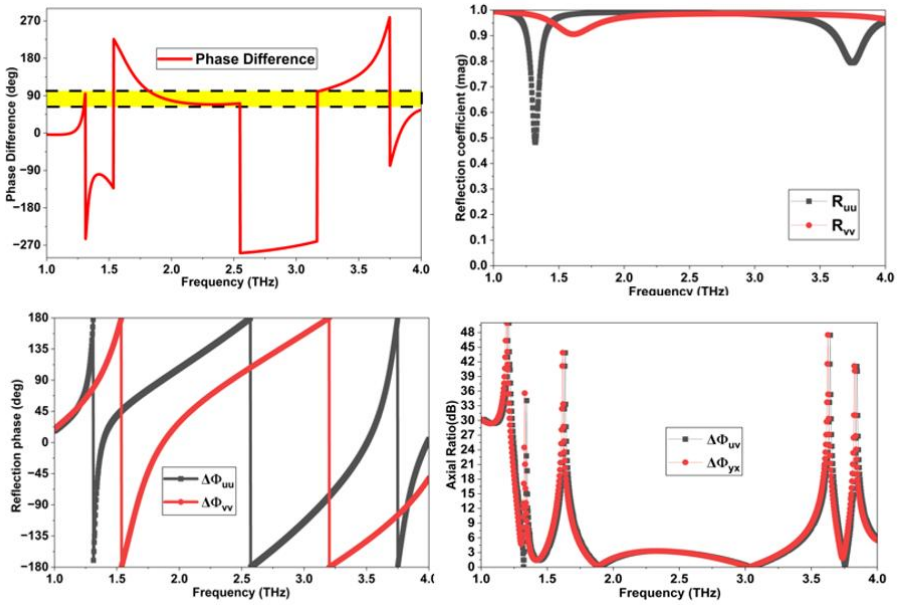


Fig. 8(a) phase difference, (b) Reflectivity, (c) Reflectivity Phase, and (d) Reflectivity Axial Ratio for u-v axes

AR can be used to calculate the LP-to-CP converter's efficiency of the resulting wave due to reflections, which is unity at  $\Delta\phi_{uv} = 90^\circ$  according to Eq. (14). As a result of negligible dielectric losses, the incident and reflected waves that have their x- and y-polarizations may be considered synthesized waves with components of the same magnitude along the u- and v-

incident polarizations directions. As a continuation of our previous research, we conducted simulations of a hypothetical reflective polarization MS using v- and u-polarized incident light to analyze the underlying physics. In Fig. 8(a), the phase difference ( $\Delta\phi_{uv}$ ) between the orthogonal reflected components  $R_{vv}$  and  $R_{uu}$  as obtained from the simulation. Over the frequency regions of around 1.8-2.6 THz and 3.2-3.6 THz, the phase difference is found to be within the desired range around  $90^\circ$  (or equivalently  $270^\circ$ ), fulfilling the basic phase criterion for the LP-to-CP polarization conversion. The frequency range in which the phase deviation is sufficiently low to generate effective circular polarization is shown in the selected region. Fig. 8(b) shows the reflection amplitudes  $R_{uv}$  and  $R_{uu}$ . The coefficients remain close to unity in magnitude ( $|R| > 0.9$ ) across most of the spectrum studied, indicating high reflection efficiency and low ohmic and dielectric losses. The presence of a few resonant regions where only amplitude reductions are observed indicates that the metasurface unit cell exhibits resonant behavior. Fig. 8(c) shows the reflection phase responses,  $(\phi_{uu})$  and  $(\phi_{vv})$ . A number of phase transitions spanning nearly  $360^\circ$  provide the necessary phase-manipulation capability for polarization conversion. The phase difference between the orthogonal components yields the required  $\sim 90^\circ$  phase offset for circularly polarized reflection. Figure 8(d) shows the computed axial ratio (AR). The AR is reduced to near-0 dB within the operating bands and remains below the standard 3-dB requirement across the desired frequency ranges, confirming high-quality circular polarization. The proposed metasurface can convert the incident linearly polarized wave into a reflected circularly polarized wave with high reflection efficiency, as confirmed by the agreement in phase-difference response, reflection amplitudes, and AR properties. The results demonstrate the broadband performance and polarization-conversion capabilities of the designed THz metasurface polarizer. Figs. 9(a) and 9(b) show the angular stability of the proposed metasurface for TE- and TM-polarized incident waves at the incidence angles of  $0^\circ$ ,  $15^\circ$ ,  $30^\circ$ , and  $45^\circ$ . In the frequency band of about 1.85-3.25 THz for the LP-to-CP conversion, the metasurface maintains an axial ratio below 3 dB, demonstrating the best performance at normal incidence ( $\theta = 0^\circ$ ). The operational bandwidth and resonant frequencies change slightly, and the resonance modes remain very stable for incident angles up to  $15^\circ$ . At the incidence angle of  $30^\circ$ , a minor resonance shift and a slight increase in axial ratio are observed, which are due to the change of effective propagation path and electromagnetic coupling in the unit cell. The degradation becomes significant when the angle of incidence approaches  $45^\circ$ , especially in the higher-frequency band (3.3-4.0 THz), due to impedance mismatch and the activation of higher-order resonant modes. This is physically due to the increased tangential component of the incoming wave vector, which modifies the induced surface-current distribution and slightly reduces the electric and magnetic coupling between the metallic resonator and the ground plane. Thus, the effective inductance and capacitance of the unit cell are slightly modified, which results in small resonance shifts and a small phase mismatch between the orthogonal components of the reflected field.

