Electronic Supplementary Material (ESI) for Nanoscale.
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Multiple-polarization-sensitive photodetector based on plasmonic metasurface

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Supplementary Notes:

Supplementary Note 1.

Understanding and designing strong circular dichroism in chiral metameterials.

Due to the rotation of electric field vector in circular polarized light, direct relating the special position and magnitude of the circular dichroism with the structure's geometry is usually challenging. Therefore, we investigate the system's optical response under linearly polarized light, simply due to the fact that the circular polarized light (CPL) electric field vector can be decomposed into two perpendicular linear polarized light (LPL) electric field vectors, E_x and E_y, that are oscillating with a 90° phase shift, as shown in equation (1) and (2):

$$E_{LCP} = \left(E_x, E_y\right)^T = \left(\frac{1}{\sqrt{2}}, \exp\left(-\frac{\pi}{2}i\right)\right)^T \#(1)$$

$$E_{RCP} = \left(E_x, E_y\right)^T = \left(\frac{1}{\sqrt{2}}, \exp\left(\frac{\pi}{2}i\right)\right)^T \#(2)$$

We considered the reflection coefficients of this system under two orthogonal linearly polarized light fields with electric field vectors of E_x and E_y. Since this system is anisotropic in the xy plane, both the amplitude and phase of the two reflection coefficients r_{xx} and r_{yy} are different. Under LPL illumination, the reflected field in the x direction, $r_{xx}E_x$, for left-handed polarized (LCP) and right handed polarized (RCP) are exactly the same whereas the reflected fields in the y direction, $r_{yy}E_y$, have a 180° phase shift when comparing LCP to RCP. The polarization conversion coefficient are labeled as r_{xy} and r_{yx} and represent the conversion from E_y to E_x, and E_x to E_y, respectively. The polarization conversion coefficients for two orthogonal fields are identical ($r_{xy} = r_{yx}$). As a result, four reflected field components were observed: the unconverted scattered fields, $r_{xx}E_x$, $r_{yy}E_y$ and converted scattered fields, $r_{yx}E_x$, $r_{xy}E_y$.

When the structure is illuminated with circularly polarized light, the unconvered scattered field, $r_{xx}E_x$, (or $r_{yy}E_y$) will interfere with the converted scattered fields, $r_{xy}E_y$ (or $r_{yx}E_x$). The reflected field with E_x or E_y polarization can be represented as

$$E_{x,sum} = r_{xx}E_x + r_{xy}E_y \#(3)$$

$$E_{y,sum} = r_{yy}E_y + r_{yx}E_x \#(4)$$

Here, we use the vector field plots to illustrate the interference for both LCP and RCP. In an ideal case, under LCP (the phase of E_x is 90° ahead of E_y) illumination, the unconverted scattered field, $r_{xx}E_x$, (or $r_{yy}E_y$) should be exactly out of phase (180° phase shift) with the covered scattered field $r_{xy}E_y$, (or $r_{yx}E_x$) while maintaining the same amplitude to completely cancel out the reflected field. Whereas for the case of RCP (the phase of E_y is 90° ahead of E_x), the unconverted scattered field, $r_{xx}E_x$, (or $r_{yy}E_y$) should be in exactly in case with the converted scattered field, $r_{xy}E_y$, (or $r_{yx}E_x$), to achieve maximum reflection. The field vectors under these ideal conditions are illustrated in Supplementary Fig. 1.

For Supplementary Fig. 1, we can summarize the ideal conditions for maximizing circular dichroism (maximizing LCP absorption, minimizing RCP absorption) in this planar chiral metamaterial as:

$|r_{xx}| = |r_{xy}| = |r_{yx}| = |r_{yy}|$

$\phi_{xx} - 90° = \phi_{xy} = \phi_{yx} = \phi_{yy} - 270°$

For the case of maximizing RCP absorption and minimizing LCP absorption, the ideal conditions will be:

