Laser Interference Lithography with a Spatial Light Modulator for Arbitrary Pattern Fabrication

Nozomu Takahiro[1] and Yuki Shimizu[2,#]

1 Graduate School of Engineering, Hokkaido University, Sapporo, Japan
2 Division of Mechanical and Aerospace Engineering, Hokkaido University, Sapporo, Japan
Corresponding Author: yuki.shimizu@eng.hokudai.ac.jp

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A new exposure method for free pattern fabrication combining laser interferometer and wavefront control has been proposed. In conventional Lloyd's mirror interferometric method, two coherent beams are superimposed in a substrate to generate interference fringe patterns. This is known as the simplicity of the principle and high stability to generate high-precision fine patterns even without a well-controlled environment. However, generated interference patterns make it difficult to adjust the position. To improve these problems, a new method of controlling the position of interference fringes by placing a spatial light modulator (SLM) in front of Lloyd's mirror interferometer to apply a phase change to the coherent beam is proposed. In this paper, experimental results about the positioning control of the interference fringes and generating the interference fringes using wavefront control are reported.

1. Introduction

In recent years, the demand for fine structures with μm-level patterns has been increasing in the field of optics, biomaterial, and microelectromechanical systems (MEMS) [1]. For example, diffraction gratings are often used in positioning sensors and CMMs [2]. In addition, micropatterns are also used in cell culture, cell analysis, surface profiling, and so on [3].

There are some techniques for fabricating fine patterns. Among them, Lloyd's mirror interferometer is known as a simple technology capable of exposing micrometer-class patterns over a wide area and high stability even without a well-controlled environment [4]. Despite such advantages, there are some issues such as the difficulty of precisely controlling the position of interference fringe generation and the low variety of pattern generation. Therefore, there is a need for a technology that improves the degree of freedom of patterns while taking advantage of the strengths of this method. In this paper, the results of the attempts to control the position of interference fringes that can be generated by a new Lloyd's mirror interferometer with a spatial light modulator (SLM) are reported.

2. Principle

Figure 1 shows a schematic diagram of a non-orthogonal one-axis Lloyd's mirror interferometer with a spatial light modulator (SLM) for controlling the wavefront of exposure beams [5]. The interferometer consists of a glass substrate and a flat mirror. When the laser beam enters the substrate, a portion of the laser beam is directly incident on the substrate (sub-beam 1), while the other part of the laser beam is reflected by the mirror and then incident on the substrate. (sub-beam 2). These two beams generate interference fringes on the substrate. One of the advantages of this method is the ease of changing the pitch of the interference fringes (g). Since the pitch (g) can be freely changed by adjusting the angle of the mirror, the opening angle of 90°+θ relative to the substrate can be freely adjusted by mounting the flat mirror on the rotation stage and rotating it. The relationship between (g) and (θ) can be given by the following equation:

$$g = \frac{\lambda}{\sin 2\theta} \tag{1}$$

where (λ) is the wavelength of the laser beam used in the setup.

Next, the principle of shifting the position of the interference fringes by phase modulation under the incoming sub-beam is explained. The pattern movement is expressed by the following equation:

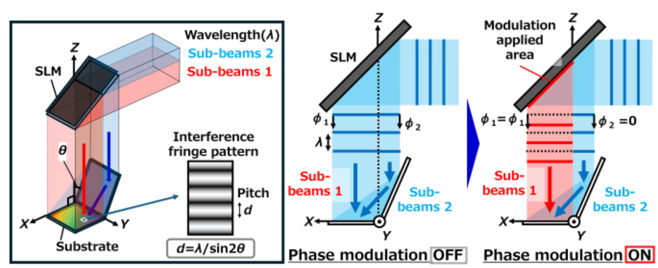

Fig. 1 Schematic diagram of a one-axis non-orthogonal Lloyd's mirror interferometer with SLM and wavefront modulation.