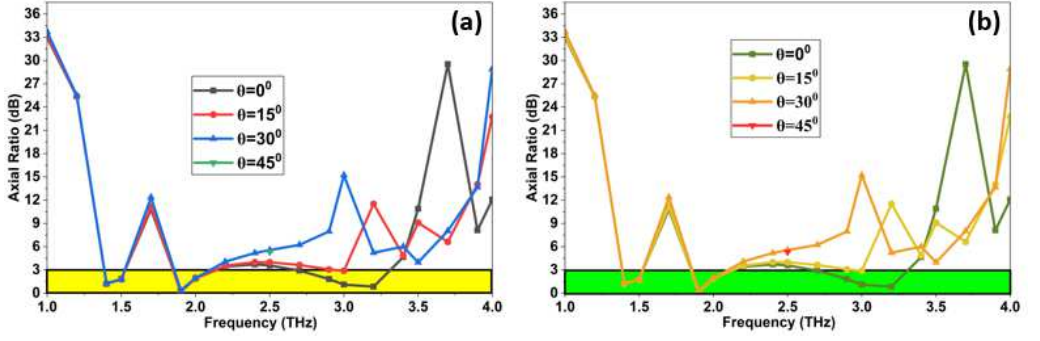


**Fig.9.** AR simulation under (a) TE and (b) TM at various oblique angles.

Nevertheless, in both TE and TM polarizations, the AR is less than 3 dB over most of the required frequency range, indicating excellent angular and polarization stability of the proposed metasurface at high incident angles.

#### 4. Equivalent Circuit Model

To provide a physical insight, we present an equivalent lumped-element circuit model (ECM) of the proposed metasurface in Fig. 10(a). The proposed ECM comprises four inductors ( $L_1$ – $L_4$ ) and four capacitors ( $C_1$ ,  $C_2$ ,  $C_m$ , and  $C_g$ ) that mimic the distributed inductive and capacitive behavior of the metallic resonator. The capacitors  $C_1$  and  $C_2$  are the electric-field energy stored in the split gaps of the metallic pattern, and the inductors  $L_1$ – $L_4$  are the magnetic energy stored due to the surface currents flowing along different metallic parts of the resonator.

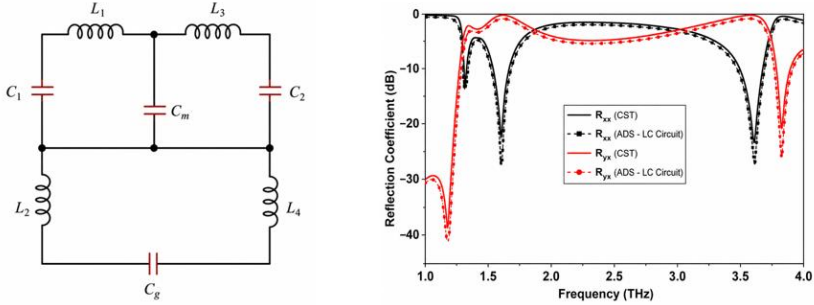


**Fig.10.** (a) Equivalent LC circuit model of the proposed metasurface and (b) validation by CST and ADS reflection coefficient responses.

Here,  $C_g$  represents the capacitance formed by the metallic resonator and the ground plane through the dielectric substrate.  $C_m$  is the capacitor that models the mutual capacitive coupling between neighboring resonant sections. Initial values of the lumped parts are estimated by conventional analytical equations. The equivalent inductance of a metallic strip may be approximated as eqn(14)

$$L = 2 \times 10^{-7} l \left[ \ln \left( \frac{2l}{w+t} \right) + 0.5 \right] \quad (14)$$

where  $l$ ,  $w$ , and  $t$  are the length, width, and thickness of the metallic strip, respectively. An

estimate of the capacitance across the split gap in eqn(15):

$$C = \epsilon_0 \epsilon_{eff} \frac{wl}{g}, \quad (15)$$

where  $w$  is the width of the strip,  $l$  is the length of the overlap,  $g$  is the gap between two adjacent metallic sections,  $\epsilon_0$  is the permittivity of free space, and  $\epsilon_{eff}$  is the effective dielectric constant. The capacitance between the resonator and the ground plane is given by eqn(16)

$$C_g = \epsilon_0 \epsilon_r \frac{A}{h}, \quad (16)$$

where  $\epsilon_r$  is the relative permittivity of the dielectric substrate,  $h$  is the thickness of the substrate, and  $A$  is the effective area of the metallic resonator. In the presence of an incident electromagnetic wave, the inductive elements store magnetic energy and the capacitive elements store electric energy. These elements exchange energy periodically and produce. The frequency at which the resonance happens is dictated by Eqn (17)

