# Twisted Plasmonic Metamaterials

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**Abstract**

In this work, twisted metamaterials composed of stacks of strongly coupled, resonant plasmonic metasurfaces with a uniform rotational twist along the stacking direction are analytically modelled and experimentally analysed. The unit cell is composed of the simplest anisotropic nanoparticle, a gold nanorod, which exhibits a large form of birefringence between retrieved effective ordinary and extraordinary refractive indices (ne and no) based on simple effective medium theory. We show, both with full-wave numerical simulations and analytical calculations, that the rotational twist of these anisotropic nanoparticles can create strong circular dichroism spanning a large frequency bandwidth in the visible spectrum. We have also experimentally verified this functionality in a four-layer stack.

## 1. Introduction

Manipulating the polarization state of light can be achieved essentially by controlling the relative relation of amplitude and phase of the electromagnetic field components. This is of central interests in the field of optics and photonics, since many phenomena in the visible spectrum are inherently polarization sensitive. Among all the polarization states, control of circular polarization over a moderate frequency bandwidth is the most challenging component. In the natural world, circular polarization can occur when light refracts at the water-air interface, or when light is reflected and diffracted by the skin of certain biological species; in manmade systems, circular polarizations can be achieved through anisotropic or chiral structures, but these applications often require bulky designs and are difficultly integrated within nanophotonic devices. In light of this, plasmonic metamaterials can provide unprecedented opportunities to manipulate light polarization at the nanoscale due to strong field localization and enhancement. Here, we exploit these advantages to design and realize precise polarization control in a broad range of the visible spectrum.

## 2. Theory and discussion

Figure 1 shows the full wave numerical simulation of the angular dependence of the transmission coefficients for left-handed (LCP, shown as $T_{LL}$) and right-handed (RCP, shown as $T_{RR}$) circular polarization inputs for a stack of two metasurfaces excited at normal incidence. The angle $\theta$ is the relative rotation between the unit cell of two adjacent metasurfaces. The corresponding configurationis shown in the inset of Fig. 1. In this case, the separation distance is fixed at 120 nm, and the unit cell is composed of gold nanorods with dimensions $250\,nm \times 50\,nm \times 50\,nm$ in a $300\,nm \times 300\,nm$ square lattice without substrate. The gold permittivity follows the experimental values in [1]. It is seen that, as the angle varies, the transmission coefficients for LCP and RCP inputs evolve with the biggest extinction ratio close to $45^o$. Here we define the bandwidth of operation to be the frequency range over which the ratio between the transmittance of RCP and LCP exceeds 2. To further investigate the bandwidth behaviour, we explore the double layer structure with an added degree of freedom on the separation

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distance $d$ ; we first performed full-wave numerical simulations with fixed rotation angle varying their separation. The results are reported in Fig.2 (b) with fixed angle of rotation at $50^o$ . The vertical axis in figure 2 (a) and (b) is the absolute value of the difference between $T_{LL}$ and $T_{RR}$ , with the maximum value related to the highest extinction ratio; the green area marks the frequency range over which the structure supports circular dichroism. Fig. 2(b) shows that the optimized bandwidth is determined by the interplay of the rotation angle and the separation distances. We have shown in earlier works that when the distance between two metasurfaces is larger than a quarter of the unit cell dimension, higher order diffraction orders can be neglected[2]. Within this condition, the metasurface can be modelled using its surface admittance tensor, which may be retrieved from the transmission coefficients. When two or more metasurfaces are cascaded, therefore, the total transmission through the stack can be obtained using transmission-line theory. For a metasurface composed of vertically aligned nanorods, the only nonzero element in the admittance tensor is $Y_{yy}$ , which indicates that the surface behaves like an artificial anisotropic thin layer. We can also consider the metasurface as a thin slab and, using effective medium theory, we retrieve the effective extraordinary $n_e$ and ordinary $n_o$ refractive indices. Figure 2(c) shows the retrieved effective values of $n_e$ and $n_o$ . The metasurface structure shows a large form of birefringence within the operational frequency range (which is also marked in green), as expected from its anisotropy, indicating that there is a direct relation between circular dichroism and the stop band of one of the birefringence indices.

