On the specially designed fractal metasurface-based dual-polarization converter in the THz regime

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ABSTRACT

A specially designed fractal metasurface-based structure was investigated as a dual-polarization converter operating in the terahertz (THz) band. The proposed converter has the ability to perform both the linear-to-cross (LX) and linear-to-circular (LC) polarization conversions. In the former kind of operation, it exhibits three unity polarization conversion ratio (PCR) peaks at 1.10 THz, 2.13 THz and 3.46 THz frequencies, whereas in the latter situation, the conversion was achieved over three operating bands, namely 1.2–1.83 THz, 2.52–3.10 THz and 3.78–3.90 THz. The effect of oblique incidence on the performance of metasurface (used in designing the converter) was also studied, and fairly stable operation could be determined. The obtained results indicate the proposed converter to have possible potentials in imaging, antenna engineering and certain other photonic devices used in the fields of medical diagnostics, sensing, and other related measurements.

Introduction

The control over the polarization state of electromagnetic (EM) waves attracts fascinating applications in antennas, beam splitters, radar cross-section (RCS) reduction, wave plates and optical communications, etc. [1–4]. Polarization converters could be realized by exploiting the conventional techniques, such as birefringence effects, dichroic crystals and optical grating [5,6]. However, due to long propagation distance, large equipment, bulky size and narrow bandwidth, the conventional methods were replaced with the artificially engineered metasurfaces having periodically arranged subwavelength-sized unit cells or meta-atoms [7–9]. The amplitude, phase and polarization of EM waves can easily be controlled through the size, shape, arrangement and rotation of meta-molecules. To date, many forms of metamaterials-based devices, such as nanoantennas, holograms, filters, perfect absorbers and sensors have been reported in the literature [10–15]. The other notable applications would be the optical vortex beam generation, plasmon-induced transparency and asymmetric transmission [16–18]. Apart from these, the applications of polarization converters in the biomedical arena are very much obvious [19–22].

Metasurface-based polarization converters are usually designed to exploit two types of geometric resonators/structures, viz. chiral and anisotropic [17,23]. Varieties of such polarizers have been developed for different spectral regimes [24–26]. Most of the polarization converters reported in the literature have dual-band, triple-band and multi-band characteristics [27–30]. However, due to the limitation in bandwidth, many of such polarizers remain unsuitable for applications where large bandwidths are required. So, the investigation of wideband polarization control devices for future applications, such as UWB antennas, RCS reduction, etc. [1,31,32], remains greatly important.

The most commonly implemented approaches to enhance the bandwidth of metasurface-based devices have been the use of multi-resonance, stacked layers and fractal geometry in the design [33–37]. In a multi-resonance method, multiple unit cells are created in a single cell to develop super-cells, whereas in stacked structures, many vertical layers are arranged from top to bottom to implement a single device. However, these techniques are not useful for practical applications owing to complexities and high costs. As such, a strong need remains to develop metasurface-based wideband polarizers that are compact, miniaturized, simple and cost-effective.

Till now, several types of metamaterial-based polarization devices have been reported in the reflective and transmissive modes. Chen et al. [33] demonstrated the circular polarization conversion effect through the double-arrow-shaped anisotropic metamaterial in the microwave regime. Zhu et al. [25] presented a dual-band polarization conversion device for microwave frequencies based on the phenomenon of...
electromagnetically induced transparency. Li et al. [38] implemented the tunable frequency polarization converter comprised of multiple vertically stacked layers for the gigahertz frequency range. Deng et al. [35] proposed wideband microwave polarization converter, composed of four metal/dielectric layers, and fabricated exploiting the 3D printing technology. Xu et al. [39] investigated the Hilbert-shaped chiral metamaterial structure for dual-band circular polarization transformation. Zeng et al. [40] and Ding et al. [41], respectively, developed the dual-band and multi-band cross-polarizers for optical frequencies. Yun et al. [42] studied the aluminum-based multi-layered anisotropic metasurface device to manipulate the amplitude and polarization of incidence waves. Jiang et al. [43] presented a broadband polarization rotator comprised of multiple stacked layers of phosphorene embedded in the dielectric spacer. However, the manipulation of polarization remains greatly important in artificially modulating the EM waves, which is owing to the inherent symmetric properties between the opposite handedness (of waves). Yuan et al. [44,45] and Li et al. [46] demonstrated varieties of ways to independently and arbitrarily manipulate the EM wave exploiting metasurfaces, thereby suggesting the realizations of various polarization-independent devices.

