

End-to-end Design of a Diffractive Optical Element

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Primary CNF Tools Used: Heidelberg MLA 150 Maskless Aligner, Zygo Optical Profilometer, Hamatech HMx900

Abstract:

Diffractive optical elements (DOEs) designed through end-to-end optimization of optics and a reconstruction network can encode task-specific features during imaging, improving downstream performance of the task. However, fabricating DOEs with high precision is a challenging task. This work addresses the fabrication of a DOE ($6.9 \text{ mm} \times 6.9 \text{ mm}$) designed for a depth-from-defocus task, with $1 \text{ } \mu\text{m} \times 1 \text{ } \mu\text{m}$ lateral resolution, and a maximum feature height of $1.19 \text{ } \mu\text{m}$. The DOE is fabricated via grayscale lithography using an MLA150 maskless aligner on S1813 photoresist spin-coated onto fused silica. A 256-step test pattern is used to calibrate the contrast curve relating gray level to feature height, correcting for the nonlinear response of the photoresist. However, grayscale exposure with the MLA150 introduces periodic stitching artifacts ($\sim 50 \text{ nm}$, $\sim 4\%$ of maximum feature height), degrading height accuracy even after calibration. To mitigate this, an n-over exposure method is applied, in which the pattern is exposed multiple times with small lateral shifts to average out stitching error. Using this method, artifact height is reduced to $5\text{--}10 \text{ nm}$ ($0.4\text{--}0.8\%$ of maximum feature height), yielding significantly improved height fidelity across gray levels.

Summary of Research:

The goal of the research is to fabricate a diffractive optical element (DOE) which is designed using end-to-end optimization of optics and reconstruction network for a specific task (e.g., depth estimation). The designed DOE is able to encode task-specific features during the imaging process which allows the reconstruction network to perform better on the task. However, fabricating the designed DOE with a high precision remains a challenging task.

This work focuses on fabrication of a DOE designed for a depth-from-defocus task. The imaging setup consists of a single lens, a DOE, and a sensor. During

the imaging, two images of the same scene are captured by defocusing the lens. These two images are used to estimate the scene depth using a bio-inspired depth estimation network [1]. In the design phase, the captured images are rendered using differentiable ray tracing and wave propagation through the imaging optics. The rendered images are fed to the depth estimation network and the result is compared with a ground truth depth map to compute the error. A gradient based optimizer is used to optimize the phase map of the DOE and the parameters of the depth estimation network to minimize the error.

The designed DOE is $6.9 \text{ mm} \times 6.9 \text{ mm}$ in size with a lateral resolution of $1 \text{ } \mu\text{m} \times 1 \text{ } \mu\text{m}$ and a maximum feature height of $1.19 \text{ } \mu\text{m}$. The fabrication process starts with spin coating a fused silica wafer with S1813 photoresist at 4500 rpm . The coated wafer is baked at 115°C for 60 seconds. Then the photoresist is exposed using the MLA150 maskless aligner. Grayscale lithography is used as the exposure method with 256 gray levels.

Prior to the fabrication of the actual DOE, a test pattern is used to calibrate the contrast curve for grayscale lithography. The test pattern is a step structure with 256 steps, each corresponding to one gray level. Initially, the wafer is exposed with multiple copies of the test pattern, each using a different base laser dosage. The exposed wafer is developed using AZ 726MIF developer in the Hamatech HMx900. Developed test patterns are measured using the Zygo optical profilometer. Using the measurements, an appropriate base laser dose is selected which covers a wide range of gray levels without saturating the height response. The measurements showed a noisy, nonlinear relationship between the gray level and feature height. By fitting a curve to the measurements, the contrast curve is calibrated to obtain a linear height variation with gray level.

However, despite the calibration, the height variation remained noisy due to severe stitching artifacts introduced by the MLA150 during the exposure. These

artifacts appeared every 40 μm with a height of ~ 50 nm ($\sim 4\%$ of the max height). To reduce this, we used the n-over method, in which the photoresist is exposed n times with lateral shifts to average out stitching artifacts. We currently use a recipe with a base dose of 2200 mJ/cm², maximum power of 19%, and 4 exposures (each shifted by 10 μm). This reduced the stitching artifact height to a range within 5-10 nm ($\sim 0.4\%$ - 0.8% of the max height), resulting in a less noisy height variation with gray level.

