Terahertz Linear to Circular Polarization Converter Based on Reflective Metasurface

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Metasurfaces are two-dimensional artificial structures which have extraordinary electromagnetic properties. They have been used in myriad of devices such as nano-antennas, cloaking coatings, imaging devices, flat lenses, and polarization converters over a wide range of frequency. Due to high dependency of many devices on incident wave polarization, manipulating the polarization of electromagnetic waves would be useful, especially in the THz regime. In this study, we propose a linear to circular polarization converter (LTC-PC) based on a THz reflective metasurface. For a TE linear polarization incident wave, this structure has two distinct bands; the first one lays in a wideband frequency range of 0.5-1.41 THz, in which the reflected wave would be a left-handed circular polarization (LHCP) with minimum efficiency of 89% and maximum efficiency of more than 95% in 80% of the bandwidth. The second band lays in the narrowband frequency range of 1.45-1.55 THz, resulting a right-handed circular polarization (RHCP) wave with a minimum efficiency of 82%. The proposed polarization converter can be used in optical communication and electronic devices.

Keywords: Metasurface, Circular polarization, Polarization Conversion, Linear to circular polarization conversion (LTC-PC), THz devices.

1. Introduction

Metamaterials are composed of periodic subwavelength structures that some of their properties have not been found in natural materials [1, 2]. A metasurface is a two-dimensional form of metamaterial with thin thickness and much less fabrication complexity. Despite having the lower thickness, they have acceptable optical responses in comparison with conventional metamaterials, and therefore they are a good replacement for bulky metamaterials [1, 3, 4, 5]. Nowadays, metasurfaces are so attractive because of their applications in sensors [6], imaging devices [7], absorption devices [8], and beam manipulation devices [9], such as holograms, cloaking devices, and polarization converters in the microwave, terahertz (THz), and optical regimes. Due to
the small volume, low absorption, and tunable optical responses of metasurfaces, they have been extensively used to linear to circular polarization converters (LTC-PC) [10, 11]. For example, in [11] a linear polarization converter which operates within a wide frequency range of 0.6 to 1.41 THz and an efficiency higher than 88% was proposed. Gao et al. also proposed a wideband LTC-PC based on graphene metasurface. This device is tunable by changing the Fermi energy of graphene [12]. A cross-polarization convertor using metasurface was introduced in three distinct frequency bands for the 9.8–12.2, 19.0–22.6, and, 24.9–29.5 GHz. The polarization conversion ratio is more than 90% [13]. Chen and Chang reported a structure composed of two cascading arrays of complementary resonators. In this LTC-PC, the bandwidth has reached 2 octaves in the range of 0.4-2.4 THz [14]. An LTC-PC aperture-coupled antenna with an ultrathin single-layer metasurface has been proposed in [15] to achieve boresight radiation gain around 10 dBic over 9.5 GHz to 11.5 GHz. The axial ratio bandwidth of the proposed antenna is also 19.23%. In 2020, Lin et al. proposed an ultra-wideband circular polarized maintaining reflector based on metasurface. The reflections of both right-handed circular polarization (RHCP) and left-handed circular polarization (LHCP) were attained between 8.79 and 27.09 GHz [16]. Another polarization convertor which is explained in [17] can convert linear polarized wave to its orthogonal polarization, in two distinct frequency bands, i.e., 7.1–8 GHz and 13.3–25.8 GHz. The proposed metasurface consists of metal patches laid diagonally on the FR4 substrate, and both of them are placed on the reflective metal sheet that enhances the linear polaratization convertor’s (LPC) performance to more than 95% polarization conversion ratio (PCR).

In this work, we propose a broad band high-efficiency LTC-PC. The output wave of the structure has an axial ratio of less than 3dB and high efficiency of 95% in 80% of the bandwidth. If a linearly polarized plane wave illuminates the proposed metasurface,
reflected wave will have a wideband LHCP in the 0.5-1.41 THz range and a narrowband RHCP in the 1.45-1.55 THz range. The remaining of this paper is organized as follows: In Section 2 the structure design and the analysis method are described. The results are presented and discussed in Section 3. Finally, the paper is concluded in Section 4.

