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ORIGINAL ARTICLE

Method of fabricating an array of diffractive optical elements by using a direct laser lithography

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Abstract

Recently, aspheric lenses have been developed to correct various aberrations and to produce optical elements with various functions. In particular, efforts have focused on fabrication miniaturized and compact elements that make the use of flat, diffractive optical elements such as zone plates to replace conventional lenses. Direct laser lithography is one of the typical methods used to manufacture such diffraction optical elements. By using a high magnification objective lens, it generates a laser beam with a spot size of less than 1 μm at the focal point. To produce a pattern, such as a diffraction grating, a chromium-coated surface is controllably exposed to this light. In this study, the process conditions for fabricating a zone plate using a direct laser lithography were studied by using an air-bearing type linear *XY* stage which can easily make various patterns including a zone plate array. The previous studies using a polar coordinate lithographic system have an advantage for fabricating the circular type zone plate because the system uses a rotational stage. It, however, is not proper to fabricate an array type diffractive optics element. In this study, we used a rectangular type lithographic system by using an *XY* stage and tested the fabrication issues such as a runout error. The optical performance of the zone plate array fabricated by the suggested method was also verified by experimental evaluation.

Keywords Laser lithography · Zone plate · Diffractive optical elements · Computer generated hologram

1 Introduction

Diffractive optical elements can be fabricated by writing a desired pattern on a thin substrate or film. Elements produced this way typically exhibit higher performance and easier integration than conventional refraction optics and therefore have many applications, such as portable imaging devices, head-up displays, and optical pick-up devices. For example, a zone plate is a diffractive optical element composed of a circular diffraction grating that has concentric, alternating transparent and opaque zones. Rays of light from a laser beam transmitted through the transparent zones will interfere with each other and this has the effect of focusing the beam at a desired focal point. Unlike a conventional lens, it is a flat plate [1]. Zone plates have important roles, primarily in the areas of extreme ultraviolet imaging [2] and X-ray imaging applications [3]. In addition, when zone plates [4] are fabricated as an array, they are used in various fields [5] such as optical imaging system [6], microscopy [7], adaptive optics [8], and Shack-Hartmann wavefront sensors [9].

The most commonly used method of fabricating zone plates array is photolithography [10], which has the advantage of being able to mass-produce patterns with the same shape. However, conventional lithography makes it almost impossible to change the pattern shape and size in real time. To overcome these limitations, we fabricated a diffractive optical element pattern using direct laser lithography. Direct laser lithography uses high magnification lithography lenses to write laser beams directly, which makes it possible to fabricate a large area pattern at low cost [11].

2 Experimental setup

In this study, as shown in Figs. 1 and 2, a laser direct exposure system was used to fabricate a diffractive optical element as a

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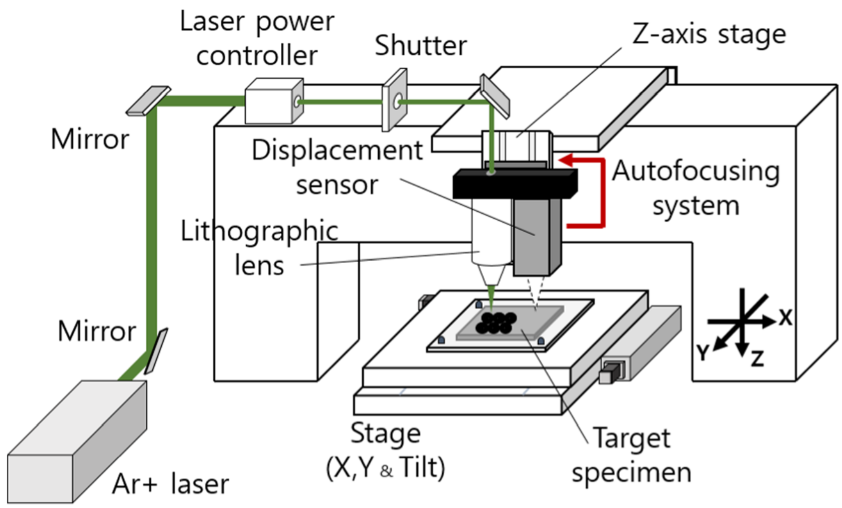

