Bandwidth optimization for applications of metasurfaces in broadband circular polarizers

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Abstract

In this work, stacks of rotated plasmonic metasurfaces are used as building blocks to create broadband circular polarizers in the visible. A single metasurface is considered as the unit cell to retrieve effective ordinary and extraordinary refractive indices (n_e and n_o), similar to what usually done in nematic liquid crystals. We apply Bloch theorem to a stack formed by rotated metasurfaces and show that these stacks can support propagating and evanescent circularly polarized modes over broad bandwidths, associated with the bandgaps of one of the retrieved effective refractive indices.

1. Introduction

Metasurfaces are the two dimensional version of metamaterials and consist of arrays of engineered sub-wavelength inclusions, designed to achieve electromagnetic phenomena that may not be available in nature at the frequency of interest. Plasmonic metamaterials, owing to their enhanced resonance [1] and frequency selective nature, provide potentials to manipulate the polarization state of light, application that has attracted growing attention in recent years [2]-[7]. We have recently investigated the performance of stacked metasurfaces with proper designs, optimized distance of separation and relative angles of rotation, in order to realize broadband circular polarizers in the visible. The stacked metasurfaces can differentiate handedness of circular polarizations over a large bandwidth, creating a broadband circular polarizer similar to what has been observed in twisted nematic liquid crystal films [8], but based on a different mechanism, which drastically enhances the bandwidth performance.

2. Theory and discussion

Nematic liquid crystals exploit the birefringence of liquid crystal molecules to differentiate left- and right-handed circular polarization. Here, we homogenize optical thin metasurfaces formed by various shapes of inclusions as an artificial birefringent medium with effective n_e and n_o, taking into account its finite thickness. In the following, we show that the bandgap associated with the retrieved n_e corresponds to what is obtained for the bandwidth of circular polarization detection in a metasurface stack obtained by properly rotating neighbouring elements. The retrieved single surface parameters can be used by applying the Bloch theorem to predict the optimal rotation, in order to design an ultra-broadband circular polarizer with small thickness, provided the separation between metasurfaces is not too small, so that only zero order Floquet mode is considered. Fig. 1 compares the retrieved n_e and n_o for two planar metasurfaces formed with same-size gold dipole inclusions but different lattice constants. In both cases, a dipole with length of 275 nm, width of 60 nm and thickness of 50 nm is used; the two periods involved are 300 nm and 400 nm respectively. It is seen that the metasurface with larger lattice constant exhibits a narrower stop-band for reflection, which may be explained by considering that the array coupling of a more densely packed array enhances the resonance bandwidth.

By following the same logic, Fig. 2 compares retrieved effective n_e and n_o for various shapes of gold inclusions with lattice constant of 400nm, and thickness of 50nm. The results show that, with same lattice

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constant and comparable length of the inclusion, the dipole shape, which exhibits stronger anisotropy, can provide larger bandwidth of stop-band transmission for one linear polarization. Fig. 3 shows, in the same panel, the retrieved n_e (blue curve) and the transmission coefficients for the two circular polarizations impinging on a stack of these arrays properly rotated with respect to one another. T_{LL} (T_{RR}) represents the transmission coefficient for left- (right-) handed circularly polarized input and output. It is seen that the bandwidth of operation for the optimized rotation of the metasurfaces corresponds to the reflection band for linear polarized inputs, which may be maximized optimizing the inclusion shape and the array density.

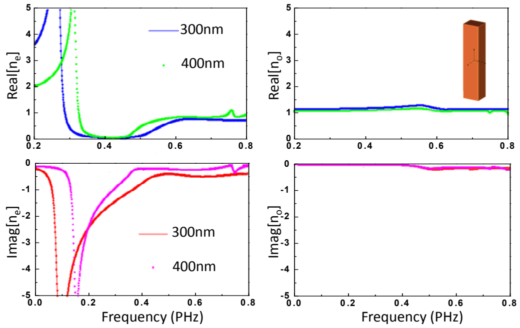

Fig. 1: Retrieved n_e and n_o for a single metasurface with gold dipole inclusions and lattice constant 300nm, 400nm.

