

Directional Plasmonic Image Sensors for Lens-Free Compound-Eye Vision

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Abstract: We describe a novel lens-free camera technology inspired by the compound-eye vision modality that combines ultrathin plasmonic metasurfaces to enable angle-resolved photodetection with computational imaging for wide field-of-view image reconstruction.

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1. Introduction

The compound-eye vision modality (commonly found in nature in small invertebrates) involves arrays of many imaging elements (normally lenses and photoreceptors), each oriented so as to detect light incident along a different direction. This architecture represents the optimally adapted solution to provide wide fields of view within the smallest possible volume, nearly infinite depth of focus, and high acuity to motion [1]. These properties favor miniaturization, wide panoramic view, and fast motion detection, and therefore are particularly attractive for applications in endoscopic imaging, surveillance, and machine vision.

Initial attempts to develop artificial compound-eye cameras have been reported in recent years, based on both planar and curved micro-lens arrays [2, 3]. However, further progress has been hindered by fabrication and packaging complexity (especially when curved substrates are involved), as well as the potential formation of ghost images [2]. Here we describe and investigate numerically a novel architecture, where each pixel is coated with a specially designed plasmonic metasurface that only allows for the detection of light incident along a small, geometrically tunable distribution of angles, whereas light incident along all other directions is reflected. With this approach, ultrathin planar cameras without any lenses can be developed based on existing CMOS or CCD image sensor arrays, with the image reconstructed from the combined inputs of all the pixels using computational imaging algorithms.

2. Directional image sensors

The pixel geometry under study consists of a photodetector coated with a metal film supporting a periodic array of rectangular metallic nanoparticles (NPs) [Fig. 1(a), where all NPs are effectively infinitely long in the y direction]. In these devices, photodetection can only take place through an indirect process where the incident light is first diffracted by the NP array into surface plasmon polaritons (SPPs) on the top surface of the metal film. A set of subwavelength slits in the metal film is then used to scatter the SPPs into radiation propagating predominantly into the absorbing active layer. In particular, SPPs propagating along the $\mp x$ direction are excited via first-order diffraction of light incident at the equal and opposite angles $\pm\theta_{\max}$ determined by the diffraction condition $(2\pi\sin\theta_{\max})/\lambda_0 - 2\pi/\Lambda = -2\pi/\lambda_{\text{SPP}}$, where λ_0 and λ_{SPP} are the wavelengths of the incident light and excited SPPs, respectively, and Λ is the array period. Light incident at any other angle is instead completely reflected (or diffracted) away from the surface.

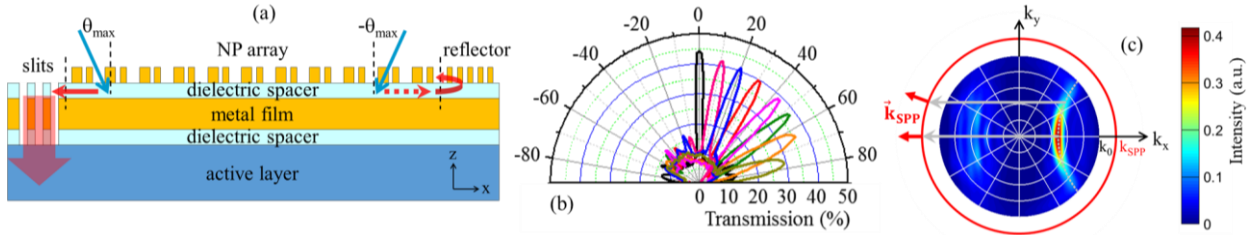


Fig. 1. (a) Schematic cross-sectional view of the device geometry under study. (b) P-polarized power transmission coefficient at $\lambda_0 = 800$ nm versus angle of incidence θ on the x - z plane, for several different periods of the NP array (ranging from 760 to 350 nm). (c) Far-field radiation pattern produced by a dipole source in the active layer of one of these devices. By reciprocity, this pattern provides an accurate description of the 3D angle-resolved transmission of the same device. The red circle indicates the available SPP modes at the emission wavelength. The grey arrows indicate diffractive scattering of the incident light into SPPs (propagating along the directions of the red arrows).