$|r_{xx}| = |r_{xy}| = |r_{yx}| = |r_{yy}|$

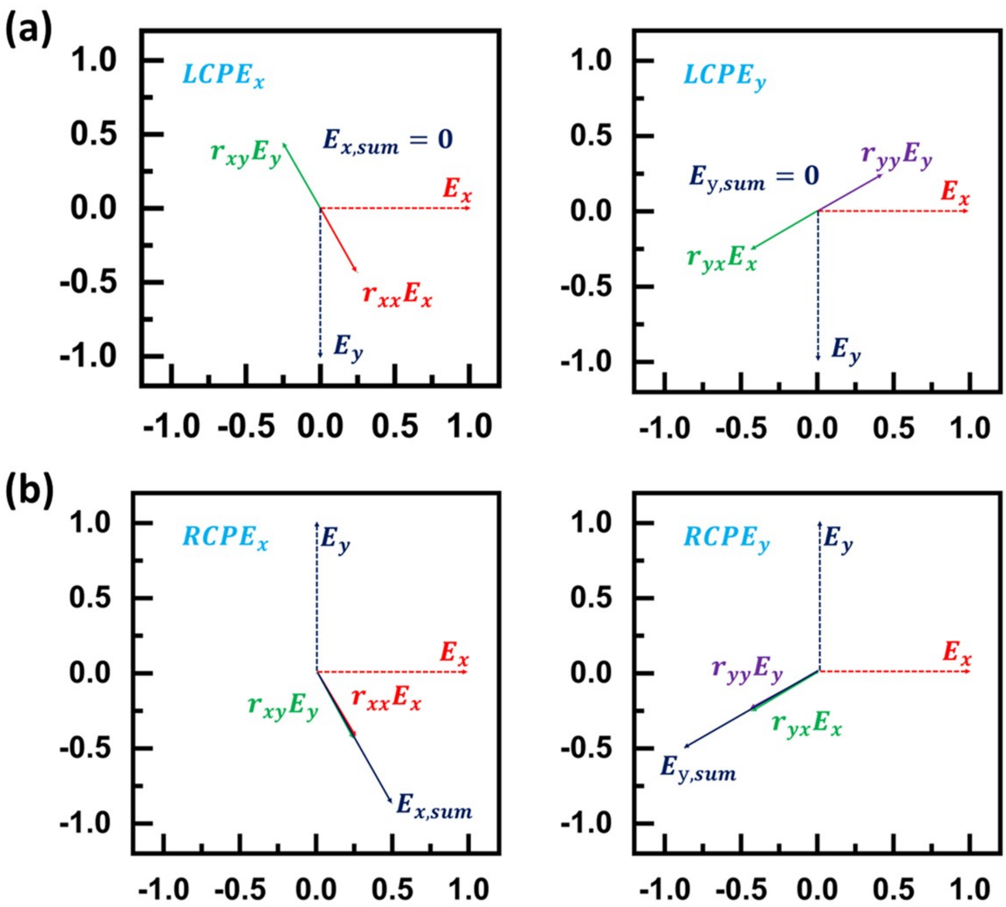
$\phi_{xx} + 90° = \phi_{xy} = \phi_{yx} = \phi_{yy} + 270°$

We choose a system with an array of symmetrical H-shaped Au nanostructure with Au backplane shown in Supplementary Figure 2a. We examined the reflection coefficients of this system under two orthogonal linearly polarized light fields with electric field vectors of E_x and E_y. Both the amplitude and the phase of the reflected light from this system are shown in Supplementary Fig. 2c, d.

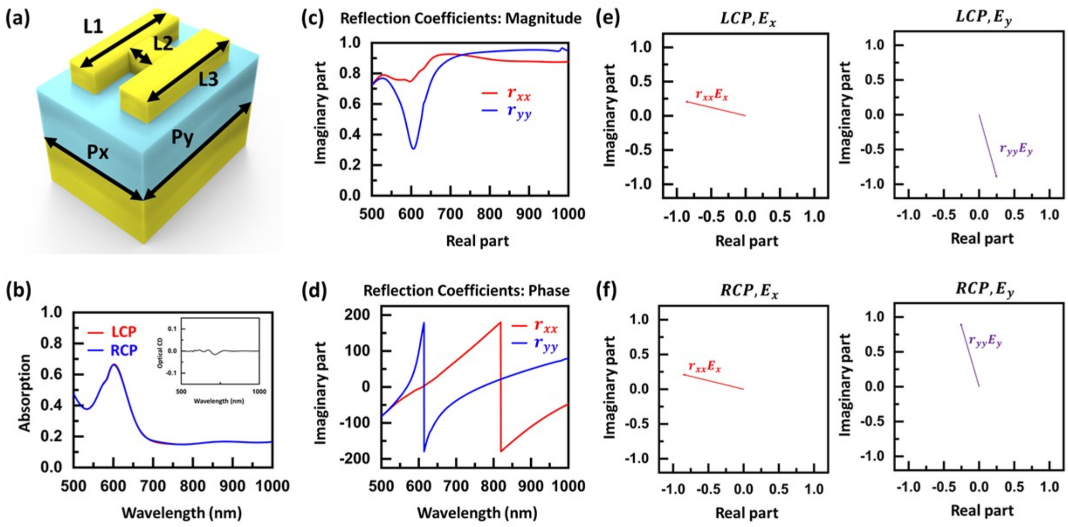
As can be seen in Supplementary Fig. 2c, d, since this system is anisotropic in the xy plane, both the amplitude and phase of the two reflection coefficients r_{xx} and r_{yy} are different. Under LPL illumination (Supplementary Fig. 2e, f), the reflected field in the x direction, $r_{xx}E_x$, for LCP and RCP are exactly the same whereas the reflected fields in the y direction, $r_{yy}E_y$, have a 180° phase shift when comparing LCP to RCP. As a result, the total reflected field intensities are the same for LCP and RCP and the material exhibits no circular dichroism (Supplementary Fig. 2b). This can be confirmed by the fact that this system is non-chiral due to the existence of two mirror symmetry phase in the system.