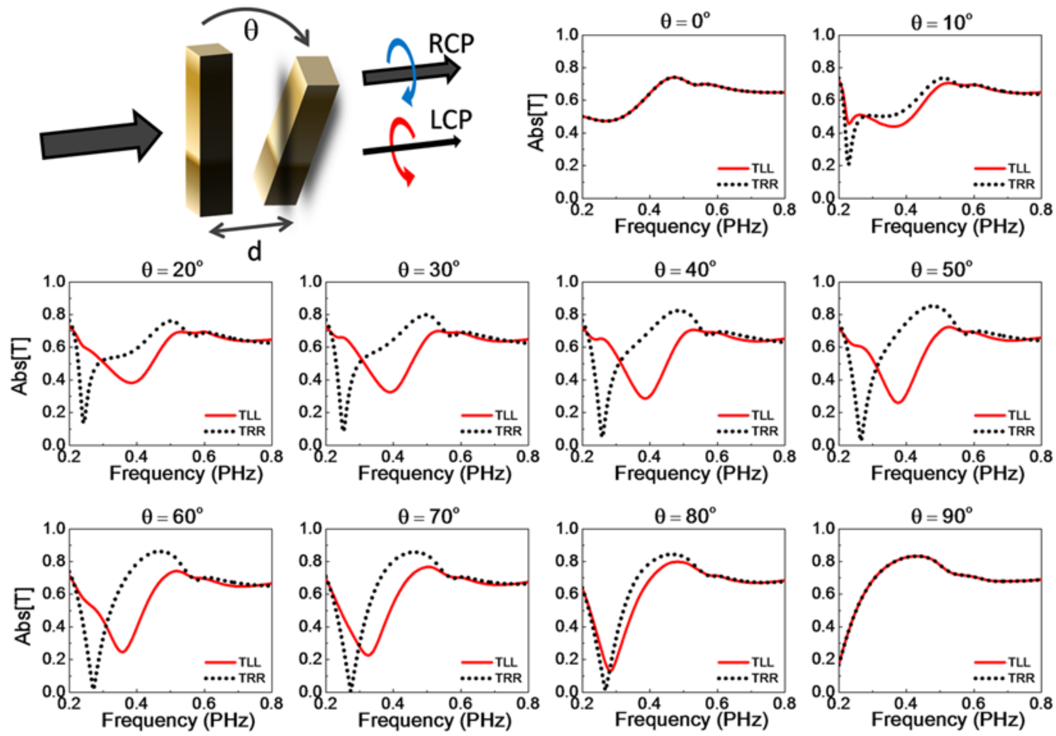


Fig. 1: The difference between transmission coefficients for right hand and left hand circular polarized light varying relative rotation angles, the inset shows the schematic configuration of the geometry under analysis.

Figure 3 shows a systematic analysis of the bandwidth optimization with respect to both angle of rotation and distance of separation for a two-layer metasurface. Figure 3(a) and (b) shows that the occurrence of minimum transmittance of LCP follows a periodic pattern. The frequency where the minimum transmittance resides coincides with the range in which the structure exhibits the highest extinction ratio as a circular polarizer. From Fig. 3(a), it is seen that such frequencies cover a fairly broad range of rotation angles from $120^o$ to $160^o$ and a range of separation between 200 nm to 500 nm, which indicates that the designed structure can tolerate moderate instabilities generated during the fabrication. In addition, Fig. 3(a) also shows the informationon how the proposed structure can permit transmission of the opposite handedness when the rotation angle is the supplementary angle. Therefore, a clockwise rotation of the angle allows transmission of RCP, while a counter-clockwise rotation prefers transmission of LCP. Figure 3(c) summarizes the optimized overall bandwidth as the function of rotation and separation. It shows that the optimized bandwidth for gold nanorods with previously mentioned dimensions can exhibit a bandwidth exceeding 200 nm when the separation in air is around 200 nm, and the rotation angle is close to $60^o$. By stacking more metasurfaces, we are able to broaden the effect and realize a twisted metamaterial with broadband resonant bianisotropic response, operating as a circular polarizer of novel generation. We have recently realized a sample with four-layers that indeed shows these exotic polarization properties over a broad range of frequencies in the visible.