All the aforementioned reports introduce complexities in practical reliability, thereby limiting the use in advanced and future miniaturized integrated optic devices. Moreover, these merely rely on a single type of polarization conversion, i.e., cross- or circular-polarization conversion. It still remains challenging to achieve efficient, broadband, miniaturized and single-layer optical device to convert the linearly-polarized (LP) wave into its cross-components and circular polarization both. Recently, it is demonstrated that due to strong inter-molecular coupling of fractal metasurface, these can convert the LP wave to the CP wave, and vice versa [47]. With this motif, we attempt to investigate a specially designed broadband polarization converter comprised of the assembly of H-shaped fractal resonators in the metasurface developed over a silicon dioxide (SiO2) dielectric spacer. We start with an H-shaped resonator to study the reflection characteristic. Based on the observed results (that indicate insufficient manipulation of the incidence wave), we attempt to incorporate other small-sized H-shaped resonators connected at the edges of the main (H-shaped) resonator so that the metasurface assumes a tree-like fractal geometry. In the design, a gold strip is introduced at the bottom, in order to prevent the transmission of waves. The polarizer metasurface has the ability to transform the LP waves into its cross-polarized components at different operating frequencies. Also, it demonstrates triple-band and wideband circular polarization (CP) conversion for different operating bands. In order to explore the omnidirectional characteristics, we study the proposed structure under different obliquity of the impinging EM waves.

**Design and modeling**

The proposed metasurface-based polarization converter device is a three-layer structure with the top H-shaped fractal geometry made of gold, developed over a dielectric SiO2 spacer (existing in the middle). The dielectric medium is backed by a bottom ground plane of gold sheet, in order to block the transmission of waves. Fig. 1 illustrates the schematic of the structure, wherein the top metasurface is patterned as an assembly of the components having H-shaped tree-like fractal resonators. Here Fig. 1a and 1b, respectively, exhibit the top-view of the metasurface and the side-view of the proposed configuration, whereas Fig. 1c illustrates the three-dimensional (3D) view of the polarizer converter.

With reference to Fig. 1, we take the thickness (h) and permittivity of SiO2 medium as 10 µm and 3.5, respectively. The other design parameters are as P = 60 µm, a = 30 µm, b = 22 µm, c = 20 µm, d = 12 µm, W = 5 µm, t1 = 2 µm and t2 = 2 µm. The meanings of all the used symbols can be understood looking at Fig. 1a and b. We use the full-wave CST Microwave Studio simulation platform to design and optimize the proposed polarization converter. The built-in frequency-domain solver is used to simulate the unit cell. In such an attempt, we impose the unit cell boundary conditions in the x- and y-directions, while the open add space boundary conditions along the z-direction. We use the linearly x-polarized EM wave to excite the top metasurface from the + z-direction.

Now, the reflection coefficients can be evaluated utilizing the S-parameters of the co- and cross-polarization components. The relationship between the incidence and reflected electric fields can be found from the equations

\[ [E_i] = R [E_r] \]

\[ \begin{bmatrix} E'_x \\ E'_y \end{bmatrix} = R \begin{bmatrix} E_x \\ E_y \end{bmatrix} \]

where \( E'_x \) and \( E'_y \) are, respectively, the reflected electric fields in the x- and y-directions. Similarly, \( E'_i \) and \( E'_r \) stand for the incidence electric fields in the x- and y-directions, respectively. Also, \( R \) signifies the general complex reflection matrix, expressed as

\[ R = \begin{bmatrix} R_{xx} & R_{xy} \\ R_{yx} & R_{yy} \end{bmatrix} \]

with \( R_{xx}, R_{xy} \) and \( R_{yx}, R_{yy} \) indicating the co- and cross-polarization reflection components, respectively. Here \( R_{xx} \) represents the reflected wave along the x-direction corresponding to the incidence wave in the x-direction. Similarly, \( R_{yy} \) denotes the reflected wave along the y-direction for the incidence radiation in the x-direction. Due to the symmetric nature of metasurface, it behaves equally for the x- and y-polarized EM waves. As such, we consider an x-polarized incidence radiation at the input port. The overall cross-polarization performance of the metasurface can be evaluated from the polarization conversion ratio (PCR), which can be expressed as [41]

\[ \text{PCR} = \frac{|R_{yx}|^2}{|R_{xy}|^2 + |R_{xx}|^2} \]

Eq. (4) can be used to study the performance of the proposed design of polarization converter.

