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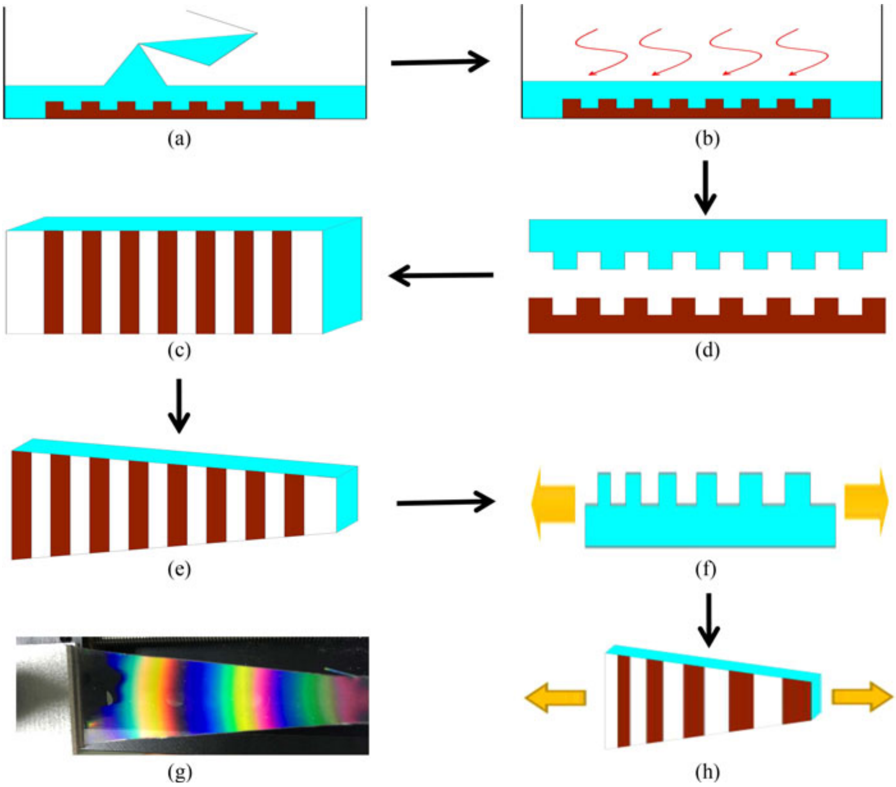

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Tailorable Elastomeric Grating With Tunable Groove Density Gradient

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Abstract: This paper describes a new method for fabrication of tailorable elastomeric gratings with tunable groove density gradients based on stretching of the grating sample in a direction perpendicular to the grating line within the grating surface. The advantage of this method is that the tunable groove density gradient can be achieved by tailoring of the shape of a grating sample with uniform thickness. The groove density gradient changes as a specific function of its spatial position on the tailored surface of the elastomeric grating. The resulting tailorable elastomeric gratings can be used in the fabrication of devices such as optical position sensors and tunable optical filters.

Index Terms: Diffraction gratings, gratings, polymers.

1. Introduction

Elastomeric lenses, mirrors and gratings are important optical elements that are used in the fabrication of compact and portable devices based on adaptive optics [1]–[10]. Among the numerous optical elements available, diffraction gratings are widely used in the fields of spectroscopy, optical measurement, optical information processing, and optical communications. When compared with ordinary gratings with equal groove spacing, the groove periods or groove densities of these gratings can be varied by following specific rules, and they have some special properties, including self-focusing, aberration correction and high resolution capabilities [11]–[15]. The main manufacturing methods used for variable-period gratings include mechanical ruling and holographic lithography. The drawbacks of the use of mechanical ruling for grating fabrication are that the grating period is changed discontinuously and the gratings are fabricated inefficiently. Holographic lithography offers the ability to fabricate continuously-variable-period gratings efficiently and the technology is suitable for the production of large-diameter, high-linear-period, variable-period gratings. Xie *et al.* also attempted to fabricate variable-line-spacing gratings on plane surfaces by direct laser writing [16], [17].