To break the mirror symmetry of system, we cut part of the structure from the H-shaped Au nanostructure in the unit cell, forming an asymmetrical H-shaped Au nanostructure as shown in Supplementary Fig. 3a. The metal backplane blocks the transmission and forms a Fabry-Perot cavity leading to multiple reflections within the film. The multiple reflections further enhance (LCP) or reduce (RCP) absorption, leading to a circular dichroism up to 0.7 (Supplementary Fig. 3b). This can also be confirmed by investigating the reflection coefficients (Supplementary Fig. 3c, d) and the interference effects (Supplementary Fig. 3e, f) as we consider the single layer H-shaped chiral metamaterial along with the metal ground plane as a single system. As can be seen in Supplementary Fig. 3e, for the case of LCP, the unconverted scattered field $r_{xx}E_x$, (or $r_{yy}E_y$) will destructively interference with converted scattered field $r_{xy}E_y$ (or $r_{yx}E_x$), resulting in a reduced total reflected field for both $E_{x,sum}$ and $E_{y,sum}$. An opposite situation is observed for the case of RCP as shown in Supplementary Fig. 3f. The strong asymmetric interference effect results in different absorption for LCP and RCP. As a result, a circular dichroism (CD) of about 0.7 is obtained as shown in Supplementary Fig. 3b.

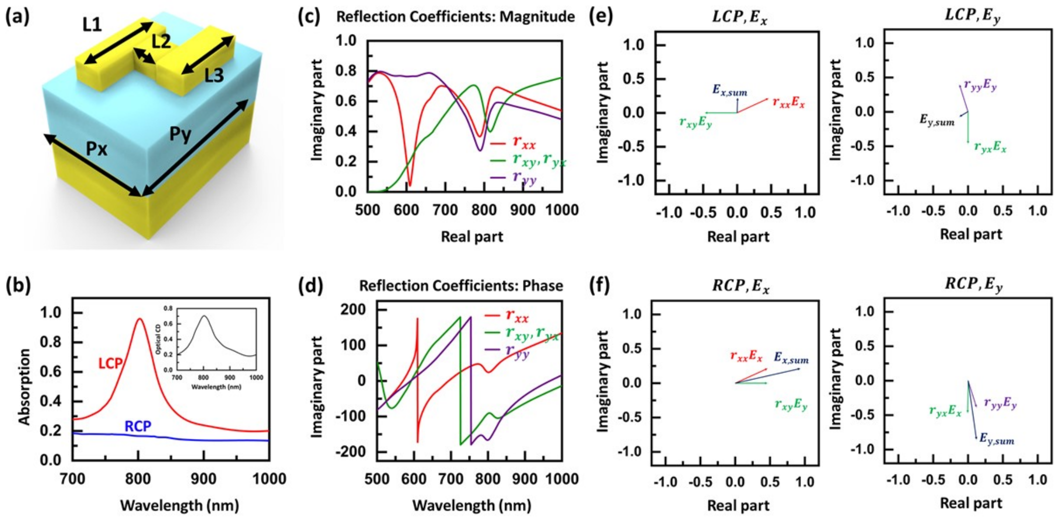
Supplementary Figures:



Supplementary Figure 1: Ideal conditions for maximizing circular dichroism in planar chiral metamaterials. Completely destructive (a) and constructive interference between the unconverted scattered field, $r_{xx}E_x$, (or $r_{yy}E_y$) and the converted scattered field, $r_{xy}E_y$ (or $r_{yx}E_x$), under LCP (a) and RCP (b) illumination at a wavelength of 800 nm. Dashed lines represent the initial incident field vectors E_x and E_y with a 90° phase shift. Solid lines represent the reflected field vectors.



Supplementary Figure 2: Optical response of symmetrical H-shaped nanostructure. a, Schematic of a H-shaped nanostructure unit cell. Dimensions are $L_1 = 200\ nm$, $L_2 = 50\ nm$, $L_3 = 200\ nm$, $W = 50\ nm$, $P_x = 210\ nm$, $P_y = 290\ nm$, and the thickness of SiO_2 is $120\ nm$. **b,** absorption spectra of LCP and RCP light. Insert shows the optical CD spectra. **c,d,** Amplitude (d) and phase (d) of reflection coefficients for E_x and E_y. **e,f,** Vector plots of reflected fields $r_{xx}E_x$ and $r_{yy}E_y$ under LCP (e) and RCP (f) illumination at a wavelength of 800 nm.



Supplementary Figure 3: Optical response of asymmetrical H-shaped nanostructure. a, Schematic of a unit cell of H-shaped nanostructure. Dimensions are $L_1 = 155\ nm$, $L_2 = 50\ nm$, $L_3 = 135\ nm$, $W = 50\ nm$, $P_x = 210\ nm$, $P_y = 290\ nm$, and the thickness of SiO_2 is $120\ nm$. **b,** absorption spectra of LCP and RCP light. Insert shows the optical CD spectra. **c,d,** Amplitude (d) and phase (d) of reflection coefficients for E_x and E_y. **e,f,** Interference between the uncovered scattered field, $r_{xx}E_x$, (or $r_{yy}E_y$) and the converted scattered field, $r_{xy}E_y$ (or $r_{yx}E_x$), under LCP (e) and RCP (f) illumination at a wavelength of 800 nm.