Pancharatnam-Berry Metalens for Polarization Conversion

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Abstract

This paper presents the methods and results obtained using the system formed by a metalens and a horn antenna with right-handed circular polarization (RHCP). The working frequency is in the millimeter-wave band at 87 GHz. The metalens unit cells are composed of two H-shaped aluminum elements printed on both faces of a thin polypropylene slab. The metalens is combined then with a horn antenna to test its properties. The structure presents an excellent behavior at the working frequency.

1. Introduction

Metamaterials are artificial structures engineered to achieve a specific electromagnetic behaviour beyond the possibilities offered by nature. They have gained increased popularity in recent years, including in the design of metamaterial lenses, so-called ‘metalenses.’ From their development, metalenses have emerged as a new way to manipulate electromagnetic waves. One can find in the literature disruptive solutions such as the hyperlens [1] that projects a near-field image in the far-field or graded index (GRIN) lenses [2] with gradual negative index modulation, among others.

Metasurfaces are considered a compact version of metamaterials as they consist of a reduced number of layers, providing advantages over the previous solutions such as ultra-thin and lightweight structures, easy fabrication, and the ability to control wave propagation. Among the developed devices, designs based on Quarter Wave Plate and Half-Wave Plate (HWP) for the manipulation of the polarization, meta-holograms [3], and optical vortex converters [4] can be found. In [5], an overview of different applications for metasurfaces is presented.

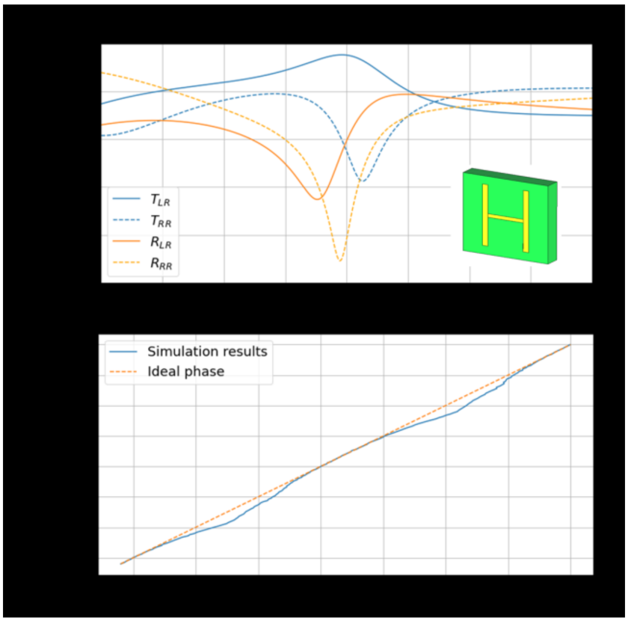

Figure 1. (a) Unit cell magnitude simulation parameters. Copolar transmission (T_{RR}) and reflection (R_{RR}) coefficients and crosspolar transmission (T_{LR}) and reflection (R_{LR}) coefficients under RHCP excitation. **(b)** Difference between ideal and simulated phase for a rotation angle θ from $-180°$ to $0°$.

According to the Pancharatnam-Berry (PB) principle, when an incident circularly polarized wave goes through an HWP unit cell with a rotation angle θ, it acquires an output phase of 2θ. Pancharatman-Berry metasurfaces are based on this concept to implement a specific phase profile varying the rotation angle of each unit cell that composes the structure. In this way, it is possible to achieve any lens phase profile.

In this work, we focus on the concept of HWP and the PB principle to implement a metalens with a polarization conversion, from right-hand circular polarized (RHCP) to left-hand circular polarized (LHCP) wave, by using a two-layer metasurface. The unit cells are rotated to achieve the desired phase using the PB concept to design the lens phase profile. All the simulations were performed using the electromagnetic simulation software CST Studio Suite.

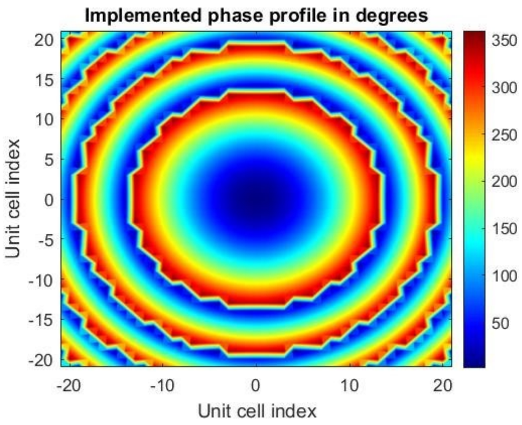

Figure 2. Implemented phase profile of the metalens using Eq. (1).

2. Metalens design

The metasurface unit cell consists of two H-shaped aluminum elements with a thickness of 0.4 µm patterned on both faces of a thin polypropylene slab with a thickness of 0.254 mm. The rest of the unit cell parameters for the metalens design are presented in [6]. Figure 1(a) shows the magnitude of the transmission and reflection coefficients when the illumination is an RHCP plane wave. As shown there, the cross-polar transmitted component has a peak at the working frequency of 87 GHz. The ideal phase at the output for this component should be $\varphi = 2\theta$ but in Figure 1 (b), it can be seen that there is a slight difference between the ideal and the simulated phase. This difference has been considered and corrected by adding a phase correction in the final design of the metalens.

