Metasurface-Enabled Mueller Matrix Imaging with SPAD Sensors

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Polarization imaging provides rich information about the physical properties of objects, including material composition, surface morphology, and scattering characteristics. Among various polarization characterization methods, Mueller matrix imaging offers a comprehensive framework for describing the polarization response of a sample. However, conventional Mueller matrix imaging systems typically rely on bulky optical components and sequential polarization modulation, which limits their compactness and integration capability.

In this work, we propose a metasurface-enabled Mueller matrix imaging approach integrated with single-photon avalanche diode (SPAD) sensors. As shown in Fig.1, the TiO_2 metasurfaces are designed to perform specific polarization transformations and can be described by 4×4 Mueller matrices. Through careful electromagnetic design and nanofabrication, a set of metasurfaces with distinct polarization responses is realized. Each metasurface acts as a compact polarization element, enabling efficient manipulation of the incident polarization states.

By exploiting the rotational properties of Mueller matrices, additional polarization transformations can be generated by physically rotating the metasurfaces with following equations. The rotation of the metasurface corresponds to a transformation of the Mueller matrix. For a rotation angle θ, where $R(\theta)$ is the Mueller rotation matrix.

$$R(\theta) = \begin{vmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\theta) & \sin(2\theta) & 0 \\ 0 & -\sin(2\theta) & \cos(2\theta) & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \quad (1)$$

$$M(\theta) = R(-\theta) M R(\theta) \quad (2)$$

Based on this principle, six fundamental Mueller matrices are implemented using different metasurface configurations. Multiple rotated measurements are then performed to reconstruct the complete Mueller matrix of a target scene on a pixel-by-pixel basis. As illustrated in Fig. 2, a 532 nm laser source is first passed through a diffuser to generate a spatially uniform illumination, which is then incident on the target sample. The light scattered or reflected from the target carries polarization information related to the intrinsic optical properties of the material.Combined with the high sensitivity and temporal resolution of SPAD sensors, the proposed system enables efficient Mueller matrix imaging with a compact and potentially chip-scale architecture.

The reconstructed Mueller matrix images provide detailed polarization information that can reveal intrinsic optical properties of materials. Such capabilities open new opportunities for applications including material characterization, biomedical imaging, remote sensing, and polarization-based object recognition. Looking forward, metasurface-based Mueller matrix imaging systems have the potential to enable highly integrated, lightweight, and high-speed polarization imaging platforms, paving the way for next-generation polarization-sensitive sensing technologies.

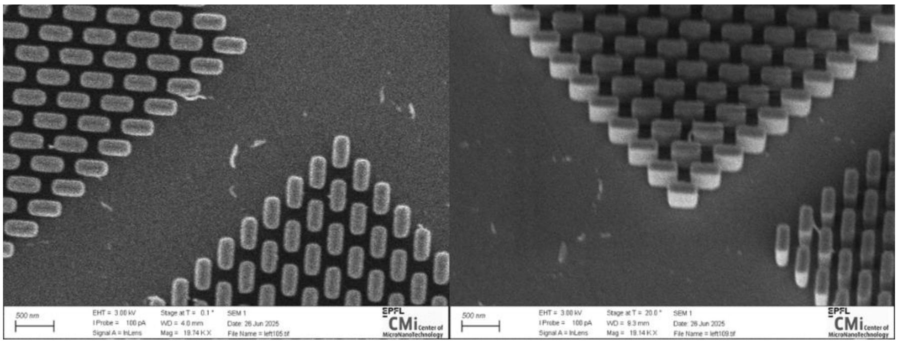

Fig. 1: *SEM image of TiO_2 nano-pillars*

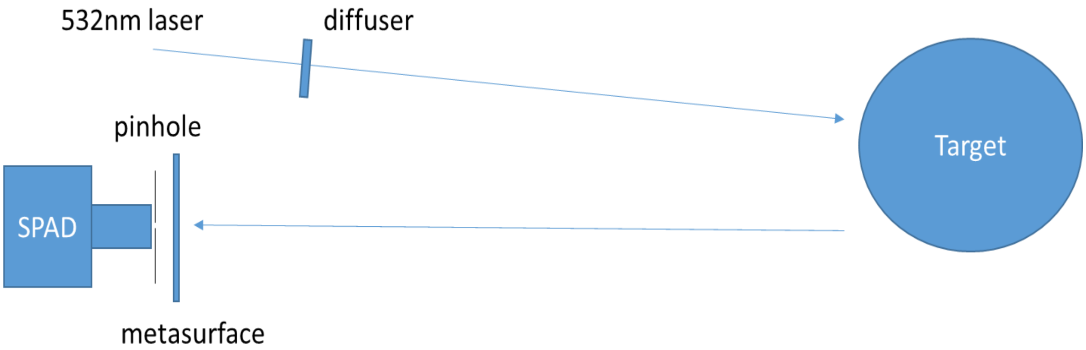

Fig. 2: *Experiment setup*

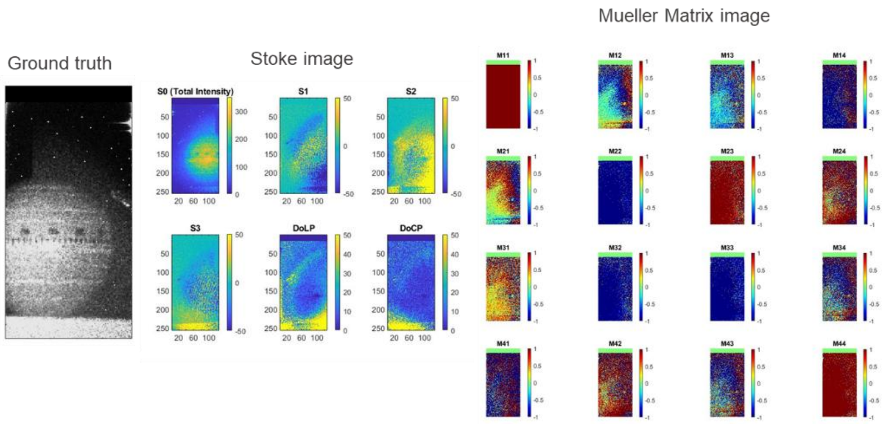

Fig. 3: *Stoke and Muller Matrix image with SPAD*