Many researchers have focused on fabrication of variable-period gratings on elastomeric materials such as polydimethylsiloxane (PDMS) [18]–[21]. Whitehead and Clark generated variable-spacing diffraction gratings using elastomeric surface waves [18]. Xie *et al.* obtained variable-period

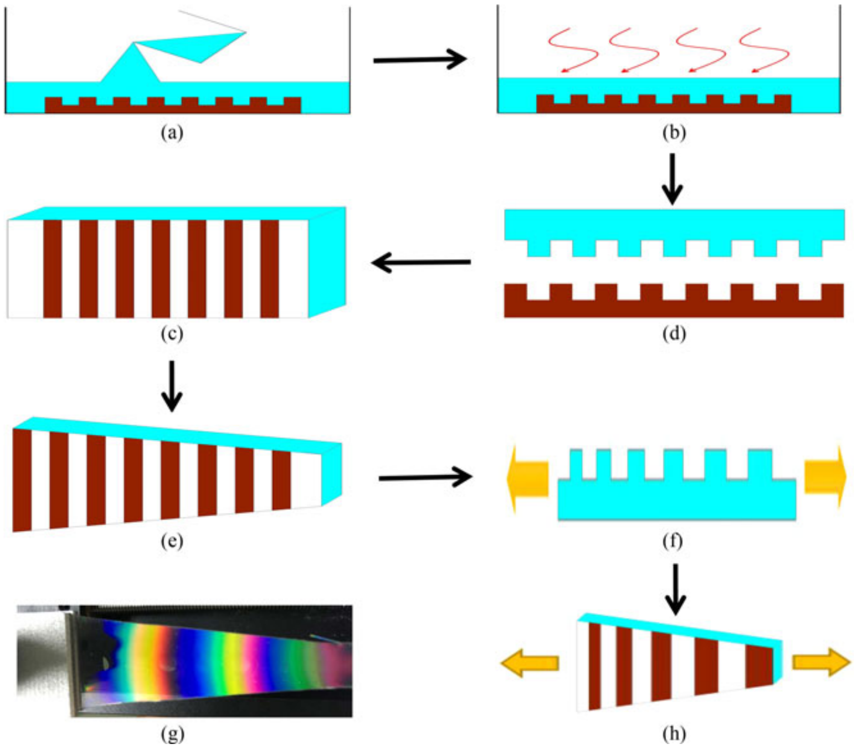


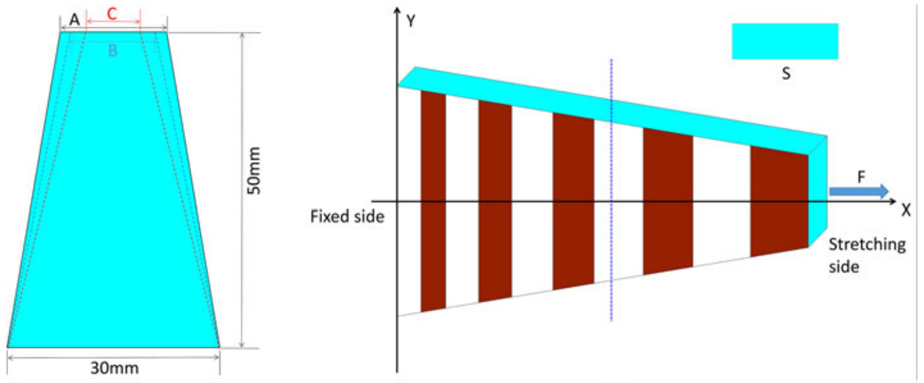
Fig. 1. The procedure for fabrication of a tunable varied-period PDMS grating. (a) Casting PDMS mixture with weight ratio of 1:20 on a master grating; (b) baked at 100 °C for 2 hours; (c) separation the PDMS grating from the master grating; (d) the schematic of the PDMS grating; (e) tailoring the PDMS grating into different trapezoidal shapes; (f) stretching the PDMS grating; (g) the schematic of the stretched PDMS grating with varied period; (h) the real picture of the stretched PDMS grating.