**Results and discussion**

In the attempt of analyzing the EM characteristics of the proposed converter, we start with the simple H-shaped metasurface (as shown in Fig. 2a), and observe the co- and cross-polarization reflection coefficients; Fig. 2b illustrates the obtained results when the incidence LP wave impinges on the top metasurface. This figure demonstrates the co-polarized reflection component \( R_{xx} \) approaching the maximum value in the frequency range of 1–4 THz, whereas the value of cross-polarized reflection component \( R_{yy} \) is vanishing. We observe in Fig. 2b that \( R_{xx} \cong 1.0 \) in the 1–2 THz range; upon increasing the frequency, its magnitude remains above 96%. Overall, we see that the reflection characteristics remain fairly uniform in the entire range of frequency.

We now modify the simple H-shaped resonator to acquire a fractal tree-like structure by joining them, as illustrated in Fig. 1a (the same is reproduced in Fig. 3a); the obtained frequency-dependence of reflection parameters is shown in Fig. 3b. We notice significant changes in the reflection patterns of both the \( R_{xx} \) and \( R_{yy} \) components in this case. To be explicit, this figure demonstrates the \( R_{yy} \) component to have maxima at three different operating frequencies, namely 1.10 THz, 2.13 THz and 3.46 THz. Also, the maxima corresponding to the \( R_{xx} \) component exist at nearly 1.40 THz and 2.75 THz frequencies. Apart from these, the magnitude of \( R_{xx} \) maxima decreases with increasing frequency, whereas that of the \( R_{xx} \) maxima remains almost unchanged for all the three stated frequency values. We further notice in Fig. 3b that the magnitudes of reflection coefficient approach nearly zero for the \( R_{xx} \) component, and unity for the \( R_{yy} \) component. These magnitudes (of reflection coefficients) approach very close for the three operating
bands, namely 1.2–1.83 THz, 2.52–3.10 THz and 3.78–3.90 THz.

Within the context, in order to achieve better cross-polarization conversion performance, the co-polarization reflection component should be the minimum, while the cross-polarized component should be at a maximum value along with the phase difference \( \Delta \phi = n \pi \); \( n \) being an integer and \( \Delta \phi = \arg(R_{xx}) - \arg(R_{xy}) \). For circular polarization conversion, the \( R_{xx} \) and \( R_{yy} \) components are equal and having \( \Delta \phi = n \pi \pm 90^\circ \).

Fig. 4 exhibits the plots of phases \( \phi_{xx} \) and \( \phi_{xy} \), and also, the phase difference \( \Delta \phi \) in the case when the top metasurface (of polarization converter) is excited by the normal incidence of LP waves. Looking at Fig. 3b and 4, we notice that the proposed H-shaped tree-like fractal metasurface exhibits the minimum co-polarization and maximum cross-polarization reflection components, and the phase difference \( \Delta \phi \) between these two parameters (i.e., \( R_{xx} \) and \( R_{xy} \)) is also 0° or 180° at the afore mentioned three different operating frequencies, i.e., 1.10 THz, 2.13 THz and 3.46 THz. This is acceptable and quite suitable for a device to convert the polarization state of LP wave to its cross-polarization components.

In order to evaluate the cross-polarization conversion performance of the proposed converter design, we evaluate the frequency-dependence of PCR; Fig. 5 depicts the results for normal incidence of waves on the top fractal metasurface. This figure makes obvious the PCR to be 100% at the above stated operating frequencies, i.e., 1.10 THz, 2.13 THz and 3.46 THz.

In order to investigate further the phenomenon of cross-polarization, we plot the electric field distribution (of the absolute z-component of the electric field) profiles at the surface of fractal metasurface corresponding to the aforementioned three different operating frequencies. Fig. 6 exhibits the obtained field patterns corresponding to the frequencies 1.10 THz (Fig. 6a), 2.13 THz (Fig. 6b) and 3.46 THz (Fig. 6c).

