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Maskless Lithography with Holographic Feedback for the Fabrication of Optical Elements

Tolga Gürcan[a], Muhammed Fatih Toy*[b,c]
[a]Department of Physics, Boğaziçi University, 34342 Istanbul, Turkey;
[b]Department of Biomedical Engineering, School of Engineering and Natural Sciences, Istanbul Medipol University, 34810, Turkey;
[c]Bioengineering and Biotechnology Research Center, Research Institute for Health Sciences and Technologies (SABITA), Istanbul Medipol University, 34810, Turkey
*mftoy@medipol.edu.tr

ABSTRACT

Photolithography has become a powerful tool in the fabrication of micro-optical elements following the advancements in grayscale approaches. However, hitting tight design tolerance goals require precise control of all parameters such as temperature, resist nonlinearity or preventing vignetting. In this work we took an alternative route to these problems by combining maskless lithography with digital holography. Addition of digital holography enables the use of feedback by measuring the quantitative phase of specimen near real time and in situ nondestructively. After each near UV exposure, phase retardation map of exposed photopolymer is measured with digital holography part of the system. Any deviation from target phase is corrected by changing the pattern displayed on the mask. We showed that the proposed method reduces the standard deviation of resulting phase compared to traditional one-shot grayscale lithography. It also does not require any precalibration of photoresist and relaxes the constraints for uniform UV illumination in sample plane.

Keywords: Maskless lithography, digital holographic microscopy, UV lithography, grayscale lithography, micro-optics, micro fabrication

1. INTRODUCTION

Grayscale lithography is a powerful microfabrication technique. Traditional photolithography applies same light intensity through whole area which results in 2-D structures. Grayscale lithography varies the applied intensity and after a development process we end up with 3-D structures. Some examples include microfluidic channels [1], lenses [2], and gratings [3]. Grayscale lithography can also be used to in the creation of properly functioning semiconductor devices. However, the efficiency of these devices depends heavily on printing quality which requires tight dimensional control. Tight production tolerances for feature size, height and growth or etching rate requires a pre-calibration run on a dummy wafer or sample. This process is repeated until error margins fall below the desired tolerances. Also, once the calibration is completed the environmental conditions should not change to not affect the system as system is inherently susceptible to environmental effects. Variations due to system drift cannot be corrected until too late because there is no feedback mechanism to correct and detect it in situ. An accurate, non-destructive, real time in situ monitoring is highly desirable for correcting the change in processing conditions as it will enable feedback control of the system.

There are some optical characterization techniques such as spectroscopic ellipsometry [4], phase sensitive ellipsometry [5], laser reflectometry [6], multi-beam interferometry [7], and emission spectroscopy [8] which checks the requirement for non destructive testing but is generally used for single point measurements. These techniques might be adequate for planar shapes but are insufficient in providing necessary feedback information to produce complex phase plates. To fully correct any deviation in the field of view, an imaging method rather than a single point method is preferred. For this job quantitative phase imaging stands out with its good performance in noisy environments. The phase of sample can be obtained by the reconstruction of digitally recorded holograms in digital holographic microscopy (DHM)[9] or by various quantitative phase microscopy methods [10-12]. There are some preliminary works which utilizes real time quantitative phase imaging, but their use is mainly limited in the characterization of etching rates [13].

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Here we propose an alternative to grayscale lithography which utilizes phase imaging as feedback to improve printing quality. Our technique relies on the phase retardance measurements coming from digital holography part of the setup to measure how phase of each point evolves in time and correct any deviations. Instead of using a long single shot exposure to create the desired pattern, we divide the single shot into multiple shorter exposures to increase number of measurements. Between each exposure, the current phase of the sample is measured and from this, their difference to the target phase is calculated for each point. The input image for grayscale lithography is then adjusted according to phase difference. Since this technique adjusts the light intensity in each step, precalibration of photoresist is not required.

2. METHODS AND RESULTS

2.1 Method

As shown in Figure 1, our proposed system uses the hologram captured by the camera to measure the optical phase map of sample at each step and apply required correction by changing the pattern projected on SLM. The digital holography part of the system utilizes a Mach Zehnder interferometer to create the hologram and applies Fourier filtering to find quantitative phase. Then a least square phase estimation method [14] is used to find the total final phase. For the grayscale lithography part, an SLM is illuminated by a 405 nm violet laser beam. The size of the beam is adjusted such that it overfills the SLM. The SLM is then placed on to the object plane of a 1 to 1 magnification 4f imaging system whereas sample is placed on the image plane.