gratings by stretching equidistant gratings formed on wedge-shaped elastomeric materials [19]. Other researchers fabricated tunable guided-mode resonance filters by casting stretched PDMS gratings with wedged cross-sections oriented perpendicular to the grating lines [20], [21]. In this paper, we describe a new method for fabrication of tailorable elastomeric gratings with uniform thickness that have a tunable groove density gradient based on stretching of the PDMS grating sample within the grating surface. Due to the great ability of reversible elastic deformation of the PDMS material and the maximum tensile of excellent elastic PDMS is 120%, the deformation and optical properties of PDMS grating sample are reversible.

2. Fabrication and Characterization

2.1 Fabrication and Theory

The procedure for fabrication of gratings with tunable groove density gradients is shown in Fig. 1. First, a mixture of a curing agent and a silicone elastomer (Dow Corning Sylgard 184) with a weight ratio of 1:20 was poured into a Petri dish, in which a master grating with a uniform grating period was fixed; the surface of the mixture is maintained at 1 mm above the grating surface. Second, the Petri dish was placed in a vacuum machine to remove any micro-bubbles from the liquid-state mixture and caused the viscous PDMS liquid to infiltrate into the microstructure of the master grating. The Petri dish was then moved into a vacuum oven, and after baking at 100 °C for 2 h, the PDMS was completely solidified and could be separated from the master grating. The elastic PDMS film had a uniform grating period on its surface and the thickness of the sample was 1.1 mm. The PDMS film was then tailored into different trapezoidal shapes, and was stretched in a direction perpendicular to the grating line within the grating surface. The groove density of the tailored PDMS grating thus



(a) (b)

Fig. 2. (a) A, B, C are three different sizes trapezoid-shaped PDMS grating with top lines of 24 mm, 18 mm, 12 mm; (b) the simplified model of the deformation of trapezoid-shaped PDMS grating.

varied according to the stretched planar width of the PDMS. A photograph of a real stretched PDMS grating with variable period is shown in Fig. 1. In Fig. 1(h), the grating line was a little bend due to the shrinkage by the two side edges of PDMS grating, under a few values of applied pulling force.

In our experiments, a diffraction grating with a uniform groove density of 600 gr/mm was used as the master mold. PDMS gratings were replicated from the master mold with a homogeneous thickness of 1.1 mm. Then, the PDMS gratings were tailored into the three different trapezoidal shapes of samples A, B and C, as shown in Fig. 2(a). The lengths of the top lines of trapezoidal samples A, B and C were 24 mm, 18 mm and 12 mm, respectively. The three samples had the same height of 50 mm and the same base line length of 30 mm. We then fixed the base line of each trapezoid-shaped PDMS grating and stretched its top line. To form gratings with groove density gradients, these trapezoid-shaped PDMS gratings were stretched with a force of 2 N acting perpendicular to the grating line within the grating surface, as shown in Fig. 2(b).

The groove density variation of each PDMS grating is related to the strain on the material during the stretching process. This strain ε is inversely proportional to the elastic modulus E and the cross-sectional area S of the material, and can be expressed as follows:

