Multi Functional Terahertz Polarization Converter Having a Wideband Almost Perfect Linear to Circular Polarization Conversion

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Abstract

In this study, a reflecting terahertz (THz) metamaterial polarization converter consisting of three hexagonal rings with two cuts is presented. The polarization converter has an almost perfect wideband linear to circular (LTC) polarization conversion over the bandwidth of 1.58-1.87 THz (i.e., 0.29 THz) with $AR \leq 0.47$ dB, $\Delta\varphi = n90° \pm 5°$ and $e = 1 \pm 0.01$. Besides, the proposed polarization converter has an almost linear to linear (LTL) polarization conversion around three frequencies such as 1.05 THz, 1.19 THz and 1.31 THz.

1. Introduction

Metamaterials are used to design different efficient devices or surfaces such as sensors [1], resonators [2], antennas [3] and polarization converters [4-10]. A polarization converter is a device or surface which transforms the polarization states of incoming waves [4]. Polarization converters have application areas such as sensitive detection, antennas and radar communication [4]. Metamaterial based polarization converters are mainly designed in two modes either transmitting or reflecting modes. Reflecting polarization converters have design simplicity compared to their transmitting counterparts. Polarization converters can be designed at different frequencies such as microwave [4-5] or THz [6-10] frequencies.

LTL polarization reflecting and transmitting converters using double split ring resonator with PCR values higher than %99.98 were proposed over the bandwidth of 0.42-1.59 THz [6]. A reflecting LTL converter over the bandwidth of 0.49-1.88 THz was proposed in [7]. A tri-layered transmitting LTL polarization converter over the bandwidth of 0.4-1.0 THz was proposed in [8]. Pan et al. [9] proposed a structure composed of two circular split rings at THz frequencies as an absorber, but actually it is a polarization converter due to its diagonal-symmetrical geometry as shown in reference [10].

In this study, a multi functional reflecting polarization converter composed of three nested hexagonal rings with two cuts is proposed at THz frequencies. The proposed converter has an almost perfect linear to circular polarization conversion between 1.58 THz and 1.87 THz (i.e., a bandwidth of 0.29 THz). Five quantities such as phase difference of reflections ($\Delta\varphi$), amplitude ratio, polarization conversion ratio (*PCR*), ellipticity (e) and axial ratio (*AR*) are taken into simultaneously consideration to prevent the situation of misinterpreting the results, which is commonly encountered in the literature [9-10]. $\Delta\varphi = n90° \pm 5°$, *Amplitude Ratio*$= 1 \pm 0.1$, $PCR = 0.5 \pm 0.05$, $e=1 \pm 0.01$ and $AR \leq 0.5$ dB conditions are simultaneously satisfied over this bandwidth. Moreover, the proposed design has an ideal linear to linear polarization conversion around the three frequencies: 1.05 THz, 1.19 THz and 1.31 THz.

2. Design

The perspective and front view of a unit cell of the proposed polarization converter are presented in Fig. 1 and Fig.2, respectively. A lossy polyimide substrate with dielectric constant $\varepsilon_r = 3.5$, loss tangent $\tan\delta=0.0027$ and thickness $t_s=26$ μm is used in the design. The back side of the substrate is made of fully gold with conductance $\sigma=4.561\times10^7$ S/m and thickness $t_m=0.4$ μm. The front side of each unit cell is composed of three hexagonal-shaped concentric gold rings. The side length of the substrate is $L=70$ μm along x and y directions. Widths of the outer, middle and inner rings are $w1= w2 = w3=3$ μm. The diagonal length of the inner hexagonal ring is $r1=30$ μm. Distance between the outer and middle rings $s1= 2$ μm. Distance between the middle and inner rings $s2= 6$ μm. $g1=4$ μm, $g2=4$ μm and $g3=8$ μm are the width of gaps along the diagonal of the unit cell.