It becomes evident from Fig. 6 that the electric field distributions follow the PCR pattern, as depicted in Fig. 5. To make this more explicit, we see in Fig. 5a that the PCR attains unity at 1.10 THz operating frequency – the value at which the electric field is maximally accumulated at the upper and lower edges of the H-shaped resonators (Fig. 6a). This essentially shows the excitation of localized surface plasmon (LSP) resonance at these edges of metasurface components. Similarly, corresponding to 2.13 THz operating frequency, the electric field remains concentrated between the two neighboring H-shaped elements (Fig. 6b). For 3.46 THz frequency, the electric field is more confined at the upper and lower diagonal edges of the H-shaped resonators, whereas the other two diagonal edges accumulate the least field (Fig. 6c). Noticeably, the PCR becomes unity at these values of frequency (i.e., 2.13 THz and 3.46 THz), as Fig. 5 exhibits too. As such, we see that the LSP waves could be excited upon the illumination of the top fractal metasurface by the LP waves, thereby resulting in resonance conditions at the surface of the resonator components – the feature primarily attributed to the phenomenon of LX polarization conversion.

We now move to the case of LC polarization conversion. We notice in Fig. 3b the magnitudes of co- and cross-polarization reflection components to be close in the 1.2–1.83 THz operating frequency band. Also, the phase difference between these two reflection components is close to 90°, thereby indicating the transformation of the linearly- (x-) polarized wave into the circularly-polarized wave, as shown in Fig. 3b and 4. Similarly, the frequency span of 2.52–3.10 THz shows the magnitudes of \( R_{xx} \) and \( R_{xy} \) to be very close, and having a phase difference of −90° – the feature that essentially determines achieving the LC polarization conversion (Fig. 3b and 4). This also happens in the frequency range of 3.78–3.90 THz with the phase difference between the \( R_{xx} \) and \( R_{xy} \) components being close to 90° in this case (apart from \( |R_{xx}| \approx |R_{xy}| \); Fig. 3b and 4).

Next, we introduce Stokes parameters [48,49] to demonstrate the performance of the proposed converter. Within the context, we write
The parameters $P_0$, $P_1$, $P_2$ and $P_3$ as

$$P_0 = |R_{xy}|^2 + |R_{xx}|^2$$

$$P_1 = |R_{xy}|^2 - |R_{xx}|^2$$

$$P_2 = |R_{xy}| |R_{xx}| \cos \Delta \Phi$$

The normalized ellipticity $e = (P_3/P_0)$ can be defined from Stokes parameters, and it determines the ability of polarization conversion. The quantity $e$ can assume values either $+1$ or $-1$, thereby determining the left-hand and right-hand circular polarizations, respectively. By the use of Eqs. (5)–(8) and Fig. 3b and 4, we evaluate the frequency-dependent ellipticity; Fig. 7 shows the obtained result. This figure depicts the ellipticity to be close to $-1$ for the operating frequency band of 1.2–1.83 THz, which indicates the reflected wave to be the right-hand circularly polarized (RHCP). Further, corresponding to the other two frequency ranges, i.e., 2.52–3.10 THz and 3.78–3.90 THz, the ellipticity becomes close to $+1$ and $-1$, respectively, thereby specifying the respective presence of the left-hand circularly polarized (LHCP) and RHCP waves.

The knowledge of surface current distribution remains interesting to investigate the physical mechanism of polarization conversion. As such, we now attempt to evaluate the magnitudes of surface current, and its distribution patterns at the top metasurface and bottom metallic layer corresponding to the aforementioned three different values of operating frequency, i.e., 1.5 THz, 2.75 THz and 3.78 THz; Fig. 8 depicts the obtained results.

We observe in Fig. 8a that, at 1.5 THz operating frequency, the current distribution patterns over the top metasurface and bottom ground plane are parallel to each other, thereby causing the electric resonance in the middle dielectric layer. Similarly, the parallel direction of surface current distributions in Fig. 8b exhibits the formation of electric resonance (in the dielectric layer) at the operating frequency of 2.75 THz, whereas the anti-parallel arrangement of currents in Fig. 8c (corresponding to 3.78 THz) results in magnetic resonance. This is essentially due to the formation of current loops in the dielectric section. The overall cause of electric and magnetic resonances at the stated three values of operating frequencies ultimately provides wideband polarization conversion using the proposed converter structure.