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (17)$$

where  $L$  and  $C$  are the equivalent inductance and capacitance of the resonance path, respectively. Then ADS optimizes the calculated values of the lumped parts so that the simulated response is close enough to the full-wave CST simulated. As shown in Fig. 10(b), the reflection characteristics from CST and ADS are in good agreement, demonstrating that the proposed ECM accurately captures the electromagnetic response of the targeted metasurface. Most of the minor differences between the two responses are due to higher-order electromagnetic effects, conductor and dielectric losses, and distributed-field phenomena that are not fully captured by the lumped-element approximation [47]– [50]. Each resonance is formed by the interaction of distributed inductive current pathways and local capacitive gaps, as evidenced by the strong consistency between equivalent circuit models and full-wave CST simulations. The fundamental LC resonance primarily determines the behavior of low-frequency resonances, whereas high-frequency resonances arise from increased mutual coupling and higher-order current pathways. The designed metasurface can accomplish LP–LP conversion, LP–CP conversion, and spin-handedness manipulation across the entire THz band, as various resonance modes generate the required amplitudes and a nearly  $\pm 90^\circ$  phase difference between the two orthogonal reflected waves.

## 5. Surface Current Analysis

Fig. 11 shows the simulated SCD in the patch and ground layers at the resonant frequencies of 1.33, 1.62, and 3.62 THz. The arrows show the main directions of current flow at each resonance. The current distribution is strongly localized in the central strip of the unit cell and in the metallic frame, suggesting that these regions are primarily responsible for the resonant behavior. At 1.33 THz, the induced currents on both levels are diagonally oriented, indicating strong electromagnetic coupling between the resonator and the ground plane. The current distribution along the inclined metallic arms partially excites the fundamental resonant mode. We observe excitation of a higher-order resonant mode at 1.62 THz, with the current distribution predominantly vertical and a higher current density around the central connecting strip. On the other hand, the surface currents are mainly distributed horizontally at 3.62 THz, indicating a different resonant mechanism associated with the metasurface's higher-frequency response. Moreover, current loops arise due to the metallic resonator and the ground plane, as the currents in both layers are opposite at resonant frequencies. The magnetic resonance generated by these oppositely directed currents can be modeled as magnetic dipoles normal

to the metasurface plane. Electric dipoles are created along with the localized charges at the metallic edges. Both electric and magnetic resonances should be excited to achieve the desired effect on the reflected electromagnetic wave. It is proven that the multi-resonance effect is present in the designed metasurface from the presence of different resonant modes of current at 1.33 THz, 1.62 THz, and 3.62 THz. Resonance effects facilitate polarization conversion by creating the required phase difference and reflections.

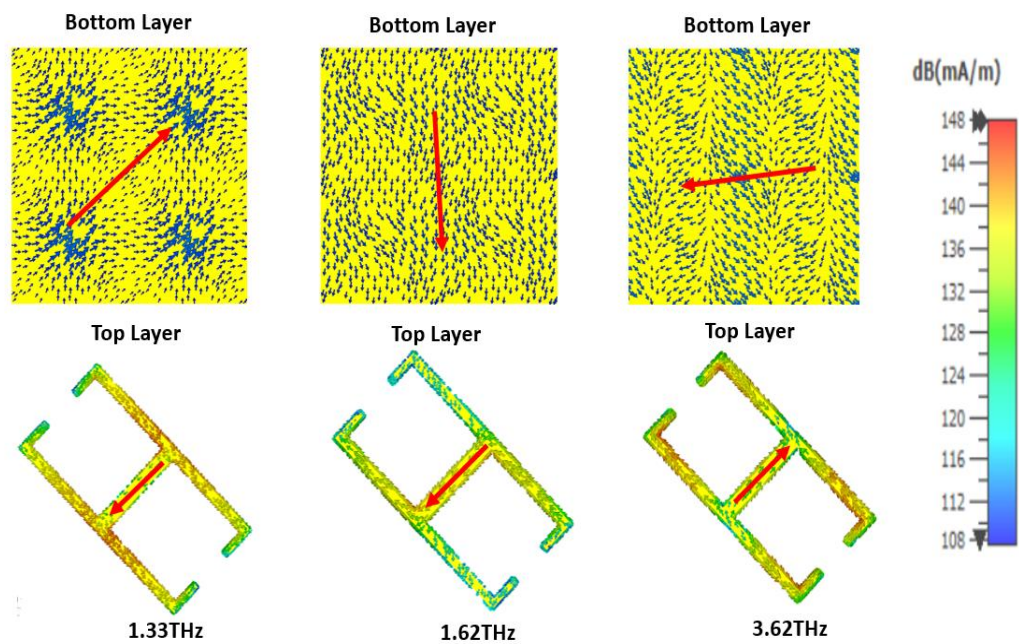
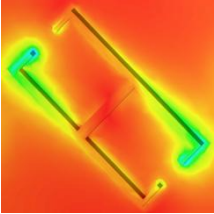
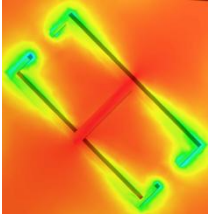
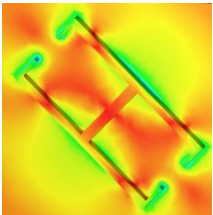
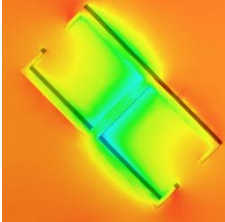
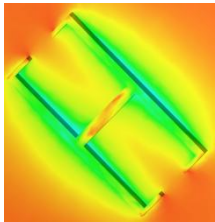
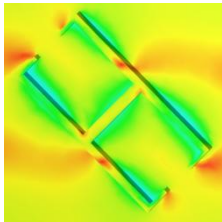