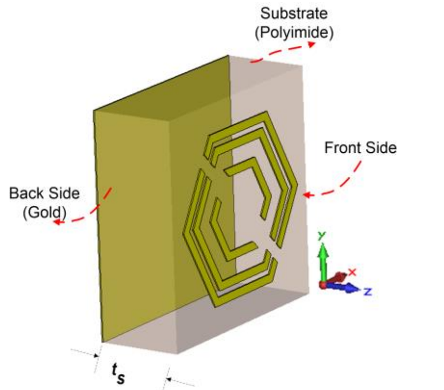

Fig. 1. Perspective view of the unit cell

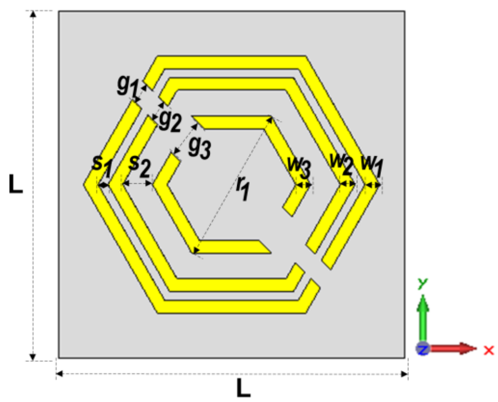

Fig. 2. Front view of the unit cell

3. Theory and Background

Metamaterial polarization converters can be designed in two modes such as reflecting and transmitting modes. Since the proposed polarization converter has fully metal back, the proposed converter is a reflecting polarization converter. Thus, reflecting waves can be analyzed to decide the polarization states. It should be noted that, since the design has a diagonal symmetrical geometry, the design has similar behavior under x- and y- polarized normal incidence waves. Hence, in this section the equation will be given only for y-polarized normal incidence waves.

The incoming and reflected electric fields can be expressed in Equation (1) [4].

$$\begin{bmatrix} E_x{}^r \\ E_y{}^r \end{bmatrix} = \begin{bmatrix} r_{xx} & r_{xy} \\ r_{yx} & r_{yy} \end{bmatrix} \begin{bmatrix} E_x{}^i \\ E_y{}^i \end{bmatrix} \tag{1}$$

Here, i and r are denoted for incoming and reflecting waves, respectively. Reflected *ryy* (co-polarized) and *rxy* (cross-polarized) components can be given in Equations (2) and (3).

$$\mathrm{r_{yy}} = E_y{}^r / E_y{}^i \tag{2}$$

$$\mathrm{r_{xy}} = E_x{}^r / E_y{}^i \tag{3}$$

Amplitude ratio, phase difference ($\Delta\varphi$), polarization conversion ratio (*PCR*), ellipticity (e) and axial ratio (*AR*) are the main parameters to decide the polarization conversion states [4]. Amplitude ratio is expressed as follows.

$$Amplitude\ ratio = |r_{yy}|/|r_{xy}| \tag{4}$$

$\Delta\varphi$ is given as follows.

$$\Delta\varphi_{xy} = \varphi_{yy} - \varphi_{xy} = arg(r_{yy}) - arg(r_{xy}) \tag{5}$$

PCR can be written as follows.

$$PCR = |r_{xy}|^2/(|r_{yy}|^2 + |r_{xy}|^2) \tag{6}$$

e is written in Equation (7).

$$e = \frac{2|r_{yy}||r_{xy}|\sin(\Delta\varphi_{xy})}{|r_{yy}|^2+|r_{xy}|^2} \tag{7}$$

AR is expressed in Equation (8)

$$AR = \left(\frac{|r_{yy}|^2+|r_{xy}|^2+\sqrt{a}}{|r_{yy}|^2+|r_{xy}|^2-\sqrt{a}}\right)^{1/2} \tag{8}$$

In Equation (8), a is

$$a = |r_{yy}|^4 + |r_{xy}|^4 + 2|r_{yy}|^2|r_{xy}|^2 \cos(2\Delta\varphi_{xy})$$

Amplitude Ratio=0, $\Delta\varphi_{xy} = n\pi$ *(n=0, ±1, ±2…)*, *PCR=1*, *e=0* and *AR*=∞ must be simultaneously satisfied for an ideal LTL conversion. *Amplitude Ratio=1*, $\Delta\varphi_{xy} = n\pi/2$ *(n=1, ±3, ±5…)*, *PCR=0.5*, *e=±1* and *AR= 1* must be simultaneously for an ideal LTC conversion [4].

