Experimental Characterization of an All-Dielectric Metasurface with Optical Activity Properties

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Abstract **─** A new microwave all-dielectric metasurface based on elliptic dielectric resonators (EDRs) with optical activity properties was fabricated and characterized experimentally. The 5.12 mm-thick metasurface is composed of two layers of connected elliptic dielectric resonators (Rogers RO3210) with elliptic slots and was excited with two orthogonal polarizations of the incident electric field. The optical activity was studied through two constitutive parameters representing the rotation angle θ and polarization state (*η*) of incident and transmitted electric fields through the metasurface. It is found that the proposed design may rotate the incident linearly polarized electric fields over many frequency bands with different transmissions levels. The obtained performances may offer to the device the possibility to be used as microwave polarization rotator.

Index Terms **─** Dielectric metasurface, optical activity, polarization state.

I. INTRODUCTION

Metamaterials [1,2] and metasurfaces [3] have emerged as potential devices for the control of transmission of electromagnetic waves in terms of amplitude, phase and polarization.

In particular, all-dielectric metasurfaces have attracted much attention due mainly to their low losses at high frequencies such as the visible and near-infrared spectral bands [3]. In addition, their high overall efficiency and various functionalities have permitted their use to develop innovative devices for different microwave, THz and optical applications [3]. The operating principle of all-dielectric metasurfaces consists on the use of dielectric resonators to excite both electric and magnetic resonant modes; and usually we use spheres, cubes, cylindrical/elliptical disks and rods with high dielectric constant to reduce the metasurface size.

On the other hand, chiral metasurfaces are emerging as new devices with original electromagnetics properties such as optical activity [4], and circular dichroism [5], which are significantly higher than higher natural chiral materials. The optical activity which describes the rotation angle between the polarization planes of the transmitted and incident waves, was widely obtained with conventional metallic metasurfaces, but rarely with all-dielectric ones.

For this reason, we have studied experimentally in this letter, the optical activity of an all-dielectric metasurface based on elliptic dielectric resonators operating at microwave frequencies. Recently, we have proved that these resonators are good candidates for the design of Quarter-Wave Plate (QWP) and Half-Wave Plate (HWP) all-dielectric metasurfaces [6-8], and in this letter, we propose their use to obtain all-dielectric metasurfaces with optical activity behavior in the frequency band 10-20 GHz.

II. METASURFACE DESIGN AND ANALYSIS

A. Simulation model

We have designed a 5.12 mm-thick all-dielectric metasurface (Fig. 1) by using two superposed arrays of dielectric resonators made of Rogers RO3210 of permittivity $\varepsilon_r = 10.2$, and loss tangent tan $\delta = 0.0027$. Each array of thickness 2.56 mm is composed of connected elliptic resonators of minor radius a, major radius b and ellipticity τ=b/a, with elliptic slots of minor radius a_s, major radius b_s and ellipticity $\tau_s = b_s / a_s$. We have rotated the resonators composing the upper and lower arrays are around their z-axis with angles ϕ= -25° and - ϕ = 25°, respectively as shown in Fig. 1, and connected them along x-direction with thin strips of length $L_c = (L_x/2)$-b and width $W_c = 1.25$ mm.

Each unit cell (Fig. 1) of size $L_x \times L_y$ (L_x = 3 mm,

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L_y = 2 mm) contains two superposed dielectric resonators of same size but with different orientations (-ϕ and + ϕ for the upper and lower resonators, respectively).

The fabricated all-dielectric metasurface of dimensions 74.5 × 74.5 mm^2 is composed of 5 × 5-unit cells made of Rogers RO3210 as shown in Fig. 2. The total height of 5.12 mm corresponds to two layers of resonators of thickness 2.56 mm.

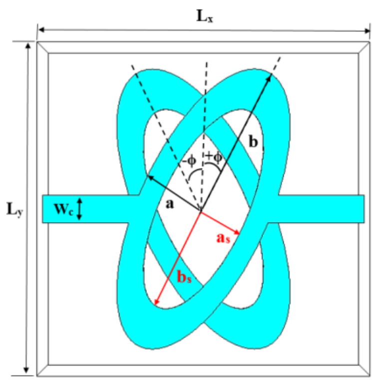


Fig. 1. CST-model for the unit cell.

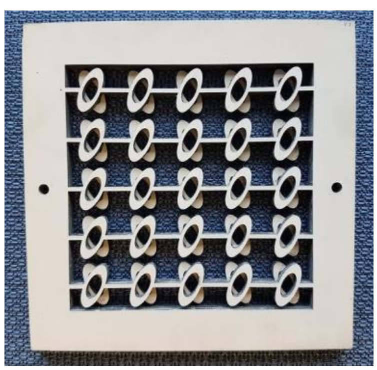


Fig. 2. Photo of the realized metasurface.

