Nature-Inspired Chiral Metasurfaces for Circular Polarization Detection and Full-Stokes Polarimetric Measurement

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Chiral metamaterials and metasurfaces enable ultra-compact devices for circularly polarized light generation, manipulation and detection. However, plasmonic metasurfaces usually suffer from low Circular Polarization Extinction Ratios (CPERs) (less than ~5) and limited optical efficiency in experiment (20-50 %). Stomatopods (or mantis shrimps) possess extraordinary capability of circular polarization vision due to the unique ommatidium designs in their eyes [1]. Each ommatidium (Fig. 1a) has a top retinular cell (R8), acting as a quarter wave plate (QWP) to convert CPL to linearly polarized light (LPL), and seven bottom retinular cells (R1–7) that function as wire-grid polarizers. Here we have demonstrated theoretically and experimentally ommatidium-like double-layer metasurface (ODLM) design composed of a dielectric nanostructured birefringent metasurface acting as a QWP, a nanograting linear polarizer, and a dielectric spacer layer between them (Fig. 1b). Our theoretical calculation and simulation show that a large CPER (peak value >400) can be obtained by designing the gold nanowires with a high LPL extinction ratio (LPER) and using a perfect QWP with $\Delta\varphi=\pi/2$.

Experimentally, we developed a fabrication scheme (Fig. 2) to monolithically integrate the microscale circular polarization filters comprising gold nanogratings and Si-based dielectric metasurface QWP. Particularly, we sputtered a SiO_x spacer layer on the nanogratings to create stronger adhesion and smoother surface for Si nanofabrication while avoiding high-temperature processes that could damage gold nanogratings. The Si QWPs were aligned on top of the nanograting polarizers, and dry-etched to yield a large height-width aspect ratios (HWAR>4) with a small inclination angle.

The performance of the metasurface QWPs and nanograting linear polarizers were characterized, respectively, using Fourier-transform infrared spectroscopy (FTIR) (Fig. 3a-d). At the operation wavelength (1.47 µm), the phase retardation between the fast (V-) and slow (U-) axis is exactly $\pi/2$ and the transmission efficiency of the QWP is close to 90%. The fabricated nanograting linear polarizer (width 120 nm, height 122 nm and period 230 nm as fabricated) exhibited a LPER of 40-50 and transmission efficiency >90% at wavelengths around 1.5 µm. Besides, we have also integrated the chiral metasurface structures on the same chip with linear polarization (LP) filters to perform full-stokes polarimetric detection (Fig. 3e-f). Arbitrary state of polarization (SoP) of incident light was generated and measured, and the average measurement errors of S_1, S_2, S_3 were found 1.9%, 2.7% and 7.2%, respectively. Compared to reported plasmonic or dielectric metasurface-based polarimetric detection techniques, our devices exhibit the best performance in measurement accuracy and optical efficiency. Our designs are advantageous for its feasibility of direct and scalable integration onto existing imaging sensors, high extinction ratio, high transmission efficiency, ultra-compact footprint (sub-wavelength thickness, micrometer scale in lateral dimension) and robustness; thus are ideal for ultra-compact imaging, sensing, communication and navigation systems.

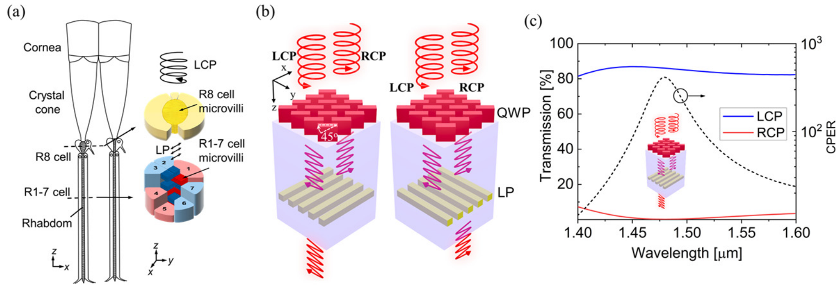

Figure 1. Bioinspired CPL-responsive detection. (a) Anatomical schematic of ommatidium in mantis shrimp's compound eye responsible for circularly polarized light detection. (b) Schematics of ommatidium-like double-layer metamaterial (ODLM) design, where dielectric metasurface behaves as artificial R8 cells and nanogratings behave as R1-7 microvilli that differentiate the linear polarization perpendicular or parallel to the microvilli axis. (c) Theoretically calculated transmission (left) and CPER (right).