4. Simulation Results

The simulation of the proposed design is performed using the frequency domain solver of the CST Microwave Studio. A "unit cell" boundary condition is applied along x and y directions during the simulations to simulate periodically repeated unit cells. An "open add space" boundary condition is also applied along the z directions. The frequency range of the simulation setup is 0.2-2 THz. Co-polarized and cross-polarized reflection coefficients and amplitude ratio of the proposed design are given in Fig. 3. *Amplitude ratio≈1* over the bandwidth of 1.58-1.87 THz where an almost perfect LTC polarization conversion occurs. Co- and cross-polarized reflection coefficients have values near to 0.7 over this bandwidth. Besides, *amplitude ratio≈0* at 1.055 THz, 1.197 THz and 1.311 THz where an almost perfect LTL polarization conversion occurs.

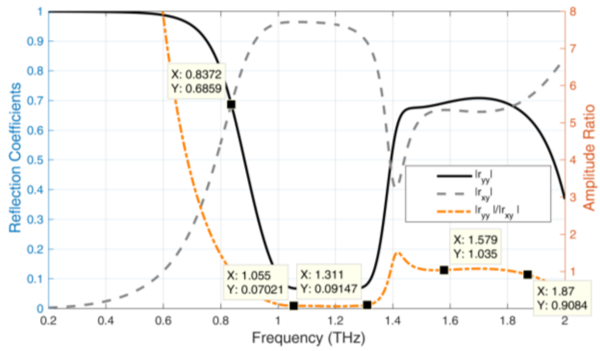

Fig. 3. Reflection coefficients (left) and amplitude ratio (right) of the proposed design.

Phase values of co-polarized and cross-polarized reflections and phase difference ($\Delta\varphi$) of the proposed design are given in Fig. 4. $\Delta\varphi_{xy} = n90°±5°$ criteria is satisfied over the bandwidth of 1.58-1.87. Besides, $\Delta\varphi_{xy} \approx 0°$ is also satisfied around the three frequencies: 1.05 THz, 1.19 THz and 1.31 THz where an almost perfect LTL polarization conversion occur.

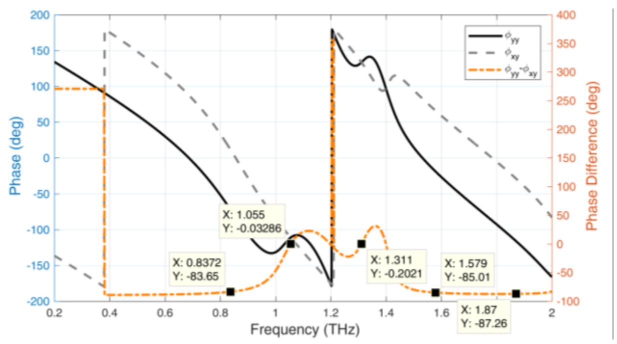

Fig. 4. Phase values (left) and relative phase differences (right) of the reflections.

The polarization conversion ratio of the proposed design is depicted in Fig. 5. *PCR ≈ 0.5* criterion is satisfied over the bandwidth of 1.58-1.87. Besides, *PCR ≈ 1* is also satisfied around the three frequencies: 1.05 THz, 1.19 THz and 1.31 THz where an almost perfect LTL polarization conversion occur.

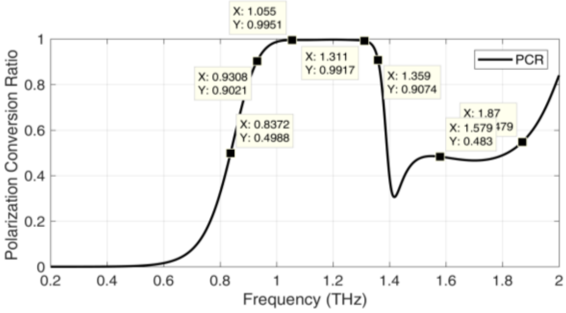

Fig. 5. Polarization conversion ratio of the proposed design.