2. Design and Analysis Method

Figure 1 shows the three-dimensional schematic view of the 3×3 and single unit cell of our proposed linear to circular polarization converter (LTC-PC). There is a fully reflective gold mirror at the backplane, the substrate is polyimide with a dielectric constant, loss tangent and thickness of 3, 0.001 and 47μm, respectively. As shown in Fig. 1(b), the front gold pattern is composed of two crossed strips on two opposed diameter points with 200 nm thicknesses. Metal strips behave as inductances and the gaps between two strips behave as capacitor. The structure dimension and shape are optimized to get the widest possible bandwidth, using the finite element method (FEM). As shown in Fig. 1 (b) the square shaped unit cell has the lattice constant (a) of 88μm. The width of gold, W, distance between each strip and the edge of the structure, S, and the thickness of the substrate, h, are 7μm, 5μm, and 47μm, respectively. The co-polarized and cross-polarized reflection amplitudes of the proposed structure are depicted in Fig. 1 (c).

As shown in Fig. 2(a), co-axial strips only reflect co-polarized wave without generating cross-polarized wave [18]. The crossed strips, however, produce both co-polarized and cross-polarized reflected waves. Angle between these two crossed strips plays an important role in amplitude difference of these two reflected waves, as shown in Fig. 2 (f), when the angle is close to 90°, The co-polarized and cross-polarized wave amplitudes will be equal, and thus we will have a more ideal circular polarized wave.
The asymmetry diagonal structural is essential to achieve the best performance of LTC-PC. For this purpose, we added extra tails of gold, d, to the crossed strips, as depicted in Fig. 1 (b), to create more asymmetry which results in extension of the bandwidth. Moreover, decreasing the distance of two adjacent gold strips, 2S, increases the coupled electric field between them. As a result, the bandwidth operation of the LTC-PC increases. 2S is decreased by increasing the width of gold strips, W, toward the edge. Figures 3 (a) and (b) show the electric field distribution for two different values of 2S and W at 1 THz. Reducing 2S, the capacitors between two adjacent strips will increase that leads to increasing the electric field, and therefore, a frequency red-shift will happen in the first resonance frequency which leads to a wider bandwidth. The variation of bandwidth versus adjacent strips distance, 2S, is demonstrated in Fig. 3(c). There is an optimum distance which is considered 10 µm for our proposed structure. According to the definition of bandwidth in LTC-PC, circular polarization occurs when amplitude of the \( r_{xy} \) and \( r_{yy} \) are between 0.45-0.9. When 2S=10 µm, amplitudes of the polarization coefficients are in the edge of bandwidth boundaries, thus the widest bandwidth is attained. For distances smaller than 10 µm, the amplitude of the first resonance is less than 0.45 which leads to a narrower bandwidth. Besides, effect of the extra tail of the gold strip, d, on the bandwidth is demonstrated in Fig 3 (d). By increasing d, the inductance of each strip increases, which results in decreasing the resonant frequency and consequently increasing the bandwidth. The optimum length for achieving the widest bandwidth is \( d=S \).

Boundary conditions are periodic in \( x \) and \( y \) directions and non-reflective in the \( z \)-direction. The tetrahedral mesh structure with a minimum mesh size of 0.2 µm is used for better accuracy in the THz regime. The structure is illuminated by a normal incident TE wave which can be expressed as \( E_i = a_y E_y \cos (wt - k_z) \) and the reflected wave:

\[
E_r = a_x E_{xr} + a_y E_{yr} = a_x E_{xy} r_{xy} \cos (wt - k_z + j_{xy}) + a_y E_{yy} r_{yy} \cos (wt - k_z + j_{yy})
\]  

(1)
where \( r_{xy} = E_{xy}/E_{yi} \), \( r_{yy} = E_{yy}/E_{yi} \), \( \varphi_{xy} \), and \( \varphi_{yy} \) represent the reflection coefficient magnitudes for y-to-x, y-to-y polarization conversion, and their corresponding angles, respectively. Circular polarization occurs when \( r_{xy} = r_{yy} \) and \( \Delta \varphi = \varphi_{yy} - \varphi_{xy} = (2n \pm 1/2)\pi \) for an integer value of \( n \). The positive and negative signs represent right-handed circular polarization (RHCP) and left-handed circular polarization (LHCP), respectively [11, 19].

