Chiral Metasurface Photodetectors for Circular-Polarization-Selective Phase Contrast Imaging

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Abstract: We report metasurface photodetectors that can selectively measure the local phase gradient of only one circular polarization component of any incident wave, in a single shot and with standard imaging optics. Pixel arrays of these devices may enable new functionalities for applications in chemical sensing, biomedical microscopy, and machine vision.

Light waves possess multiple degrees of freedom besides intensity, including phase and polarization, that can contain important information of interest but require complex and bulky systems for their measurement. As a result, recently there has been growing interest in the development of miniaturized multifunctional photodetectors that can provide direct access to the same information [1]. Within this general context, the present work introduces an entirely new functionality for an integrated device – the ability to selectively measure the local phase gradient of only one circular polarization component of the incident light [2].

These devices consist of planar photodetectors stacked with a plasmonic gradient metasurface that introduces a strong dependence of responsivity on illumination angle and polarization. Specifically, the metasurface is designed to couple light incident at the desired detection angles and polarization into surface plasmon polaritons (SPPs) supported by an underlying metal film, which are then scattered into the photodetector active layer by a set of subwavelength slits perforated through the metal film [Fig. 1(a)]. A similar architecture (with a periodic diffraction grating instead of a gradient metasurface) has been used in our prior work focused on lensless compound-eye vision [3] and linearly polarized phase contrast imaging [4]. For phase imaging, the target detection angle θ_p should be small enough so that the resulting peak in the angular response overlaps asymmetrically with normal incidence, leading to large variations in responsivity with illumination angle around $\theta = 0$. The resulting devices can therefore be used to measure any deflection in the local direction of light propagation away from normal incidence, which in turn is proportional to the local transverse phase gradient of the incident light.

For the angle- and circular-polarization-selective excitation of SPPs, here we rely on the combined use of the plasmonic resonance and Pancharatnam-Berry (PB) phase of the individual meta-units, which consist of rectangular Au nanoparticles (NPs) of different size and orientation [Fig. 1(b)]. The NP array is designed so that, for one circular polarization component, the resonance and PB scattering phase profiles cancel each other, leading to specular reflection. At the same time, for the other circular polarization, these two phase profiles add up to each other to match the incident-light wavevector at the target detection angle to that of an SPP on the Au film. Using this design strategy, we have developed two devices (labeled R and L) providing angle-sensitive photodetection peaked at $\theta_p \approx -2°$ for right and left circularly polarized (RCP and LCP) light, respectively.

Figures 1(c)-(e) show the measured responsivity data of device R, illustrating the expected angle and polarization dependence. For circular-polarization-selective phase imaging, the key feature of these data is the large versus near-zero responsivity slope $d\mathscr{R}/d\theta$ at normal incidence ($\theta = 0$) for RCP and LCP light, respectively [see Fig. 1(e), where the shaded region indicates the range of angles incident on the sensor array in a typical microscope]. In particular, our measurements show that the ratio $|d\mathscr{R}_{RCP}/d\theta|/|d\mathscr{R}_{LCP}/d\theta|$ is 37× on average over a bandwidth of ~70 nm around the 1.55-μm design wavelength, which provides a measure of the polarization selectivity of this device with respect to phase gradient. Similar results with the two states of circular polarization interchanged were obtained with device L. A detailed analysis of these data also provides a direct illustration of spin-momentum locking in SPPs and the role of spin conservation in photon/plasmon interactions.

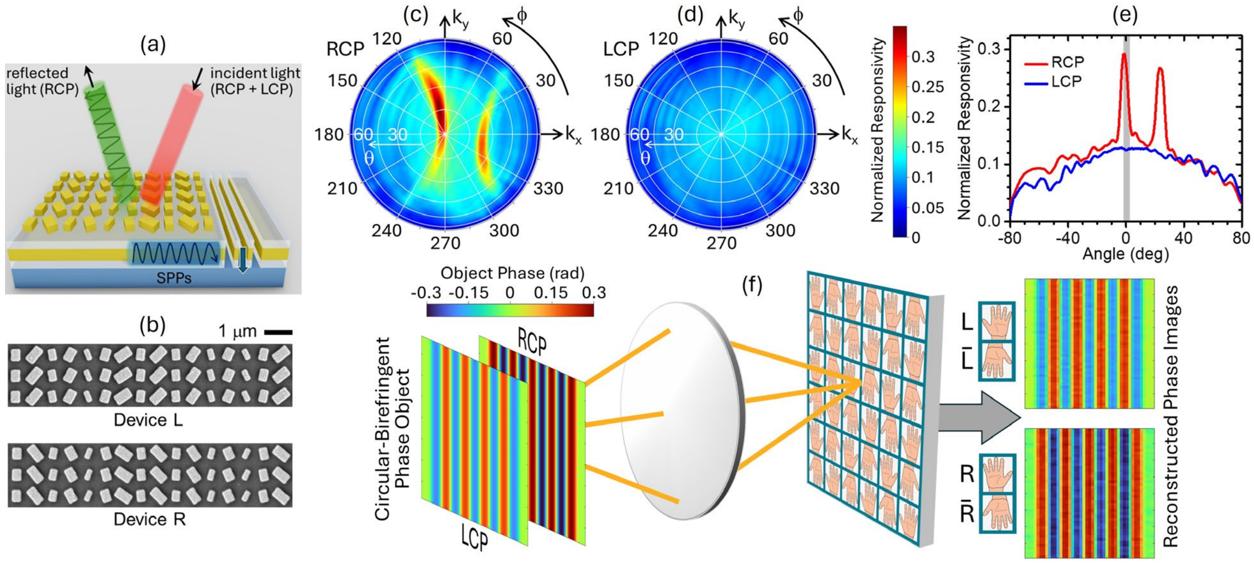

Fig. 1. (a) Schematic device structure. (b) SEM images of the metasurfaces of devices L and R. (c), (d) Measured responsivity of device R versus illumination angles under RCP (c) and LCP (d) illumination. (e) Horizontal line cuts of the color maps of (c) and (d). (f) Computational imaging results for a pixel array combining both types of devices.

Finally, we have conducted computational imaging simulations based on the measured angular response maps to show how these devices can be combined in a pixel array that allows for the simultaneous separate mapping of the RCP and LCP incident wavefronts [Fig. 1(f)]. This capability could benefit multiple imaging applications involving chiral matter, e.g., for drug development, studies of live cells, and biomedical diagnostics. Furthermore, these devices provide a key enabling ingredient for the development of a sensor array that could directly measure, in a single shot and with standard imaging optics, the spatial distribution of the incident optical intensity, phase, and polarization. In turn, such a system could dramatically improve our ability to sense visual information in low-contrast environments, with broad applicability in machine vision and image processing.

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References

1. Yuan, S., C. Ma, E. Fetaya, T. Mueller, D. Naveh, F. Zhang, and F. Xia, "Geometric deep optical sensing," Science, vol. 379, eade1220 (2023).
2. Erturan, A. M., J. Liu, M. A. Roueini, N. Malamug, L. Tian, and R. Paiella, "Chiral phase-imaging meta-sensors," arXiv:2412.16084, 2024.
3. Kogos, L. C., Y. Li, J. Liu, Y. Li, L. Tian, and R. Paiella, "Plasmonic ommatidia for lensless compound-eye vision," Nat. Commun., vol. 11, 1637, 2020.
4. Liu, J., H. Wang, Y. Li, L. Tian, and R. Paiella, "Asymmetric metasurface photodetectors for single-shot quantitative phase imaging," Nanophotonics, vol. 12, 3519-3528, 2023.