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Inverse Design of Multilayer Broadband "RGBP" Freeform Metalens for Dual-Functional Color-sorting and Polarization Imaging

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1. Introduction

Traditional camera systems rely on Bayer color filters and polarizing filters for image reconstruction, limiting energy utilization efficiency and sensitivity. To overcome these constraints, metalens-integrated camera sensor systems incorporate sub-wavelength structures that reshape wavefronts, enabling enhanced image quality in low-light conditions [1,2]. We present an inverse-designed multilayer freeform dual-functional metalens using FDTD and adjoint optimization for full-color imaging and polarization sorting, achieving 60% average color sorting efficiency and 51% polarization sorting efficiency, outperforming the existing single layer color sorting metalenses while simultaneously demonstrating effective polarization sorting capabilities.

2. Inverse Design

Freeform multilayer metalens inverse design is accomplished through topology optimization, utilizing adjoint-based methods within MEEP simulator [5]. Each metalens unit cell measures 3.2 μm by 3.2 μm, featuring a 0.5 μm thick SiO_2 substrate and SN nanopillars with height of 0.7 μm. Optimization is achieved through an iterative loop that integrates the NLopt algorithm with the FDTD solver. Periodic boundary conditions were applied along the metalens plane, with perfectly matched layer (PML) boundaries in the propagation direction, and the simulation covered the visible range. As shown in Fig. 1a. and Fig. 1c., the initial design phase began by defining four distinct target phase profiles, each centered in a quadrant of the unit cell to match an RGGB Bayer arrangement.

A library was used to map subwavelength nanopillar dimensions to corresponding phase shifts. The first layer's initial design consist of nanopillar dimensions that minimize phase error across all four target profiles, while the second layer started with dummy nanopillars. Fig. 1d. shows the initial configuration, optimizing the phase distribution and providing a solid starting point for optimization. In Fig. 1b., forward simulation evaluates focal plane intensity and checks for convergence. Adjoint optimization then computes gradients to update design parameters. Target focal plane intensity is achieved through iterative forward simulation and gradient-based optimization. Full-color imaging was demonstrated with a virtual metalens-integrated camera sensor system. Fig. 1e. shows the experimental setup with an imaging lens positioned three focal distances from the scene and the metalens array placed 75 mm from the imaging lens. The image sensor pairs with the metalens array, a 2D periodic Bayer cell with optimized design weights at a focal distance of $f = 4\mu m$. After 360 optimization iterations, the final Bayer cell with optimized freeform nanopillars in both layers is shown in Fig. 1f.

We evaluated performance by virtually measuring the focal plane intensity of a single pixel under collimated white beam illumination. Fig. 1g. shows the pixel's focal plane intensity distributions under horizontally polarized light (top), vertically polarized light (middle), and unpolarized white light (bottom). The color sorting performance of the proposed and baseline metalenses was evaluated by color sorting efficiency, the ratio of power collected in each color quadrant to the total incident power on the unit cell for a given wavelength. Table 1 summarizes a comparison of these efficiencies. The color sorting efficiencies at 635 nm (red), 520 nm (green), and 430 nm (blue) are 55%, 72%, and 52%, respectively, significantly outperforming baseline approaches [1,2]. Polarization sorting efficiency is defined as the ratio of correctly sorted polarized light power to the total incident power on the unit cell for a given wavelength. The average polarization sorting efficiency of the proposed metalens is 51%, which is comparable to that of the leading polarization imaging metalenses [3,4]. We evaluated imaging performance across the visible spectrum by using sample scenes and measuring each pixel's Bayer spectral response with our metalens

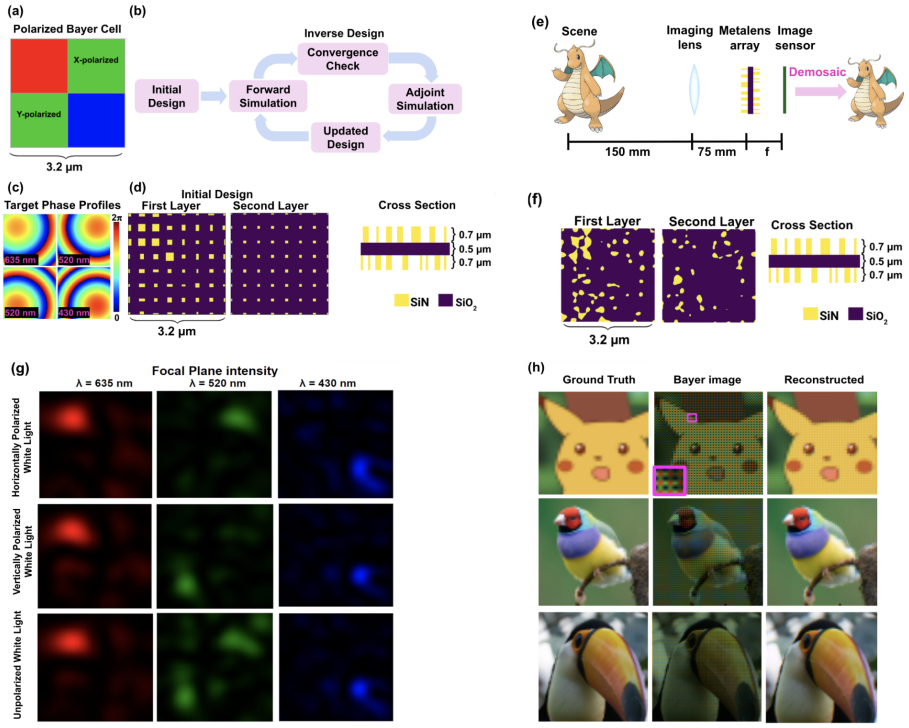

Fig. 1. (a) Target Bayer cell: incident light is sorted and focused into four color-specifFinite-difference time-domainic pixels, with the two green pixels focusing horizontally and vertically polarized light. (b) Inverse design flowchart. (c) Target phase profiles for red, green, and blue. (d) Initial design and its cross-section view. (e) Color imaging experimental Setup. (f) Optimized Bayer cell structure. (g) Focal plane intensity at 635 nm, 520 nm, and 430 nm for a pixel illuminated by horizontally polarized, vertically polarized, and unpolarized white light. (h) Full-color imaging: the left column shows ground truth images, the middle shows RGGB Bayer images by spectral response, and the right shows reconstructed images.

array. The image sensor then captured a raw grayscale mosaic, with each pixel corresponding to a single Bayer cell. To reconstruct three-channel color image from the grayscale RGGB Bayer image, standard demosaicing interpolation is applied. Fig. 1h. shows the ground truth images, RGGB Bayer images, and reconstructed images, demonstrating the high-fidelity color reconstruction of our proposed metalens array.

Table 1. Comparison with Baseline Methods

	Red	Green	Blue	Average Color Sorting Efficiency	Average Polarization Sorting Efficiency	Numerical Aperture
Zou et al [1]	58%	59%	49%	55%	N/A	0.19
Miyata et al [2]	65%	50%	25%	47%	N/A	0.2
Proposed	**55%**	**72%**	**52%**	**60%**	**51%**	**0.4**

In summary, we demonstrated a visible-range multilayer freeform metalens for full-color imaging and polarization sorting, with the freeform structure and second layer provide additional degrees of freedom for optimization. Our simulation results validated the optimized design, showing superior color sorting efficiency over baseline methods and effective polarization sorting comparable to leading metalenses.

References

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