Optimal Single Metagrating for Robust Polarization Measurements

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Abstract: We formulate a new conceptual approach for full Stokes polarization measurement with a single metagrating, and develop novel design through advanced computational optimization of individual nano-resonator properties delivering robust operation even under strong fabrication inaccuracies.

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The implementation of one-shot optical polarimetry using ultra-thin nanostructured metagratings opens up new opportunities for diverse applications associated with the polarization of light [1], facilitating the measurement of both classical [2] and quantum [3] polarization states. A key working principle in these schemes lies in the splitting of specific polarization components between different spots. The detection of optical powers in multiple spots then effectively realizes several measurements in parallel, which would traditionally require reorientation of bulk optical components. Despite the significant progress, there appeared fundamental limitations associated with a need to interleave multiple metagratings on a metasurface in order to split several distinct pairs of polarization components, which limited diffraction efficiency and negatively affected the beam quality [2, 3]. A recent study demonstrated polarimetry with a single metagrating [4], however it required an additional linear polarizer with the associated detrimental effects of attenuating the detected optical power, reducing the device compactness, and increasing the setup complexity.

We formulate, for the first time of our knowledge, a new conceptual approach for polarization measurements with a single metagrating, which allows us to overcome the limitations that were inherent to the previous schemes [2–4]. We find that those limitations occurred due to the attempts of replicating traditional polarimetry based on close-to-perfect polarizers, where each measurement characterizes a definite polarization component. Yet in general, metasurfaces can behave like sets of imperfect (partial) polarizers, and it is our key finding that full Stokes polarization reconstruction is possible in this regime. Specifically, we develop a rigorous polarimetry approach based on the positive operator-

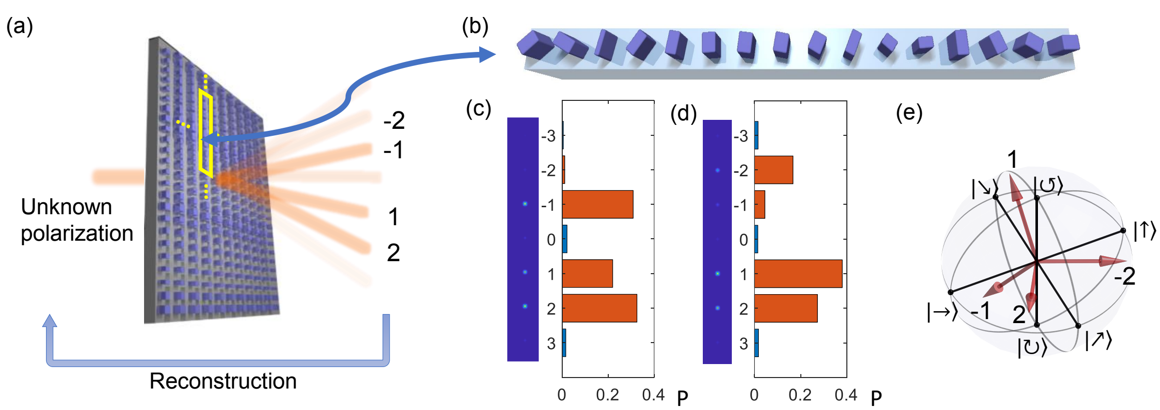

Fig. 1. (a) Conceptual sketch of our single-metagrating polarimetry. (b) One period of the metagrating with optimized nano-resonator dimensions and orientations. (c,d) Examples of far-field images and relative powers at different diffraction orders for input states with (c) horizontal and (d) right-hand-circular polarization, where red color highlights four diffraction orders sufficient for full polarization reconstruction. (e) The polarization analysis states associated with imaging spots of $\pm 1\&2$ diffraction orders indicated with arrows on the Poincaré sphere.