The selective detection of only one incident direction (e.g., $+\theta_{\max}$) is finally enabled through two complementary design prescriptions. First, asymmetric unit cells are used in the NP array to suppress the diffractive scattering of incident light into forward traveling SPPs (via destructive interference between the contributions of the individual NPs

in each cell [4]), relative to diffraction into backward SPPs. Second, the subwavelength slits are placed only on one side of the NP array (in the $-x$ direction), so that only the backward traveling SPPs (excited by incident light at $+\theta_{\max}$) propagate directly towards the slits, where they are preferentially scattered into the substrate. On the other side of NP array, an SPP grating reflector is used to provide optical isolation from the neighboring pixel in the envisioned camera.

Figure 1(b) shows the power transmission coefficient through the metal film into the substrate (proportional to the photocurrent produced in the active layer), computed as a function of polar angle of incidence θ (on the x - z plane) for a set of devices of different array periods. The incident wavelength in these FDTD simulations is 800 nm, and the active-layer, dielectric, and metal materials are Si, SiO₂, and Au, respectively. Tunable directional photodetection is clearly obtained, with a wide tuning range for $\theta_{\max}$ of up to $\pm 75^\circ$ and relatively narrow angular resolution. The peak transmission is in the range of 30-45 % for all devices considered. The full 3D angular response of one of these devices is shown in the color map of Fig. 1(c), computed via FDTD simulations based on the principle of reciprocity.

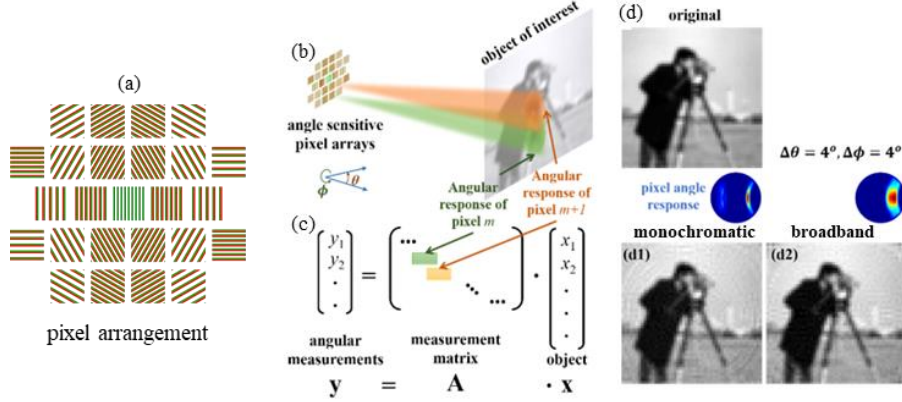


Fig. 2. (a) Schematic pixel arrangement of the compound-eye cameras under study. (b) Imaging setup: each angle-sensitive pixel integrates the light intensity from a set of incident angles. (c) The measurement from the pixel array is related to the object by a linear equation, in which the measurement matrix contains the pixel angular response. (d) Original object, and simulated reconstruction assuming monochromatic illumination (d1) and broadband light (d2).

3. Image reconstruction

The incident polar and azimuthal angles of maximum photodetection can be tuned by varying, respectively, the period and in-plane orientation of the NP array. Figure 2(a) illustrates a possible pixel arrangement for a planar lens-free compound-eye camera based on these devices. To evaluate the camera ability to resolve complex scenes, we consider the geometry of Fig. 2(b), where each pixel integrates the total incident intensity according to its angular response. The image formation process can therefore be described by a linear equation, which relates the object intensity distribution (x) to the captured data (y) by a measurement matrix (A) [Fig. 2(c)]. The angular response of each pixel (obtained from the FDTD simulation results summarized in Fig. 1 and their interpolations for additional designs) forms a row vector of A , which describes the intensity contributions to each pixel from different points on the object.

The simulation results shown in Fig. 2(d) indicate that high-quality images (nearly identical to the original object in this example) can be reconstructed using a relatively small but fully realistic inter-pixel spacing of 4° in both polar and azimuthal angles. The corresponding number of pixels needed to cover the entire field of view considered in this figure ($\pm 75^\circ$) is less than 1800. Importantly, high-resolution imaging is obtained not only under monochromatic illumination at the design wavelength $\lambda_0 = 800$ nm [Fig. 2(d1)], but also assuming broadband illumination with $\Delta\lambda/\lambda_0 = 40\%$ [Fig. 2(d1)], at the expense of somewhat increased complexity in the image reconstruction analysis. These results suggest that the combination of metasurface design and computational imaging may allow for the development of entirely new imaging systems with unique attributes, such as (in the present case) lens-free operation leading to extreme miniaturization in the vertical direction and nearly infinite depth of focus.

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4. References

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