Single-exposure Volumetric Photolithography Producing Ultra-high Aspect Ratio Microstructures

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Abstract:

We demonstrate a single-exposure volumetric photolithography strategy that reconstructs an inverse-designed 3D UV intensity distribution in SU-8, enabling high-aspect-ratio structures with a theoretical 4 µm resolution. With ~20 s exposure, it achieves aspect ratios >120:1 and throughputs up to 83 mm^3 h^{-1} (≈0.36×10^6 voxels s^{-1}), outperforming existing volumetric additive manufacturing methods.

Results:

Three-dimensional (3D) micro/nanofabrication [1] is critical for applications such as micro-optics, Metasurfaces, MEMS, and photonic crystals, where high-aspect-ratio, sub-10-µm features and large volumes demand both high resolution and fast throughput [2]. Conventional 2D or serial techniques, including two-photon polymerization and layer-building projection, are either slow or limited in scalability, while volumetric additive manufacturing improves speed but sacrifices resolution.

Here, we introduce a single-exposure volumetric photolithography approach based on inverse-designed computer-generated holography (CGH) that reconstructs a prescribed 3D UV intensity distribution in SU-8 (XFT-100, Kayaku), achieving ~4 µm lateral resolution and fabricating high-aspect-ratio architectures within ~20 s. The printed hexagonal-cell lattice (Fig. 1) has overall dimensions of 800 × 800 × 720 μm^3 (width × length × height) and a ring thickness of ~6 µm, yielding aspect ratios >100:1 with smooth, well-defined sidewalls.

Exposures were performed using a custom-built single-exposure lithography system based on a 405 nm diode laser, which was spatially filtered, collimated, and directed through a hologram mask to reconstruct the target 3D intensity distribution in SU-8 photoresist. Precise alignment and monitoring were achieved using multi-axis translation stages and a CMOS camera with a 1:1 relay imaging system for conjugate-plane observation. Representative structures, including hexagonal- and square-cell lattices and Penrose tilings (800 × 800 × 720 μm^3), were fabricated with 20 s exposure, as shown in Fig. 2c–f. The measured wall thickness is ~6 µm and the total height matches the target depth, with slight top-surface shrinkage attributed to thermal effects during post-exposure baking.

Future implementations can integrate higher-power lasers to shorten exposure time, larger holographic phase masks (up to 20×20 cm^2), and thicker SU-8 layers via multi-spin coating or drop casting to enable deeper structures. Together, these improvements could increase printing rates to 10^8–10^9 voxels s^{-1}.

References:

[1] Somers, Paul, et al. "The physics of 3D printing with light." Nat. Rev. Phys. 6.2 (2024): 99-113.

[2] Hahn, Vincent, et al. "Rapid assembly of small materials building blocks (voxels) into large functional 3D metamaterials." Adv. Funct. Mater. 30.26 (2020): 1907795.