$$\varepsilon = \frac{F}{ES} \tag{1}$$

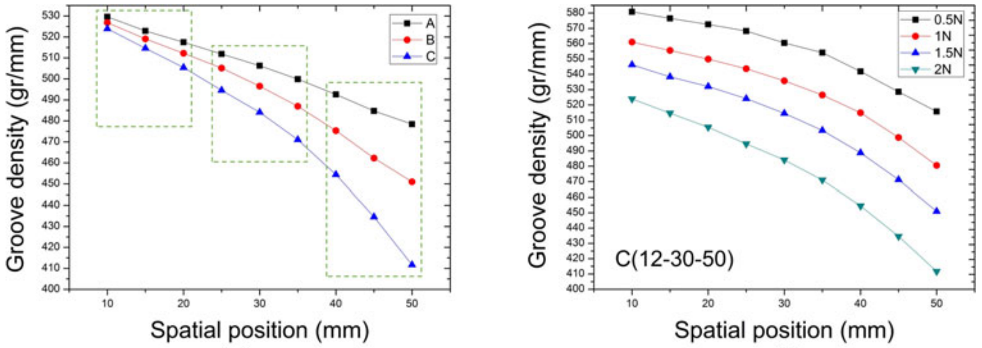
where F is the tension force. Because the PDMS grating has a trapezoidal shape, the plane width of the grating changes monotonically along the stretching direction, and this results in gradual variation of both the elastic modulus and the cross-sectional area S, which is a function of the length coordinate x. The trapezoid-shaped PDMS grating experiences inhomogeneous strain, which is dependent on the spatial position of the PDMS grating. The reciprocal of the groove period is defined as the groove density, which is more commonly used in the diffraction grating field. As a result, the groove density distribution of the PDMS grating changed with the strain and can be expressed as:

$$f_2 = \frac{f_1}{1+\varepsilon} \tag{2}$$

where f_1 and f_2 are the groove densities of the trapezoid-shaped PDMS grating before and after stretching. When the force is applied and stretches the PDMS grating sample, the groove density of the PDMS grating changes with the resulting strain on the sample.

According to the formulas above, the groove density f_2 of the stretched trapezoid-shaped PDMS grating can be calculated using the following differential equation:

$$\frac{df_2}{ds} = \frac{Ff_1}{E(S+F/E)^2} \tag{3}$$



(a) (b)

Fig. 3. (a) The average groove density distribution of stretched PDMS grating sample A(24-30-50), B(18-30-50) and C(12-30-50) measured by diffraction method in Littrow mode; (b) the groove density distribution of one trapezoid-shaped PDMS grating sample C(12-30-50) was stretched of 0.5 N, 1 N, 1.5 N, 2 N.

TABLE 1

Average Tangent Slopes at Three Areas of the Different Trapezoid-Shaped PDMS Gratings

PDMS grating	Slope #1	Slope #2	Slope #3
A(24-30-50)	-1.221 gr/mm^2	-1.228 gr/mm^2	-1.397 gr/mm^2
B(18-30-50)	-1.469 gr/mm^2	-1.835 gr/mm^2	-2.386 gr/mm^2
C(12-30-50)	-1.904 gr/mm^2	-2.486 gr/mm^2	-4.165 gr/mm^2

Therefore, the variation of the groove density Δf can be expressed based on the variation of cross-sectional area ΔS:

$$\Delta f = \frac{F f_1}{E(S+F/E)^2}\Delta S \tag{4}$$

2.2 Results and Discussion

To measure the groove densities of the grating samples, we used a diffraction method in the Littrow mode with a He-Ne laser operating at a wavelength of 632.8 nm and a precision rotating platform. The spot size of the incident beam is about 1 mm. The baseline side of the trapezoid-shaped PDMS grating was defined as its initial position ($x = 0$), and we then measured the groove density of the stretched PDMS grating along the stretching direction X at intervals of 5 mm. The groove density varied with position along its central line. Fig. 3(a) shows the groove density distributions of stretched PDMS grating samples A (24-30-50), B (18-30-50) and C (12-30-50).

Different trapezoid-shaped PDMS gratings have different abilities for tuning of the groove density distribution with respect to spatial position. The trapezoid-shaped PDMS grating with the shortest top line has the maximum groove density gradient. In contrast, the trapezoid-shaped PDMS grating with the longest top line has the minimum groove density gradient. The average slopes of three areas in the trapezoid-shaped grating samples were calculated and are shown in Table 1.

