Inverse Design of Manufacturable Optical Metasurface for Full-color Reflective Displays

Sushmit Hossain, Zerui Liu, Nishat Tasnim Hiramony, Ting-hao Hsu, Hongming Zhang, Jiacheng Ye, Himaddri Roy and Wei Wu†
Ming Hsieh Department of Electrical and Computer Engineering, University of Southern California, Los Angeles, California 90089, United States
†*wu.w@usc.edu*

Reflective display technologies present a sustainable alternative to emissive displays, offering benefits such as energy efficiency, bistability, and improved readability in bright conditions. However, achieving full-color functionality in reflective displays is challenging, as traditional approaches rely on color filter arrays, limiting optical efficiency to about 33%. These constraints hinder the complete utilization of the ambient light in these displays. Recently, color router-based approaches have gained popularity to solve similar issues in color filter-based image sensors [1]. In this work, we propose a novel manufacturable metasurface-based reflective display technology by employing inverse design methods with a color router-based approach (Fig. 1). This approach enhances light utilization, breaking the 33% efficiency barrier. Combining metasurface-based color routing with the reflectance of e-ink, this technology offers a pathway to high-performance reflective displays, rivaling emissive counterparts in brightness, color saturation, and efficiency. Furthermore, by optimizing the height effectively, this approach improved the manufacturability of the metasurface, addressing a common challenge faced by most freeform metasurfaces.

We use adjoint method-based topology optimization to inverse design our metasurface. Fig. 2a depicts our design region and the source and monitor positions for the framework. The background is used as air, and the metasurface material is SiO_2. Here, the design region width and height are set to be $9\mu m$ and $6\mu m$, respectively, with a resolution of 20 points per micron, resulting in 10800 design degrees of freedom. The optical efficiency of each color is defined as the amount of light entering a specific monitor when a source is a broadband source. Using the optical efficiency as our Figure of Merit (FOM) for our topology optimization, our framework has converged to the freeform structure shown in Fig. 2b. Although the freeform structures offer higher optical efficiencies, these are challenging to fabricate because they require numerous layers to achieve the desired design accuracy. To make our design manufacturable, we employ additional constraints into the system that can be illustrated as height optimization of the metasurface (Fig. 2c). As shown in Fig. 2d, this inverse-designed metasurface can be readily manufactured using techniques like 3D Nanoimprint lithography in any fabrication facility.

Fig. 3 shows the performance of our freeform design. As shown in Fig. 3a, our design shows an average optical efficiency of 85%, whereas the traditional color-filter-based approach has a theoretical limit of 33% optical efficiency. Fig. 3b shows the spatial distribution of energy when the metasurface is lit with three different wavelengths. It is evident from the results that the metasurface provides a superior level of color separation. More results from the height-optimized structure will be presented at the conference.

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[1] Zou, Xiujuan, et al. "Pixel-level Bayer-type colour router based on metasurfaces." *Nature Communications* 13.1 (2022): 3288.

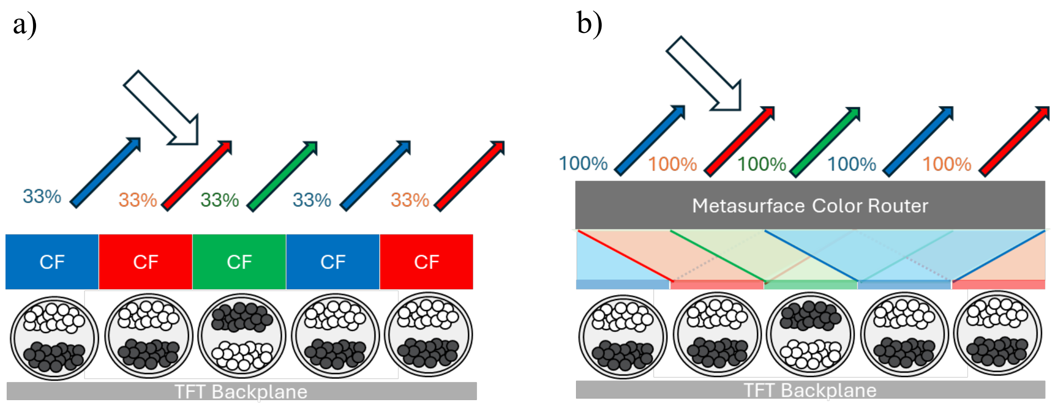

Figure 1: **a)** Conventional color filter (CF) based approach in full-color reflective displays **b)** Proposed color router-based approach to increase theoretical optical efficiency.