**Fig. 11.** SCD on structure at (a) 1.33 THz, (b) 1.62 THz, and (c) 3.62 THz

The distributions of electric and magnetic fields for the three resonant frequencies of 1.33, 1.62, and 3.62 GHz (THz, if you design according to your requirements) are provided in Table 1 to illustrate the physical principles of the proposed metasurface. The notable collection of charges occurs at the split gaps and sharp corners of the metallic resonator due to the concentration of the electric field at 1.33. These gaps behave like capacitors, storing electric-field energy. The notable surface currents, which store magnetic field energy and exhibit inductive behavior, have been identified as present primarily along the metallic strips. However, the electric field distribution remains localized in the split gaps at the second resonant frequency (1.62), and although the field spread is larger than in the first, it remains confined to a larger area of the resonator. The higher, more uniform distribution of the magnetic field along the resonator arms indicates an increase in the circulating currents that form the second resonant mode. At the high resonant frequency (3.62), the field distribution becomes more uniform across the whole resonator, while the field localization near the corners and gaps remains strong. Such an action implies the excitation of the high-order resonant mode, where several paths for the circulating currents operate simultaneously.

**Table1.** Electric field and Magnetic field at Resonant Frequency  $f=1.33,1.62,3.62$  THz

| Source Field   | Resonant Frequency (THz)                                                          |                                                                                   |                                                                                    |
|----------------|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
|                | 1.33                                                                              | 1.62                                                                              | 3.62                                                                               |
| Electric Field |  |  |  |
| Magnetic Field |  |  |  |

Both inductive and capacitive effects contribute to the generation of resonance, owing to strong magnetic-field confinement along the metallic strips and high electric-field localization at the gaps. Resonance is generated by the constant interchange between the electric and magnetic fields, enhancing the polarization converter's broadband performance. Therefore, from the analysis of the equivalent circuit, electric and magnetic field distribution, and surface current distribution, we are able to conclude that excitation of several LC resonances in connection results in multifunctionality of the proposed metasurface. The dual-band LP-LP and broadband LP-CP conversions, as well as control of the spin handedness, become possible owing to these resonances, which provide the required amplitude ratio and phase difference between the orthogonal reflected fields within a single passive cell.

## 6. Parametric Analysis

Parametric studies were performed on the periodicity ( $p$ ) of the unit cell, varying  $p$  from  $47\text{ }\mu\text{m}$  to  $53\text{ }\mu\text{m}$  while keeping other geometrical parameters fixed to achieve maximum performance of the proposed metasurface. The axial ratio (AR) and polarization conversion ratio (PCR) characteristics of the metasurface for the above-mentioned variation are illustrated in Figs. 12(a) and 12(b), respectively. It can be observed that the structure's periodicity significantly affects the electromagnetic coupling between adjacent unit cells. Coupling due to near-field effects increases with lower periodicity ( $p=47\text{ }\mu\text{m}$ ), whereas higher periodicity ( $p=53\text{ }\mu\text{m}$ ) reduces interaction between neighboring resonators and lowers the polarization conversion efficiency. Among all the values considered,  $p=51\text{ }\mu\text{m}$  exhibits the

best PCR across the entire operational frequency range.

