Lithographic fabrication of diffractive optical elements in hybrid sol-gel glass on 3-D curved surfaces

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Abstract: We demonstrate the lithographic fabrication of diffractive optical elements (DOEs) in hybrid SiO_2/TiO_2 sol-gel glass on 3-D curved surfaces. The concentric circular gratings with periods of 20μm, 10μm and 5μm have been fabricated in sol-gel glass on concave lens by laser direct writing successfully. Continuous 3-Dimensional surface relief with a height of 435nm, 110nm and 50nm has been obtained for the period of 20μm, 10μm and 5μm respectively. The optical test results of the fabricated DOE shows only a little bit deviation from the theoretical calculated results which can be explained by 3-D curved surface effect. We believe this technology can be an effective method to fabricate DOEs with even more complex surface profile on 3-D curved surfaces in terms of its simplicity and cost-effectiveness.

OCIS codes: (220.3740) Lithography; (050.6875) Three-dimensional fabrication; (220.4000) Microstructure fabrication; (050.1970) Diffractive optics.

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1. Introduction

Diffractive optical elements are widely used in many areas such as hybrid refractive-diffractive imaging systems, measurement of convex secondary mirrors, ultraviolet spectroscopic instruments, and test large-aperture convex aspheric surface [1–3]. Several technologies including diamond milling, soft lithography and laser direct writing can be adopted to fabricate DOEs with continuous 3-D surface relief structures on 3-D curved surfaces [4,5]. Diamond milling can fabricate the simple microstructures, but the limited resolution restricts its applications to the fabrication of the relatively smooth, slowly varying relief structures [4]. 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 needs to overcome the difficulty of precise alignment with a curved substrate. Laser direct writing, which enables a complex continuous-relief microstructure to be fabricated in a single exposure scan, can precisely control the process parameters. Therefore, it has a great advantage over the other technologies for the fabrication of DOEs on a curved surface with precise alignment. Recently, the authors of Ref [6] made some advance in laser lithography on non-planar surfaces and claimed that they can produce nearly arbitrary high quality nonperiodic structures.

It is well known that the hybrid sol-gel material has been used for the fabrication of micro-optical elements such as phase holograms, kinoform lenses and blazed gratings in a single step due to its good optical properties, cost effectiveness, and process simplicity. In the past decade, various hybrid sol-gel materials and fabricating methods have been reported. The authors of Ref [7,8] presented the fabrication of gratings in SiO_2/ZrO_2 based sol-gel by employing contact imprinting and optical interference techniques. Rantala *et al* demonstrated the fabrication of surface relief diffractive grating in the SiO_2/ZrO_2 sol-gel glass using direct variable-dose electron-beam lithograph [9]. A SiO_2/TiO_2 sol-gel glass was also developed to fabricate saw-tooth gratings by the direct laser writing and microlenses by using the high-energy beam-sensitive (HEBS) gray scale mask [10,11]. Fuhua Zhao *et al* reported the fabrication of microlens arrays with hybrid HfO_2-SiO_2 sol-gel glass on conventional lens surface [12]. We have demonstrated that a large computer-generated DOE pattern can be fabricated in photoresist coated on a concave lens surface by using laser direct writing method [13,14]. However, a further dry etching step is normally needed to transfer the photoresist pattern into the glass substrate, which will make the fabrication process more complex and time consuming.

In this paper, the fabrication of DOEs in hybrid SiO_2/TiO_2 sol-gel glass on 3-D curved surfaces by laser direct writing is reported. The fabricated DOEs are optically characterized and compared with simulation results. To our knowledge, this is the first time that the DOEs are fabricated in sol-gel material on 3-D curved surfaces by laser direct writing method.

