

# Metasurface-integrated Polarimetric Sensors in Foundry-Compatible Process

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## Abstract

*Metasurfaces offer optical engineers unprecedented control over the degrees of freedom of light. These single-layer, lithographically defined structures can dictate light's flow, dependent on its incoming polarization, angle, or color. We report on the integration of a functional, polarization-splitting metasurface layer on a near-infrared (NIR) image sensor, demonstrating high-quality snapshot polarimetric imaging for biometric applications, where polarization is used as a discriminating signal for spoof detection.*

## Author Keywords

Polarimetry; metasurfaces; image sensors; biometrics

## 1. Objective and Background

Face-based biometric recognition systems, matching attempted authentication attempts against an enrolled representation of the subject's face, have been deployed on hundreds of millions of mobile devices throughout the world. Despite progress in computer vision-based approaches, rejecting adversarial attacks based on simple color or near-infrared (NIR) images remains intractable to the standards demanded by financial and identity-focused consortia. To prevent such attacks from gaining access to the underlying system, hardware-based mechanisms have been developed to ensure authenticity, typically by checking the attack's three-dimensional shape or material make-up for consistency with the enrollee. To this end, optical markers such as laser coherence [1], hyperspectral information [2], and polarization [3], sometimes coupled with three-dimensional imaging techniques like structured light or time-of-flight, have been deployed within such spoof-proof biometric sensing systems.

Despite their widespread success, integration and deployment of facial biometric authentication systems remains costly and subject to size, weight, and power concerns, which are particularly demanding in consumer electronics.

In recent years, metasurfaces have emerged as a powerful tool to wrest information from the flow of light, with industry reports charting their now-widespread adoption across multiple consumer electronic categories, and their design principles subsumed within optical engineering workflows. Metasurface design is predicated on specifying local regions of dielectric to affect light propagation. In the canonical example, subwavelength unit cells are constructed which, by varying some geometric parameter such as pillar diameter, results in a mapping between design parameters (diameter) and optical function (phase delay through the metasurface). For optical design, a desired phase profile is then translated to a pillar placement. More generally, for optical systems which require some polarization-dependent functionality, the individual unit-cell design can be conceived of in terms of Jones matrix elements, with geometrically asymmetric structures forming their foundation [6, 8]. The design parameters can independently influence how different polarizations (formalized as Stokes parameters) are affected – in transmission, phase delay, and cross-polarization effects – as they pass through

the polarization-sensitive unit cells. This design perspective has led to several reports of metasurface-based polarimetric imaging systems, including full-Stokes polarimetry via a metasurface located near an imager's pupil plane [9], and a snapshot Mueller matrix polarimeter based on additionally modulating the polarization of the illuminating light [10].

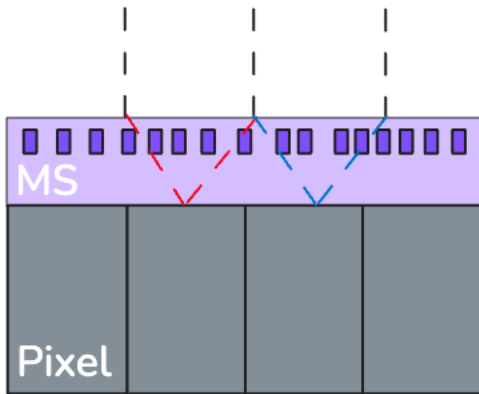
On a system level, metasurfaces have been introduced throughout the optical stack, with demonstrations both on transmission and receive ends of imaging devices. Metasurface-integrated sensors, a recent area of focus, have been shown as promising candidates for red/green/blue color routing (as a potential evolution of standard color filter arrays) [4], hyperspectral imaging, and full-stokes polarimetry [5, 7].

In this report, we discuss the implementation of a mobile-ready polarimetric image sensor by integration of a CMOS-compatible metasurface on a consumer-grade NIR image sensor. In contrast to implementations relying on wire-grid polarizers placed over the pixel [7, 12], by sorting polarization states we are able to maintain high transmission efficiency and compatibility with mobile illumination system requirements.

