Inverse-design of 3D computer generated holograms for additive manufacturing of micron-scale geometries

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Additive manufacturing (AM) has revolutionized the speed of prototyping across many industries, but its utility on the micro and nanoscale is limited by speed: existing microsystem AM methods are layer by layer, or voxel by voxel, only exposing locations one at a time [1]. One method of overcoming this limitation is through development of single-exposure AM methods for micro and nanoscale geometries. By projecting a 3D hologram created through computer generated holography (CGH) into a high-resolution photopolymer resin, it is possible to fully cure the geometry in a single shot. Obtaining single-shot printing represents a dramatic increase in manufacturing speed over existing methods. With the ability to quickly create geometries, it will be possible to prototype many kinds of devices such as micro-optics, electronics, or MEMs.

The success of this method depends on the quality of the CGH method used to create the hologram: the requirements for manufacture using single-exposure projection of these holograms are that the hologram be high-contrast enough to sufficiently cure the geometry without curing sections of the VOI outside of it. We demonstrate high-contrast phase-only 3D holograms with features as small as 10μm, such as the one in Fig. 1, and discuss the development of the method for use in AM technologies, creating cured geometries from these holograms as shown in Fig. 2.

In order to maximize flexibility in the simulation, our CGH method utilizes a neural-net type structure that propagates light using the angular spectrum method (ASM) through simulated optical elements as if they are layers in the network [2]. Simulated intensity is measured at locations along the direction of propagation over the full volume of interest (VOI), and then the phase-only hologram is optimized using a custom loss function. With such a framework, it is possible to do large-scale inverse design for geometries with nanometer resolution–these could have billions of voxels. This has not been previously achieved at this scale due to the limitations of computing such large scale CGH problems.

[1] W. Haske, V. W. Chen, J. M. Hales, W. Dong, S. Barlow, S. R. Marder, and J. W. Perry, 65 nm feature sizes using visible wavelength 3-D multiphoton lithography, Opt. Express 15, 3426 (2007)

[2] M. J. Filipovich and A. I. Lvovsky, TorchOptics: An open-source Python library for differentiable Fourier optics simulations, arXiv preprint arXiv:2411.18591 (2024)

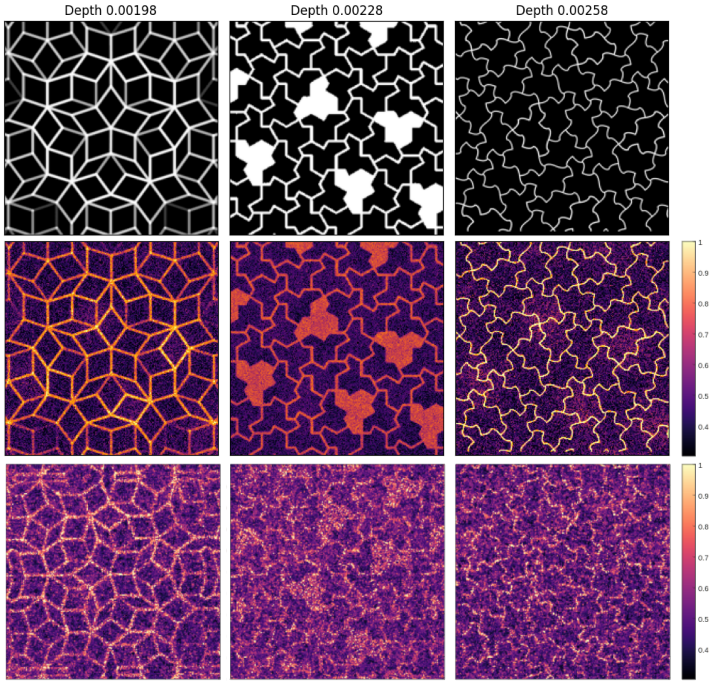

Figure 1: Results from the design and manufacture of a 200x200 pixel hologram with 2μm pixels. Each column explains a plane at a location along the direction of propagation, or depth, notated above the figure. The top row is the hologram targets, a selection of aperiodic tiling patterns with features as small as 10μm. The middle row displays optimized simulation results for those targets, while the bottom is the intensity pattern at those depth locations in the actual, manufactured hologram.

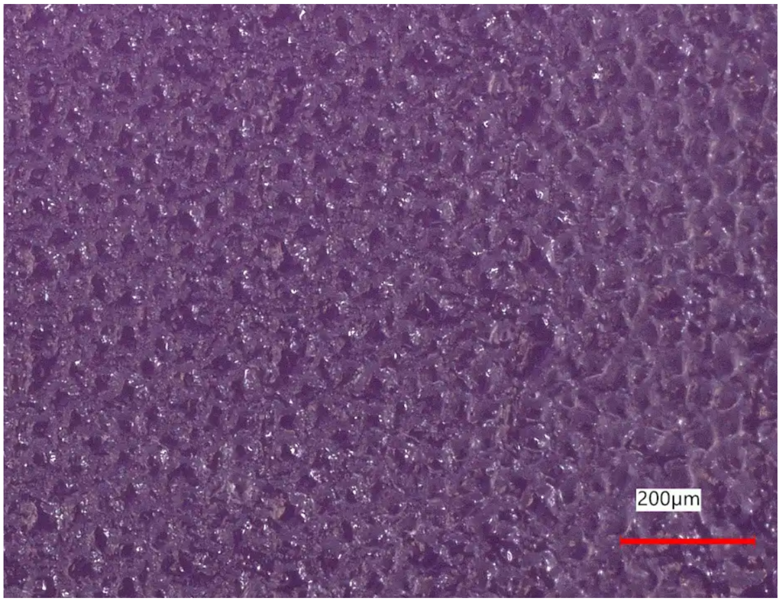

Figure 2: Top view of a test print in SU-8 XFT 100 photoresin using an expanded (5x5 grid of the Fig. 1 pattern) tiling hologram. This expansion makes the geometry self-supporting, as the fine features are delicate.