Fig. 1 Schematic diagram of the direct laser lithographic system

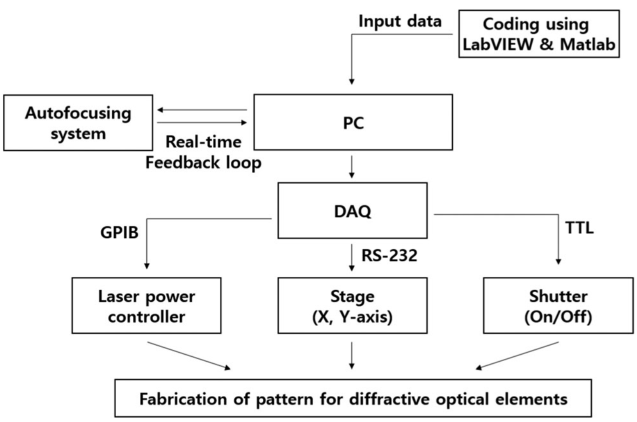

Fig. 2 Block scheme of fabricating patterns for diffractive optical elements; data acquisition (DAQ), general purpose interface bus (GPIB), recommended standard-232(RS-232), transistor-transistor logic (TTL)

zone plate. A laser whose wavelength is 488 nm was used as the lithographic source, and the laser power was stabilized at a level of 0.03% with a controller at the front part of the system [12]. The stabilized laser beam was focused onto the surface of the specimen through a 100× objective lens at 0.7 nA. The specimen was fixed and aligned on a precision stage and a tilt stage driven by an air-bearing linear motor on the X and Y axes.

As shown in Fig. 3, the zone plate was modeled to fabricate the diffractive optical element.

The zone plate is a circular diffraction grating used as a diffractive optical element for focusing. It consists of transparent and opaque zones, as shown in Fig. 3

$$r_n = \sqrt{n\lambda f + \frac{n^2\lambda^2}{4}} \quad (1)$$

$$f = \frac{2r_n \Delta r_n}{\lambda} \quad (2)$$

The transparent and opaque zones that make up the zone plate are determined by Eq. (1) and the position where the diffracted light converges at one point is defined by Eq. (2). f is the focal length of the zone plate, λ represents the wavelength of the laser used for focusing, and n represents the nth zone of the zone plate.

The zone plate is made of a flat plate with no curvature. The line width of the zones decreases with increasing distance

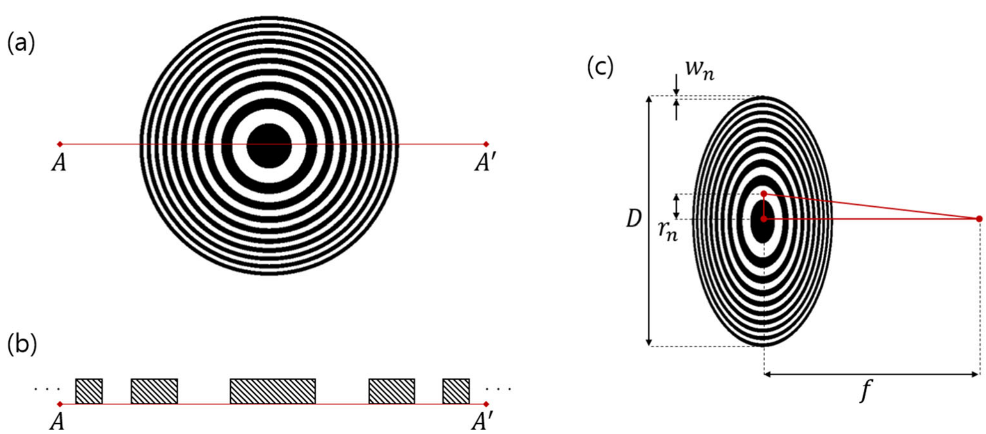

Fig. 3 Modeling zone plate. **a** Top view, **b** section view, and **c** side view