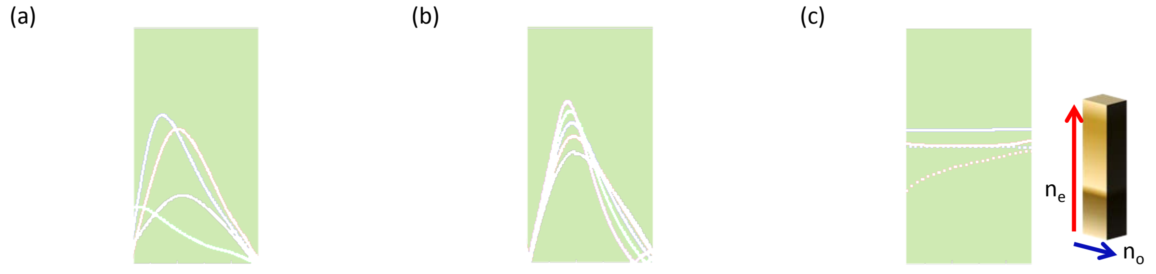


Fig. 2: Difference between $T_{LL}$ and $T_{RR}$ transmission for (a) selected rotation angles; (b) varying the separation distance. (c) Extracted effective ordinary and extraordinary index of refraction. The green area marks the corresponding frequency range over which the structure shows circular dichroism.

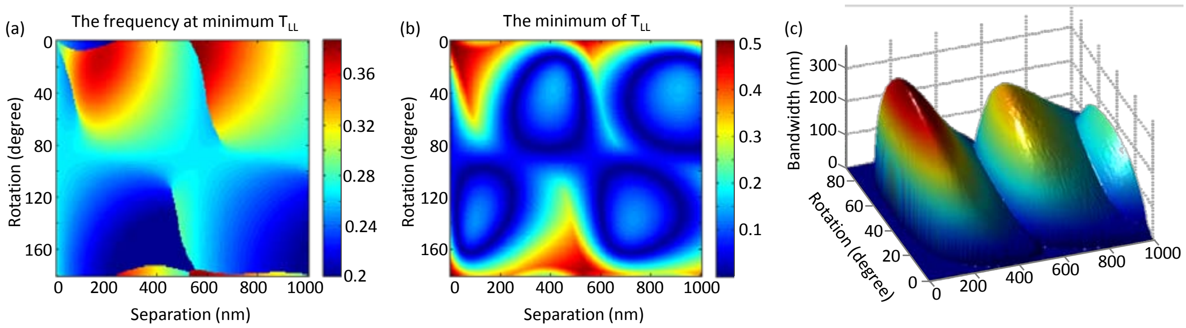


Fig. 3: (a) Color map of the frequency of minimum $T_{LL}$ for a pair of metasurfaces consisting of gold nanorods with varying separations distances from 0 nm to 1000 nm and a rotation angle between 0° and 180°. (b) The difference between $T_{LL}$ and $T_{RR}$ with varying separation distances. (c) 3D view of the bandwidth variation with separation and rotation angle.

## 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 form birefringence of plasmonic metasurfaces, optimized with shape, rotation and relative orientation of the unit cells. We use transmission-line theory and Bloch theorem to optimize the maximum bandwidth of operation. It is possible to connect these concepts to the homogenization of infinite twisted periodic metamaterials or stacks formed by a larger number of metasurfaces, as we will detail in future works.

## References

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