

Enhanced Penetration for Metallic 3D Lithography Using Self-Healing Bessel Beams Generated by Micro-Axicons

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Three-dimensional (3D) lithography enables high-resolution fabrication of complex microstructures and architected materials.¹ Beyond geometry, the material composition is also critical in the performance of the patterned nanostructures. Photoresists formulated with metallic precursors or nanoparticles enable single-process printing of polymer-metal architectures with engineered mechanical, electrical, and optical properties.² However, conductive metals such as Ag and Au strongly absorb light at common lithography wavelengths. Once a continuous metal-rich layer forms, the optical dose decreases rapidly downstream, which severely limits the achievable structure thickness. Overcoming this metal-induced penetration limit is critical for volumetric 3D lithography of metallic and metal-polymer hybrid devices.

We investigate self-healing Bessel beams to increase curing depth in metal-containing resins. Bessel beams have transverse profiles described by Bessel functions of the first kind, exhibiting quasi-non-diffracting, self-healing behavior. Such beams maintain tight high-intensity cores over long distances and reconstruct central lobes after partial obstruction.³ Our key hypothesis is that when the light is blocked by metal-rich regions, energy from surrounding rings refills the axis, maintaining exposure dose beyond the first metal layer, as shown in Figure 1 (a). The self-healing effect is demonstrated in Figure 1 (b) using a micro-axicon simulated with finite-difference time-domain (FDTD) methods.

We fabricated a multilayer micro-axicon capable of generating Bessel beams in a stereolithography setup and characterized its curing performance using a silver-salt resin. We first examined the relationship between exposure dose and the size of the central lobe using photoresist, followed by tests with silver-salt samples, with the initial results shown in Figure 2. We observed increased curing depth of metallic features, suggesting that the self-healing effect partially compensates for metal absorption. This micro-axicon approach enables the fabrication of thicker and more complex 3D metallic architectures in photon-based lithography, and we plan to present experimental results showing that Bessel beams can produce thicker silver layers than conventional Gaussian illumination.

¹ A. A. Bhanvadia, R. T. Farley, Y. Noh, and T. Nishida, *Commun. Mater.* 2, 41 (2021).

² D. Kam, O. Rulf, A. Reisinger, R. Lieberman, and S. Magdassi, *Nat. Commun.* 15, 2285 (2024).

³ L. Chen, S. Kanwal, B. Yu, J. Feng, C. Tao, J. Wen, and D. Zhang, *Nanophotonics* 11, 967 (2022).

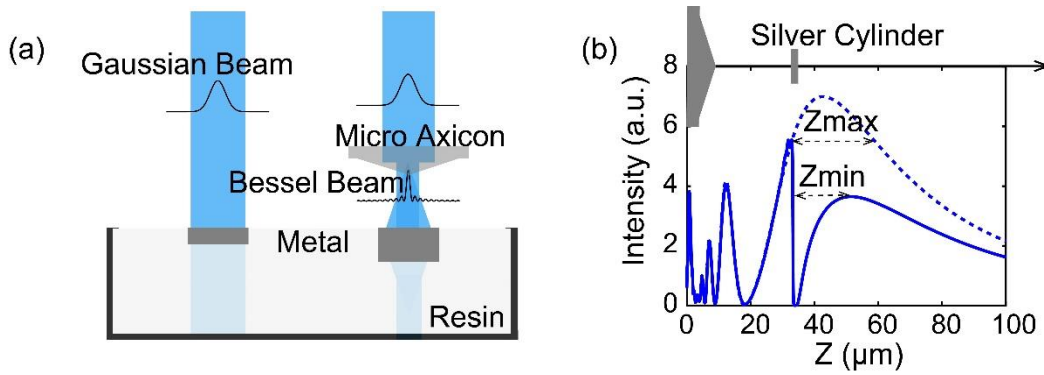


Figure 1. Concept and simulation demonstration of Bessel-beam-assisted curing in metallic resins. (a) A Gaussian beam is transformed into a Bessel beam by a micro-axicon, enabling increased optical penetration depth in metal-containing resin. (b) Finite-difference time-domain (FDTD) simulation illustrating the self-healing behavior of the Bessel beam generated by the designed micro-axicon. Z_{max} denotes the nominal focal distance of the axicon, and Z_{min} characterizes the self-healing distance; a silver cylinder is placed at the beginning of Z_{max} to emulate metal-induced optical blocking.

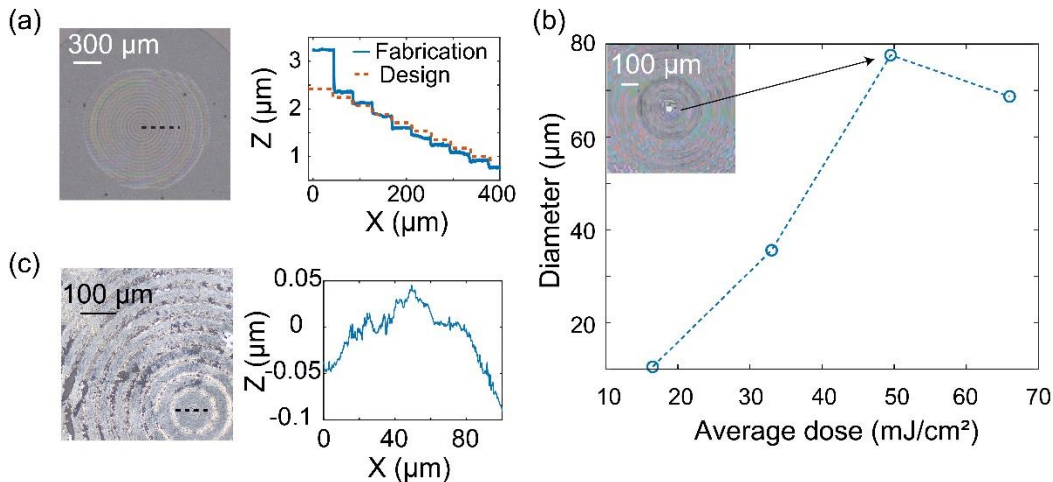


Figure 2. Experimental demonstration of Bessel-beam-assisted curing in metallic resins. (a) Microscope image and axial height profile of the fabricated micro-axicon produced using a Heidelberg MLA 150. The solid line corresponds to the measured height profile along the dashed bar in the image, while the dashed line represents the designed geometry. (b) Relationship between the average exposure dose and the diameter of the cured central lobe. The sample consists of a $1.5\ \mu\text{m}$ -thick AZ1518 layer exposed under a 365 nm light source. (c) Silver-containing structure cured from a silver-salt resin using the Bessel beam generated by the micro-axicon; the axial thickness profile along the dashed bar indicates a feature thickness of approximately 150 nm.