Analog Lithography of Complex Phase Plates for Sub-Diffraction Lithography

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Abstract:

Analog phase plates enable one to arbitrarily tailor the shape of a laser focus with lower loss than alternative methods such as computer-generated holograms. Applications of these shaped foci include sub-diffraction microscopy and lithography. A half-wave step and a full-wave spiral phase plate are fabricated using analog, maskless photolithography. The phase plates are characterized with a Shack-Hartmann wavefront sensor, a profilometer, a scanning electron microscope (SEM) and other microscopic analysis techniques.

Introduction:

The fabrication of the phase plates was performed using the IMP SF-100 Xpress maskless lithography system. The system used 1024 × 768 grayscale bitmap images, which can vary the intensity of the UV dosage for a given pixel corresponding to a 3.5 × 3.5 μm feature size. This process utilized reflective microoptoelectromechanical (MOEM) elements to vary the intensity of each pixel.

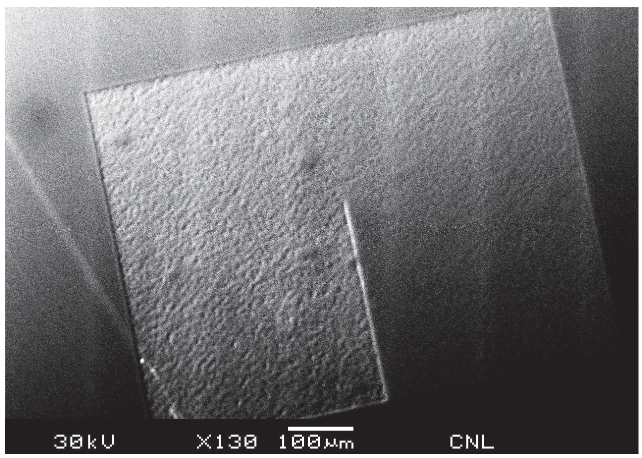


Figure 1: An SEM image of a full-wave spiral phase plate.

Experimental Procedure:

Samples were prepared on 1 × 1 inch glass microscope slides by spinning on a hexamethyldisilazane surface modifier followed by a 1.8 μm layer of AZ-P4210 positive photoresist. The samples were exposed to 365 nm radiation using the IMP SF-100 Xpress maskless lithography system. There was no closed-loop intensity control of the mercury lamp used to expose the samples, causing results to vary on a daily basis. Therefore, each time the lamp was illuminated, recalibration was required.

Samples were tested using a Dektak profilometer to quantify the depth of features. Further examination of the phase plates was provided with optical microscopy and interference microscopy, as well as SEM for sub-micron surface topography information. A Shack-Hartmann wavefront sensor was used to observe the functionality of the phase plates when incident with Gaussian laser radiation.

Results and Conclusions:

Two distinct types of phase plates were fabricated: a half-wave step plate and a full-wave spiral plate. Each phase plate was confirmed to have the correct step height to within 10 nm. The spiral phase plate was created with 20 consecutive gray values. One such spiral phase plate can be observed in Figure 1, where lighter regions indicate a deeper feature.

Profilometer measurements and SEM images indicated that the surface of the exposed region was extremely rough compared to the unexposed region. The intensity of this surface roughness increased with the depth of the feature. When the phase plates were tested with a Shack-Hartmann wavefront sensor, it became apparent that a significant fraction of the light was diffracting off the rough surface and didn't convert into the desired mode.