By illuminating an incident TM wave, this behavior is inverted. Elliptically polarized wave is approximately considered as a circularly polarized wave because a perfect circular polarization is not achievable practically. By using Stokes parameters in free space, the normalized Stokes parameters of the reflected wave can be expressed as [11, 20]:

\[
I_n = \left| r_{xy} \right|^2 + \left| r_{yy} \right|^2 \tag{2}
\]

\[
Q_n = \left| r_{xy} \right|^2 - \left| r_{yy} \right|^2 \tag{3}
\]

\[
U_n = 2 \left| r_{xy} \right| \left| r_{yy} \right| \cos \Delta \varphi \tag{4}
\]

\[
V_n = 2 \left| r_{xy} \right| \left| r_{yy} \right| \sin \Delta \varphi \tag{5}
\]

\[
I_n^2 = Q_n^2 + U_n^2 + V_n^2 \tag{6}
\]

where \( I_n, Q_n, U_n, \) and \( V_n \) are , total reflection, horizontal or vertical linear polarization, linear +45 or -45 polarization, and circular polarization of the reflected wave, respectively. These four Stokes parameters describe the wide-band waves and their polarization. For a perfect circular polarization, \( Q_n \) and \( U_n \), which are linearly polarized waves, should be equal to zero [20].

According to definitions of the Stokes parameters, the mathematical equation of ellipticity can be defined as the ratio of \( V_n/I_n \). In special cases, where \( V_n/I_n = -1 \), the reflected wave is RHCP. On the other hand, where \( V_n/I_n = +1 \), the reflected wave is LHCP [18]. The axial ratio (AR) is used for evaluating the circular polarization.
characteristic which can be defined as $AR = 10 \log(tan \beta)$, where $\beta$ is the ellipticity angle, representing the shape of the ellipse which can be calculated by $\beta = 1/2 \sin^{-1}(V_n/I_n)$. Where the value of AR is less than 3dB, the reflected wave is approximately considered as a circularly polarized wave [21].

3. Results and Discussion

As shown in Fig. 4, in the bandwidth of 0.5-1.41 THz and 1.45-1.55 THz, the magnitudes of $r_x$ and $r_y$ are approximately the same and the difference of $\varphi_x$ and $\varphi_y$ is 90° or -270° in the first frequency band and -90° or 270° in the second one. The equal amplitudes and ±90° phase differences show that the reflected wave is a circularly polarized wave. According to Fig. 5, and Stokes parameters, in the range of 0.5 to 1.41 THz, the ellipticity is close to +1, and the reflected wave is LHCP. In the range of 1.45-1.55 THz, there is also an approximate ellipticity of -1 and an RHCP reflected wave. Also, performance of the LTC-PC remains good even when illuminated by an oblique incident wave. It is also interesting that for less than 15 degrees of deviation from normal incident wave, the bandwidth of PC is approximately the same and hence the structure has a very low sensitivity with respect to the incident wave angle, but for farther angles, the bandwidth decreases.

The axial ratio spectrum of the output wave of the optimized structure of Fig. 1 is depicted in Fig. 6. The proposed LTC-PC operates satisfying and converts the polarization from linear to circular in the range of 0.5 to 1.41 THz and 1.45 to 1.55 THz, because of the axial ratio value of less than 3dB. LHCP works in a wide range of frequency and RHCP works in the narrower range. The bandwidths of LHCP and RHCP have been increased up to 15% and 66% in comparison with, respectively [11].
The thickness of the substrate and the length of the arm have significant effects on the results. The spectra of the magnitude of the reflection coefficients and the axial ratios for three different values of the thicknesses of the structure substrate, $h$, and the length of the arm, $L$, are respectively illustrated in Figs 7(a), 7(b) and 8(a), 8(b). The optimum value of $h$ and $L$ is 47µm and 55µm, respectively.

