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ABSTRACT

To fabricate a scale grating for a surface encoder in a cost-effective way, a blue laser diode with a wavelength of 405 nm is employed in a Lloyd's mirror interferometer to carry out interference lithography (IL) of the grating. The beams from the laser diode are collimated by an aspherical collimating lens to form beams with a diameter of 50 mm. These beams are then projected towards the Lloyd's mirror and the grating substrate, which are aligned perpendicularly with each other and are mounted on a rotary stage. One half of the beam directly goes to the grating substrate, and the other half reaches to the grating substrate after being reflected by the mirror. The direct beam and the reflected beam interference with each other to generate and expose the interference fringes, which correspond to the scale grating structures, on the substrate coated with a photoresist layer. The pitch and area of the grating structures are set to be 570 nm and around 300 mm^2, respectively. The fabricated grating structures are evaluated with an AFM to investigate the influence of the spectrum width of the laser beam.

Keywords: Grating, Interference lithography, Surface encoder, Laser diode, Semiconductor laser, Blue laser diode, Planar motion stage

1. INTRODUCTION

Planar motion stages are widely utilized in the fields of precision manufacturing and metrology. Multi-degree-of-freedom (MDOF) position measurements of such stages are mainly accomplished by combining multiple single axis laser interferometers[1-4]. For the laser interferometer-based measurement systems, the accuracy is greatly influenced by changes of operating environment, and usually these systems are bulky and expensive. For solving these problems, a compact surface encoder had been proposed to carry out MDOF positioning for a surface motor stage, into which the surface encoder can be incorporated[5]. In the surface encoder, a scale grating with periodic grating structures is employed as the reference for the position measurement. The area of the scale grating, which determines the measurement range of position, is typically designed to be from 10 mm^2 to 10000 mm^2. The grating pitch, which determines the resolution of position measurement, is around 1 μm.

The scale gratings can be fabricated by mechanical cutting or interference lithography[6-9]. In the mechanical cutting method, a single point diamond cutting tool is moved over the grating substrate to remove materials at each of the cutting points. Although the mechanical method has an advantage of producing complicated profiles with high form accuracy and good surface finish, this makes the process time-consuming. It is also difficult to fabricate grating structures with a sub-micrometer pitch because of the tip geometry of the cutting tool[6, 7]. In contrast to the diamond cutting method, the interference lithography (IL) method can make the fabrication more effective[8, 9], In the interference lithography method, light interference patterns are exposed on the grating substrate to generate grating structures over a large area structures in a short time. Sub-micrometer pitched gratings can also be made by using a proper optical system[10].

On the other hand, for the large area grating fabrication (more than 10 mm^2), the interference lithography typically needs an expensive and large-sized gas laser with a long coherence length L_c, which makes the fabrication costly and bulky.

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For example, a commercial 180 mW HeCd laser with an L_c of 0.30 m usually costs more than 25,000 USD and has a bulky size with a length larger than 1.4 m. The Kr-ion laser, which has larger power and longer coherence length, is even more expense and has lager size. For reduction of the cost and size of the fabrication system, interference lithography systems using compact semiconductor lasers, such as 405 nm GaN diode laser and 405 nm AlInGaN diode laser, have been reported[11,12]. It has been demonstrated that sub-micrometer pitched grating structures over a small area of 1 mm^2 can be fabricated by such an IL system[11]. However, typically the semiconductor lasers have smaller power and shorter coherence length compared with gas lasers, which requires longer exposure time and limits the fabrication area. The stabilities of the semiconductor lasers in power and wavelength are also worse than those of gas lasers, which can be a significant problem in fabrication of large area gratings. For the above reasons, there have been few reports on large area grating fabrication by using semiconductor lasers.

The motivation of this research is to investigate the possibility and limitations of using semiconductor lasers in fabrication of the scale grating for surface encoders. This paper reports a Lloyd's mirror interferometer-based IL system by using a low cost and compact blue laser diode used in a blu-ray disc driver as the light source. The system is designed in such a way that the maximum exposure area is 300 mm^2. Fabrication experiments were carried out to generate 570 nm pitched grating structures. The fabricated gratings were also evaluated by an atomic force microscope (AFM).

2. THE INTERFERENCE LITHOGRAPHY FABRICATION SYSTEM

Figure 1 shows a schematic view of the Lloyd's mirror interferometer[9], based on which the interference lithography (IL) system is constructed. A low cost and compact blue laser diode used in a blu-ray disc drive as the light source. The wavelength λ of the laser diode is 405 nm. The beams from the laser diode are collimated by an aspherical collimating lens to form the beams with a diameter of D. The collimated beams are then projected towards the Lloyd's mirror placed normally to the substrate, which is mounted on a rotary stage. The beam center is aligned symmetrically along the intersection of the mirror and the substrate. One half of the beam directly goes to the grating substrate and the other half reaches to the grating substrate after being reflected by the mirror. These two beams coincide and superimpose with each other to generate and expose the interference fringes on the substrate coated with photoresist, which correspond to the scale grating structures. Figure 2 shows the interference pattern generated by the interferometer, which corresponds to the grating structure. The pitch p of the interference pattern can be given by[13].