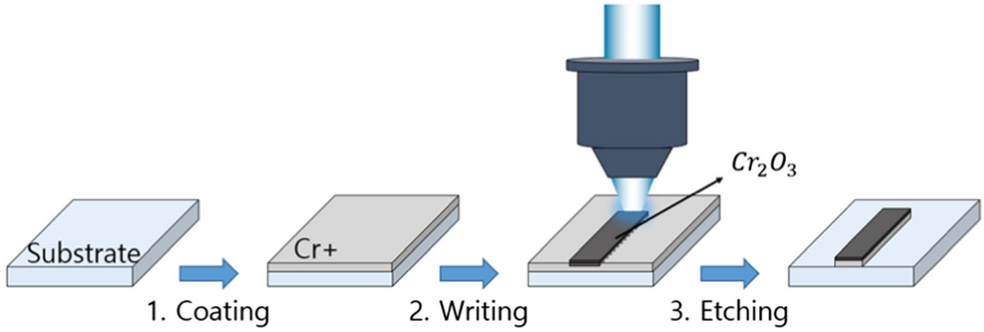

Fig. 4 Mechanism for fabricating diffractive optical elements by using the direct laser lithographic technique [13]

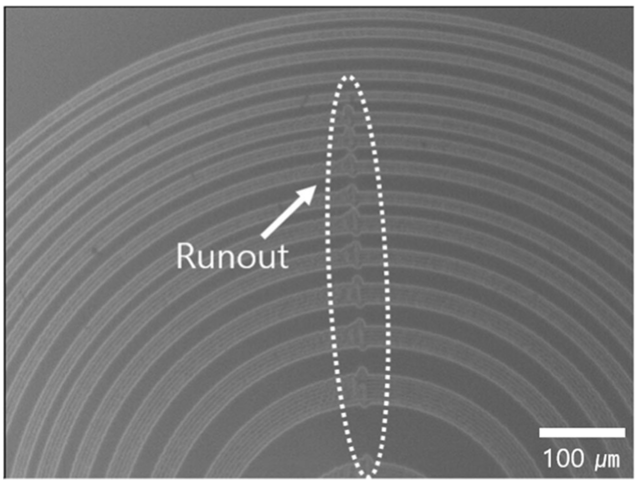

Fig. 5 Photographic view of the runout phenomenon

from the center. The greater the zone number, the higher the diffraction efficiency.

3 Zone plate array fabrication process

In this study, direct laser lithography using the thermal chemical technique was used to fabricate a diffractive optical element [14]. For this method, a glass substrate coated with chromium was used as a specimen, as illustrated in Fig. 4. When a laser is focused on chromium using an objective lens, the chromium thermally reacts with heat and ionizes, and the chromium ions bond with oxygen in the air to form chromium oxide (Cr_2O_3). The exposed specimen is then developed in an etchant consisting of 6 parts of 25% solution of $K_3Fe(CN)_6$

