Quantitative Phase Contrast Imaging with Plasmonic Metasurface Photodetectors

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Abstract: We report a new technique for single-shot quantitative phase retrieval from transparent objects, based on plasmonic metasurface photodetectors featuring an asymmetric angular response around normal incidence combined with a particularly simple optical setup. © 2023 The Author(s)

1. Introduction

Phase contrast imaging capabilities are attractive for a variety of applications such as microscopy of transparent biological samples and surface profiling (e.g., for wafer inspection), where the transmitted or reflected light has uniform intensity. Such phase objects generally produce a deflection in the direction of light propagation that is proportion to the local phase gradient [Fig. 1(a)]. However, traditional image sensors (where the responsivity is constant with angle of incidence) can only detect the intensity distribution of the incoming light, and as a result any information about the phase profile is lost during the image acquisition process. Many techniques for phase contrast imaging have been developed [1], but usually require bulky or complex setups that limit their potential applications.

Here, we introduce angle-sensitive image sensors that can directly measure the local phase gradient of the incident light wave, without the need of any additional optical components other than standard imaging lenses. Each device consists of a photodetector with a sub-wavelength layered structure stacked on top, where a composite metasurface is patterned to create a strong asymmetric response $\mathcal{R}$ on illumination angle θ [Fig. 1(b)-(d)]. Similar devices were developed in prior work where this design strategy was used to achieve peaked responses within an ultrawide field of view for lensless compound-eye-vision [2], or to demonstrate high-pass spatial filtering with a symmetric angular response [3].

In order to detect small phase variations of a transparent object with high sensitivity, a sharp asymmetric angular response to the incident light around normal incidence is desirable. In this work, we design a composite metasurface that selectively transmits into its substrate (an underlying photodetector) light incident at a small angle $\theta \approx 2°$, while at the same time reflecting light incoming from all other angles. As a result, the low-angle tail of the responsivity peak crosses normal incidence [Fig. 1(d)], so that a large responsivity slope $d\mathcal{R}/d\theta$ can be obtained near $\theta = 0$. With an array of such devices, even a small phase gradient $\nabla\varphi$ in the object can therefore produce a noticeable contrast in the image captured by the array. 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.

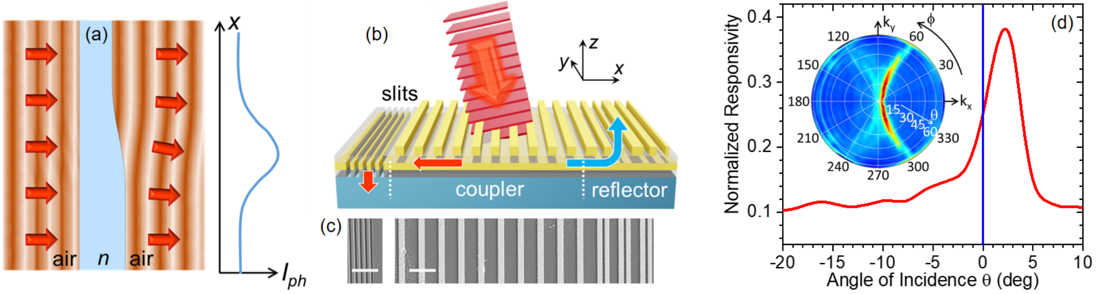

Fig. 1. (a) Schematic illustration of a plane wave travelling through a transparent phase object and the photocurrent signal correspondingly measured by an angle-sensitive photodetector array. (b) Proposed device structure. (c) Top-view SEM images of an experimental sample. The scale bars are 2 μm. (d) Inset: measured responsivity of an experimental device vs. polar and azimuthal angles of incidence at 1550 nm wavelength. Main plot: horizontal line cut of the polar plot. The vertical blue line indicates normal incidence.

2. Results and Discussion

In our device structure illustrated by Fig. 1(b), a photodetector is coated with a $SiO_2/Au/SiO_2$ stack. On the top SiO_2 surface, a periodic array of Au nanostripes is introduced to act as a grating coupler, surrounded on one side by a group of subwavelength slits penetrating through the stack and on the other side by a gradient-metasurface section (reflector). The Au film is sufficiently thick to block all incoming light from propagating directly into the underlying photodetector active layer, so that a photocurrent signal can only be produced through a plasmon-assisted process. Specifically, light incident at the target detection angle $+\theta_p$ is diffracted by the grating into surface plasmon polaritons (SPPs) travelling in the –x direction, which are then preferentially scattered through the slits into the photodetection substrate. In contrast, for light is incident at $-\theta_p$, SPPs travelling in the +x direction are produced and then scattered away from the device by the reflector (designed based on the concept of gap-plasmon metasurfaces). For all other angles of incidence, the incoming wave is either diffracted by the grating or reflected by the Au layer into the air above. The device geometric parameters were optimized by FDTD simulations to maximize the responsivity slope while maintaining a reasonably high transmission efficiency (38% at the angle of peak detection).