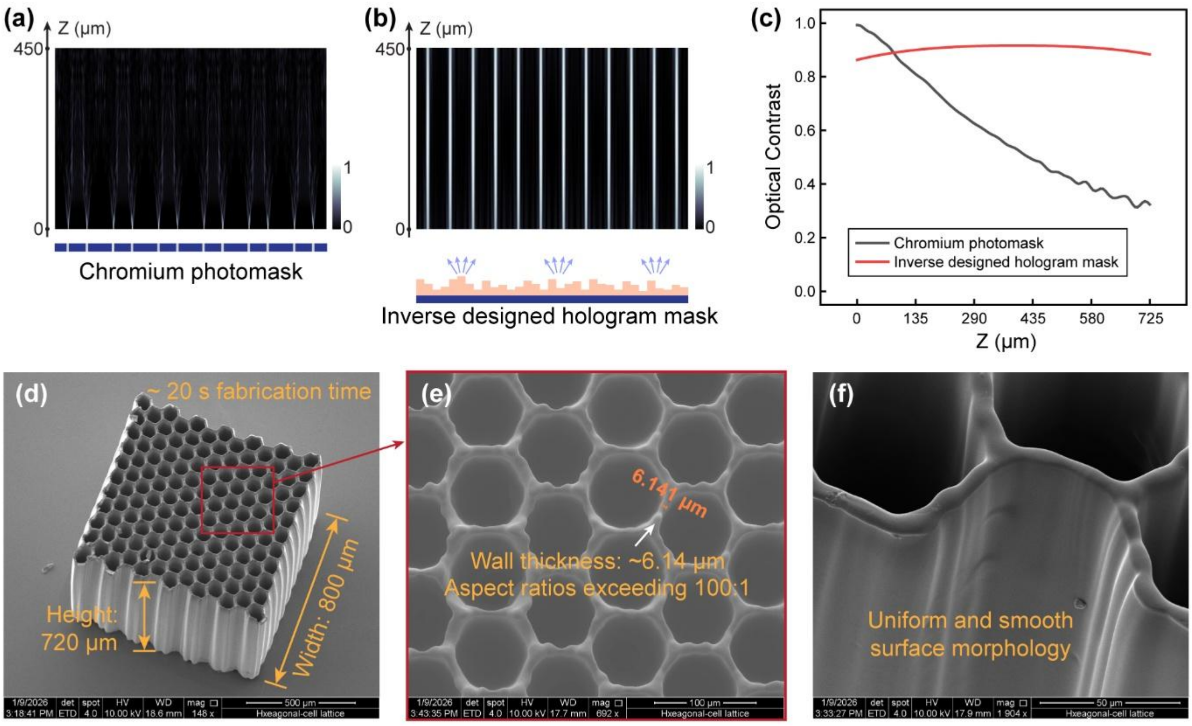

Fig. 1 Single-exposure fabrication of high-aspect-ratio 3D structures. (a) Conventional photomasks exhibit reduced intensity contrast when patterning ultra-thick structures. (b) The inverse-designed hologram mask generates a diffraction-free 3D light field, enabling single-exposure volumetric fabrication. (c) Comparison of achievable optical contrast as a function of propagation depth. (d) Fabricated hexagonal-cell lattice after a 20-s exposure, with overall dimensions of 800 × 800 × 720 μm³ (width × length × height), imaged by SEM. (e) The hexagonal-cell lattice exhibits a wall thickness of ~6.14 μm, corresponding to aspect ratios exceeding 100:1. (f) The single-exposure fabricated hexagonal-cell lattice shows excellent uniformity and smooth surface morphology.

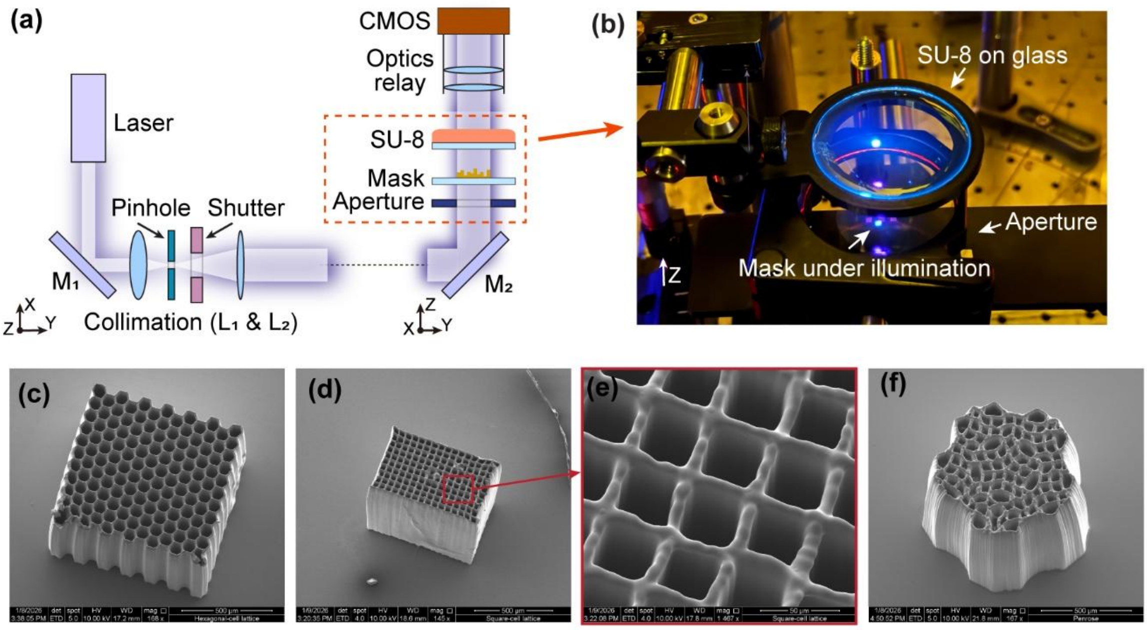

Fig. 2 Experimental exposure of micro-structures. (a) Illustration of Lab-built single-exposure volumetric photolithography setup. (c-f) Printed structure of hexagonal-cell lattice, square-cell lattice, and Penrose tiling structure.