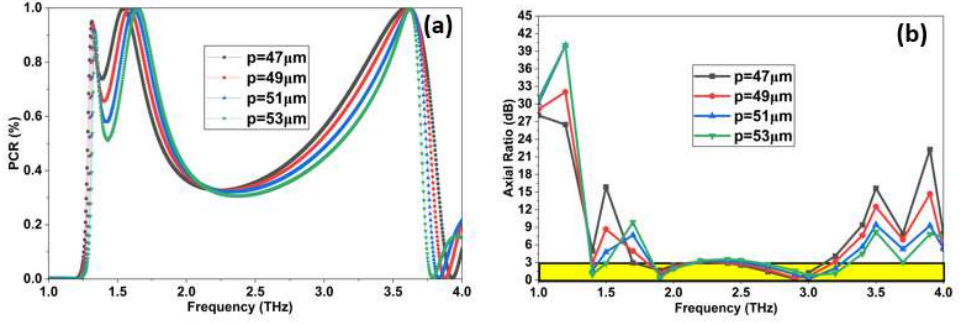


**Fig 12.** (a) Polarization Conversion Ratio (PCR) and (b) Axial Ratio (AR) for various periodicity values in a parametric study of periodicity ( $p$ ).

This periodicity is also confirmed through AR measurements. At this periodicity, the axial ratio within the expected operating range is minimized at  $p = 51 \mu\text{m}$ . This periodicity meets the 3 dB criterion in the polarization conversion region. As  $p = 51 \mu\text{m}$  provides a good balance between impedance matching, circular polarization, and polarization conversion ratio, it is selected as the optimized periodicity of the proposed metastructure. To study the effect of substrate thickness on polarization conversion performance, a parameter analysis was conducted by varying substrate thickness ( $h$ ) from  $8 \mu\text{m}$  to  $14 \mu\text{m}$  while keeping the geometrical parameters unchanged. The resulting PCR and AR responses are shown in Fig. 13(a) and Fig. 13(b), respectively. The substrate thickness significantly affects the electromagnetic coupling, effective optical path, and impedance matching of the metasurface, as shown in Fig. 13(a). This gives rise to considerable differences in the resonant characteristics and the polarization conversion efficiency. Among the studied examples,  $h=10\mu\text{m}$  shows the most significant and uniform PCR in the entire working band, indicating effective polarization conversion and ideal resonance excitation. The related AR response in Fig. 13(b) is also consistent with the minimum AR at  $h=10 \mu\text{m}$ , and the 3 dB criterion is met for the desired circular-polarization conversion band. On the other hand, the performances of PCR and AR deteriorate when the substrate thickness deviates from the optimum value, due to impedance mismatch and weaker resonance coupling. The ideal substrate thickness for the proposed metasurface is  $h = 10 \mu\text{m}$ , as it provides the optimal balance among polarization conversion efficiency, circular-polarization performance, and broadband operation.

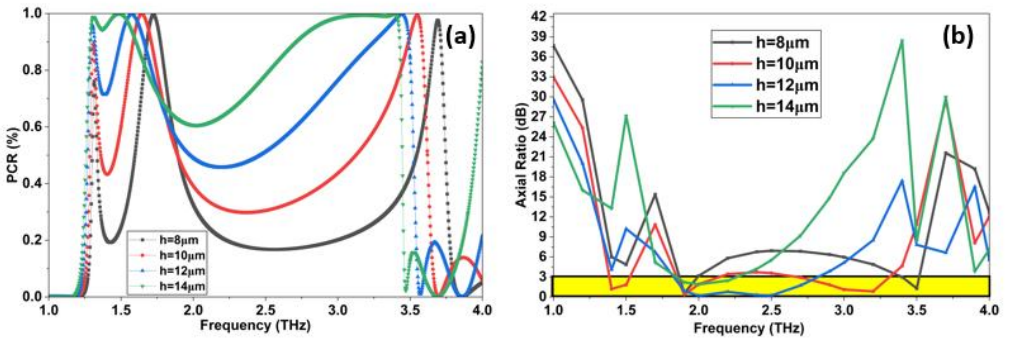


**Fig. 13.** Parametric evaluation of the substrate thickness ( $h$ ): (a) the proposed metasurface's Polarization Conversion Ratio (PCR) and (b) its Axial Ratio (AR).

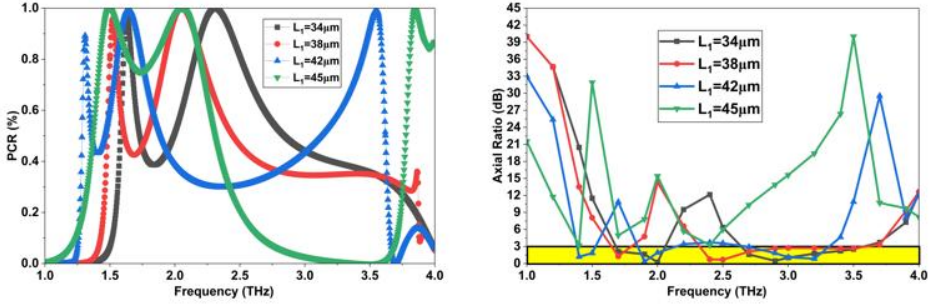


**Fig14.** Parametric analysis of resonator length ( $L_1$ ): (a) the proposed metasurface's polarization conversion ratio (PCR) and (b) its Axial ratio (AR).