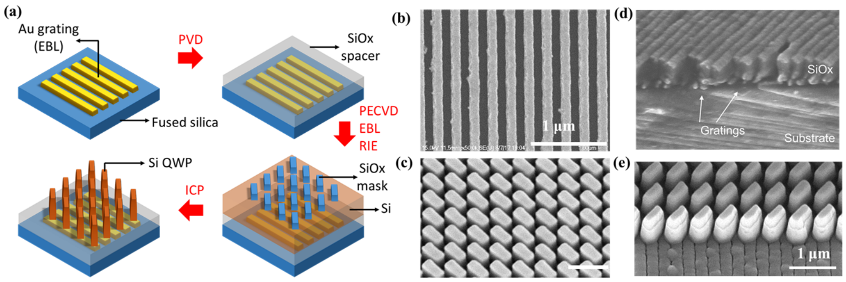

Figure 2. Fabrication of ODLM-based CPL filters. (a) Schematic illustration of major fabrication steps. (b) Scanning electron microscope (SEM) image of the nanograting before QWP metasurface integration. (c) SEM image of silicon QWP. (d) Cross-section of grating covered by fused silica. (g) Tilted-view SEM image of ODLM structure. The bright thin layer on top of each Si QWP pillar corresponds to residual SiOx mask. All the SEM scale bars are 1 μm.

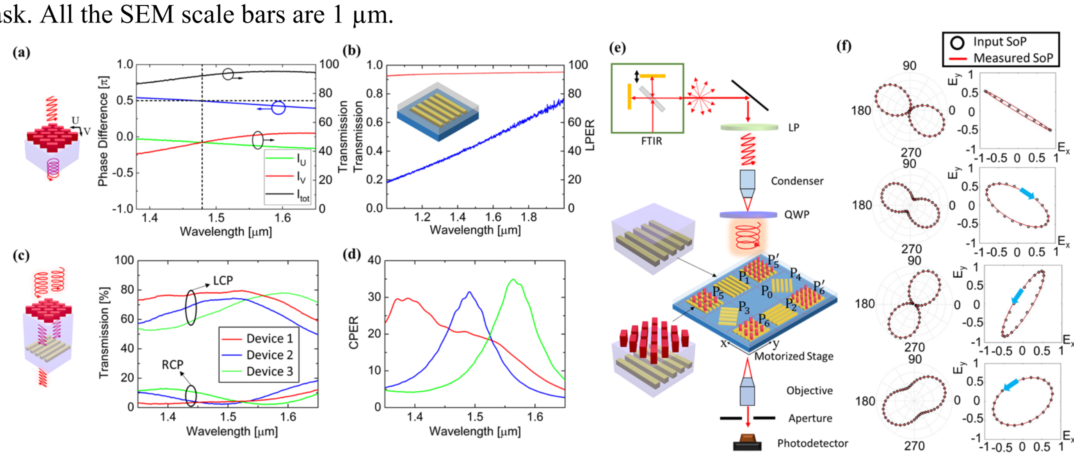

Figure 3. Characterization of ODLM-based CPL filters and Full-Stokes polarimetric measurement. (a) Phase difference (left axis) and transmission spectrum (right axis) of a fabricated QWP. (b) Measured transmission perpendicular to the nanograting orientation (red curve, left axis) and the corresponding linear polarization extinction ratio (blue curve, right axis). (c) Total transmission measurements of device for LCP and RCP incident lights at working wavelengths of our samples (1.35 - 1.65 μm), with identical grating orientation on a single chip. (d) Extracted extinction ratio from pairs of transmission spectra in part (c)**.** (e) Schematics and optical microscope image of metasurface design to fully characterize the state of polarization (SoP) of incident light. The required units are marked by P_0 to P_6. The two additional units labeled by P_5' and P_6' provide flexibility to identify Stokes parameters at a different working wavelength. (f) Comparison of SoP using conventional polarization analyzer (black circles) and ODLM-based CPL filters (red solid lines), using polar plots and polarization ellipses, at the working wavelength of metasurface.

References:

1 Land, M. F. & Osorio, D. Extraordinary Color Vision. *Science* **343**, 381-382, (2014).