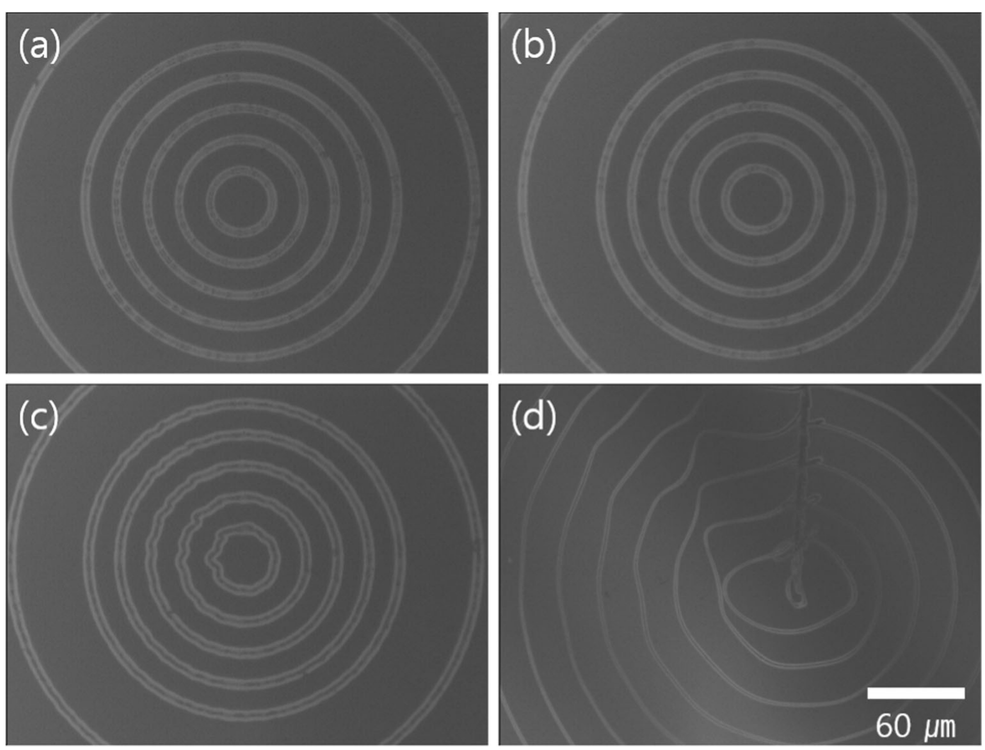

Fig. 6 Experimental results showing the runout phenomenon at writing speeds of **a** 0.1 mm/s, **b** 0.3 mm/s, **c** 1 mm/s, and **d** 10 mm/s

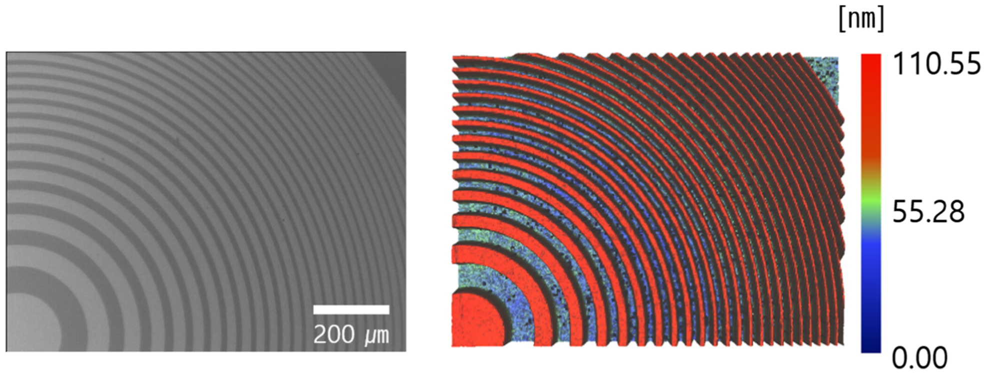

Fig. 7 Measurement of the zone plate using a white-light scanning interferometer after removing the runout phenomenon

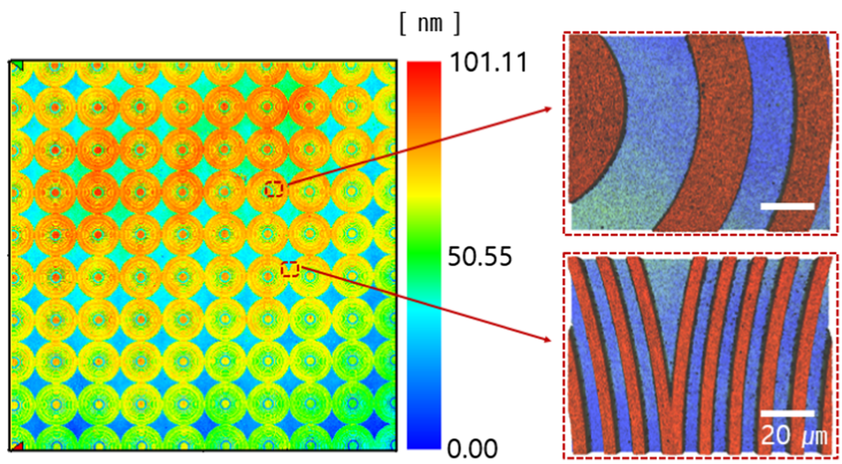

Fig. 8 Measurement of the zone plate array pattern produced using the proposed fabrication technique

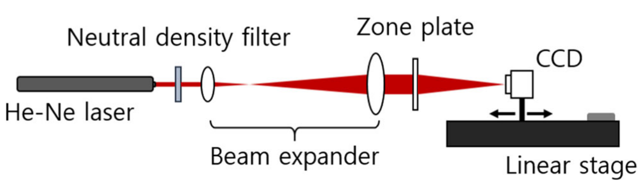

Fig. 9 Schematic diagram of the optical evaluation system

and 1 part of 25% solution of NaOH. After the etching process the desired pattern is washed with DI water and dried.