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

Where λ is the wavelength of the laser source, and θ is the angle between mirror and the beam axis.

On the other hand, the radius of the maximum exposure area can be expressed by Eq.(2). In the IL system, the maximum exposure area was designed to be about 300 mm^2.

$$R = \frac{D}{2\cos\theta} \tag{2}$$

The grating structures fabricated by the IL system are greatly influenced by the characteristics of the laser source, especially the coherence length L_c, which is determined by the frequency width of the laser source spectrum. Assuming that λ is the central wavelength of the incident laser for exposure and Δf is the frequency width, the spectrum width $\Delta\lambda$ can be expressed by

$$\Delta\lambda = \frac{\lambda^2}{C} \cdot \Delta f \tag{3}$$

The coherence length L_c is determined by the spectrum width $\Delta\lambda$ as follows:

$$L_c = \frac{\lambda^2}{\Delta\lambda} \tag{4}$$

The width W_A of the grating area where continuous grating structures are generated can thus be written as:

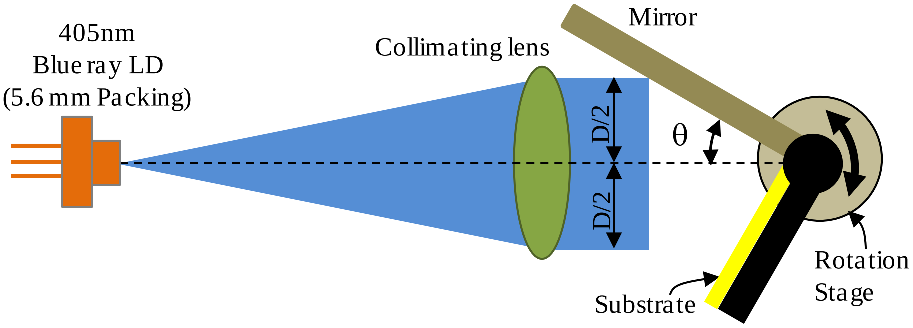


Figure 1. Optical configuration of Lloyd's mirror Interferometer

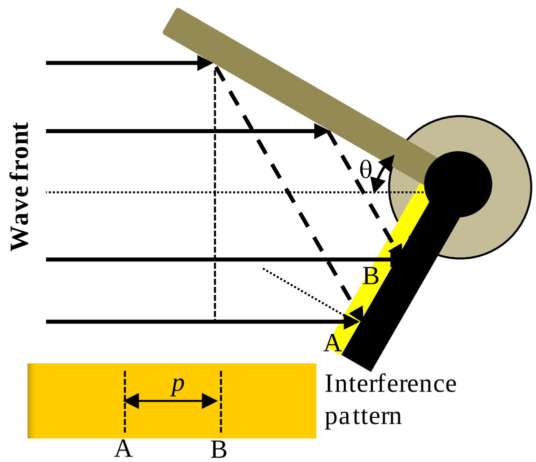


Figure 2. The interference pattern for generation of the grating structures

$$W_A = m \cdot p \tag{5}$$

Where m is the number of grating lines, which is given by

$$m = \frac{L_c}{\lambda} \tag{6}$$

Assuming that the 405 nm laser diode has a frequency width Δf of 1 GHz and the grating period p is 570 nm, the coherence length L_c and the width W_A of the grating area are calculated to be 300 mm and 422 mm, respectively.

Selection of the photoresist, which can strongly absorb the 405 nm laser light, is another important task. After an investigation, a commercial photoresist (Shipley S1800) was chosen for the fabrication experiment. Figure 3 shows the absorbance curve of the photoresist. It can be seen that the photoresist can be exposed with light sources in the spectral output range of 350 to 450 nanometers [14]. Although it is optimized for use at 436 nm, it also has a fairly good absorbance at 405 nm. In the fabrication experiment, the photoresist was coated on the substrate with a thickness of less than 1 μm.

3. EXPERIMENT AND RESULTS

A blu-ray laser diode was used as the light source in the fabrication experiment of gratings. The output power of the laser diode was 125 mW. Because no data of the laser diode on the frequency width Δf are available, a simple Michelson interferometer was established to evaluate the coherent length. The coherent length L_c was measured to be approximately 0.68 mm. The grating pitch p was set to be 570 nm. The width W_A of the continuous grating area was calculated to be 0.96 mm based on Eq. (5).