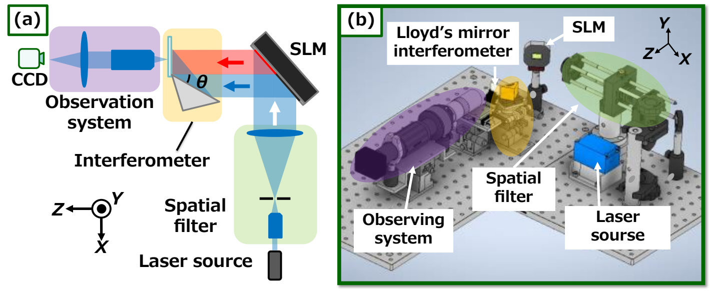

Fig. 2 (a) Schematic of the designed optical setup; (b) a 3D model of the entire optical setup.

$$I(\boldsymbol{r}) = E_1^2 + E_2^2 + 2E_1E_2\cos\{(\boldsymbol{k}_1 - \boldsymbol{k}_2)\cdot\boldsymbol{r} + (\phi_1 - \phi_2)\} \quad (2)$$

where E_i (i = 1, 2) is the amplitude of the electric field, ϕ_i (i = 1, 2) is the amount of phase modulation given by an SLM. $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ are the wave vectors of the sub-beams 1 and 2, respectively, given as follows:

$$\boldsymbol{k}_1 = \frac{2\pi}{\lambda}(0,0,-1)\ ,\ \boldsymbol{k}_2 = \frac{2\pi}{\lambda}(\sin 2\theta, 0, -\cos 2\theta)\ . \quad (3)$$

3. Experiments

A setup was designed and constructed to experimentally verify the feasibility of the proposed method [6]. Figures 2(a) and 2(b) show a schematic of the designed optical setup and a 3D model of the entire optical setup, respectively. A single-frequency laser diode with a wavelength of 405.1 nm was employed in the system. The laser beam passes through a spatial filter to remove spatial noise and enlarge the diameter. The magnified laser beam was incident at an angle of incidence of 45° to the liquid crystal surface of the SLM (SLM-200, Santec AOC Corp., Japan). The SLM with a pixel size of 8 μm is capable of 1024 steps of wavefront control per pixel with modulation stability better than 0.001π rad. Therefore, the optical setup can realize independent wavefront control of sub-beams 1 and 2. The interferometer employed a mirror with a flatness of λ/10. In addition, a glass substrate was placed at the interference fringe generating area. An optical microscope unit based on an infinity-corrected optical system with a CCD camera was placed behind the glass substrate.

The experiment was extended to verify the possibility of moving the interference fringes by changing the amount of wavefront modulation of sub-beam 1 (direct incidence side). After adjusting the pitch of interference fringes to 4000 nm, the position of the interference fringes on the glass substrate without photoresist coating was captured. Figure 3(a) shows the results. In this graph, the horizontal axis represents the signal values given to the SLM and the vertical axis represents the amount of fringe shifts. As a result, the pitch of each interference fringe showed an almost linear relationship, confirming reproducibility.

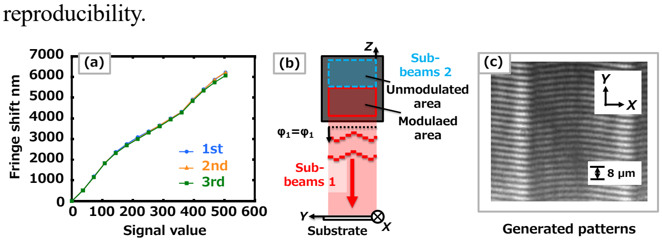

Fig. 3 (a) The relationship between signal value applied to the SLM and the moving amount of interference fringe; (b) Schematic diagram of different partial modulations; (c) Generated discontinuous interference fringe.

Finally, several types of interference-based exposure patterns were generated using this property. Figure 3(b) shows a schematic diagram of different partial modulations, and Fig. 3(c) shows one of the diagrams of interference patterns that occur when different partial modulations were applied. As a result, a wavy pattern was observed, proving the feasibility of an optical prototype that creates arbitrary patterns based on interference fringes.

4. Conclusions

In this paper, an attempt has been made to generate two-dimensional arbitrary interference patterns by introducing a spatial wavefront modulation technique into a non-orthogonal one-axis Lloyd's mirror interferometer. Through this study, it was found that the position of the interference fringes can be moved with a certain reproducibility depending on the signal value given to the SLM. In addition, it was confirmed that arbitrary two-dimensional patterns differing from the linear shapes can be generated by applying discontinuous modulation patterns to the SLM in the setup.

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