Fabrication of FDTD-based inverse design enables f/0.27 flat microlens array for integral imaging

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Integral imaging relies on microlens arrays to capture and reconstruct full light-field information, enabling the creation of 3D images. Traditionally, refractive microlens arrays (MLAs) were used for such purposes, but they suffered from issues like chromatic aberration and low focusing resolution[1]. Our diffractive MLA addresses these challenges by reducing thickness and enabling ultra-low f-number imaging. This is crucial for security features, such as those on banknotes, where complexity, number of colors, and image quality contribute to enhanced security[2].

Our MLA, designed via inverse design using the finite-difference-time-domain (FDTD) model, consists of microlenses with a diameter of 70 µm and a short focal length of 19 µm in air, and is capable of focusing incident light at three design wavelengths (480nm, 550nm, and 650nm) into a focal spot with a measured full-width at half-maximum (FWHM) of less than 1 µm.

The fabrication process involves patterning the MLA on one surface of a polymer film through UV casting. The film has a thickness of 28 µm, with an effective f-number (NA) inside the polymer of approximately 0.4 (0.78). The microlenses are close-packed with a diameter of 70 µm, and the focal plane is situated on the distal end of the film. The use of UV casting not only facilitates low-cost manufacturing but also results in a reduction in thickness by over three times compared to refractive MLAs, providing an advantage for manufacturability.

In the fabrication process, we first created a 200×200 micro-MDL array master through grayscale lithography on a glass substrate. This master was then replicated onto a ~28 µm-thick polymer film using WaveFront Technology Inc.'s UV cast & cure process, constituting a high-volume manufacturing technique. The resulting flexible MLA on the polymer film can be readily integrated with high-resolution prints, showcasing its practical application in integral imaging. The replicated film and its fabrication accuracy are shown in Fig. 1.

The MLA, characterized with a FWHM under 1 µm, integrates seamlessly with high-res prints, showcasing RGB integral imaging for document security, as shown in Fig. 2. Our research introduces a cost-effective, high-volume process, combining ultra-low f-number and high-NA in diffractive optics, paving the way for advanced document security features.

1. S. Li, Q.-H. Wang, Y.-P. Xia, Y. Xing, H. Ren, H. Deng, "Integral imaging 3D display system with improved depth of field using a colloidal scattering layer," Optics Communications, vol. 484 (2021).
2. https://www.uscurrency.gov/denominations/100

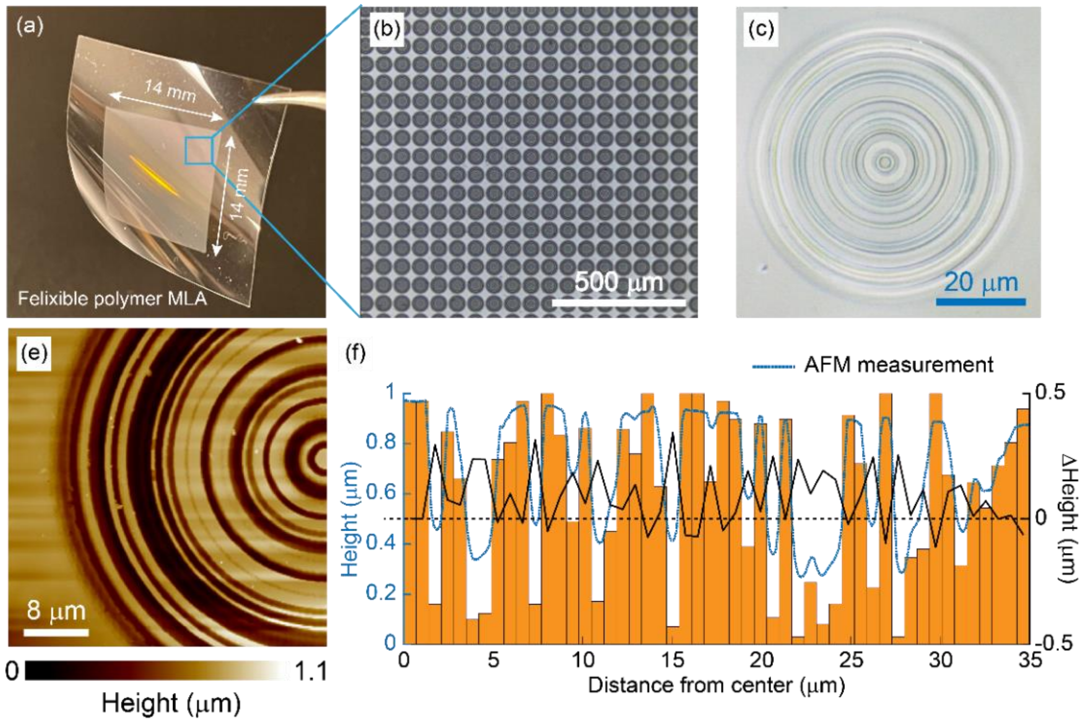

Fig. 1. Replicated MLA. (a) Photograph of the MLA film. (b-c) Optical micrographs. (d) Atomic force micrograph (AFM) of one of the micro-MDLs in the array. (e) Measured ring-heights (blue) compared to corresponding design values (orange bars). Black curve denotes the error in ring heights.

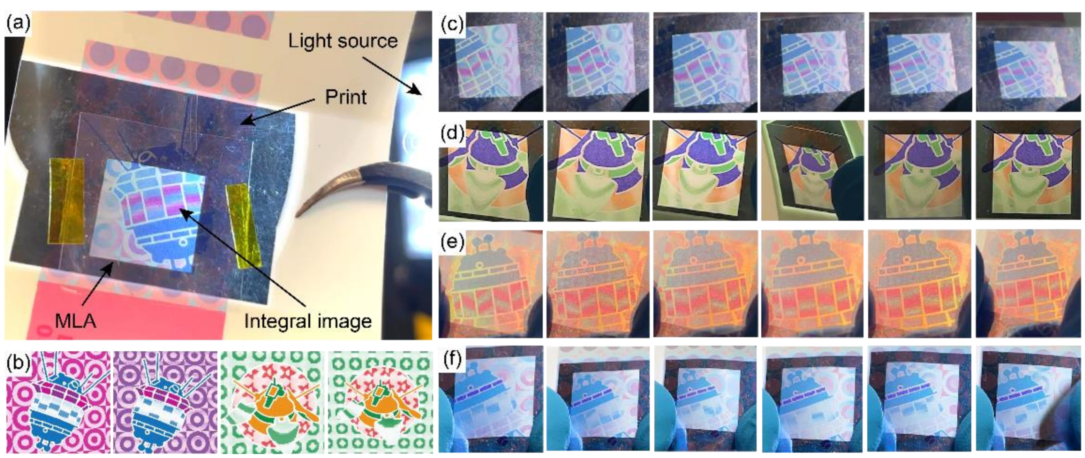

Fig. 2. Summary of integral imaging. (a) Photograph of the MLA on offset print held together using Kapton tape, exhibiting integral imaging. (b) Simulated images at 2 viewing angles from 2 exemplary prints. (c-e) Images at different viewing angles for two exemplary prints (also see Visualizations 2 and 3). The illuminations used were (c) an LED flashlight, (d) fluorescent ceiling lights and (e) ambient sunlight, captured outside around 5 pm, on November 08, 2023 at Salt Lake City, Utah, USA.