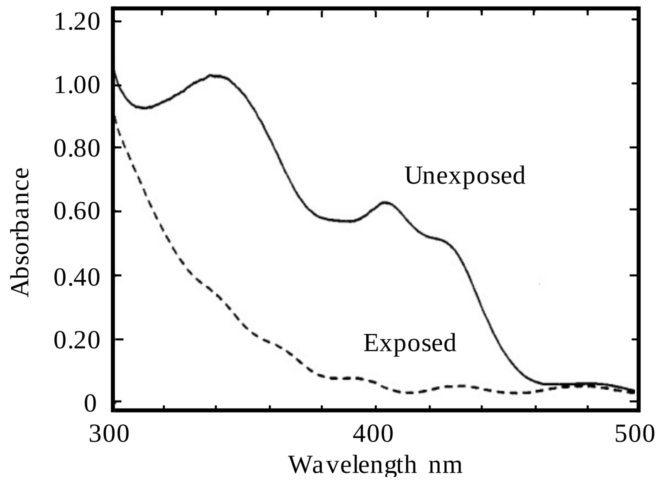


Figure 3. Absorbance spectrum of Shipley S1800 series Photoresist

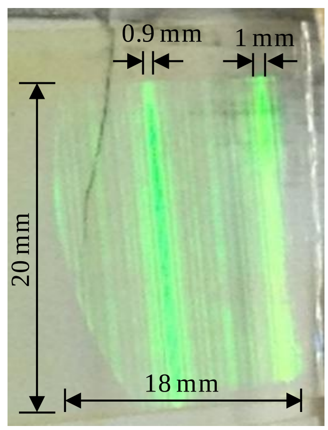


Figure 4. Picture of the fabricated grating

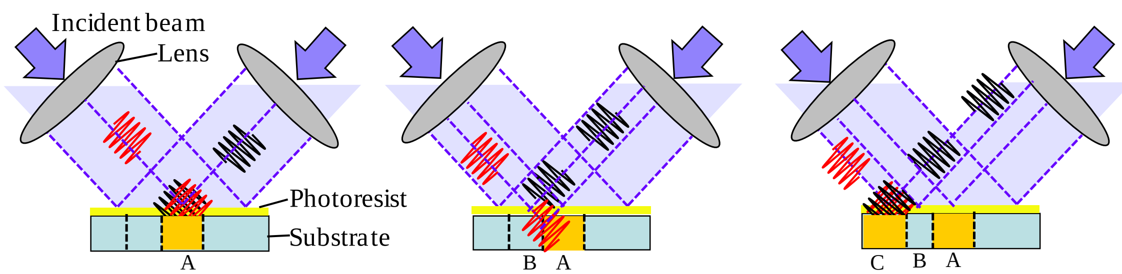
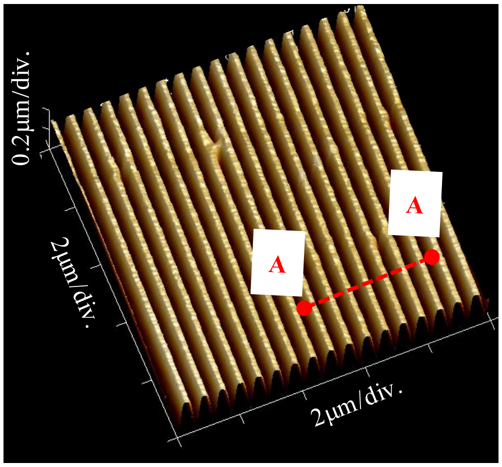


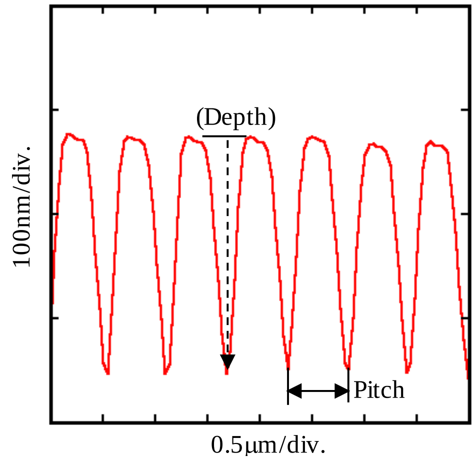
Figure 5. Interference patterns distribution along the surface of substrate

The substrate was prepared by coating a 50 nm-thickness adhesion promoting agent and a 300 nm-thickness photoresist on a glass plate with a length of 30 mm, a width of 25 mm and a thickness of 1 mm. The power of the laser used for exposure was 45 mW. The exposure time was set to be 15 s. The exposed grating plate was developed in NaOH solution with a concentration of 0.5 %. The development time was determined to be 6 seconds by trial and error in the experiment.

