Plasmonic Directional Photodetectors for Edge Enhancement

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Abstract: Angle-sensitive plasmonic photodetectors that can perform optical-domain spatial filtering operations are developed. The edge enhancement capabilities of these devices are demonstrated via computational imaging simulations based on their measured angular response.

1. Introduction

Traditional image sensors used in photography and microscopy are only sensitive to the intensity distribution of the incident light, whereas all information related to the local direction of light propagation is lost in the image acquisition process. Access to this additional information, however, would allow for more advanced imaging capabilities, including wavefront sensing, lightfield reconstruction for 3D imaging, and optical-domain spatial filtering. In particular, basic considerations from Fourier optics indicate that the selective detection of light as a function of angle of incidence could be used to produce filtered images of any object of interest, where only a subset of all spatial frequency components is preserved. In turn, this capability is desirable for a wide range of coherent image processing applications, such as filtering for noise reduction, pattern recognition in computer vision, and phase imaging (e.g., for label-free visualization of biological samples that are generally transparent).

In recent work [1], we have reported a new family of image sensors based on plasmonic nanostructures that can selectively detect light incident along a small, geometrically tunable set of directions. The simulated and measured angular characteristics of these devices were then used to demonstrate image reconstruction over an ultrawide field of view of 150° in a planar lensless compound-eye camera architecture. In the present work we investigate the use of similar devices for edge enhancement by optical spatial filtering with transparent phase objects. Compared to traditional solutions for the same functionality (typically involving the use of a filtering mask in a two-lens configuration [2, 3]), this approach does not require any additional optics, besides a standard imaging lens. Therefore, it can provide significant size miniaturization for enhanced portability and integration capabilities. Furthermore, our design offers the unique ability to tailor the angular response (i.e., the filter transfer function) of each photodetector on a pixel-by-pixel basis, so that multiple filtering operations could be performed simultaneously with the same image sensor array.

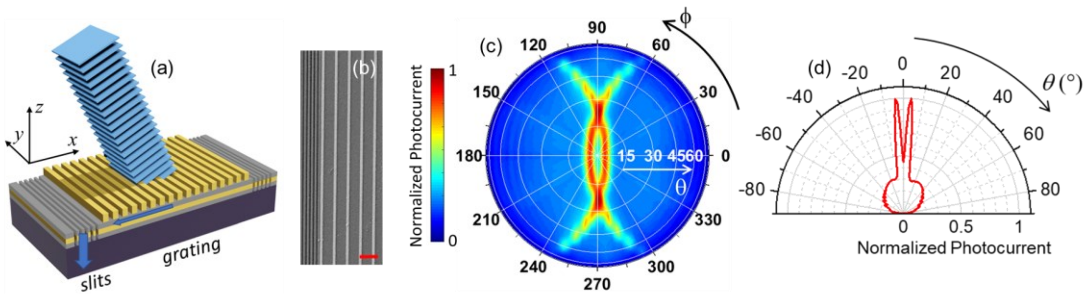

Fig. 1. Plasmonic directional photodetectors. (a) Schematic illustration of the device geometry and operation principle. (b) Top-view SEM image showing the slits and a few adjacent nanoparticles. The scale bar is 2 μm. (c) Measured photocurrent versus polar and azimuthal angles of incidence for *x*-polarized illumination at 1550 nm. (d) Horizontal line cut of the color map of (c).

2. Results and discussion

The basic device structure employed in this work is shown schematically in Fig. 1(a). The photodetector active material is coated with a metal film stacked with a periodic grating of rectangular metallic nanoparticles (NPs). The metal film is sufficiently thick (~ 100 nm) to block any externally incident light from propagating directly into the underlying active layer. As a result, photodetection can only take place through an indirect process where light incident at the target detection angle is first diffracted by the NPs into surface plasmon polaritons (SPPs) propagating on the top surface of the metal film. A small set of subwavelength slits perforated through the metal film is then used to scatter these SPPs into radiation propagating predominantly into the absorbing active layer, and as a result a photocurrent signal is produced. Light incident along any other direction is instead reflected by the metal film away from the photodetector.