2. Fabrication and characterization

The detailed synthesis process of the hybrid SiO_2/TiO_2 sol-gel material used in this work can be found elsewhere [15]. To make the hybrid sol-gel material photosensitive, 4% of photoinitiator (bis(cyclopenta-1,3-diene)bis(1-(2,4-difluorophenyl)-3H-pyrrol-3-yl)titanium) is added into the final homogeneous sol solution so that it is photosensitive to a wavelength of 442nm. The sol-gel material is spin coated onto the concaved glass substrate with a diameter of 40mm and a curvature radius of 196mm. Film thickness of as large as 550nm can be obtained with a spinning speed of 3000rpm and spinning time of 40s. The refractive index of the sol-gel film is measured to be 1.52. Before exposure, the sample is pre-baked on a hotplate at 65°C for 15mins and 95°C for 10mins sequentially to remove the excessive solvent and

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improve the adhesion of the sol-gel film to the glass substrate. After exposure, the sample is developed in the isopropyl alcohol for 2mins to remove the unexposed area to reveal the patterns written by laser direct writer. Finally, the sample is post-baked on a hotplate at 160°C for 60mins for further solidification.

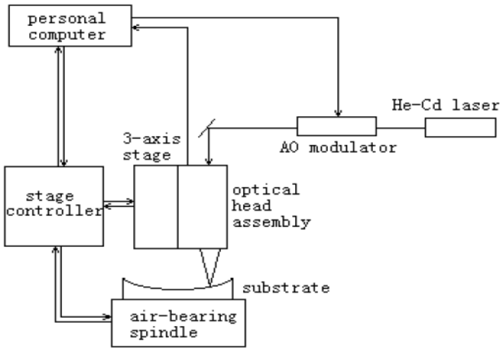

Fig. 1. Schematic of laser direct writer

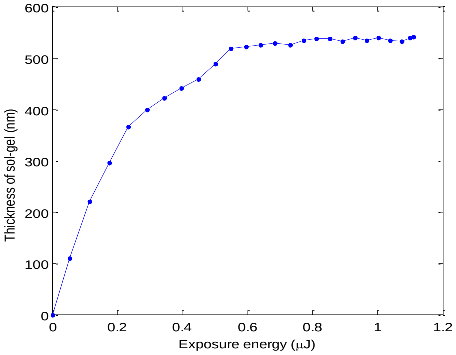

Fig. 2. The thickness of sol-gel film against the exposure energy

Figure 1 shows the schematic of our laser direct writer. Where a 150mW He-Cd laser at wavelength of 442nm is used to write the DOEs. Stage movement is 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. The alignment of the DOEs is determined by the precise alignment between the optical system that focuses the laser beam onto the substrate and the air-bearing rotating mechanical system. While the alignment of the optical system with the mechanical axis is realized by employing the grating phase modulation methods which is reported in detail in Ref [16]. A misalignment error of less than 0.5μm can be easily achieved by using this method in our experiment, which is small enough to meet the application demand of the fabricated DOEs, such as the test of the large-aperture convex aspheric surface [3]. The output laser power is controlled by an acousto-optic modulator (AOM) which is connected to a personal computer operated by an operator. Through AOM, the exposure energy of the laser beam can be tuned precisely. To characterize the relationship between the polymerized film thickness of sol-gel material and exposure energy, a concentric circular grating with 25 zones and 50μm period is written, and every zone is exposed at different energy. The patterns written by the laser direct writer are measured by a surface profiler, and the result is shown in Fig. 2. It can be seen from Fig. 2 that the thickness of hybrid sol-gel glass increases with the exposure energy of the laser beam increasing from 0μJ to 0.55μJ, and then keeps almost invariable when exposure energy is higher than 0.55μJ.