The resonator length ( $L_1$ ) was parametrically analyzed over 34  $\mu\text{m}$  to 45  $\mu\text{m}$ , while the other geometrical parameters were kept constant to optimize the performance of the proposed metasurface. The relevant PCR and AR responses are shown in Fig. 14(a) and Fig. 14(b), respectively. As shown in Fig. 14(a), the effective current path length is significantly altered by varying  $L_1$ , thereby altering the metasurface's resonance characteristics and polarization conversion performance. A longer resonator length ( $L_1=45\mu\text{m}$ ) results in a reduced broadband response due to excessive current path extension, whereas shorter resonator lengths ( $L_1=34\mu\text{m}$  and  $38\mu\text{m}$ ) shift the resonant frequencies and degrade PCR over the operating band.

On the contrary,  $L_1=42\mu\text{m}$  shows the largest and most stable PCR over the targeted frequency range, suggesting better impedance matching and optimal resonance excitation. The corresponding AR measurements in Fig. 14(b) also show that  $L_1=42\mu\text{m}$  keeps the axial ratio below the 3 dB requirement over the circular polarization conversion band while maintaining a high polarization conversion ratio. The optimized resonator length for the final metasurface design is  $L_1 = 42\mu\text{m}$ , providing an optimal trade-off among polarization conversion efficiency, circular polarization performance, and broadband operation. To maximize the performance of the suggested metasurface, a parametric analysis of the split gap width ( $g$ ) was conducted, varying it from 6  $\mu\text{m}$  to 12  $\mu\text{m}$  while keeping the other geometrical parameters constant. The corresponding PCR and AR properties are shown in Figs. 15(a) and 15(b),

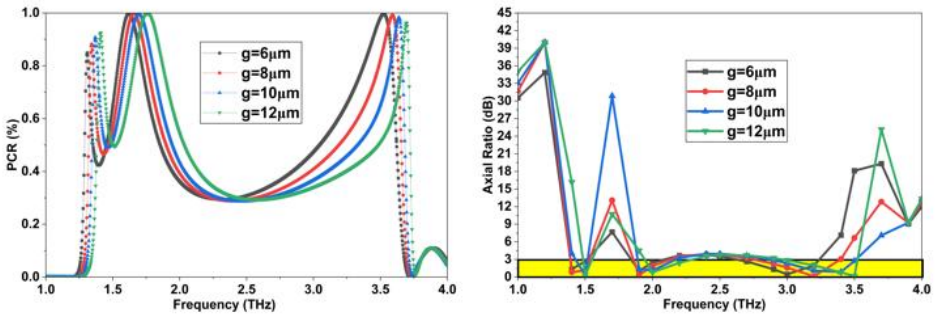


**Fig 15.** Parametric analysis of resonator gap ( $g$ ): (a) the proposed metasurface's polarization conversion ratio (PCR) and (b) its Axial ratio (AR).

respectively. As shown in Fig. 15(a), the gap width significantly affects the capacitive coupling between adjacent metallic parts, thereby modifying the resonance characteristics and the polarization conversion efficiency. When the gap is larger ( $g=10\text{ }\mu\text{m}$  and  $12\text{ }\mu\text{m}$ ), capacitive coupling is reduced, leading to worse polarization conversion performance. When the gap is smaller ( $g=6\text{ }\mu\text{m}$ ), the capacitance increases and the resonant frequencies shift. For the analyzed cases,  $g=8\text{ }\mu\text{m}$  has the most stable PCR response with values close to unity at the resonant frequencies and excellent impedance matching over the desired operating band. The AR measurements in Fig. 15(b) also confirm AR in the region of circular polarization conversion, with AR fluctuation suppression for  $g=8\text{ }\mu\text{m}$  less than 3 dB. Hence,  $g=8\text{ }\mu\text{m}$  is selected as the optimal gap width for the final metasurface design, as it provides the best compromise among polarization conversion efficiency, circular polarization performance, and broadband operation. To enhance the efficiency of the proposed metasurface, a parametric analysis of the resonator width ( $W_1$ ) was performed, varying it between  $18\text{ }\mu\text{m}$  and  $24\text{ }\mu\text{m}$  while keeping all other geometric parameters constant. The corresponding results for PCR and AR are shown in Fig. 16(a) and Fig. 16(b), respectively. As shown in Fig. X(a), varying the resonator width results in substantial changes in the effective current flow and capacitive coupling, thereby altering the resonant behavior and polarization conversion performance. A narrow width ( $W_1=18\text{ }\mu\text{m}$ ) leads to poor impedance matching and a significant decrease in PCR across the bandwidth.