B. Metasurface analysis

The optical activity can be analyzed with two constitutive parameters; the azimuth rotation angle θ, and the polarization state η [9]:

$$\theta = [\arg(T_{++}) - \arg(T_{--})]/2, \quad (1)$$

$$\eta = \tfrac{1}{2} \arcsin [(|T_{++}|^2 - |T_{--}|^2) / (|T_{++}|^2 + |T_{--}|^2)], \quad (2)$$

where T_{++} and T_{--} are the transmitted coefficients of right-hand circularly polarized (RCP) and left-hand circularly polarized (LCP) waves, respectively.

We can determine the coefficients T_{++} and T_{--} from the linear transmission coefficients T_{xx}, T_{xy}, T_{yx} and T_{yy} by using the following equations [9]:

$$T_{++} = \frac{1}{2}\left[\left(T_{xx} + T_{yy}\right) + i\left(T_{xy} - T_{yx}\right)\right], \quad (3)$$

$$T_{--} = \frac{1}{2}\left[\left(T_{xx} + T_{yy}\right) - i\left(T_{xy} - T_{yx}\right)\right], \quad (4)$$

where, $T_{xx} = \frac{E_x^t}{E_x^i}$, $T_{xy} = \frac{E_x^t}{E_y^i}$, $T_{yx} = \frac{E_y^t}{E_x^i}$ and $T_{yy} = \frac{E_y^t}{E_y^i}$.

Here, the first subscript represents transmitted polarizations, and the second subscript denotes the incident ones.

C. Design procedure

First, we have numerically studied the structure with the commercial software CST Microwave Studio by exciting it under normal incidence and by taking periodic boundary conditions along x- and y-directions.

Next, we have identified the main design parameters affecting the metasurface performances which are the ellipticities τ and τ_s of the resonator and the slot, respectively, and the orientation ϕ of the resonator. These parameters were optimized to improve the metasurface optical activity described by Eqs. (1) and (2), within the band 10-20 GHz.

Finally, we have optimized parameters τ and ϕ for the metasurface without slot, and the parameter τ_s when we have added the slot. So, the optimized values giving good optical activity in terms of azimuth rotation angle θ, and polarization state η [9] are a=3 mm, b=7 mm, a_s=2 mm, b_s=4 mm giving resonator and slot ellipticities of τ=2.33 and τ_s=2, and rotation angles ϕ = ±25°. Details on the parametric study can be found in [10].

III. RESULTS AND DISCUSSIONS

Fabrication of the final prototype and measurements of the metasurface transmission coefficients (amplitude and phase) were performed at the University of Montreal in Canada (Dr. Christophe Caloz research, Ecole Polytechnique de Montréal) by using the home-made measurement setup [7].

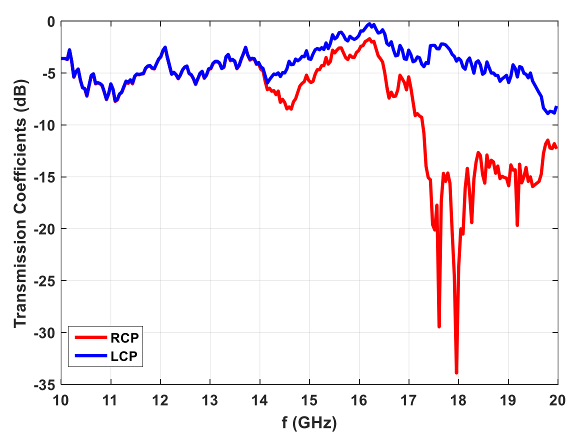
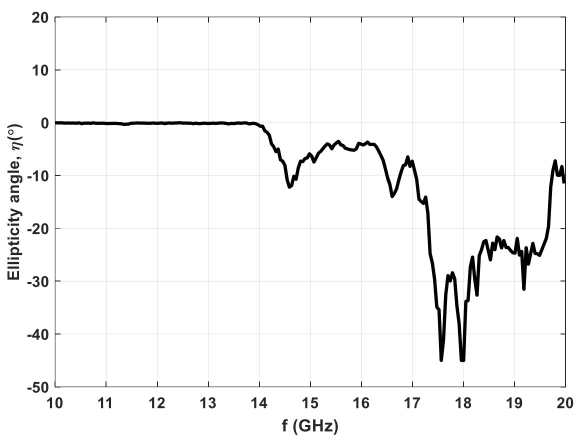