We next look at the effect of incidence obliquity on the performance of polarization converter in terms of the frequency-dependence of PCR. In such an attempt, we vary the incidence angle $\theta$ in a range of $10^\circ$–$50^\circ$ in a step of $10^\circ$, and observe the PCR spectrum; Fig. 9 illustrates the obtained results. However, the PCR spectrum using the normal incidence excitation was discussed before in Fig. 5. We notice in Fig. 9 that the increase in incidence obliquity results in a very small amount of blue-shift in the PCR peaks, which occurs more prominent corresponding to higher frequencies. Furthermore, the increase in incidence angle causes more flickers to appear in the PCR spectrum in the high-frequency regime, which is attributed to the larger amount of anisotropy experienced by the incidence excitation. Also, it results in some narrowband PCR peaks within the frequency range of 2.5–3.5 THz. Interestingly, for all the chosen values of incidence angle, the first PCR peak remains at 1.10 THz, thereby making the proposed polarization...
The converter is insensitive to the incidence obliquity at this operating frequency (Fig. 9).

We also explore the effect of incidence angle $\theta$ on the ellipticity of the proposed converter. Within the context, the case of normal incidence excitation was discussed in Fig. 7. We now consider the TE and TM mode incidence excitations. With such operating situations, using the increased incidence obliquity (with the values as chosen above), Fig. 10a and 10b, respectively, depict the ellipticity patterns against the operating frequency corresponding to the cases of TE- and TM-polarized incidence radiations. Comparing Fig. 10a and b, we notice that the TE and TM modes exhibit closely opposite trend of ellipticity. We find in these figures that the increase in $\theta$ results in blue-shifts in the operational bands, along with the presence of sharp narrow peaks, as compared to that noticed in Fig. 7 corresponding to the normal incidence excitation. The frequency-dependence of ellipticity in Fig. 10 also determines the reflected waves undergoing the RHCP and LHCP conditions in certain operational bands, thereby showing fairly good and stable polarization response under the oblique incidence of waves.

Fig. 6. Electric field patterns over the fractal metasurface at (a) 1.10 THz, (b) 2.13 THz, and (c) 3.46 THz.

Fig. 7. Frequency-dependence of ellipticity of the proposed H-shaped fractal metasurface.

Fig. 8. Surface current distributions at the top and bottom metallic layers corresponding to (a) 1.5 THz (b) 2.75 THz and (c) 3.78 THz; the upper and lower panels (of figures) represent the current distributions over the metasurface and the bottom layer, respectively.

Fig. 9. Plots of PCR vs. frequency corresponding to different incidence angles.
Within the context, it would be interesting to give a look at some other previously reported results on metamaterial-based polarization converters and their characteristics in respect of configurations and operating conditions. Table 1 illustrates such a cursory description in support of comparison, considering the features of some of those and their relative merits and demerits. The last row in this table corresponds to the work taken up in the present communication. We notice here that most of those works describe achieving either of the cross- or circular-polarization conversions. On the other hand, it becomes clear that the use of the proposed fractal metasurface kind of structure remains prudent in attaining both the cross- and circular-polarization conversions by using a single form of the unit cell. Furthermore, the proposed design is a single layer configuration that exhibits fairly wideband polarization conversion, and also, the structure remains relatively easy to fabricate.

Conclusion

The afore discussed results indicate that the proposed fractal metasurface-based polarization converter can perform both the LX and LC kinds of conversion in the THz regime of EM spectrum. To be more specific, it converts the linear x-polarized THz wave into its cross-components with three different operating points as 1.10 THz, 2.13 THz and 3.46 THz with a PCR of unity. It also exhibits the LC polarization conversion with three different wideband operating frequencies, namely 1.2–1.83 THz, 2.52–3.10 THz and 3.78–3.90 THz. The study of the effect of incidence obliquity shows that the increase in incidence angle results in very small amount of blue-shift of the operating bands. Nevertheless, the proposed structure exhibits fairly good angular stability in the polarization conversion operation. Such broadband polarization converter with high PCR and fairly good stability against incidence obliquity remains of great potentials in many EM applications that include antenna engineering, photonic communications and other THz applications.

CRediT authorship contribution statement

R.M.H. Bilal: Conceptualization, Formal analysis, Methodology, Writing - original draft. M.A. Baqir: Conceptualization, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Writing - original draft. P.K. Choudhury: Funding acquisition, Investigation, Resources, Supervision, Validation, Writing - review & editing. M.M. Ali: Conceptualization, Methodology. A.A. Rahim: Formal analysis, Investigation, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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