The ellipticity of the proposed design is given in Fig. 6. $e \approx 1$ criterion is satisfied over the bandwidth of 1.58-1.87. Besides, $e \approx 0$ is also satisfied around the three frequencies: 1.05 THz, 1.19 THz and 1.31 THz.

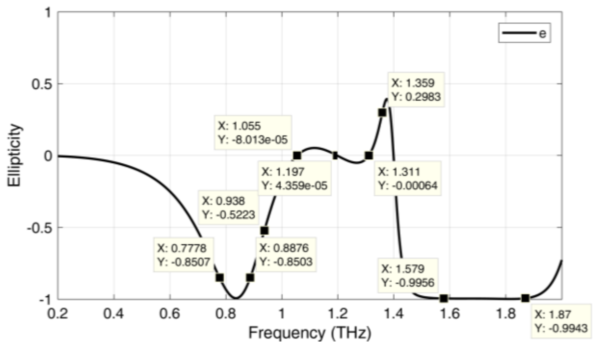

Fig. 6. Ellipticity of the proposed design.

The axial ratio of the proposed design in dB is given in Fig. 7. AR=∞ and *AR=1(i.e., 0 dB)* conditions must be satisfied for a LTL and LTC polarization conversion, respectively. AR is smaller than 0.47 dB over the bandwidth of 1.58-1.87 THz. Besides, *AR* is higher than *34 dB* at three frequencies: 1.05 THz, 1.19 THz and 1.31 THz where an almost perfect LTL polarization conversion occurs.

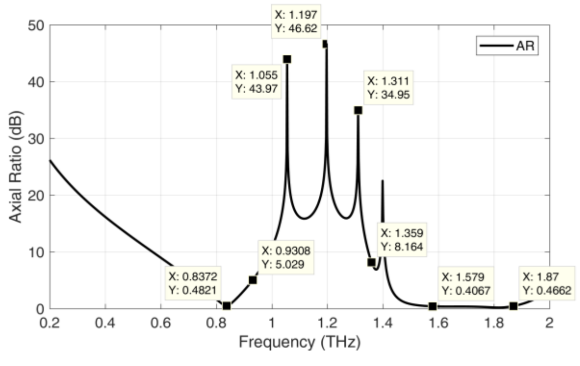

Fig. 7. Axial ratio of the proposed design in dB.

In literature, *AR ≤ 3 dB* is a frequently used criterion to decide LTC polarization conversion regions. In Fig. 7. *AR ≤ 3 dB* condition is satisfied over two bandwidths: 0.89-0.77 THz and 1.437 THz-2 THz. At 1.437 GHz, *PCR= 0.35*, *e= 0.81* and *Δφ= -58.74* which is far beyond for the LTC conversion. Besides, *PCR ≥ %90* is a frequently used criterion to decide LTL polarization conversion bands in literature. In Fig. 5. *PCR ≥ %90* condition is satisfied over the bandwidth of 0.93-1.36 THz. Over this bandwidth, *Δφ* has a value between -72.65° and 30.96°. Over this bandwidth, e has a value between -0.52 and 0.3. Thus, *Δφ* and *e* values are far beyond LTC polarization conversion criteria. As a result, *Δφ*, *PCR*, *e* and *AR* must be evaluated simultaneously for a fair decision of polarization conversion bands.

5. Conclusions

A reflecting terahertz metamaterial polarization converter with an almost perfect wideband LTC polarization conversion over the bandwidth of 1.58-1.87 THz is presented in this study. *AR ≤ 0.47 dB*, *Δφ =n90°±5°* and *e = 1±0.01* are simultaneously satisfied over this bandwidth. Furthermore, the design offers an almost perfect LTL polarization conversion around three frequencies such as 1.05 THz, 1.19 THz and 1.31 THz.

6. References

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