Several devices based on this approach with different angles of peak detection were designed via FDTD simulations for operation at 1550-nm wavelength, and then fabricated in conjunction with simple Ge photoconductors [Fig. 1(b)]. The color map of Fig. 1(c) shows the photocurrent signal measured with one such device as a function of polar θ and azimuthal ϕ illumination angles. The incident directions of high photocurrent form a rather narrow region within the full hemisphere with a double-C shape, consistent with the SPP-diffraction mechanism described above and in good agreement with numerical simulations. The $\phi = 0°$ horizontal line cut of the same color map is plotted in Fig. 1(d), showing a rather narrow angular selectivity of about 6° FWHM for both peaks and a relatively large peak-to-average-background ratio of about 4×. It should also be noted that, while the present devices feature a symmetric angular response (with respect to the polar angle of incidence), asymmetric angle-sensitive photodetectors can also be developed with the same approach, by replacing the slits on one side of the NP array with a suitably designed back-scattering element [1].

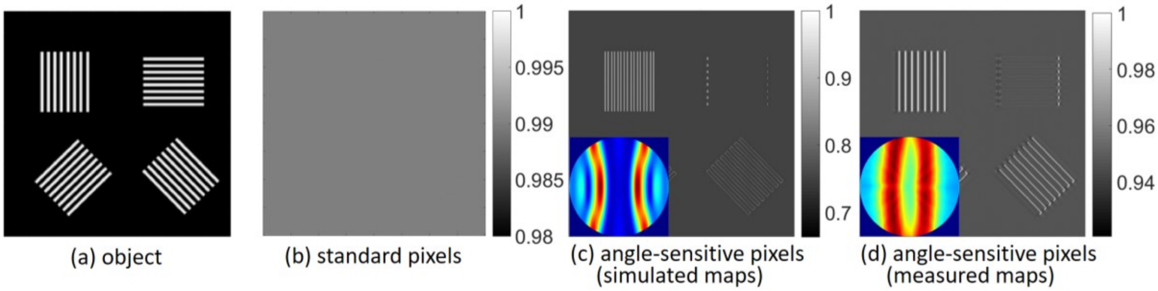

Fig. 2. Phase imaging simulation results. (a) Phase object used in these simulations. (b) Image produced with standard photodetectors featuring a uniform angular response. (c), (d) Images produced with simulated (c) and measured (d) directional photodetectors. The angular response map of each device within the numerical aperture of the camera lens (NA = 0.2) is shown in the figure inset.

Figure 2 illustrates the ability of these devices to perform optical-domain spatial filtering. Specifically, we present the results of computational imaging simulations for a photodetector array used to image the phase object of Fig. 2(a) (a collection of phase gratings oriented along different directions) under coherent illumination at 1550 nm. Figure 2(b) shows the image obtained with standard photodetectors featuring a uniform angular response, which are not able to visualize the grating lines as expected (i.e., phase-only objects are essentially invisible to a standard camera). In contrast, in the simulations of Figs. 2(c) and 2(d) each device in the sensor array is described by the angular response map shown in the figure inset (responsivity versus illumination angles within the NA = 0.2 numerical aperture of the imaging lens). The response map of Fig. 2(c) was computed via FDTD simulations, whereas the map of Fig. 2(d) was measured with an experimental sample [same as Fig. 1(c)]. In both cases, the edges of the phase object along the direction perpendicular to the high-responsivity bands are clearly enhanced, with only a relatively mild reduction in image contrast produced by the higher background levels of the experimental maps. Isotropic edge enhancement could also be obtained with the same devices using pixels with two orthogonal orientations of the NPs within the same image sensor array.

These edge-enhancement capabilities (applied to amplitude as well as phase objects) can also be employed for automated pattern recognition, where the ability to selectively detect edges along specific directions is actually particularly attractive. Importantly, the angular response of each device can be further tailored to match any specific application through the design of the plasmonic nanostructure (for example, increased contrast in phase imaging could be achieved with devices featuring a highly asymmetric response map). Furthermore, the ability to independently control the filter transfer function of each pixel in an image sensor array could provide greatly enhanced parallelism for a wide range of optical-domain image processing applications.

This work was supported by NSF under Grant ECCS-1711156.

3. References

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