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Fabrication of Silicone Grating Using a Photoimprinted Polymer Mold and Period Control by Mechanical Distortion

Takaaki Ishihara[1], Itsunari Yamada[1], Junichi Yanagisawa[1], Kentaro Koyama[2], Takuma Inoue[2], Junji Nishii[3], and Mitsunori Saito[2]

[1] Univ. of Shiga Pref.
Hassaka-cho, Hikone, Shiga, 522-8533, Japan
[2] Ryukoku Univ.
Seta, Otsu, Shiga 520-2194, Japan
[3] Hokkaido Univ.
Sapporo 060-0812, Japan

Abstract

We fabricated a tunable transmission grating by molding a silicone elastomer (polydimethylsiloxane), and evaluated its optical characteristics during a compression process. A glass plate with a photoimprinted polymer grating film was used as a mold. The grating period of the molded elastomer was measured as functions of the compressive stress. The grating period changed from 3.02 to 2.86 µm by compressing the elastomer in the direction perpendicular to the grooves.

1. Introduction

Recently, elastomers have been studied in optical devices to realize mechanical or electrical control of a periodic structure. Particularly, tunable optical devices such as a lens [1], waveplate [2], waveguide [3], laser [4], and grating [5,6] have been developed using silicone elastomers or gels. Regarding gratings using silicone, control of the diffraction angle by external strain of stretching or compressing has been reported. Regarding a transmissive grating using transparent silicone elastomer, however, no discussion of the compressed grating and diffraction angle or diffraction efficiency has been reported. Furthermore, some pieces of damaged silicone left on the mold surface after imprinting cannot be removed irrespective of immersion in organic solvent because this material is chemically stable. Therefore, the life of the expensive mold becomes short.

In this study, we fabricated a silicone grating by molding process using the polymer mold fabricated by photoimprinting, which can be fabricated very easily and low costly, and examined the relationship between the grating period and deformation by compression of the direction perpendicular to the grating axis.

2. Experiment and results

Figure 1 shows a schematic diagram for the formation of a grating on the surface of silicone by imprinting using a silicon carbide (SiC) mold. The process is composed of three main steps: preparation of the master mold with a SiC substrate, photoimprinting of polymer using the SiC mold, and molding of silicone solution using the fabricated polymer mold. A SiC substrate of 25 × 25 × 2 mm^3 size (Admap Corp.) was used for the mold because of its hardness [7,8]. The photoresist was coated onto the SiC substrate coated onto a WSi film using sputtering method and was exposed by drawing of He-Cd laser (442 nm wavelength) beams for generation of the 3 µm pitch grating structure. After development of the exposed resist, the WSi mask layer and the SiC substrate were patterned using inductively coupled plasma reactive ion etching. The WSi mask layer and the SiC substrate were etched, respectively, using SF_6 and CHF_3 gases. The etching conditions were adjusted to fabricate the tapered grating considering the secure demolding [7,8]. Figure 2 presents scanning electron microscope (SEM) photographs of the fabricated SiC mold. The mold was a one-dimensional periodic tapered structure with 3 µm pitch, 1.8 µm depth, and a fill factor of 0.4, as presented in Fig. 2.

The polymer grating structure was fabricated by photoimprinting a photocurable monomer on the glass substrate. The SiC mold surface was treated with a releasing agent of a fluoroalkylsilane (EGC-1720; 3M Co.). Imprinting was conducted through photopolymerization of the monomer (PAK-01; Toyo Gosei Co. Ltd.) by ultraviolet irradiation (365 nm wavelength).

To fabricate tunable silicone grating, a commercial curing silicone elastomer (KE-103, Shin-Etsu Corp.) was used because of a transparent, chemically stable, and elastic material. This silicone elastomer can be cured by adding a curing agent to the raw liquid. It was carefully mixed with 5% of curing agent and air bubbles were removed by putting the liquid mixture. The mixture was poured onto the fabricated polymer mold, which consisted of the fabricated grating with ~3 µm period. After putting it at room temperature for 1 day, the molded grating was peeled off the polymer mold. Figure 3 shows an optical microscope image of an across-sectional view of the fabricated silicone grating. The mold pattern was successfully transferred to silicone elastmer at least 8 × 8 mm^2 area uniformly. As shown Fig. 3, the grating with 3 µm pitch and 1.24 µm depth, and a fill factor of ~0.6 was successfully obtained on the silicone elastmer surface. The fabricated silicone grating profile was sinusoidal. Considering optical evaluation, the sample size was adjusted to around 10 × 10 × 10 mm^3 to deform the fabricated grating.

