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Fabrication of a High Efficiency Multilayer Diffractive Phase Grating

L. Yu,[1] M. Davanco,[1] L. Chen,[1] S. Abrahamsson,[2] B. Hajj, [2] J. Wisniewski,[2] M. Dahan,[2] J. A. Liddle,[1] T. Lionnet,[2] V. K. Luciani[1]

[1]*Center for Nanoscale Science and Technology, National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899*
liya.yu@nist.gov
[2]*Howard Hughes Medical Institute, Janelia Farm Research Campus, Ashburn, VA 20147*

Digital diffractive optical elements (DOEs) can be designed via computational optimization methods to produce specific far-field spatial light distributions for a variety of applications in optics and microscopy.[1] Such DOEs generally consist of two-dimensional phase gratings etched into an appropriate substrate. Binary gratings have maximum efficiencies of ≈ 70 %, which is not ideal for photon-limited applications such as super-resolution microscopy. Multilevel gratings can provide theoretical efficiencies ≈ 90 %, but only if precise control over etch depths, sidewall angles, feature edge placement and level-to-level alignment is maintained.

We report on the fabrication process of an eight-level DOE designed to improve the optical throughput and image contrast of a fast, multicolor, aberration-corrected, 3D, super-resolution microscopy system in which nine spatially separated images, each corresponding to a different depth in the imaged object, can be recorded simultaneously on a single CCD array. [2]

The eight phase levels are distributed as shown in Figs. 1(a) and 1(c). In order to optimize the fabrication process and the resulting DOE efficiency, it is essential to understand the effect of fabrication errors on the DOE performance. Simulated diffraction results (Figs. 2(a) and (b)), suggest that etch depth deviations at each step of 20 nm may reduce the efficiency by only a few percent, but relatively small (< 80 nm) misalignments between the lithographically defined layers may affect it significantly.

Using an error budget analysis, we have developed and integrated a fabrication process capable of generating such DOEs with performance close to the theoretical maximum. This process is flexible and can be tailored for customized designs. Comparison of the results from the prototype shown in Figs. 2(c) and 2(d) with computational simulations enable us to identify the most likely fabrication imperfections. We will present details of the data conversion, lithography and etch processes, together with a discussion of the effects of fabrication errors and the error budget that must be satisfied to ensure optimum DOE performance.

[1] J. N. Mait, "Understanding diffractive optic design in the scalar domain", *J. Opt. Soc. Am. A* 10 2145 (1995)
[2] S. Abrahamsson, *et al.*, "Fast multicolor 3D imaging using aberration-corrected multifocus microscopy", *Nat. Methods* 10 60 (2013)

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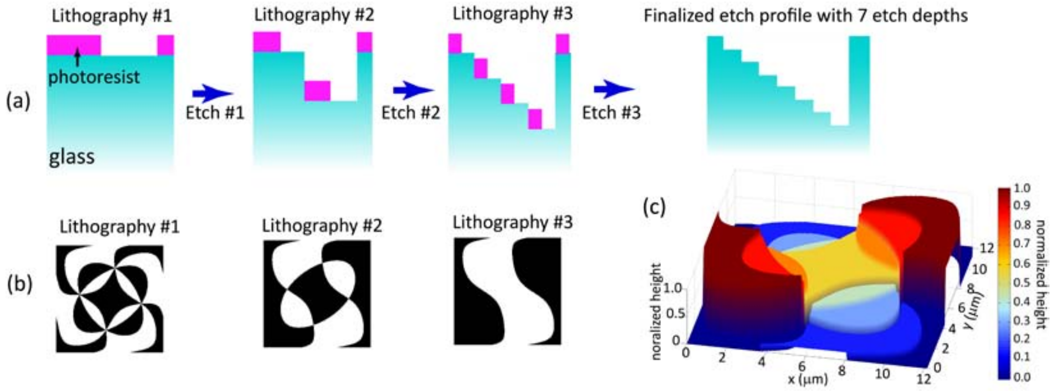

Fig. 1: (a) Eight phase layer DOE fabrication sequence, showing cross-sectional etch depths at each step. (b) Photolithography patterns used at each step. (c) Rendering of DOE surface topography in 3D.

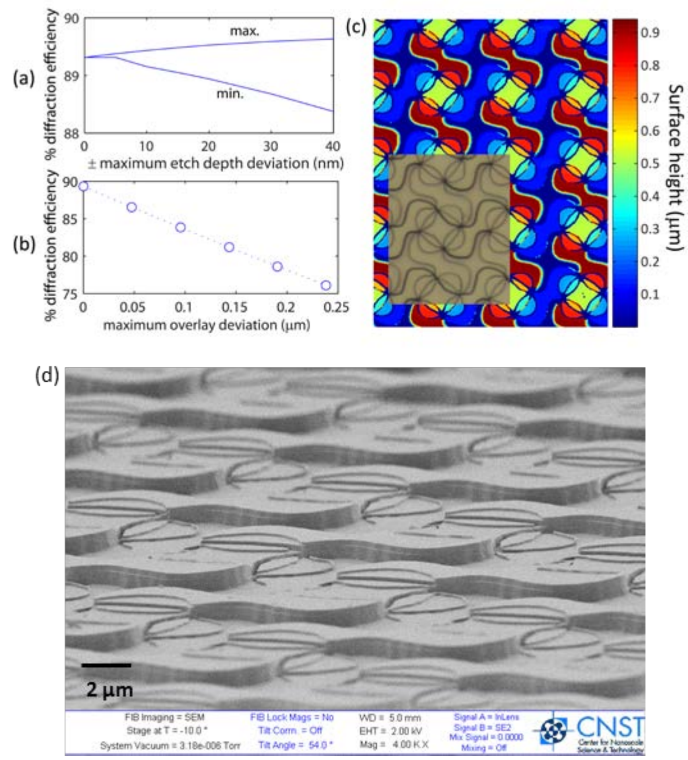

Fig. 2: (a) Overall grating efficiency as a function of the etch depth deviation from optimal. The area under the maximum and minimum efficiency curves corresponds to the efficiency uncertainty. (b) Overall grating efficiency as a function of overlay deviation between the three lithography patterns. (c) Optical profilometer measurement of a fabricated DOE (shown in inset optical microscope image). (d) SEM image of fabricated DOE.