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In the fabrication process of the DOEs on concave lens surface by using the laser direct writer, the exposure energy of 1.0μJ, 0.2μJ and 0.1μJ is used to write the concentric circular grating with period of 20μm, 10μm and 5μm respectively in sol-gel film coated on concave lens surface. The surface relief height of the fabricated DOE is 435nm, 110nm and 50nm for period of 20μm, 10μm and 5μm respectively. Figure 3 gives a panorama of the fabricated DOE on concave lens surface. As can be seen in Fig. 3 that there is a blank circular area with 2mm diameter in the center of the concave lens without grating structure. The reason for the existence of the blank area is that the lower output power of laser beam is chosen by AOM to write the grating zone at smaller radius due to the exposure energy must be invariable for every zone and the rotate speed of mechanical system is constant. In our experiment, when the radius is less than 1mm, the needed power is so low as to reach the lowest limit of the AOM. This issue can be settled by increasing the exposure energy, but it is difficult to write smaller period structure (such as 5μm) using the higher exposure energy. Figure 4 shows the 200 × images of the DOEs fabricated in the hybrid sol-gel glass on the concave lens surface captured by optical microscope. Figure 5 to Fig. 7 show the 3-D and 2-D profiles of the fabricated DOEs measured by atomic force microscope (AFM). As can be seen from Fig. 5 to Fig. 7, the smaller the period, the lower the surface relief thicknesses of the fabricated microstructures in sol-gel due to the proximity effect.

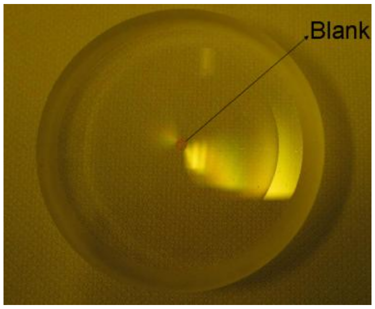

Fig. 3. Photo of the fabricated DOE on concave lens surface with the curvature radius of 196mm.

Fig. 4. 200 × magnified images of the fabricated DOEs with the period of 20μm (a), 10μm (b) and 5μm (c) captured by optical microscope.

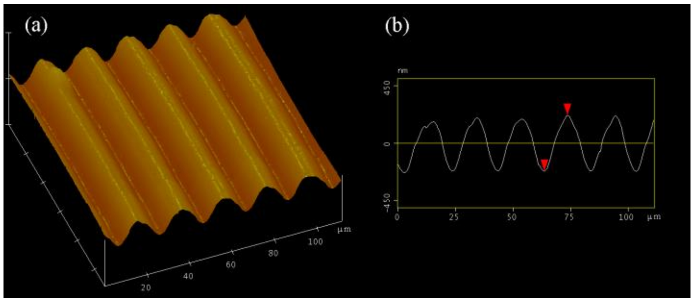

Fig. 5. 3D (a) and 2D (b) surface profiles of the fabricated DOE with 20µm period measured by AFM.

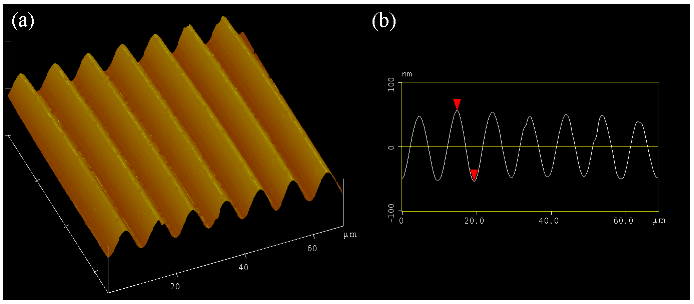

Fig. 6. 3D (a) and 2D (b) surface profiles of the fabricated DOE with 10µm period measured by AFM.

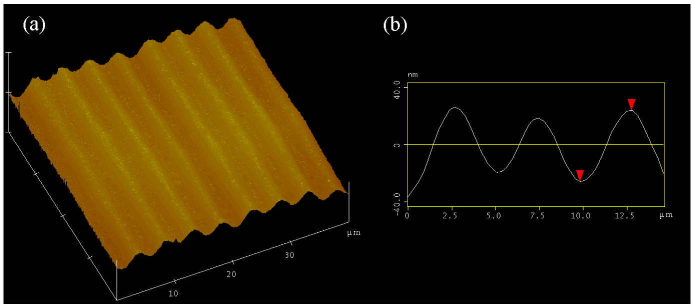

Fig. 7. 3D (a) and 2D (b) surface profiles of the fabricated DOE with 5µm period measured by AFM.

