Integrated plasmonic gradient metasurfaces for directional photodetection

Jianing Liu and Roberto Paiella
Department of Electrical and Computer Engineering and Photonics Center, Boston University, 8 St. Mary's St., Boston, MA 02215, USA
Email address: ljn@bu.edu

Abstract: We demonstrate the use of plasmonic gradient metasurfaces to tailor the angular response of generic planar photodetectors. The resulting devices are promising for a wide range of computational imaging applications with enhanced miniaturization and functionality.

1. Introduction

Photodetectors are usually designed for the sensitive detection of optical intensity, at the expense of all other degrees of freedom of the incident light including its local direction of propagation. At the same time, however, the ability to sense incident angles and wavefronts is highly desirable for multiple advanced imaging functionalities. Examples include lensless compound-eye vision with ultrawide field of view, lightfield sensing for 3D photography and microscopy, optical edge detection for computer vision, and quantitative phase imaging in biomedicine. As a result, different device technologies for angle-sensitive photodetection have been investigated in recent years, including integrated diffractive elements (such as stacked gratings based on the Talbot effect [1] and plasmonic grating couplers [2]) and micro-apertures across adjacent pixels [3].

Here we report the development of directional photodetectors based on the gradient metasurface (GMS) design platform [4], motivated by its distinctive ability to provide enhanced miniaturization and multifunctional operation. Specifically, we have developed GMSs integrated on the illumination window of generic photodetectors and designed to couple light incident at select detection angles to surface plasmon polaritons (SPPs) on an underlying metal film. The excited SPPs are then scattered into the photodetector active layer by a set of subwavelength slits perforated through the metal film. Compared to grating couplers, GMSs can provide smaller footprint for the same angular selectivity and lower radiative losses due to the suppression of all undesired diffractive channels [5]. When combined with image sensors, as in the present work, these advantages translate into higher spatial resolution and improved sensitivity. Furthermore, through the use of more complex meta-units, the GMS platform presented below can be extended to enable capabilities that are intrinsically not accessible with diffractive devices (similar to extensive prior work with metasurface free-space optical components [4]). Examples include broadband achromatic operation and multifunctional operation such as simultaneous wavefront and polarization sensing.

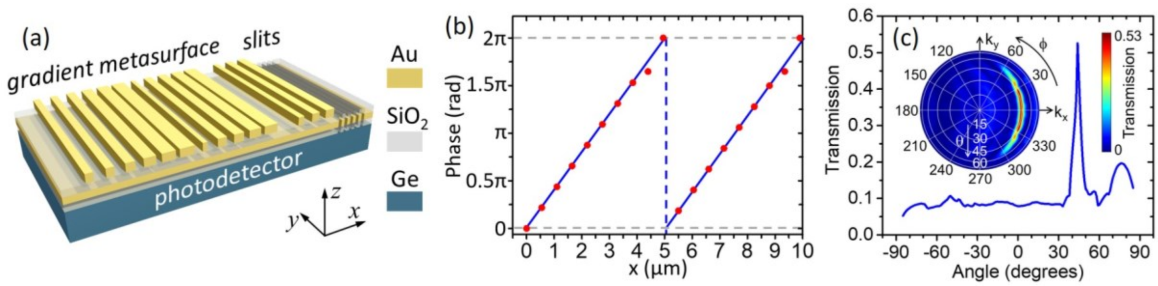

Fig. 1. (a) Schematic device geometry. (b) Reflection phase versus nanostripe center position for a GMS designed to promote directional photodetection peaked at $\theta_p = 45°$. (c) Transmission coefficient of the GMS of (b) computed as a function of polar illumination angle on the x-z plane. Inset: transmission coefficient versus in-plane wavevector of the incident light.

2. Results and discussion

The device structure developed in this work is shown schematically in Fig. 1(a). The illumination window of a Ge photodetector is coated with a $SiO_2/Au/SiO_2$ stack supporting an aperiodic array of Au nanostripes. In this configuration, the p-polarized reflection phase of each unit cell can be tuned across a large fraction of the entire 2π phase space by varying the nanostripe width L_x, while the reflection coefficient remains consistently large (> 90%). To enable directional photodetection, the nanostripe widths are selected so that their reflection phase varies linearly with their center position along the x direction, leading to a discretized version of the linear phase profile $\Phi_x = \xi x$ [Fig. 1(b)]. As a result, SPPs on the underlying metal film can be excited by incident light with in-plane wavevector

$\mathbf{k}_{||}$ satisfying the phase-matching condition $\mathbf{k}_{||} + \xi\mathbf{x} = \mathbf{k}_{SPP}$. These SPPs are then intercepted by the adjacent slits where they are preferentially scattered into the substrate (the photodetector active layer). Light incident along any other direction is instead reflected or diffracted back, leading to a highly directional asymmetric angular response.