While this metasurface architecture could be applied to any type of image sensors, here we study its functionality based on simple Ge photodetectors at a working wavelength of 1550 nm. The measured responsivity of an experimental sample as a function of polar θ and azimuthal ϕ illumination angles is shown in Fig. 1(d), where the desired sharp asymmetry near normal incidence is clearly observed. To demonstrate phase contrast imaging, we consider a sample of epithelial cells with fibrocystic disease (MCF 10A) [Fig. 2(a)]. Figure 2(b) shows the image of this transparent object produced by a 512×512 pixel array of our angle-sensitive devices in a 40×-magnification imaging system. Specifically, this image was computed with the frequency-domain model developed in ref. 3 combined with the experimental data of Fig. 1(d). Even though the object transmits light with no intensity modulation, clear edges are displayed on the acquired image as a result of the angular variations of the pixels responsivity. Additional analysis based on the noise properties of high-performance image sensors shows that this approach is capable of detecting a phase contrast as small as 10 mrad. This value is comparable to that of state-of-the-art phase imaging systems which involve significantly bulkier and more complex setups [4].

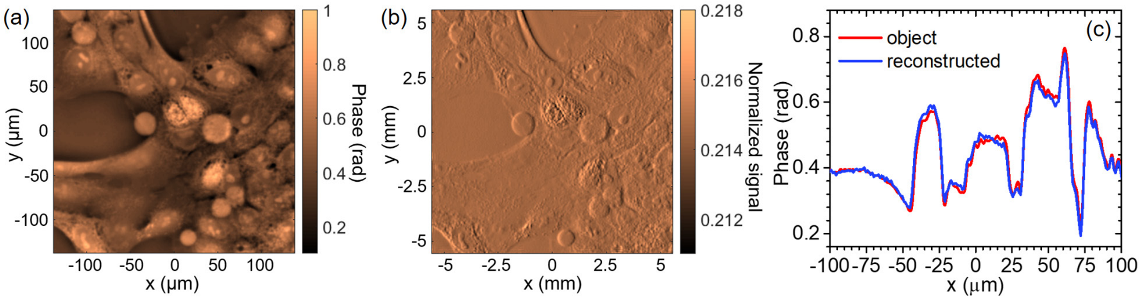

Fig. 2. Phase imaging results. (a) Phase object (MCF 10A). (b) Corresponding image produced by a pixel array of the angle-sensitive devices of Fig. 1(d). (c) Quantitative phase reconstruction. Red trace: line cut of the object of (a) at y = 0. Blue trace: reconstructed phase profile from an array partitioned into block of four pixels with different metasurface orientations.

Finally, the devices reported in this work can also be employed for quantitative phase reconstruction in a single shot. For this purpose, we consider an image-sensor array partitioned into blocks of four adjacent pixels, each coated with the metasurface of Fig. 1 oriented along one of four orthogonal directions. The four images recorded by the different types of pixels can be used to cancel out the unknown background as required for quantitative phase retrieval. The effectiveness of this approach is illustrated in Fig. 2(c), where the reconstructed phase was computed using a Tikhonov regularization protocol with transfer function derived from the experimental data of Fig. 1(d). Importantly, this approach does not require multiple sequential image acquisitions and does not involve any external filtering components, different from existing methods based on optical spatial filtering, interferometry, or structured illumination. Thus, this approach is particularly promising for imaging applications where space and time are highly constrained, such as point-of-care and in vivo microscopy.

3. References

[1] T. L. Nguyen, S. Pradeep, R. L. Judson-Torres, J. Reed, M. A. Teitell, and T. A. Zangle, "Quantitative phase imaging: recent advances and expanding potential in biomedicine," ACS Nano 16, 11516-11544 (2022).

[2] L. Kogos, Y. Li, J. Liu, Y. Li, L. Tian, and R. Paiella, "Plasmonic ommatidia for lensless compound-eye vision," Nat. Commun. 11, 1637 (2020).

[3] J. Liu, H. Wang, L. C. Kogos, Y. Li, Y. Li, L. Tian, and R. Paiella, "Optical spatial filtering with plasmonic directional image sensors," Opt. Express 30, 29074–29087 (2022).

[4] C. Bonati, T. Laforest, M. Kunzi, and C. Moser, "Phase sensitivity in differential phase contrast microscopy: limits and strategies to improve it," Opt. Express 28, 33767-33783 (2020).