Knowing that the phase profile introduced by a lens is:

$$\varphi(x,y) = -\frac{2\pi f}{c}\left(\sqrt{x^2+y^2+FL^2}-FL\right), \qquad (1)$$

where f is the working frequency, c the speed of light in the background medium (free space in our case), and FL the focal length. With Eq.(1), the required phase, φ, can be obtained at each unit cell position (see Fig. 2). From here and using Figure 1(b), it is possible to obtain the rotation of each metalens unit cell.

The designed metalens can be combined with an antenna to study the performance of a realistic system. The antenna used in this work can be found in Anteral S.L. webpage [7], and consists of a septum polarizer fed transmitting corrugated horn antenna with a low axial ratio at the frequencies of interest which delivers LHCP polarization over the lens. The directivity of radiation pattern of the antenna used in this paper at the frequency of 87GHz is shown in Fig. 3(a).

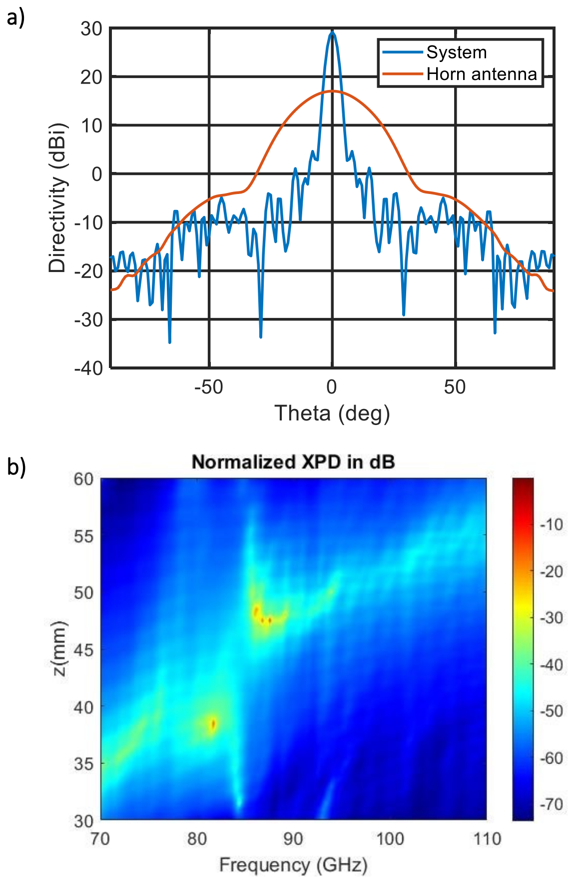

Figure 3. (a) Far field Directivity at the cutting plane of the horn antenna alone (orange solid line) and the system antenna-metalens (blue solid line). RHCP component for the horn antenna and LHCP component for the system (antenna and metalens). (b) Normalized Cross Polar Discrimination coefficient in dB. The XPD presents the difference between the copolar and the crosspolar components along the studied frequencies and for different focal lengths.

In order to match the metasurface to the illumination horn antenna, the diameter d of the metalens has been calculated with the following equation:

$$d = tan\left(\frac{\alpha}{2}\right)\cdot 2FL, \qquad (2)$$

where $\alpha = 60°$ and corresponds to the lens angle for a taper of 15 dB. A focal length of 50 mm has been chosen because we aim to place the metalens within the antenna's Fresnel zone, which varies between 24.4 mm and 177 mm. After making the necessary adjustments and considering the size of the unit cells (1.4×1.4 mm), a metalens of 43×43 unit cells is designed. In Fig. 2, the phase profile implemented (using Eq. (1)) on the final structure is shown.

3. Simulation Results

Once we have calculated the rotation of the 43-by-43 unit cells of the metalens, we can calculate the cross-polar discrimination coefficient (XPD) of metalens without the antenna. For this, we obtain the transmission coefficient of each unit cell at a different evaluation distance from the lens (from 30 to 60 mm). Then, we apply the summation of all the magnitudes of unit cells using the Huygens-Fresnel method, which we calculate for the LHCP and the RHCP E-field components. The XPD is then calculated as the division between the RHCP and the LHCP. Figure 3(b) shows the XPD for a frequency range from 70 to 100 GHz for different evaluation points. The peak at the working frequency of 87 GHz is close to 50 mm. Therefore, the focal length chosen before is optimal for the designed metalens.

For the simulation of the system consisting of a horn antenna and the designed metalens, first, the antenna's phase center has been calculated to align it with the metalens FL. In Fig. 3(a), the comparison between the simulated far field of the horn antenna (solid orange line) and the metalens-antenna system (solid blue line) is shown. We can appreciate an improvement of the directivity of more than 12 dB for the antenna and metalens system compared to the case of the antenna alone.

3. Conclusions

In this paper, a metalens made of 2 layers of H-shaped unit cells separated by a thin polypropylene slab with a circular polarization conversion is presented. The metalens is tested with a horn antenna at a focal distance of 50 mm, exhibiting an improvement in the directivity of 12 dB. At the conference, the measurements of the system antenna-metalens will be presented.

4. Acknowledgements

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[7] See www.anteral.com for antenna datasheet.