Figure 1(c) presents FDTD simulation results for the power transmission coefficient of a GMS designed for peak detection at a polar angle $\theta_p = 45°$, computed as a function of illumination angles at a wavelength of 1.55 μm. As shown in the inset, high transmission through the GMS is obtained only for a narrow set of values of $\mathbf{k}_{||}$ determined by the SPP phase matching condition. For light propagating on the x-z plane, the transmission peak is centered at the target detection angle with a small linewidth $\delta\theta = 6.0°$ FWHM and maximum value of $T_{max} = 53\%$ [main trace in Fig. 1(c)]. For comparison, the Fresnel transmission coefficient of Ge/air interface is about $T_{ref} = 62\%$, so that the transmission penalty introduced by the GMS is quite small ($T_{max}/ T_{ref} = 85\%$).

Measurement results for a GMS photodetector based on this design [Figs. 2(a) and 2(b)] are in good agreement with the design simulations. A sharp peak centered at $\theta_p = 42°$ with FWHM of about 9° is observed in the plot of photocurrent versus polar angle of incidence on the plane perpendicular to the nanostripes [red trace in Fig. 2(b)]. The angular response map across the full hemisphere shown in the inset contains a similarly narrow region of high responsivity. At the angle of peak detection, the measured photocurrent is as large as 75% of that of an otherwise identical reference sample without any metasurface measured under the same conditions [blue trace in Fig. 2(b)], reasonably close to the predicted ratio $T_{max}/T_{ref} = 85\%$ discussed above. The background signal in Fig. 2(b) is somewhat larger than in the simulations of Fig. 1(c) due to surface roughness in the Au film, which can be minimized with further optimization of the fabrication process. Finally, Figs. 2(c) and 2(d) show angle-resolved photocurrent data measured with two other devices based on the same GMS architecture but with different angles of peak detection (30° and 60°, respectively), illustrating the geometrical tunability of this design platform.

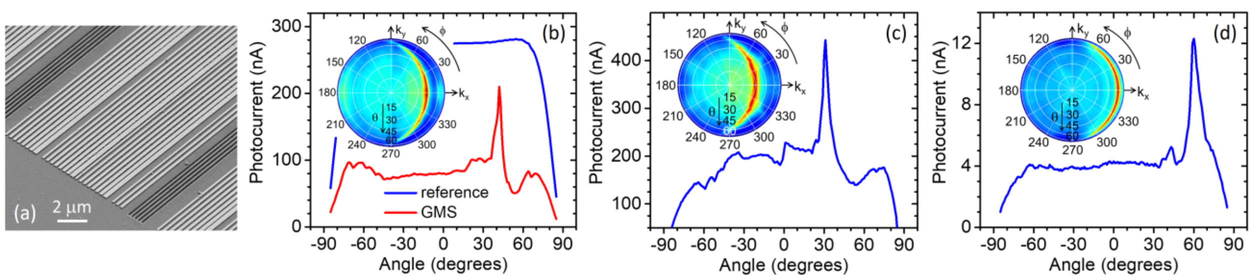

Fig. 2. Characterization results. (a) Scanning electron microscopy (SEM) image of a GMS based on the design of Fig. 1. (b) Photocurrent measured with the same device (red trace) and with an identical photodetector without any metasurface (blue trace) versus polar angle of incidence on the plane perpendicular to the nanostripes. Inset: angular response map of the same device, showing the measured photocurrent as a function of polar θ and azimuthal ϕ illumination angles. (c), (d) Similar data measured with two other devices with angular response map peaked at 30° (c) and 60° (d).

This work demonstrates the ability to tailor the angular response of generic photodetectors through the integration of plasmonic GMSs and offers general guidelines for the design of suitable metasurfaces. The resulting directional image sensors are promising for multiple advanced applications within the growing field of computational imaging. More broadly, these results also highlight a promising new direction of work in flat optics, where gradient metasurfaces are integrated within image sensors to enable unconventional capabilities with enhanced system miniaturization and design flexibility.

This work was supported by NSF under Grant ECCS-2139451.

3. References

[1] S. Jayasuriya, S. Sivaramakrishnan, E. Chuang, D. Guruaribam, A. Wang, and A. Molnar, "Dual light field and polarization imaging using CMOS diffractive image sensors," Opt. Lett. 40, 2433-2436 (2015).

[2] L. C. 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] S. Yi, J. Xiang, M. Zhou, Z. Wu, L. Yang, and Z. Yu, "Angle-based wavefront sensing enabled by the near fields of flat optics," Nat. Commun. 12, 6002 (2021).

[4] P. Genevet, F. Capasso, F. Aieta, M. Khorasaninejad, and R. Devlin, "Recent advances in planar optics: from plasmonic to dielectric metasurfaces," Optica 4, 139-152 (2017).

[5] A. Pors, M. G. Nielsen, T. Bernardin, J.-C. Weeber, and S. I. Bozhevolnyi, "Efficient unidirectional polarization-controlled excitation of surface plasmon polaritons," Light: Sci. Appl. 3, e197 (2014).