The energy conversion efficiency ($\eta$) is also calculated by the ratio of output wave energy to the incident wave energy. According to normalization of the Stokes parameters, values of $I_n$ and $\eta$ are equal. The spectrum of the energy conversion efficiency of the proposed device is illustrated in Fig. 9. $\eta$ is more than 89% for LHCP and more than 85% for RHCP. The efficiency of the LHCP wave is more than 95% in 80% of the bandwidth. The results indicate the high efficiency of our proposed structure. The efficiency and bandwidth of our proposed LTC-PC are compared with three other similar works in Table 1.

### 4. Conclusion

In this study, a high efficiency metasurface-based wideband linear-to-circular (LTC) polarization converter (PC) is proposed in the terahertz frequency range. It is shown that when the angle between two crossed strips is close to 90°, the reflection wave is closer to circularly polarized. Furthermore, Different parameters of the structure, such as thickness of the substrate ($h$), gold strips length ($L$), distance between two adjacent gold strips ($2S$), and length of extra tails ($d$) are optimized to gain highest efficiency and widest bandwidth. Efficiency of the proposed structure is more than 89% within an ultra-wideband frequency range of 0.5-1.41 THz and reflected wave is left-handed circularly polarized if a linear TE polarization input wave was applied. The efficiency of the conversion is more than 95% in 80% of this bandwidth. Within the frequency range of 1.45-1.55 THz, the
efficiency is more than 85% and the reflected wave is right-handed circularly polarized. The LTC converter has potential applications in electromagnetic measurement, antenna design, and cloaking technology.

5. References

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6. Captions

Fig 1. (a) The schematic view, (b) Single unit cell of the proposed linear to circular polarization converter (LTC-PC), and (c) Amplitude of the co-polarized and cross-polarized reflected wave for $a=88\mu\text{m}$, $W=7\mu\text{m}$, $S=5\mu\text{m}$, and $L=45\mu\text{m}$.

Fig. 2. Unit cell of (a) the single strip, and two crossed strips with (c) less and (e) more than 90° angle. (b), (d), and (f) are amplitude of the co-polarized and cross-polarized reflected wave for (a), (b), and (c), respectively.

Fig. 3. Distribution of the electric field of our proposed structure with (a) $S=8\mu\text{m}$ and $W=4\mu\text{m}$ and (b) $S=5\mu\text{m}$ and $W=7\mu\text{m}$. Amplitude of bandwidth for different (c) adjacent strips distances, and (d) length of strips tails.

Fig. 4. The $x$- and $y$-components of reflection coefficients of the structure of Fig. 1. (a) amplitude, (b) phases, and phase differences. The dotted-dashed lines show the narrow- and wide-band bandwidths.

Fig. 5. The ellipticity of the output wave of the structure of Fig. 1 which is excited by a $y$-polarized plane wave.

Fig. 6. Axial Ratio of the output wave of the linear to circular polarization converter (LTC-PC) of Fig. 1.

Fig. 7. Spectra of the (a) Reflection coefficient amplitude and (b) Axial Ratio (AR) of the output wave for three different thicknesses of the structure substrate.

Fig. 8. Spectra of the (a) Reflection coefficient amplitude and (b) Axial Ratio (AR) of the output wave for three different strip lengths.

Fig. 9. Spectrum of the energy conversion efficiency ($\eta$) of the proposed linear to circular polarization converter (LTC-PC) of Fig. 1.

Table 1. Comparison of the efficiency and bandwidth of the proposed structure with some earlier similar reports.

7. Figures and Tables
Fig 1.
Fig. 2.
Fig. 3.

Fig. 4.
Fig. 5.

Fig. 6.
Fig. 7.

Fig. 8.

Fig. 9.

Table 1.

| Reference   | Efficiency | Bandwidth          |
|-------------|------------|--------------------|
| [22]        | >95%       | 7.5-11.9 GHz       |
| [23]        | High       | 9.38-20.36 GHz     |
| [11]        | >85%       | 0.6-1.4 THz        |
| This work   | >95%       | 0.5-1.31 THz       |