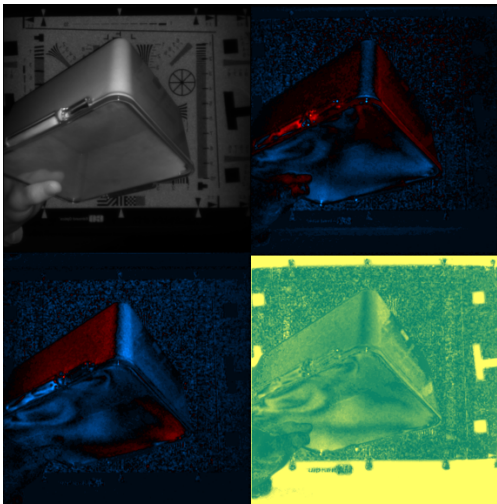
## 2. Results

A polarization-sensitive metasurface was designed based on an amorphous silicon rectangular pillar geometry embedded in a low-index dielectric. The silicon pillar degrees of freedom included width, length, and rotation, while height and pitch were held constant over the entire design. A Samsung S5K931S image sensor, a global-shutter sensor designed for high-efficiency NIR imaging, was integrated with the metasurface. On top of a spacer layer of a few microns, the metasurface layer is placed at a slight stand-off to the surface of the sensor. The metasurface optical functionality is designed to split and focus orthogonal polarizations to different pixels, combining both a birefringent functionality with a collimating aspect. The design is optimized to ensure separation of different polarization states through different pixels, high transmission efficiency, and fidelity with the design intent. The metasurface is arrayed so that light incident on the pixels is tuned to respond to  $0^\circ$  and  $90^\circ$  (horizontal and vertical polarizations) or  $45^\circ$  and  $135^\circ$  (diagonal and anti-diagonal polarizations).

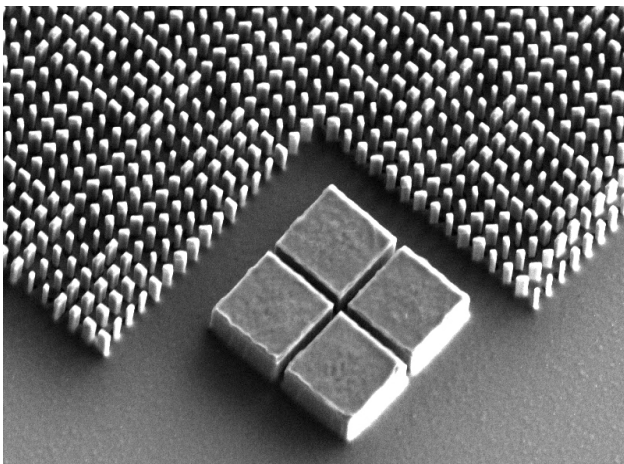
The image sensor shutter is synchronized with a diffuse, flash illumination. After image acquisition, the raw signal is operated on by the image signal processing pipeline. The image is demosaicked from its raw capture, resulting in an image with channels corresponding to three Stokes components (S0: intensity, S1: linear polarization, S2: diagonal polarization), with the latter two being signed quantities.



**Figure 1:** Schematic depiction of metasurface (MS) layer, directing light into pixel. Light is split into one of two orthogonal polarization targets, with like-polarized light being directed to the same pixel. Minimal light is reflected back into the imaging system.



**Figure 2:** Image of plastic box under illumination with system, showing polarization birefringence and details. (Top-left): NIR intensity image (top-right): S1 polarization (bottom-left): S2 polarization, (bottom-right): Degree of linear polarization.



**Figure 3:** Cut-through SEM image of metasurface on image sensor, showing anisotropic pillar detail.



**Figure 4:** Image of subject under illumination, showing polarization birefringence and details. (Top-left): NIR intensity image (top-right): S1 polarization (bottom-left): S2 polarization, (bottom-right): Degree of linear polarization.