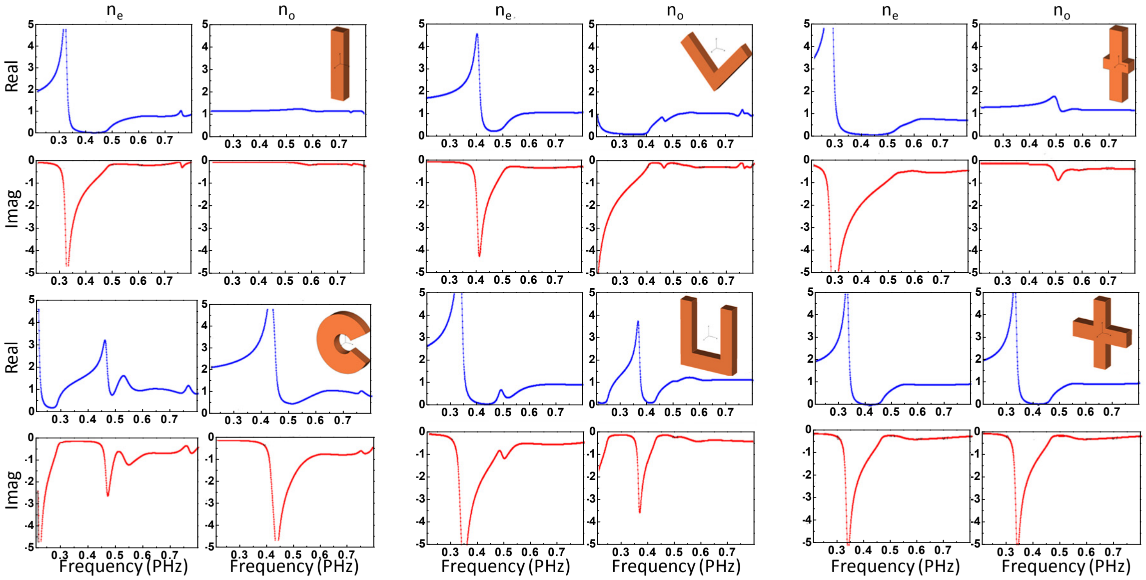

Fig. 2: Retrieved n_e and n_o for a single metasurface with various inclusion shapes, lattice constant 400nm and thickness 50nm.

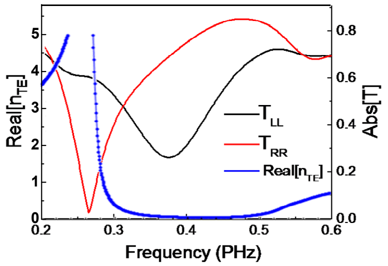

Fig. 3: Comparison of the reflection band from the retrieved n_e for a single metasurface (Fig. 1) and the transmission of right- and left-handed circular polarization from a stack of such metasurfaces.

To optimize the stacked metasurface array, we apply transmission-line theory in combination with the Bloch theorem [9]. The stacked metasurfaces and the gaps around them are treated as a four port network, which are E_y, H_x, E_x, H_y, respectively. The ABCD matrix for a transmission line with length d is

$$ABCD = \begin{pmatrix} \cos(\beta d) & j\eta_0 \sin(\beta d) & 0 & 0 \\ j\dfrac{1}{\eta_0}\sin(\beta d) & \cos(\beta d) & 0 & 0 \\ 0 & 0 & \cos(\beta d) & -j\eta_0 \sin(\beta d) \\ 0 & 0 & -j\dfrac{1}{\eta_0}\sin(\beta d) & \cos(\beta d) \end{pmatrix}, \qquad (1)$$

where β is the propagation constant in the background, η_0 is the background impedance. The rotation matrix that takes into account that each unit cell is effectively rotated by an angle θ with respect to its neighbor is

$$Q = \begin{pmatrix} \cos\theta & 0 & -\sin\theta & 0 \\ 0 & \cos\theta & 0 & \sin\theta \\ \sin\theta & 0 & \cos\theta & 0 \\ 0 & -\sin\theta & 0 & \cos\theta \end{pmatrix}. \qquad (2)$$

Therefore, the Bloch mode may be calculated in terms of (1) and (2) combining these matrices with the single metasurface effective impedance tensor. This analytical approach has been be used to derive the optimal bandwidth of operation of these circular polarizers as a function of the distance among metasurfaces and relative angle of rotation. Our numerical results show that with this setup one may achieve bandwidths comparable to those obtained with 3D metamaterials [4], but using arguably simpler geometries. These bandwidths are significantly larger than what achievable with classic nematic liquid crystals, which are based on a Bragg reflection rather than the metasurface plasmonic response.

3. Conclusion

We have discussed here how a stack of rotated metasurfaces may be used to differentiate right- and left-handed circular polarization over a broad bandwidth, exploiting the large birefringence of plasmonic metasurfaces, optimized with the shape, thickness and array period, and the rotation of each element compared to the next in the stack. We have used simple transmission line theory and Bloch theorem to optimize the setup to achieve maximum bandwidth of operation.

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