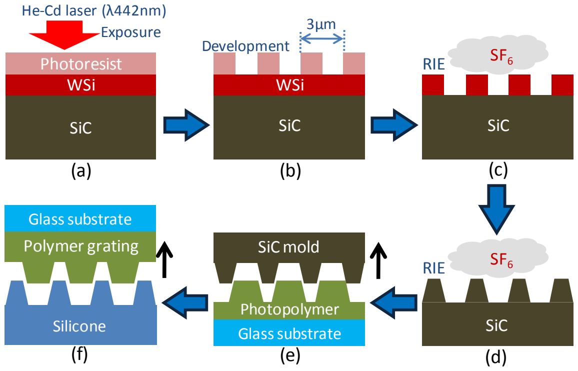

Fig. 1. Schematic illustration of the fabrication process of the silicone grating. (a) After a WSi layer is deposited on a SiC substrate by using the sputtering method, a photoresist is coated on the WSi layer, and the He-Cd laser beam is irradiated by the drawing system. (b) A photoresist grating is patterned by the development. (c), (d) The WSi layer and a SiC are etched by using the RIE. (e) The SiC mold is imprinted into photopolymer film on a glass plate. (f) The fabricated polymer mold is imprinted into silicone solution.

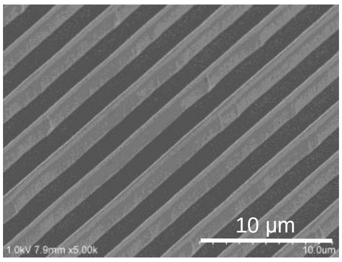

Fig. 2. SEM images of the SiC mold.

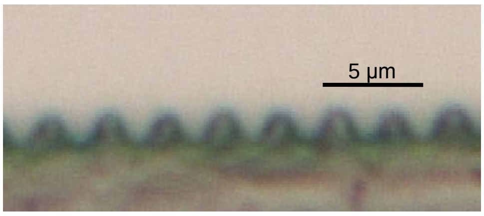

Fig. 3. Cross-sectional image of the fabricated silicone grating.

3. Optical evaluation

The deformation effect was studied by pressing the sample sides with a micrometer. The fabricated elastomeric grating is mounted on a clamp holder. The clamp holding the fabricated silicone grating is attached to a screw mechanism. When that is turned manually, the silicone grating is compressed in one direction. In the current experiment, the silicone grating was pressed in the direction perpendicular to the grating axis. As the sample width (10.30 mm) decreases, the grating period shrinks in the same direction and the diffraction angle expands.

The diffraction angle of each compression was measured at a wavelength of 632.8 nm wavelength (He-Ne laser). This beam was incident to the fabricated element at normal incidence. Diffraction angles show good agreement with the diffraction equation shown below.

$$m\lambda = d \sin \theta \qquad (1)$$

where m is the diffraction order, λ is the wavelength of the incident laser beam which here is 632.8 nm, and d is the grating period. The grating period was evaluated by measuring the diffraction angle of the fabricated element, and the first order diffraction angle of each grating was calculated using eq. (1).

The element was pressed from the side with a micrometer; i.e., the fabricated sample was deformed from 10.30 mm width to 9.35 mm width, that is, the compressing ratio was 9.2%. The compression ratio of the measured periods did not agree with the theoretical values. As a result of period calculations using the above equation, the grating period changed from 3.02 μm (measured diffraction angle; 12.1˚) to 2.86 μm (12.8˚) under 9.2% strain, and we found that the change of grating period was 0.16 μm.

4. Discussion

As the fabricated element is pressed up to 9.2% compression, the angle of first order diffraction was spread, and the period shrunk from 3.02 μm to 2.86 μm. When we observe the period for the compressions of 0 mm and 0.95 mm using an optical microscope, the values calculated by eq. (1) corresponded well to these values. This means that the compression ratio of the grating period did not correspond to that of sample. This difference might be due to the convex distortion of the silicone grating. We infer that this distortion caused longer period than our assumption.

5. Conclusions

We fabricated a tunable transmission grating by molding process onto a silicone elastomer, and evaluated optical characteristics in case of compression of the fabricated element. We fabricated the grating pattern on a silicone surface by molding process with the polymer mold fabricated by photoimprinting process, which can be fabricated very easily and low costly. We also examined the relationship between the grating period and compressive stress to the fabricated element. Consequently, we succeeded in changing the period from 3.02 μm to 2.86 μm by compressing the fabricated element.

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