Lithographic fabrication of large diffractive optical elements on a concave lens surface

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Abstract: We demonstrate experimentally the lithography technique to fabricate a large computer-generated diffractive optical element (DOE) pattern on a concave lens surface with precise alignment by using a laser direct writer. We obtained photoresist film with uniform thickness on the large concave substrate by selecting proper spin-coating parameters, which mainly involve spin rate, spin acceleration, and viscosity of the photoresist. We obtained a square line profile on the concave lens surface. We can write lines that range in width from 0.7 to 10 μm using a single pass of the laser beam. We have designed and fabricated a grating on the concave lens surface using the laser direct writing lithography technique. It is believed that this technique can also transfer large DOE patterns, with a continuous surface relief, onto a convex or concave lens (mirror) surface.

OCIS codes: (220.3740) Lithography; (050.1970) Diffractive optics

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1. Introduction

It is useful in many applications to fabricate large computer-generated diffractive optical elements (DOEs) on curved surfaces such as convex and concave lenses (mirrors) for use in the measurement of convex secondary mirrors, [1] and ultraviolet spectroscopic instruments. [2] There are several approaches to the fabrication of DOEs with continuous surface relief. These approaches include diamond milling, soft lithography, and direct writing [3-6]. Simple

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microstructures can be fabricated by diamond milling, but limited resolution restricts applications to relatively smooth, slowly varying relief structures [3]. Digitization of the desired surface figure, or binary optics as it has been called, has produced a significant breakthrough in the fabrication of DOE devices and, in particular, lens arrays [4]. However, this approach would not work well for the fabrication of DOEs on a curved surface because it is generated by integrated circuit microfabrication technology which can only fabricate pattern on the flat substrate. Soft lithography technology, in which an elastomeric stamp is used to transfer the pattern, has the ability to fabricate DOEs on a curved surface [5]. However, this approach would not work when the pattern needs precise alignment with a curved substrate. Direct writing technologies (laser beam writing or electron-beam writing), in which structures are built directly without the use of masks, allow for rapid prototyping and are of increasing importance in material processing. Direct writing by a focused laser beam, in which accurate control of the process parameters enables a complex continuous-relief microstructure to be fabricated in a single exposure scan and development step, has significant advantages (writing area and scanning speed) over the electron-beam direct writing technology for the fabrication of large DOEs on a curved surface with precise alignment. To overcome the difficulty of processing photoresist on a large curved substrate, one can use the nonlithography technique that was developed at the University of Arizona Optical Sciences Center [6] . The technique involves thermally selective oxidization to transfer a large DOE pattern onto a metallic film on a curved substrate. However, the line profile produced with this nonlithography technique is of inferior quality in comparison with that produced by use of lithography.

2. Fabrication and Characterization

We demonstrate the use of lithography to transfer a large DOE pattern onto a concave lens surface with precise alignment by using a laser direct writer. The substrate is 110 mm in diameter and has a radius of curvature of 504 mm. To our knowledge this is the first time that a laser direct writer has been used to transfer with precise alignment a large DOE pattern onto a concave lens surface by means of lithography. It is believed that this technique can also transfer large DOE patterns with a continuous surface relief onto a convex or concave (mirror) surface.

We have designed and fabricated a large concentric circular grating on a concave lens surface using the laser direct writing lithography technique. The fabrication began by spin coating a photoresist onto the concave substrate surface. To overcome the obstacles of coating uniform photoresist film on a large concave substrate, we built equipment that allowed us to coat substrates as large as 400 mm in diameter. One can obtain photoresist film with uniform thickness on a large concave substrate by proper selection of the spin-coating parameters, which mainly involve spin rate, spin acceleration, and viscosity of the photoresist. For our experiment we used the Shipley S1813 Microposit developer, which we diluted with Shipley Type P Microposit thinner in a volume ratio of 1:4 mliter (photoresist:thinner). The photoresist was dispensed in liquid form onto a concave substrate with a 504-mm radius of curvature. The spin rate was controlled to reach 4000 rpm within 15 s. A uniformly thick substrate was obtained after it was subjected to a spin rate of 4000 rpm for 60 s. The photoresist film was approximately 0.9 μm thick. Before UV exposure, we prebaked the sample in a 90° C oven for 30 min to remove the excess solvent and to improve the adhesion of film to substrate.

A schematic diagram of our laser direct writing system is shown in Fig. 1. It should be noted that we used a 150-mW He–Cd laser at a wavelength of 442 nm. Stage movement was controlled to a precision of 0.1 μm in three Cartesian axes by use of feedback from distance measurements with linear encoders from Heidenhain GmbH.

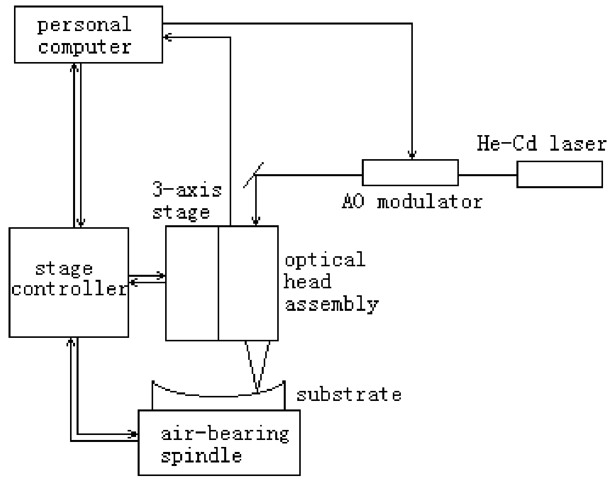

Fig. 1. Schematic of our laser direct writer.