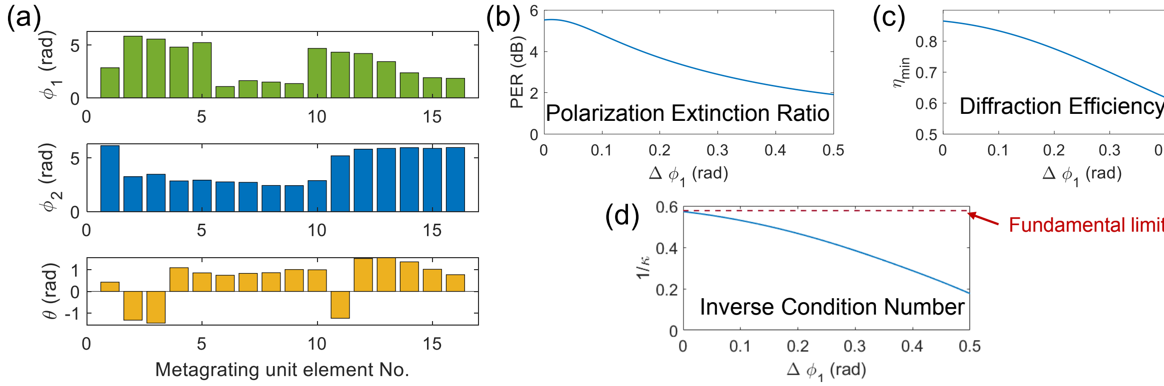

Fig. 2. (a) Optimal metagrating design: phase retardance ϕ_1 and ϕ_2 along two axes of each nanoresonator, and the orientation angle θ. (b,c,d) Influence of an error $\Delta\phi_1$ added to ϕ_1 on (b) the polarization extinction ratio (PER), (c) efficiency of diffraction to the four selected spots, and (d) inverse of the condition number (κ^{-1}), where the dashed line in shows the best possible maximum value.

valued measure (POVM) formalism originating from quantum mechanics. This fundamentally lifts the restrictions on metasurface design and enables robust operation even under significant fabrication inaccuracies.

The operating principle is based on the splitting of light with a metasurface between several diffraction orders [Fig. 1(a)]. The metasurface is composed of a periodically repeated metagrating, a single period of which is highlighted by the yellow frame and sketched in Fig. 1(b). We perform advanced multi-stage optimization of metagrating parameters targeting the most robust polarization reconstruction from the polarization-insensitive detection of powers in several diffraction orders. The robustness is rigorously defined in the framework of POVM formalism as an inverse condition number (κ^{-1}) of the instrument matrix, expressed through the parameters of individual nano-resonators forming a metagrating. We obtain a novel design of all-dielectric metagrating [Fig. 1(b)] enabling reconstruction with the minimum number of four power detectors at the $\pm1\&2$ diffraction orders. In Figs. 1(c,d), we show the simulated far-field images and powers in the diffraction orders for different polarization inputs. The set of four bases for polarization analysis spread out evenly in the Poincaré sphere [Fig. 1(e)], approaching the optimal frame that provides a minimum amplification of error in reconstruction. Additionally, the fraction of power diffracted to the four spots highlighted in red color, is no less than $\eta_{min} = 86\%$, which ensures high signal-to-noise ratio in measurements.

The designed metagrating can be realized on all-dielectric platforms for highest transmission efficiency with the established fabrication techniques [3]. An important advantage of our approach based on POVM formalism is that it can facilitate accurate polarization reconstruction even in presence of significant fabrication errors, by only performing a single post-fabrication device calibration. We show the optimal designed metagrating parameters in Fig. 2(a): the phase retardances (ϕ_1 and ϕ_2) along the two axes of each nano-resonator and their angles of rotation (θ). We note that the design is highly nontrivial, yet it is highly robust through the targeted computational optimization. We illustrate the effect of possible fabrication imperfection in Figs. 2(b-d) by considering an offset $\Delta\phi_1$ for all ϕ_1. We find that for larger errors $\Delta\phi_1$, the average polarization extinction ratio drops from over 5dB (when metasurface acts as a set of reasonably good polarizers) to around 2dB (metasurface implements quite poor polarizers) [Fig. 2(b)]. Nevertheless, the minimum diffraction efficiency to the four selected spots remains quite high (over 55%) [Fig. 2(c)] and the inverse condition number of a calibrated metasurface remains within 30% of the fundamental limit indicated with the dashed line [Fig. 2(d)]. This corresponds to a moderate increase of reconstruction error by a factor of 3, even under extreme structural deviations that are much worse then the standard fabrication accuracy.

To summarize, we provide the first example of single metagrating optimized to perform robust polarimetry without any ancillary polarization optics, which is enabled by our generalized reconstruction approach using POVM formalism. We anticipate that our new concept will facilitate diverse applications and lead to the development of optimal polarization state imaging tailored for computer vision and quantum state characterization.

References

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