Metasurface Image Sensors for Optical Spatial Filtering and Quantitative Phase Imaging

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Abstract: We report the development of angle-sensitive photodetectors based on specially designed metasurfaces that can map the phase distribution of the incident light and visualize transparent phase objects without any external spatial-filtering elements. Pixel arrays of these devices can provide quantitative phase reconstruction in a single shot with state-of-the-art sensitivity.

Traditional image sensors detect light incident from all directions with equal responsivity, and as a result can only measure the intensity distribution of a visual scene. At the same time, all information associated with the phase profile and local directions of light propagation is lost in the image acquisition process. The ability to capture such information, however, would allow for more advanced image sensing and processing functionalities, such as image differentiation by optical spatial filtering and the visualization of transparent phase objects, which normally require rather bulky and complex setups. In turn, these functionalities have important applications ranging from computer vision to biomedical microscopy.

Here we report the development of angle-sensitive image sensors that can measure the phase profile of the incident optical field directly, without the need for any external optical elements other than standard imaging lenses. These devices consist of photodetectors stacked with a composite plasmonic metasurface that introduces a strong dependence of responsivity on illumination angle. Specifically, the metasurface is designed to couple light incident at the desired detection angles into surface plasmon polaritons 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 [Figs. 1(a) and 1(b)]. Light incident along all other directions is instead simply reflected back or diffracted away from the device.

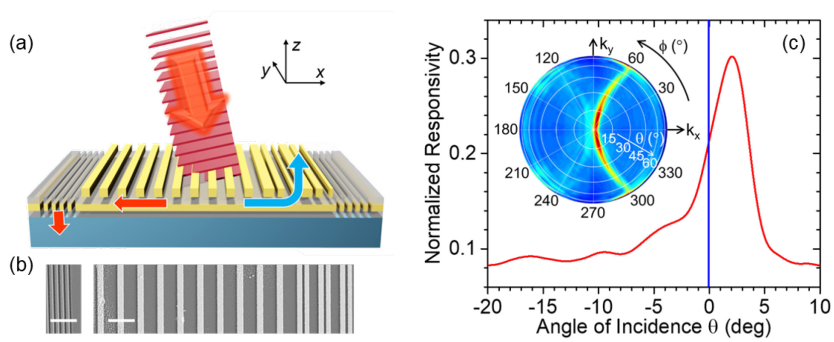

Fig. 1. Angle-sensitive metasurface photodetectors. (a) Schematic device structure. (b) Top-view SEM images of an experimental sample, showing the slits (left image) and nanostripes (right). The scale bars are 2 μm. (c) Inset: measured responsivity of this device at λ = 1550 nm versus polar θ and azimuthal ϕ illumination angles, normalized to the responsivity of an identical photodetector without any metasurface. Main plot: horizontal line cut of the color map. The vertical blue line indicates normal incidence.

In prior work, similar devices have been developed to demonstrate a planar lensless camera with ultrawide field of view, based on the compound-eye vision modality [1]. The same devices can also be used as optical spatial filters, based on the notion that different spatial-frequency components of an illuminated object correspond to optical plane waves propagating from the object along different directions [2]. Here we focus on the ability of angle-sensitive photodetectors to visualized transparent phase objects, where light transmission generally involves a deflection in the direction of light propagation proportional to the local phase gradient. To maximize the device sensitivity to small deflection angles, the metasurface is designed to produce an asymmetric dependence of responsivity on angle of incidence around the surface normal. The measured angular response of this device (i.e., responsivity versus polar and azimuthal angles of incidence) is shown in Fig. 1(c).

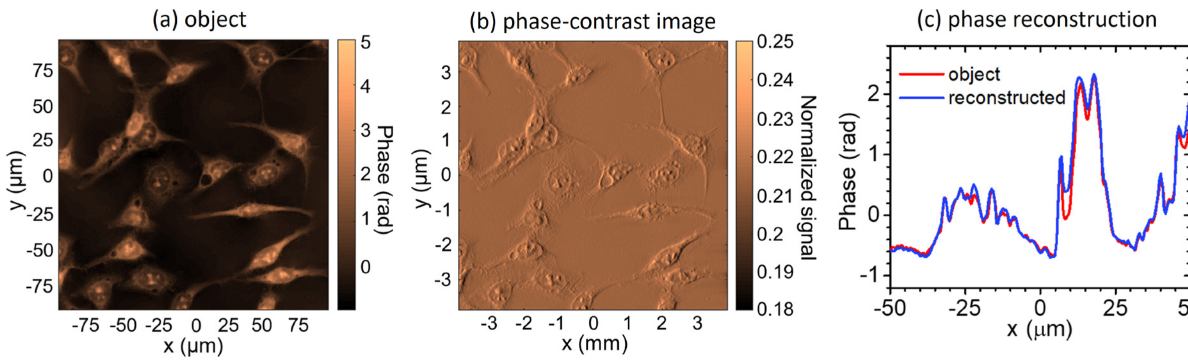

Fig. 2. Phase imaging results. (a) Representative phase object. (b) Corresponding image detected by an array of identical angle-sensitive pixels. (c) Red trace: phase distribution along the horizontal line at y = 0 in the object of (a). Blue trace: reconstructed phase profile from an array partitioned into blocks of four adjacent pixels, each coated with the metasurface of Fig. 1 oriented along one of four orthogonal directions.

These measurement results, combined with computational imaging simulations, indicate that a standard camera or microscope based on such devices can directly map the phase gradient of the incident light and therefore visualize any phase object in its field of view. As an illustration, Figs. 2(a) and 2(b) show, respectively, a phase object of practical interest (HeLa cancer cells) and its phase-contrast image recorded with this approach. A detailed analysis based on the noise properties of high-performance image sensors also show that the minimum detectable phase contrast is smaller than 10 mrad, which is comparable with state-of-the-art phase imaging systems involving significantly more complex and bulky setups [3].

Furthermore, the combination of sensors with equal and opposite angular response on the same pixel array can be used to perform quantitative phase reconstruction in a single shot with a straightforward computational protocol [Fig. 2(c)]. At the same time, with this approach the overall imaging system can be significantly simplified and miniaturized compared to traditional setups for quantitative phase imaging, e.g., based on optical spatial filtering, interferometry, or structured illumination. As a result, this approach is particularly promising for applications where space is highly constrained, such as point-of-care and in vivo microscopy and measurements involving freely moving objects.

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References

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