Closed-loop Simulation, Image processing and Data Preparation for Large Scale Structural Color Printing by EBL

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Structural coloration offers vibrant, non-fading coloration by manipulating light using sub-wavelength structures, offering a promising alternative to pigmentary coloration in some applications [1-3]. Precision and scalability of patterning and color printing are essential to realizing its promise [3]. In this context, we introduce a closed-loop design method incorporating simulation, image processing and data preparation to facilitate the printing of large scale, arbitrary color images with structural colors in various metasurface nanostructures, using metal-insulator-metal (MIM) configurations as a primary example.

Our approach employs a finite-difference time-domain (FDTD) simulation process using ANSYS Lumerical to generate visible spectra from various MIM structures. Through a MATLAB script, the spectra are converted into an RGB color map, showing their visual appearance. This translation creates a detailed color reference for selecting appropriate MIM structures for specific colors in large-scale printing. Following this, the chosen structures are applied to an arbitrary color image through a sequence of image processing and data preparation steps using Python scripting. First, the image is segmented with a manageable number of colors using the k-means clustering algorithm, and then a series of processes are applied with GenISys Beamer to impose the previously simulated structures on the defined areas. The output of this workflow, a prepared data file, can be readily executed in EBL, coupled with several nanofabrication steps, to print the final color patterns. The successful fabrication of centimeter-scale color patterns with MIM metasurfaces demonstrates the capability of the proposed strategy in producing a broad range of structural colors across the visible spectrum and printing any color image on a relatively large scale in a fully programmatic and closed-loop process.

[1] Maowen Song, Di Wang, Samuel Peana, et al. Colors with plasmonic nanostructures: A full-spectrum review. Appl. Phys. Rev. 6, 041308 (2019); https://doi.org/10.1063/1.5110051
[2] Masashi Miyata, Hideaki Hatada, and Junichi Takahara. Full-Color Subwavelength Printing with Gap-Plasmonic Optical Antennas. Nano Lett., 16, 5, 3166–3172 (2016); https://doi.org/10.1021/acs.nanolett.6b00500
[3] Gang Li, Meiying Leng, Shancheng Wang, Yujie Ke, Wei Luo, Huiru Ma, Jianguo Guan, Yi Long. Printable structural colors and their emerging applications. Materials Today, 69, 133-159 (2023); https://doi.org/10.1016/j.mattod.2023.08.022

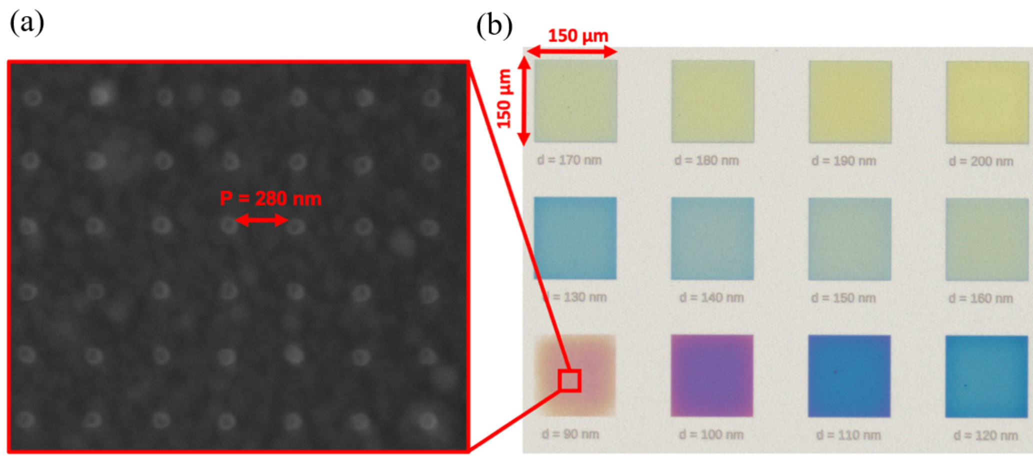

Figure 1: (a) SEM image of the 90 nm nanodot array; (b) Fabricated Al-Al2O3-Al metasurfaces in three-by-four square nanodot arrays for color calibration, each array featuring a distinct nanodot diameter ranging from 90 nm to 200 nm with a fixed periodicity of 280 nm.

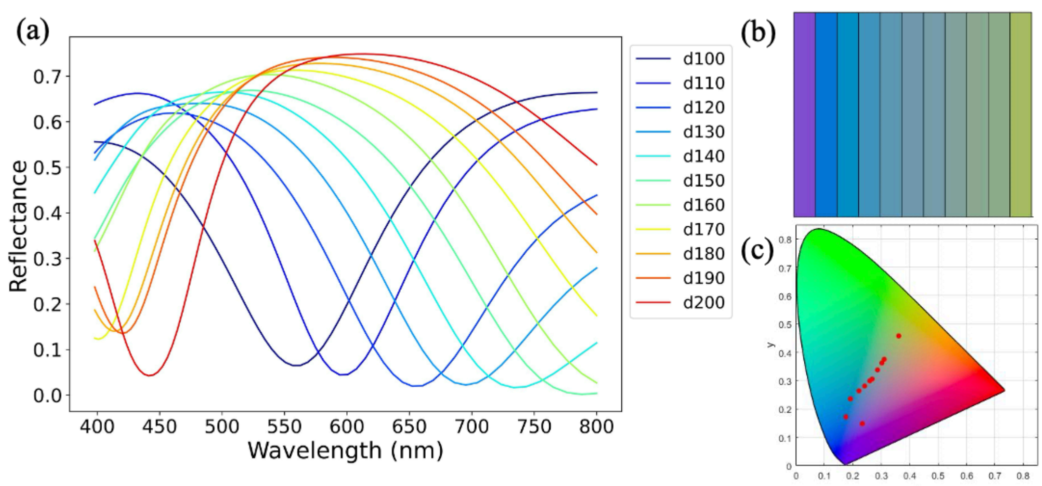

Figure 2: (a) Ansys Lumerical simulated spectra of Al-Al2O3-Al metasurfaces with nanodot diameter ranging from 90 nm to 200 nm with a fixed periodicity of 280 nm; (b) RGB colors translated from the simulated spectra; (c) Chromaticity diagram of the simulated colors.