Investigation of Contrast Degradation due to Varying Incident Angles in Phase-Shift Lithography

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Periodic three-dimensional (3D) nanostructures offer distinctive properties and hold great promise across diverse fields in nanoscience and engineering. Unlike traditional bulk materials, these nanostructures display unique dispersion behaviors and can find applications in nanophotonics [1,2]. Various techniques have been explored to generate periodically distributed light intensity profiles, such as interference or phase-shift lithography. However, for widespread implementation of 3D nanostructures, an economically viable and high-yield manufacturing approach is essential. In our prior work, we proposed a roll-to-roll (R2R) system capable of manufacturing these structures in high volume based on the Talbot effect [3]. In that work, an array of colloidal particles is illuminated by collimated light from a laser diode to create a volumetric intensity pattern for 3D patterning. One challenge is that the light source has a relatively large beam divergence compared to a laser source. This can be problematic for larger systems with multiple diodes, which can introduce variations in the illumination angle. While this effect is inevitable, it can be managed based on the optical design.

In this study, we investigate the contrast degradation resulting from exposure with multiple illumination angle during phase-shift lithography. The system to be studied is illustrated in Figure 1, where a grating is illuminated by light at different incident angles. Initial computational results, based on scalar Fresnel diffraction model using a sinusoidal amplitude mask shows the intensity profile in the volume immediately below the element. Figure 1 shows the different intensity pattern within the 2D space of interest depending on the illumination angle from 0 ° - (a), to 10° - (c). To account for the beam divergence, the intensity vs incident angle is assumed to follow a Gaussian distribution. The beam intensity at each angle can then be calculated to examine the contribution of the angle variations. Based on this property, the calculated intensity profile within the volume depending on the standard deviation of 1 ° and 5 °, as shown in Figure 2 (a-c). To evaluate the degradation of the intensity pattern for lithography, we examine the fringe contrast. The figure next to the contrasts of each scenario are plotted next to the intensity patterns and are calculated by finding the maximum and minimum intensity values of the associated intensity distribution within each depth layer. These results illustrate that the variability in illuminating light significantly impacts the uniformity in the resulting structures. The figure illustrates that even at small beam divergence the contrast can be degraded sufficiently to limit lithography depth.

We will investigate further computational and experimental studies related to this phenomenon. Computational analyses will involve a comprehensive 3D simulation of a hexagonally close-packed colloidal nanosphere mask simulation. Experimental characterization will utilize a 405 nm laser diode, with optics focused to achieve desired divergence for experimental target thicknesses. These results will inform the optical design for phase-shift 3D lithography systems.

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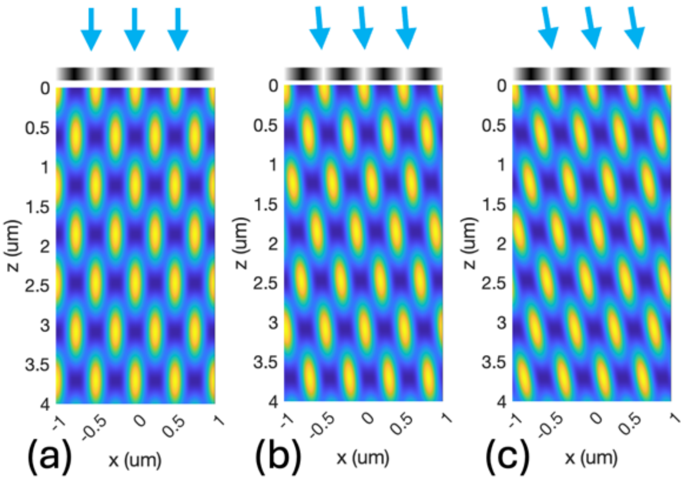

Figure 1. Illumination intensity after a sinusoidal phase grating with varying incident angles. (a) 0° tilt, (b) 5° tilt, (c) 10° tilt. The sinusoidal grating and the illuminating light angles are represented at the top.

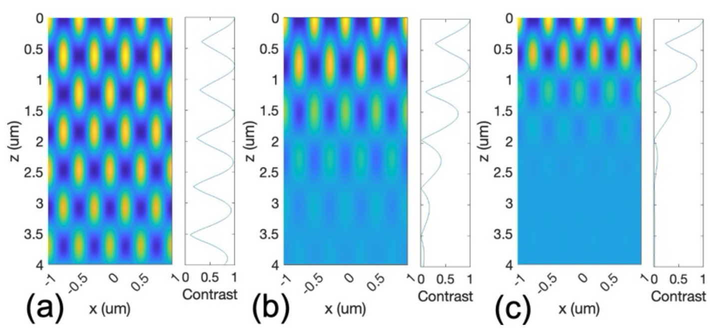

Figure 2. Gaussian variation of angle and intensity with standard deviation, σ, of (a) 1°, (b) 3°, (c) 5°. The optical design is based on an incoming light wavelength of 405 nm, and a sinusoidal grating period of 500 nm.

References

[1] S. Jeon, *et.al.*, *Fabricating Complex Three-Dimensional Nanostructures with High-Resolution Conformable Phase Masks*, Proc. Natl. Acad. Sci. U.S.A. **101**, 12428 (2004).

[2] J.-H. Jang, C. K. Ullal, M. Maldovan, T. Gorishnyy, S. Kooi, C. Koh, and E. L. Thomas, *3D Micro- and Nanostructures via Interference Lithography*, Adv. Funct. Mater. **17**, 3027 (2007).

[3] I.-T. Chen, E. Schappell, X. Zhang, and C.-H. Chang, *Continuous Roll-to-Roll Patterning of Three-Dimensional Periodic Nanostructures*, Microsyst Nanoeng **6**, 22 (2020).