### 3. Impact

In this report, we presented on a face-biometric compliant image sensor, capable of power- and space-efficient NIR polarimetry across prescribed operating conditions. Due to its foundry-compliance and use of existing sensor parts, it presents an affordable, small-form factor system for hardware-secure presentation attack detection, broadening the reach of secure payments and access technologies to more demographics.

The development of the integrated metasurface-sensor advanced technical milestones in metasurface design, showing precise control over directing different polarization states of light to small ( $2.2 \mu\text{m}$ ) pixels, maintaining an overall high transmission efficiency, and integrating the final raw sensor outputs with an on-device image processing pipeline for real-time (180 frames per second) imaging. Future efforts point towards improving metasurface performance (for instance, using parametric differentiable design frameworks), further shrinking the module, and demonstrating other wavelengths, target polarizations, or sensor form factors.

### 4. References

1. Chatterjee, A. (2023). Biometric presentation attack detection using speckle metrology. In 2053-2563. Biometric Presentation Attack Detection (pp. 4-1 to 4-22). doi:10.1088/978-0-7503-5202-4ch4
2. Cong, P. H., & Antonio, R. K. (2010). Hyperspectral imaging for skin recognition and biometrics. Proceedings - International Conference on Image Processing, ICIP, (September 2010), 2325-2328. <https://doi.org/10.1109/ICIP.2010.5654042>
3. Rudd, E. M., Gunther, M., & Boulton, T. E. (2016). PARAPH: Presentation Attack Rejection by Analyzing Polarization Hypotheses. IEEE Computer Society Conference on Computer Vision and Pattern Recognition Workshops, 171-178.

- <https://doi.org/10.1109/CVPRW.2016.28>
4. Q. Chen, X. Nan, M. Chen, D. Pan, X. Yang, L. Wen, Nanophotonic Color Routing. *Adv. Mater.* 2021, 33, 2103815. <https://doi.org/10.1002/adma.202103815>
  5. Roberts, G., Ballew, C., Zheng, T., Garcia, J. C., Camayd-Muñoz, S., Hon, P. W. C., & Faraon, A. (2022). 3D-Patterned Inverse-Designed Mid-Infrared Metaoptics. Retrieved from <http://arxiv.org/abs/2209.07553>
  6. Rubin, N., Shi, Z., & Capasso, F. (2021). Polarization in diffractive optics and metasurfaces. *Advances in Optics and Photonics*, 13(4), 836–970. <https://doi.org/10.1364/aop.439986>
  7. Zuo, J., Bai, J., Choi, S., Basiri, A., Chen, X., Wang, C., & Yao, Y. (2023). Chip-integrated metasurface full-Stokes polarimetric imaging sensor. *Light: Science and Applications*, 12(1). <https://doi.org/10.1038/s41377-023-01260-w>
  8. Rubin, N. A., Zaidi, A., Dorrah, A., Shi, Z., & Capasso, F. (2020). Jones matrix holography with metasurfaces. 1–10. Retrieved from <http://arxiv.org/abs/2012.14874>
  9. Rubin, N. A., D'Aversa, G., Chevalier, P., Shi, Z., Chen, W. T., & Capasso, F. (2019). Matrix Fourier optics enables a compact full-Stokes polarization camera. *Science*, 364(6448). <https://doi.org/10.1126/science.aax1839>
  10. Zaidi, A., Rubin, N. A., Meretska, M. L., Li, L. W., Dorrah, A. H., Park, J. S., & Capasso, F. (2024). Metasurface-enabled single-shot and complete Mueller matrix imaging. *Nature Photonics*, 18(7), 704–712. <https://doi.org/10.1038/s41566-024-01426-x>
  11. Android Open Source Project. (2024). Android 15 Compatibility Definition: Biometric sensors. [https://source.android.com/docs/compatibility/15/android-15-cdd#7310\\_biometric\\_sensors](https://source.android.com/docs/compatibility/15/android-15-cdd#7310_biometric_sensors)
  12. Sony. (2024). Polarization Image Sensor Technology Polarsens. <https://www.sony-semicon.com/en/technology/industry/polarsens.html>