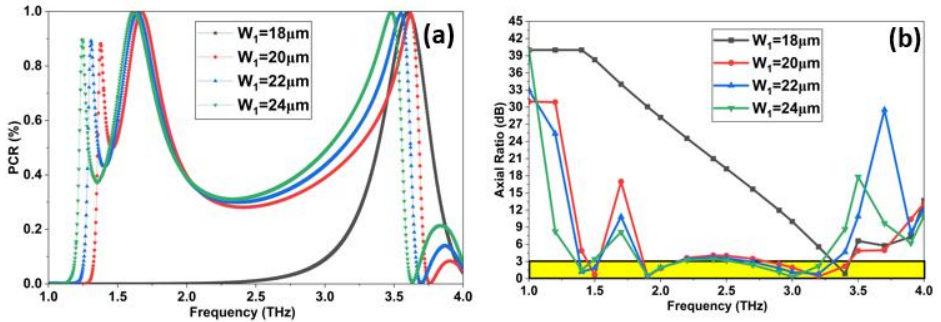


**Fig 16.** Parametric analysis of resonator Width( $W_1$ ) (g): (a) the proposed metasurface's polarization conversion ratio (PCR) and (b) its Axial ratio (AR).

Since all the AR responses have nearly unity values at the resonant frequencies,  $W_1 = 22\text{ }\mu\text{m}$  provides the most stable PCR responses for the considered sample resonators. Even though the other widths produce more AR variations, the AR responses shown in Fig. 16(b) demonstrate that  $W_1 = 22\text{ }\mu\text{m}$  maintains the axial ratio below the 3dB threshold in the required region of circular polarization conversion. In summary, given the above factors for the resonator's optimal design, the choice of width  $W_1 = 22\text{ }\mu\text{m}$  is justified.

## 7. Fabrication Feasibility and Manufacturing Tolerance

The proposed reflective terahertz metasurface can be fabricated using a conventional microfabrication technique commonly used for THz passive devices, as shown in Figure 17. The production process begins with the deposition of a continuous gold (Au) ground plane on a silicon or quartz carrier substrate by electron-beam evaporation or magnetron sputtering. Next, a dielectric layer of  $\text{SiO}_2$  with a thickness of  $10\text{ }\mu\text{m}$  is fabricated using spin coating or plasma-enhanced chemical vapor deposition (PECVD), depending on the fabrication platform. Finally, the top

metallic resonator is fabricated by a lift-off process, metal deposition, and standard UV photolithography. The fabrication process is significantly simpler than those reported for graphene- or  $\text{VO}_2$ -based THz metasurfaces, as the proposed design requires only one patterned metallic layer and does not require multilayer alignment, active materials, biasing circuits, or phase-change materials. The proposed unit cell has a minimum split gap of  $8\ \mu\text{m}$  and a minimum feature size of  $2.5\ \mu\text{m}$  from a fabrication perspective. These dimensions can be manufactured with high precision using commercially available microfabrication facilities and are well within the resolution limits of conventional UV photolithography. Advanced nanolithography techniques such as electron-beam lithography are therefore not strictly needed, thereby simplifying and reducing manufacturing costs.

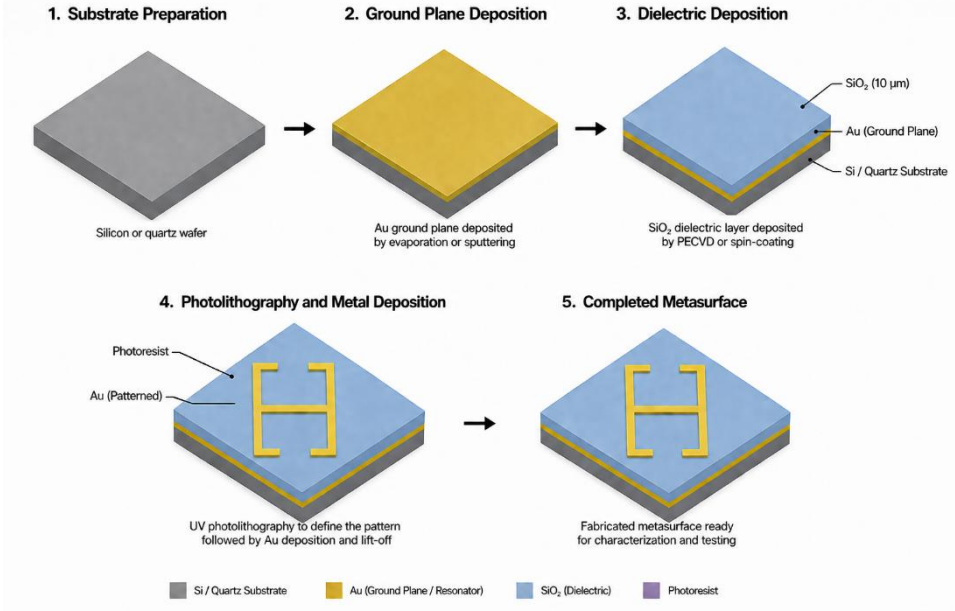


Fig.17. Fabrication process of proposed reflecting THz metasurface: (a) Preparation of Si/Quartz substrate; (b) Deposition of Au Ground Plane; (c) Deposition of dielectric  $\text{SiO}_2$  Layer; (d) Top Au Resonator Pattern and UV photolithography, and (e) Completed metasurface fabrication process.