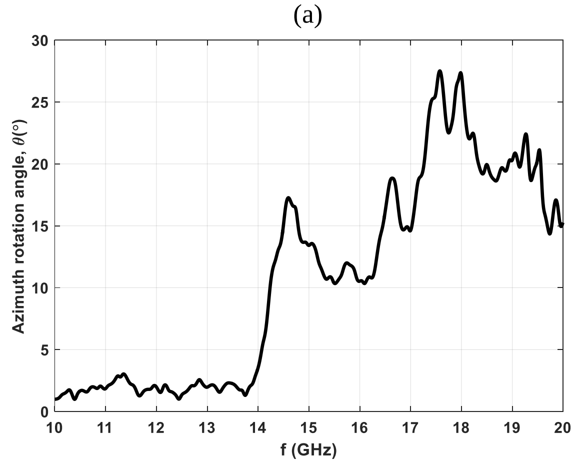
Fig. 3. Variation of the experimental RCP and LCP transmission coefficients over the frequency band 10-20 GHz.

In Fig. 3, we have superposed moduli of both RCP and LCP transmitted coefficients for the realized prototype over the frequency band 10-20 GHz. These moduli were obtained from measured linear transmission coefficients T_{xx}, T_{xy}, T_{yx} and T_{yy}, where the first and second subscripts denotes transmitted and incident polarizations, respectively.

Analysis of the curves presented in this Fig. 3, shows that RCP and LCP moduli are equal up to 14.1 GHz, whereas for higher frequencies, a visible difference between them is observed, which means that the pure optical activity ($|\eta|\approx 0°$) may appear only for frequencies lower than 14. 1 GHz. However, an optical activity with small ellipticity ($|\eta|<10°$) can be achieved for upper frequencies with a slight tendency to transmit LCP waves more than RCP ones ($\eta<0$).



(a)



(b)

Fig. 4. Variation of the measured parameters over the frequency band 10-20 GHz: (a) polarization state η, and (b) azimuth rotation angle θ.

To better analysis the metasurface optical activity, we have given in Fig. 4 the experimental constitutive parameters (η and θ) evolution with the frequency, and the main related data are resumed in Table 1.

We can notice from Table 1, that a small and wideband (33.3%) pure optical activity can be obtained over the band 10-14 GHz; for example, an optical activity of 8° per wavelength at 10.17 GHz, with transmission level of 77%. However, by considering optical activity with small ellipticity ($|\eta|<10°$), we can achieve higher values such as 66° per wavelength with transmission levels of 42% and 63%, for RCP and LCP waves, respectively at 14.54 GHz within a large frequency range (14.68-16.51 GHz) of fractional bandwidth 2%.Also, we can get higher transmission levels (i.e., 83% and 96%, for RCP and LCP waves, respectively at 16.16 GHz) over less wider frequency band (11.73%) but with lower optical activity (39° per wavelength).

Table 1: Main results deduced from Fig. 3 and Fig. 4, related to the metasurface optical activity

Ellipticity	Range (GHz) Bandwidth (%)	Transmission Level	Optical Activity (Degrees/ Wavelength)
$\|\eta\|\approx 0°$	10-14 (33.33%)	75% @ 10.17 GHz 77% @ 12.1 GHz 77% @ 13.71 GHz	8 @ 10.17 GHz 7 @ 12.1 GHz 6 @ 13.71 GHz
$\|\eta\|<10°$	10-14.54 (37%)	42% for RCP 63% for LCP @ 14.54 GHz	66 @ 14.54 GHz
	14.68-16.51 (11.73%)	83% for RCP 96% for LCP @ 16.16 GHz	39 @ 16.16 GHz
	16.73-17.08 (2%)	51% for RCP 71% for LCP @ 16.77 GHz	56 @ 16.77 GHz
	19.73-19.96 (1.15%)	30% for RCP 41% for LCP @ 19.87 GHz	50 @ 19.87 GHz

IV. CONCLUSION

We have fabricated a multiband all-dielectric metasurface based on EDRs with optical activity performances bands within the range 10-20 GHz. The meta-device can rotate an incident linearly polarized wave with relatively good transmission levels and the transmitted waves lose only slightly their linearity. The optimum cases correspond to the frequency 14.54 GHz, where the metasurface shows the highest optical activity (66° per wavelength) with moderate transmission levels, and the frequency 16.16 GHz where transmission levels are higher but with lower optical activity (56° per wavelength).

The proposed metasurface design may be a good solution for the design of all-dielectric devices such as polarization rotator operating at microwave frequencies.

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