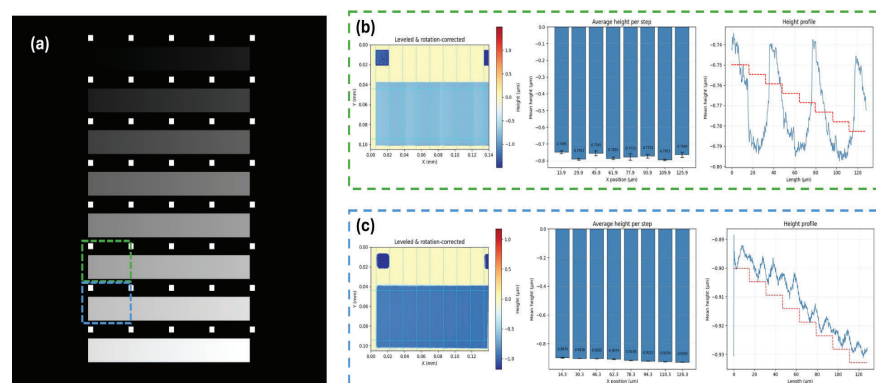


Figure 1: (a) Test pattern used for the contrast curve calibration. (b) and (c) show the profilometer measurements from sections of the (b) single exposure, and (c) 4-over exposure test patterns. Each subfigure shows the 2D height profile (left), mean step heights for the shown sections (middle), and the variation of mean height along the shown sections (right).

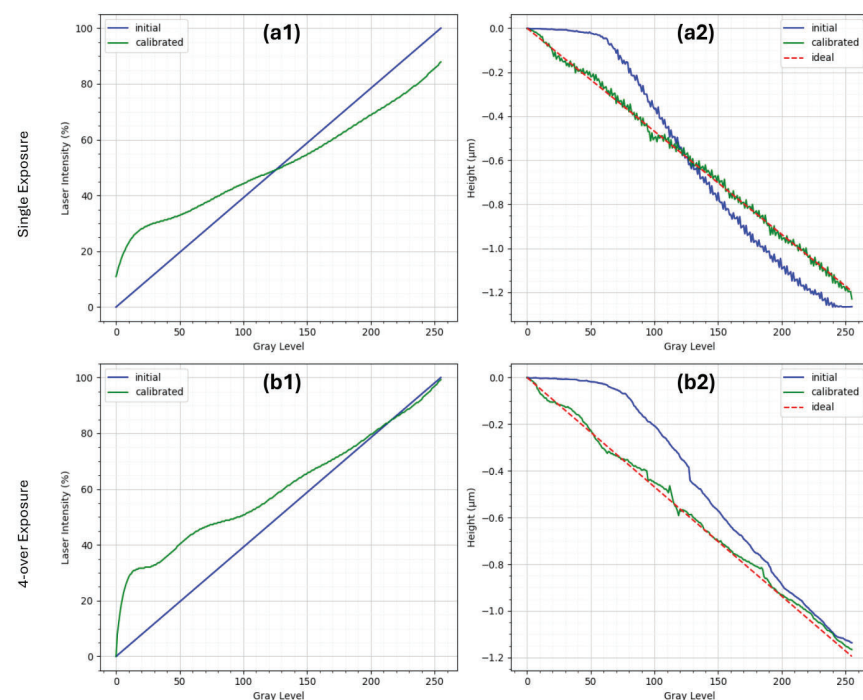


Figure 2: Contrast curve calibration and height response for the test pattern with single exposure (top row) and 4-over exposure (bottom row). (a1) and (b1) show initial and calibrated contrast curves. (a2) and (b2) show the initial and calibrated height response curves for the two exposure settings. The single exposure is performed with a base dose of 1334 mJ/cm² and 100% maximum power. For the 4-over exposure, a base dose of 2200 mJ/cm² and 19% maximum power is used.

Conclusions and Future Steps:

Grayscale lithography provides a faster method of fabricating diffractive optical elements with high precision. MLA150 allows grayscale lithography with 256 gray levels, but introduces severe stitching artifacts during the exposure. We use the n-over method to expose the wafer with shifted versions of the same pattern to reduce these artifacts. Through this method, our process brings down the stitching artifact height more than 5 times leading to much smoother feature height variations. The future work includes transferring the test pattern to the wafer using the Oxford 100 ICP-RIE etcher, calibrating the etching recipe, and fabricating the final diffractive optical element.

References:

- [1] Ferreira, Marcos A., et al. "SpiderCam: Low-Power Snapshot Depth from Differential Defocus." Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. 2026.