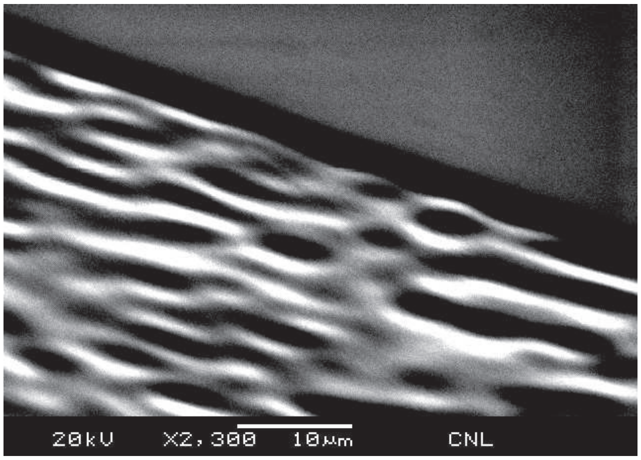
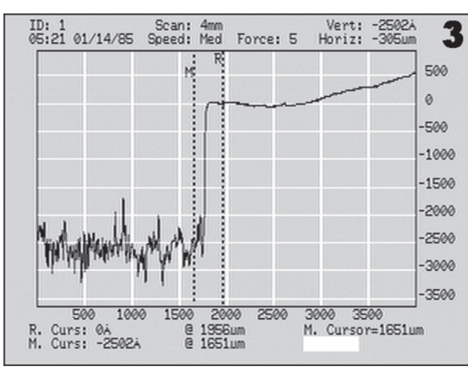


Figure 2: An SEM image of a step transitioning from the exposed to unexposed region, observed from a shallow angle.

Observing Figure 2, there is a very sharp, vertical step transitioning from the exposed region to the unexposed surface of the spun-on photo resist. This SEM image also demonstrates that the regions of the rough surface were approximately 5 to 10 μm. There was no surface roughness on the vertical step, suggesting that the developing process was not the cause of the surface roughness. Therefore, in an attempt to compare exposure methods, new samples were underexposed using a mask aligner, with every other processing step identical to the samples prepared with grayscale lithography.

Comparing profilometer measurements from a half-wave step plate fabricated with maskless lithography (Figure 3) to a sample underexposed with a mask-aligner (Figure 4), it is evident that the mask aligner resulted in a much smoother surface, independent of the depth of the feature. Not only was the surface smoother, but the surface topography was completely different altogether, as there was no trace of the peaks and valleys that occurred in the maskless lithography samples.

This difference in surface roughness between two samples with different exposure methods reveals that the surface roughness results from the method in which the exposure is controlled in the maskless lithography system. The reflective MOEM elements that control the exposure intensity are believed to be causing this roughness, but it is unclear as to why the regions created on the exposed surface are on the order of 5-10 μm when the spot size for each pixel is 3.5 × 3.5 μm. The roughness is also very randomly oriented, which wouldn't be expected if it was being generated from a regular array of reflective MOEM elements. Any non-uniformities resulting from the focusing optics would be expected to produce large regions of distortion as opposed to micron-scale imperfections.



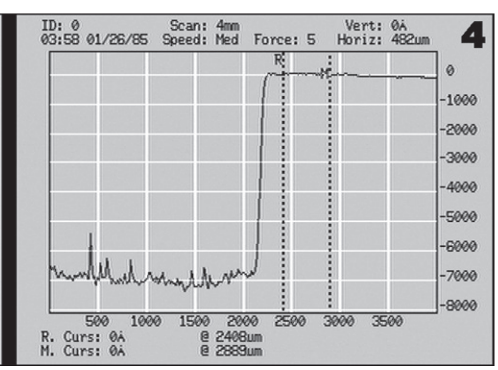


Figure 3, left: Profilometer measurement of a 255 nm step fabricated with the maskless lithography system.

Figure 4, right: Profilometer measurement of a 700 nm step fabricated with a mask aligner.

It has been demonstrated that complex phase plates can be fabricated using grayscale lithography, although there is a very rough surface in the exposed region. If the source of the surface roughness can be located and corrected, fully functional, cheap and efficient phase plates will be able to be fabricated.

Future Work:

Work will be directed towards locating the source of the surface roughness. The first step in this process involves placing a camera in the maskless lithography system in an attempt to detect variations in intensity. If the source of error can be corrected, complex phase plates will be able to be produced for the desired wavelength.

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References:

[1] Scott, T. F., B. A. Kowalski, A. C. Sullivan, C. N. Bowman, and R. R. McLeod. "Two-Color Single-Photon Photoinitiation and Photoinhibition for Subdiffraction Photolithography." Science 324.5929 (2009): 913-17. Print.

[2] Saleh, Bahaa E. A., and Malvin Carl. Teich. Fundamentals of Photonics. Chichester: John Wiley and Sons, 2007. Print.