3. Optical test results and discussions

To characterize the optical property of the fabricated DOEs in sol-gel on curved substrates, a He-Ne laser with a 1.5mm-diameter beam is used to illuminate the DOEs fabricated on the surface of the concave lens to generate the diffractive pattern. As the center of the sample is blank, the laser beam does not illuminate the center of the sample and that is to say the laser beam does not coaxis with the optical element during the optical testing, and the beam goes through the DOE before the substrate. The diffractive patterns of the fabricated DOEs on 3-D curved substrate received by a white plane screen are shown in Fig. 8. As can be seen in Fig. 8, the actual diffractive pattern is similar to the one generated by the curved grating on a planar surface, except that the focus of the different diffraction order lies in different plane, and the pattern is symmetric in one direction with the higher the order, the larger the focusing spot. As shown in Fig. 8(a), the sample with 20µm period shows the strongest diffractive effect and more than ten diffraction orders can be observed. However, only five diffraction orders can be observed for the samples with 10μm and 5μm period, as shown in Figs. 8(b) and 8(c), due to their small step height and thus very weak diffractive effect.

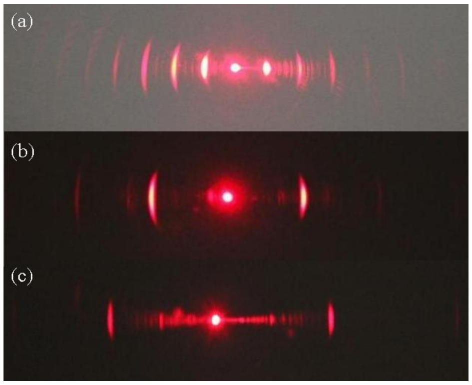

Fig. 8. Diffractive patterns of the fabricated DOEs with period of 20μm (a), 10μm (b) and 5μm (c).

The diffraction efficiency of seven orders are measured for the sample with 20μm period by a power meter with a resolution of 0.01μW and an effective detecting area of more than 100mm^2. The detecting area of the power meter is big enough to cover the spots though the beam spot of some higher orders is not well focused into a small dot. The measurement result is compared with the theoretical result simulated by a diffractive model which employs the rigorous coupled wave analysis method. The calculated and measured diffraction efficiency of seven diffraction orders are listed in Table 1. As shown in Table.1, there is a little bit deviation between the theoretical and experimental result. The reason is that the simulation model is based on 2-D planar substrate but not 3-D curved substrate. As the radius of curvature of the concave lens is as large as 196mm and the laser beam spot is only 1.5mm, thus the tested part of the DOE on the concave lens surface can be regarded as a planar grating approximately without major discrepancy. A new diffractive model is yet to be established to fully understand the diffractive effect of the DOE on a 3D curved substrate.

Table 1. Calculated and measured diffraction efficiency of the fabricated DOE with 20μm period.

Diffraction order	–3	–2	–1	0	1	2	3
Calculated diffraction efficiency	0.0003	0.0154	0.1968	0.5359	0.1968	0.0154	0.0003
Measured diffraction efficiency	0.0026	0.0167	0.1825	0.4653	0.1440	0.0103	0.0013

4. Conclusions

The new contribution of the work lies in the single step fabrication of sol-gel DOEs on a 3-D concave surface by using laser directing method. The fabricated hybrid optical elements can be applied for the aspherical surface optical testing, or it can be used to fabricate DOEs with a continuous surface relief on a refractive lens surface to fulfill the purpose of correcting the achromatic aberration of the optical system. The former application has been demonstrated by our team [3]. The latter application is being pursued by our research team right now and further work will be published soon. However, further work needs to be done to optimize the process to achieve DOEs with a high aspect ratio to make this technology more attractive.

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