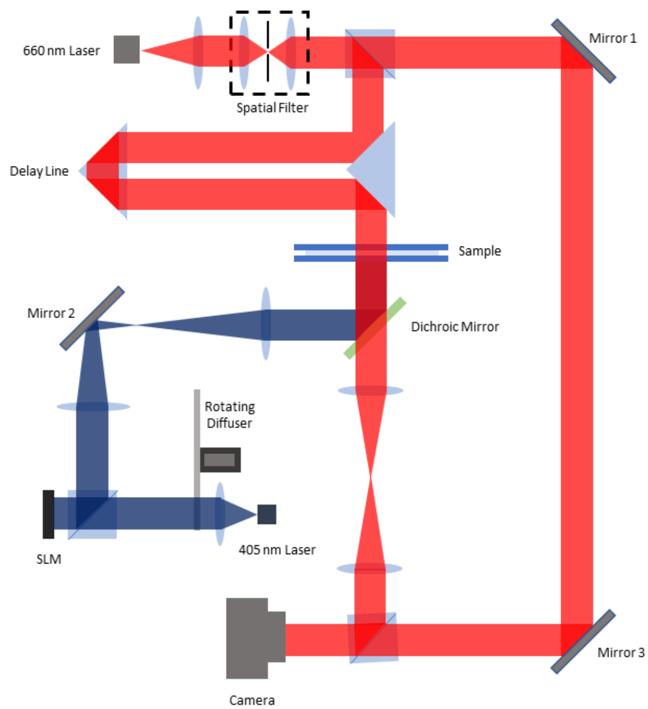

Figure 1. Schematic of experimental setup.

The light intensity on the sample plane is correlated to image projected on SLM. By controlling the projected image, we can control the total light dose projected on a point and hence control the phase retardance of that point. This allows us to create any desired phase plate accurately without any prior calibration of photoresist. Because the phase retardance is not directly proportional to the dose and there is a threshold value for phase retardance to start, desired phase plates are placed on a background value. For the break condition of feedback loop, the average difference between current and target phase is calculated. If the average falls below a certain threshold value loop terminates. The overall flowchart of this method can be seen in Figure 2.

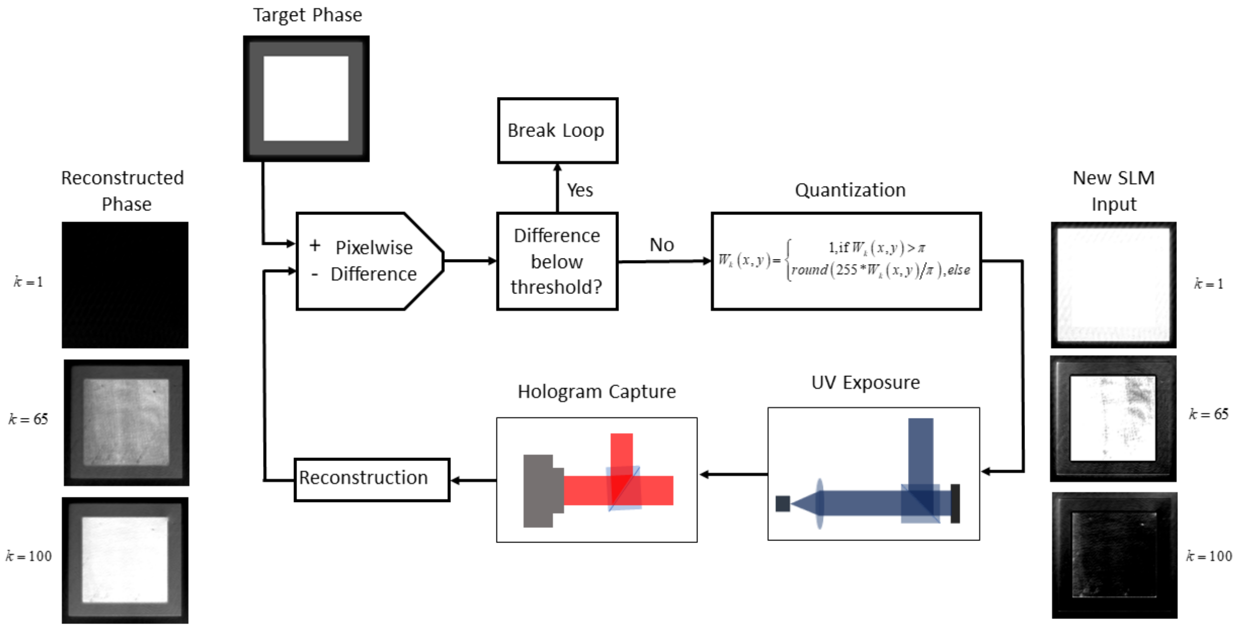

Figure 2. Flowchart for the proposed process. k indicates the iteration number.