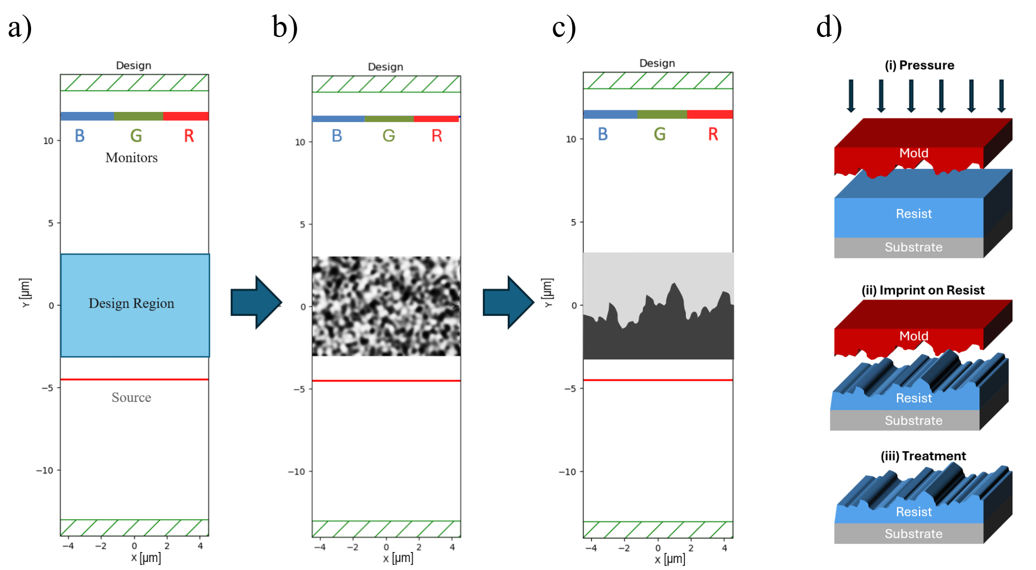

Figure 2: **a)** The simulation setup shows the source, design region, and monitors. **b)** Optimized freeform design for color routing. **c)** Fabrication-constrained design. **d)** Nanoimprint lithography.

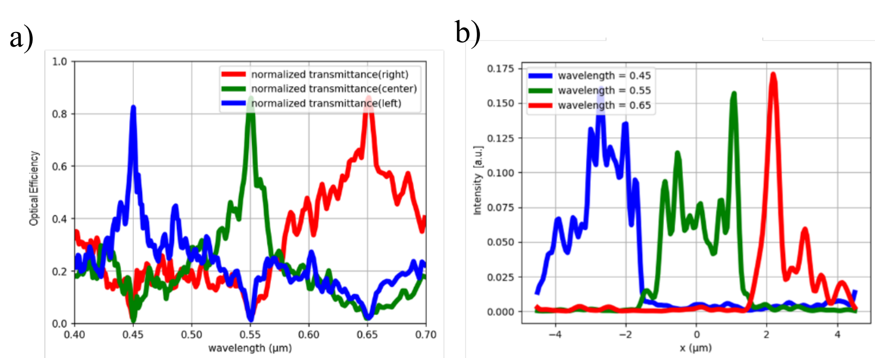

Figure 3: **a)** Optical efficiency of the freeform structure showing 85% average optical efficiency. **b)** Intensity distribution along spatial coordinate.