The concave substrate coated by photoresist film is aligned with the air-bearing spindle by means of a high-precision alignment apparatus [7]. In this system, a binary phase grating is used as the beam splitter. The 632.8-nm wavelength laser beam, after it passes through the grating only to first orders, is rereflected by the lens surface, recombined by the same grating, and shows that good contrast interference fringes can be attained. When the lens together with the spindle is rotated, the interference fringes remain motionless only when the lens rotates around its axis of symmetry. If the lens rotates around an axis of asymmetry, the fringes will move. We used a CCD camera to monitor the fringes. A precise alignment of less than 1 μm can be achieved with our experiment. The grating constant and the lens relative aperture ultimately determine the centering accuracy. We aligned the axis of the optical head assembly with the air-bearing spindle's center of rotation by means of spinning a diffraction grating [8].

When the concentric DOE patterns are written, the three-axes stage is used to position the writing beam at the proper radial location on the substrate and to adjust for correct focus. While writing one ring of a circular pattern, all three axes of the stage are held stationary and we used the spindle to rotate the substrate under the focused laser beam. The radial locations and width of the rings that form the DOE pattern are stored in a data file that is accessed by the control software. The proper power levels and the focal position required with respect to the curvature of the surface are also stored in the data file. The spin rate of the air-bearing spindle can range from 60 rotations/min to as much as 600 rotations/min. By selecting the proper focal diameter and the correct laser power level we can write lines that range in width from 0.7 to 10 μm by using a single pass of the laser beam. When wider lines are required they can be formed if we overlap consecutively written traces by 30%.

Using an atomic force microscope we evaluated the line profiles of the grating with a 10-μm period produced by laser direct writing lithography. A three-dimensional plot of the line profiles is shown Fig. 2, and a two-dimensional plot of the line profiles is shown in Fig. 3. The square line profiles can be achieved with our experiment. However, the line profiles produced by thermally selective oxidization fall somewhere between a sinusoidal and a square shape [6]. A higher-quality line profile and fabrication efficiency are achieved with our technique compared with that produced by thermally selective oxidization.

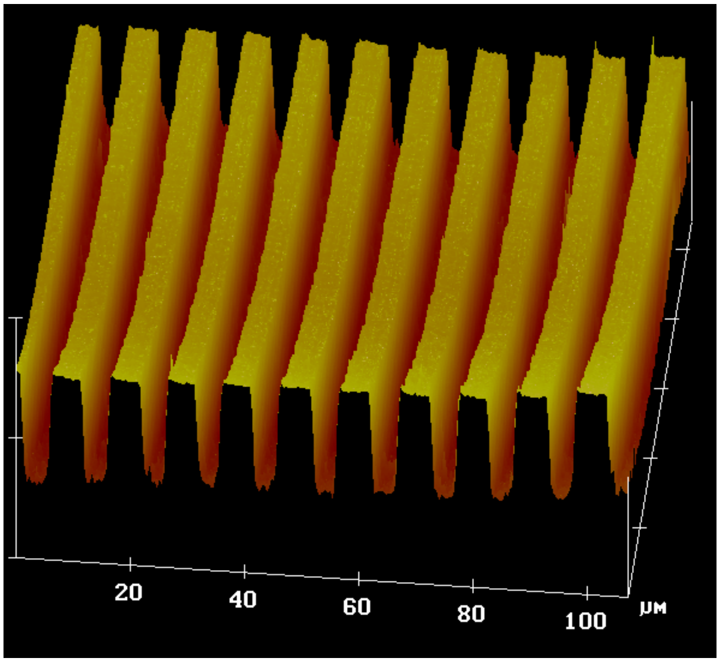

Fig.2 Three-dimensional plot of the grating profile.

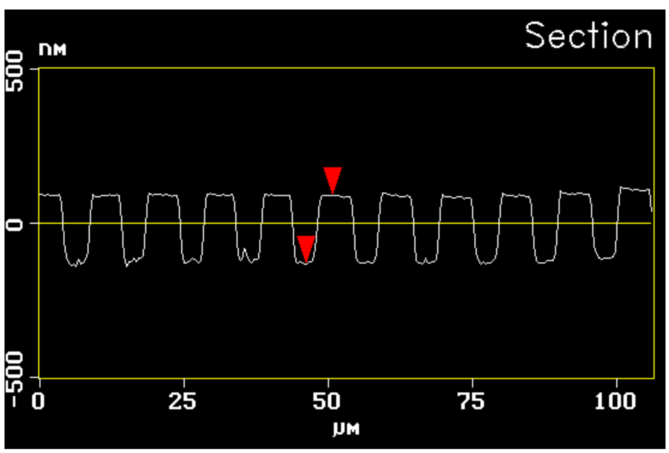

Fig.3 Two-dimensional plot of the grating profile.

We believe that the character of resist thickness variety in the radial coordinate direction after develop can represent that before develop because the develop rate of all the points on the whole unexposured film surface is same in the develop process. Using an atomic force microscope we evaluated the resist thickness after development at several random points in the radial coordinate direction. The results show that the resist increased in thickness from the center to the edge in the radial coordinate direction on a concave lens surface. The change of the resist thickness was 0.041 μm from the center to a distance of 50 mm (the margin of the lens is 5 mm of the radius) in the radial coordinate direction. The thickness variation in the

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radial coordinate direction of an approximately 0.9-μm-thick resist film before development can be considered to be 0.041μm.

3. Conclusion

In conclusion, we have fabricated a concentric circular grating on a concave lens surface by using laser direct writing lithography. The line profile produced by laser direct writing lithography is of higher quality compared with that produced by thermally selective oxidization. It is believed that this technique can also transfer large DOE patterns with a continuous surface relief onto a convex or concave lens (mirror) surface.

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