2.2 Results

In order to test capabilities of the system, a phase plate with a square step is fabricated. The phase retardation of the middle square and framing background is selected 3π and π respectively. The resulting phase plates produced by traditional single shot method and proposed iterative method can be seen in Figure 3. Although flatness of top surface may be acceptable for classical method, our method improves this by also decreasing the standard deviation across the sample. The mean phase difference figures from the target for classical and iterative case are 0.62 and 0.29 radian, respectively. We can see that iterative method provides immunity to nonhomogeneous UV illumination as the background and top part has an increasing profile in classical method whereas it stays close to ideal for iterative case.

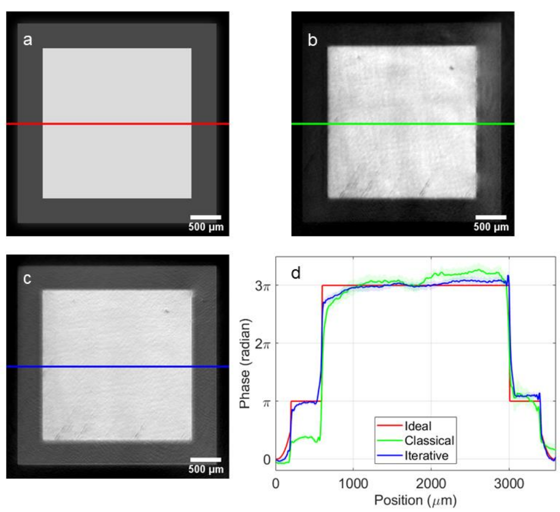

Figure 3. (a) Target phase image; (b) Resulting phase map for traditional method; (c) Resulting phase map for proposed iterative method; (d) Phase profiles along colored lines in (a), (b), and (c)

To verify the phase measurement, a spiral phase plate, which creates a doughnut beam is realized. Resulting doughnut beam, which is formed after the phase plate and a 750 mm lens, is imaged by a CCD camera. Results can be seen in Figure 4.

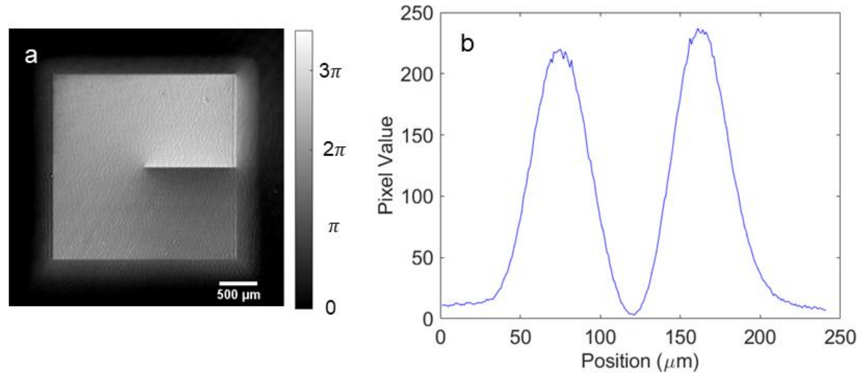

Figure 4. (a) Resulting phase plate for 2π spiral phase target; (b) Intensity profiles along resulting doughnut beam.

The center portion of the beam carries %1.3 and %2.6 intensity of lower maxima in the x and y axis, respectively.

3. CONCLUSION

A new UV grayscale lithography method is realized. This presented method finds the current phase change of specimen near real time, nondestructively by utilizing a digital holographic imaging setup. Using the information about phase change, method decides on the new intensity mask to be shown in SLM which reduces both standard deviation and mean difference in resulting phase plate. This system reduces the effect of homogenous UV intensity in target plane, nonlinearity of photoresist etc. on the final phase distribution.

4. ACKNOWLEDGEMENTS

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