Dimensional parametric studies were performed to evaluate fabrication resilience by varying the most sensitive geometric factors, including the unit-cell periodicity, substrate thickness, resonator length, split-gap width, and resonator width. The simulation results indicate that the proposed metasurface exhibits high polarization conversion efficiency in the desired operating bands, although dimensional variations cause slight shifts in resonance. The best dimensions ( $P = 51\ \mu\text{m}$ ,  $h = 10\ \mu\text{m}$ ,  $L_1 = 42\ \mu\text{m}$ ,  $g = 8\ \mu\text{m}$ , and  $W_1 = 22\ \mu\text{m}$ ) yield the best combination of impedance matching, resonance excitation, and polarization conversion performances. These findings suggest that the proposed design is appropriate for experimental implementation in subsequent work and exhibits good tolerance to realistic fabrication errors.

## Conclusion

A multifunctional terahertz metasurface comprising an asymmetric split-square resonator loaded with a diagonal metallic strip is proposed. The designed metasurface provides dual-

band LP–LP and broadband LP–CP polarization conversion in a single compact structure. Polarization-selective LP–LP conversion with high reflection efficiency is demonstrated for two separate operating bands. LP–CP functionality is provided in a broad frequency range with an axial ratio of < 3 dB. The underlying polarization conversion principle is based on the excitation of numerous resonances, which generate the necessary phase shift (+90<sup>0</sup>) and a proper balance of the amplitudes of the orthogonal field components. Furthermore, the examination of surface currents indicates that electric and magnetic resonances coexist, providing a physical explanation for the previously observed multiband polarization manipulation characteristics. Excellent consistency of the reflection coefficient, phase response, axial ratio, ellipticity, and current distribution verifies the effectiveness of the proposed design. This proposed metasurface structure is a potential candidate for terahertz communication systems, polarization-sensitive imaging applications, sensing devices, stealth techniques, and antennas, owing to its compact structure, wide operating bandwidth, multifunctional polarization conversion, and high polarization conversion efficiency. The proposed passive single-layer structure can achieve multifunctional polarization conversion without any active materials, external biasing mechanisms, or phase-change techniques, unlike the latest publications on THz metasurfaces that use graphene and VO<sub>2</sub>. Such a simple structure provides a practical solution for future THz applications due to its low fabrication complexity, cost-effective implementation, power savings, and reduced overhead.

**Table 1: Comparative analysis of other recent articles.**

| Ref.      | Operation Bandwidth (THz)                                      | Thickness (μm) | Unit Cell dimension (μm) | 3-dB AR Bandwidth (%) | Angular Stability                                     | Electric al Size                         | Fabric ation Compl exity | Passiv e Vs Active | PCR (%) | Performance                      |
|-----------|----------------------------------------------------------------|----------------|--------------------------|-----------------------|-------------------------------------------------------|------------------------------------------|--------------------------|--------------------|---------|----------------------------------|
| [17]      | 3.75–6.00                                                      | 12             | 12                       | 46.20                 | Broadban d LP–CP up to 20°; Dual-band LP–CP up to 40° | $8.33\lambda_o \times 8.33\lambda_o$     | High                     | Active             | 90      | LP–CP                            |
| [18]      | 0.50–1.41; 1.45–1.55                                           | 47             | 88                       | 95.00; 6.60           | NR                                                    | $0.147 \lambda_o \times 0.147 \lambda_o$ | Low                      | Passiv e           | 95      | LP–CP                            |
| [20]      | 0.67–0.85; 1.04–1.11; 1.61–1.76                                | 33             | 116                      | -                     | NR                                                    | NR                                       | High                     | Active             | 95      | LP–LP                            |
| [30]      | 1.50–1.75; 2.00–2.08                                           | 28             | 92                       | 15.38; 3.90           | NR                                                    | $0.215 \lambda_o \times 0.215 \lambda_o$ | High                     | Active             | 82      | LP–CP                            |
| [36]      | 1.20–1.83; 2.52–3.10; 3.78–3.90                                | 10             | 60                       | 41.58; 20.64; 3.10    | Fairly stable under oblique incidence                 | $0.26 \lambda_o \times 0.26 \lambda_o$   | Low                      | Passiv e           | 90      | LP–CP                            |
| This Work | LP–CP: 1.25–1.45; 1.83–3.02<br><br>LP–LP: 1.45–1.75; 3.10–3.75 | 10             | 51                       | 14.81; 49.07          | ≤15 <sup>0</sup>                                      | $0.17\lambda_o \times 0.17\lambda_o$     | Low                      | Passiv e           | 97      | Multifunctio nal (LP–LP & LP–CP) |

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#### Statement of Data Availability

Upon reasonable request, the corresponding author will provide the data that support the study's conclusions.

#### Statement of Ethics

Since there are no human subjects, human data, or human participants in this study, ethical approval was not needed.

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