Figure 4 shows a picture of the fabricated grating plate. The picture was taken by tilting the grating plate under a white light source so that the area of the fabricated grating structures can be recognized in green color. It can be seen that the grating structures were able to be fabricated over an area of 20 mm x 18 mm, which meets the requirement for use in the surface encoder[6]. On the other hand, however, the grating structures were not uniform over the fabricated area. The widths of the most two visible areas were approximately 0.9 mm and 1 mm, respectively. This corresponds to the



(a) 3-D view of the AFM image



(b) Section view along the line A-A

Figure 6. AFM image of the fabricated grating by 405nm LD

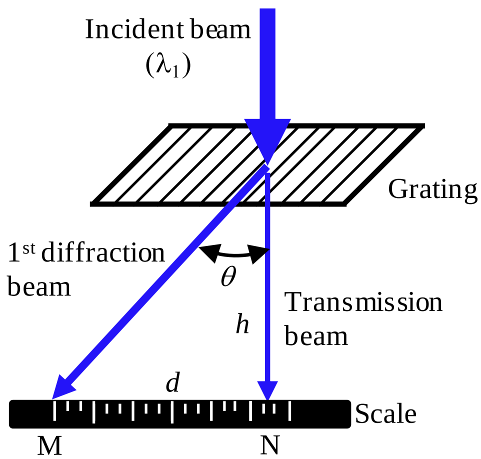


Figure 7. The optical method for evaluation of the grating pitch

calculated width of the continuous grating area. The discontinuity of the grating areas was related to the short coherence length of the laser diode.

Figure 5 shows a schematic of the interference patterns generated by two laser light beams with short coherence lengths. Assume that the two beams have the same optical paths at point A. The two beams will generate a continuous fringe pattern with a width W_A defined at Eq. (5) centered at A. The optical path difference will increase along the direction from A to C. Assume that the optical path difference at point B equals to the coherent length L_c, the interference pattern will disappear. The interference pattern will appear again at point C when the optical path difference becomes to be equal to the integral multiple of the distance between two adjacent wave trains. The area of the continuous grating structures can be expanded by scanning the grating substrate with respect to the interferometer.

The surface form of the fabricated grating structures were measured with an atomic force microscope (AFM) working in the tapping mode. A three-dimensional image and a sectional profile of the grating structures at the most visible grating area are shown in Figures 6. As can be seen in the figures, the pitch of the grating structures is approximately 565 nm, which is very close to the 570 nm designed value. The pitch error is approximately 1 %, which also satisfies the requirement for the surface encoder. On the other hand, the measured depth of the grating structures is approximately 210 nm. When the grating is used for the surface encoder, the depth of the grating structure determines the diffraction efficiency, which influences the signal to noise ratio of the encoder output. Control of the depth of the grating structures, which can be carried out by adjusting the exposure time and development time, will be further investigated in the future experiment. It should be noted that the depth measurement by the AFM is limited by the geometry of the AFM probe tip.

In the measurement shown in Figure 6, the AFM probe tip had a cone shape with a length of 20 μm, a cone angle of 35 degrees and a tip radius of less 12 nm. Based on the geometries of the probe tip and the grating structures, it can be seen that the tip could not reach the bottoms of the grating structures. This means that the measured depth of 210 nm is less than the actual depth. A better way is expected to evaluate the actual depth of the grating structures.

The pitch of the grating structures was also measure by an optical method shown in Figure 7. In this method, a laser beam is projected onto the grating plate. The transparent zeroth-order and first-order diffraction beams are observed on a screen with a distance *h* from the grating plate. The pitch of the grating structures can be obtained by Eq. (7).

$$p = \frac{\lambda_1}{\sin(\arctan\frac{d}{h})} \tag{7}$$

Where, λ_1 is the wavelength of incident laser beam, *d* is the distance between the spot of the zeroth-order diffraction beam and that of the first-order diffraction beam on the screen. In the experiment a 532 nm (λ_1) laser light source was used. The pitch was measured to be 575 nm, which is consistent with that by the AFM.

4. CONCLUSIONS

A 405nm blu-ray laser diode was employed for fabrication of gratings by using the interference lithography method. A Lloyd's mirror interferometer has been constructed for experiment. The system has been designed in such a way that the maximum exposure area was 300 mm^2. Experiments have been carried out to investigate the possibility and limitation of using low-cost and compact blue laser diode for grating fabrication. It has been demonstrated that the system was capable to fabricate 570 nm-pitched grating structures. The relative pitch accuracy was approximately 1 %, which meets the requirement for the scale grating used in a surface encoder.

The influence of the coherence length of the laser diode, which is typically shorter than the conventional gas lasers, has also been investigated experimentally. It has been demonstrated that the continuous grating structures can be generated within an area determined by the coherence length. The continuous grating structures will repeat to appear when the optical path difference between the two interference beams are equal to the integral multiple of the distance between two adjacent wave trains. The area of the continuous grating structures can be expanded by scanning the grating substrate with respect to the interferometer. It is also possible to use a laser diode with a longer coherence length.

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