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Digital Holography-Enabled Parallel 3D Lithography: Breaking the Speed-Resolution Barrier

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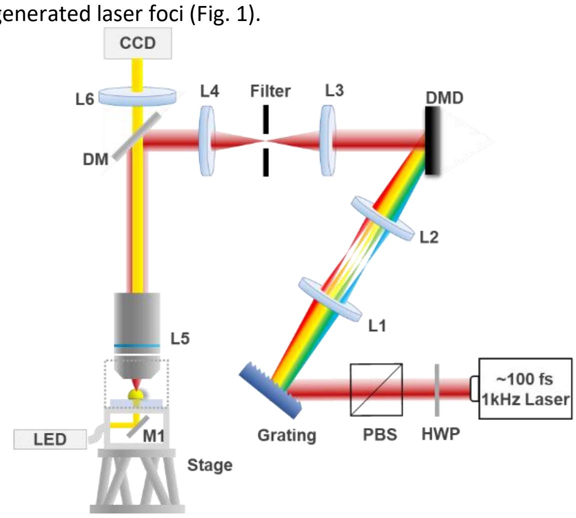
Abstract
This study presents a novel digital holography-based two-photon lithography (TPL) platform for high-resolution, large-scale 3D nanofabrication. The platform employs a 1 kHz femtosecond laser amplifier in combination with digital holography, enabling parallel writing with up to 2000 individually controllable laser foci. This configuration achieves an unprecedented fabrication rate of 2,000,000 voxels per second and a lateral resolution of 90 nm. With a thorough understanding of the underlying printing mechanism, the system successfully fabricates complex 3D nanostructures, thereby advancing applications in photonics, materials science, and biomedicine.

3D nanofabrication, Digital holography, Two-photon lithography (TPL), Femtosecond laser amplifier, Digital micro-mirror device, Multi-focus, Polymerization kinetics

Two-photon lithography (TPL) is one of the most precise 3D printing methods and serves as a powerful tool for nanoscale engineering and fabrication in optics, mechanics, robotics, biomedicine, and related fields[1-4]. However, its serial scanning process is both expensive and slow. Although parallel printing strategies have been developed[5-9], they are often limited by low device pattern rates or insufficient laser power. A femtosecond regenerative laser amplifier could potentially overcome these power limitations, though further investigation is required to assess the feasibility of employing low-repetition-rate laser sources for TPL.

In this study, we introduce an ultrafast, high-resolution digital holography-based two-photon lithography platform for 3D nanofabrication. The system is designed to utilize a 1 kHz femtosecond regenerative laser amplifier to support parallel writing with up to 2000 individually controllable, hologram-generated laser foci (Fig. 1).



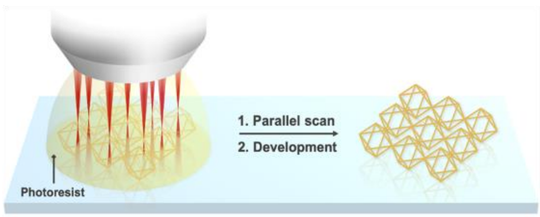


Figure 1. Schematic diagram of the two-photon polymerization (TPP) setup and the multi-focus printing process.

A custom-designed photoresist was developed to be compatible with the ultrahigh-peak-power light source, and the polymerization kinetics were meticulously optimized. Moreover, a single-pulse exposure strategy was adopted to minimize diffusion effects, thereby achieving optimal resolution and scanning rates (Fig. 2).

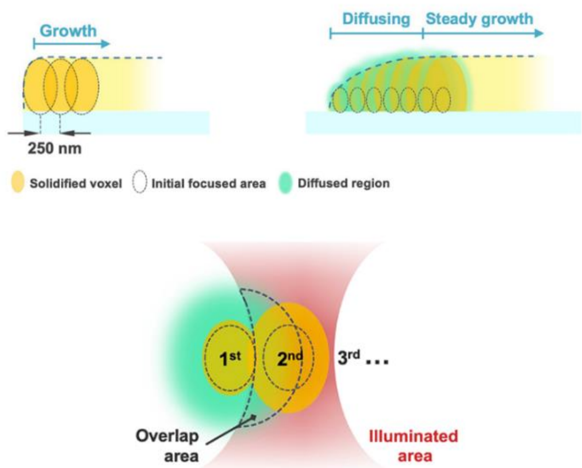


Figure 2. Schematic diagrams illustrating the polymerization-diffusion mechanism. As the number of pulses per voxel increases, the solidified region expands along the scanning direction due to the diffusion of the reacted material.

This unique configuration yields a volumetric printing speed of up to 54.0 mm^3/h, with lateral and axial resolutions of 90 nm and 141 nm, respectively. The platform's performance was demonstrated through the successful fabrication of complex 3D nanostructures and functional micromachines. The random-access scanning capability conferred by digital holography renders the system particularly efficient for fabricating structures with low material filling ratios (e.g., 1–12%). Demonstrations include large-scale mechanical metastructures, sub-wavelength diffractive optical neural networks, and other intricate nanostructures, all of which validate the platform's performance. This innovation effectively overcomes the trade-off between resolution and fabrication rate, showcasing the TPL platform's potential for large-scale applications beyond laboratory prototyping—in fields such as photonics, materials science, mechanics, biomedicine, and micro-robotics. The results highlight a promising solution for scaling up TPL in nanotechnology, thereby opening new possibilities for industrial applications.

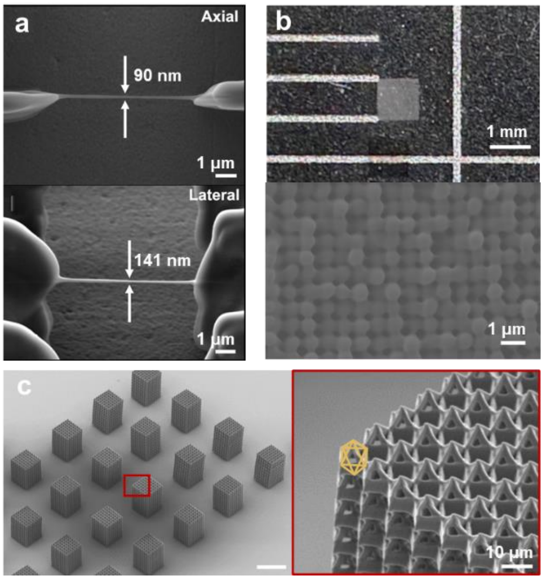


Figure 3. Printing Results: (a) SEM images of hanging lines that demonstrate a lateral resolution of 90 nm and a vertical resolution of 141 nm. (b) A large-scale diffractive neuron network device along with the SEM image of its individual pixels. (c) SEM images of a mechanical metastructure array.

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