When fabricating a circular type diffractive optical element such as a zone plate, an undesirable runout phenomenon can be produced, as shown in Fig. 5, depending on the acceleration/deceleration of the stage at the start point and the end point of writing. In this study, the pattern runout phenomenon was experimentally investigated according to the exposure speed to determine the appropriate exposure speed needed to avoid creating the runout.

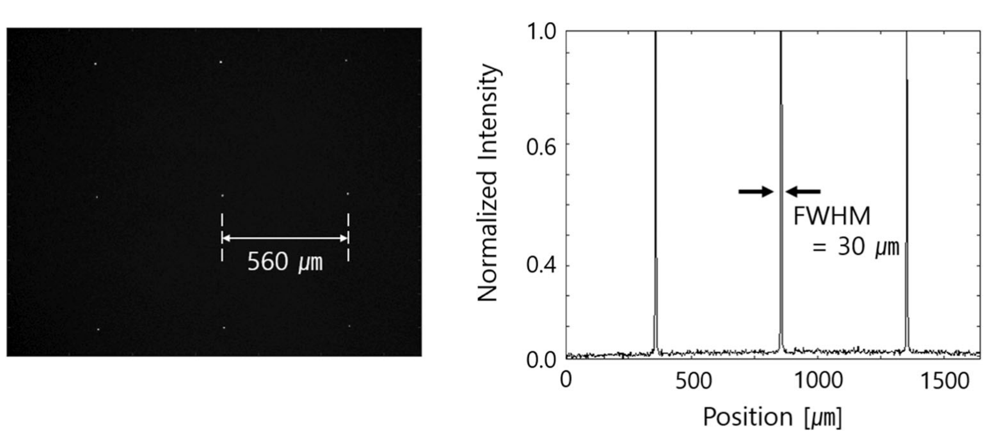

Fig. 10 Diffraction image of the zone plate array in the focal plane

Figure 6 shows the circular type pattern produced at a speed of 0.1 to 10 mm/s. The faster the writing speed, the greater the runout phenomenon of the pattern is. As a result, it was experimentally determined that a constant pattern can be formed at a speed of less than 0.3 mm/s.

To fabricate a pattern with a constant line width, a pattern was made using an exposure speed of 0.3 mm/s and an appropriate laser intensity based on previous studies [15]. The zone plate runout phenomenon was avoided by applying by the processing technique above, and it was confirmed that a constant line width was fabricated.

Figure 7 shows the results when the zone plate was measured by using a white-light scanning interferometer [16, 17]. Process conditions for the zone plate fabrication were found using direct laser lithography. A zone plate array was fabricated, as shown in Fig. 8. The fabricated zone plate has a diameter of 560 μm and a focal length of 5 mm.

4 Optical performance verification of the fabricated zone plate array

A zone plate array pattern was fabricated using the process conditions presented in this paper. To verify the optical performance of the fabricated pattern, optical evaluation system, shown in Fig. 9, was used. The zone plate was examined using a He-Ne laser, and the diffraction image was confirmed by placing a charge-coupled device (CCD) camera at the focal position. A neutral density (ND) filter was used for the appropriate amount of light, and the beam was expanded using a beam expander. By measuring the intensity at the CCD, we confirmed that the point light source was distributed the same distance as the zone plate diameter at the designed focal position, as shown in Fig. 10.

5 Conclusion

In this study, we tried to determined process conditions that can be fabricated by using a rectangular type direct laser lithographic system for a zone plate which is widely used among circular type diffractive optical elements. In particular, we used the *XY*-coordinate stage to effectively produce various types of patterns and repetitive array patterns. We fabricated a zone plate with a small radius concentric circular pattern and observed the runout phenomenon of the circular type pattern. We then determine the optimum fabrication conditions to achieve a constant line width, by combining the writing speed of 0.3 mm/s and appropriate writing intensity. We fabricated a zone plate array with a focal length of 5 mm and a diameter of 560 μm and performed an optical performance evaluation to verify its performance.

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