Fig. 3(b) shows the groove density distributions of trapezoid-shaped PDMS grating sample C (12-30-50) when it was stretched using different forces of 0.5 N, 1 N, 1.5 N, and 2 N. The groove density gradient remains almost the same when the grating is stretched with the different forces. The groove density distribution of the grating when stretched with a force of 2 N changes from 523.9 gr/mm to 411.7 gr/mm at a distance of 40 mm; in contrast, the groove density distribution of

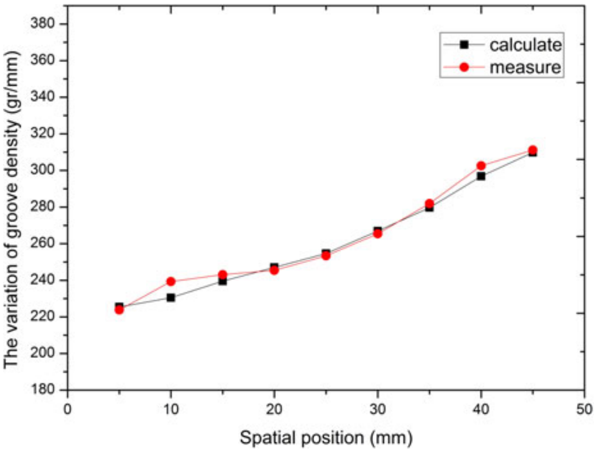


Fig. 4. Black line indicates the variation of the experimental results of groove density, red line indicates the variation of groove density calculated in formula (4).

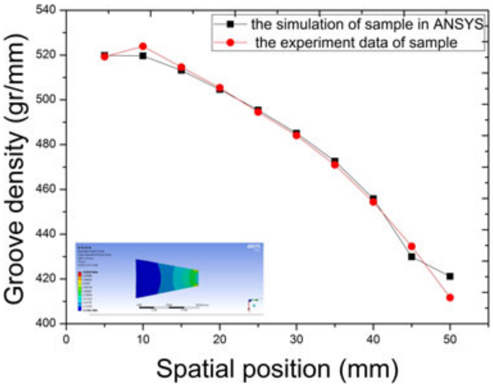


Fig. 5. The result of simulations and experiments for the trapezoid-shaped PDMS grating sample C(12-30-50); the insert picture was the strain distribution of trapezoid-shaped PDMS grating simulated in *ANSYS 14.5*.

the grating when stretched with a force of 0.5 N changes from 580.0 gr/mm to 514.9 gr/mm at a distance of 40 mm.

If the stretched trapezoid-shaped PDMS gratings maintain their normal trapezoid shapes, then the variation of the cross-sectional area in the X direction will be linear, which could result in linear variation of the groove density. However, in the experiments, both sides of the stretched trapezoid-shaped PDMS gratings shrank inhomogeneously and the centers of the trapezoid-shaped PDMS gratings experienced greater shrinkage when compared with the other areas. This leads to an inhomogeneous groove density gradient on each stretched PDMS grating.

A trapezoid-shaped PDMS grating was marked along the stretching direction (X) at intervals of 5 mm before stretching commenced. We then measured the groove density of the stretched PDMS grating and the cross-sectional area at each mark. As shown in Fig. 4,, both the experimental results and the data calculated using (4) obviously deviated from the linear variation profile. Additionally, these two data sets showed similar variations to each other. It is obvious that the groove density variation deviated as a function of the shrinkage on both sides of the stretched trapezoid-shaped PDMS grating.

We used Ansys 14.5 software [22] to simulate the strain distributions of the different trapezoid-shaped PDMS gratings under the same horizontal load of 2 N, and the results are shown in Fig. 4. The corresponding strain values were put into (2) and the groove density of the grating could then be calculated at different spatial positions. The curves shown in Fig. 5 represent the results of simulations and experimental evaluations of the trapezoid-shaped PDMS grating sample C, which had dimensions of 12 mm × 30 mm × 50 mm and was stretched with a force of 2 N. The experimental results coincided well with the simulated results along the central line of the trapezoid-shaped PDMS grating.

3. Conclusion

In summary, a new approach was developed for fabrication of a tailorable PDMS grating with a tunable groove density gradient. The fabrication approach is based on formation of a shape-tailorable PDMS grating and subsequent stretching of the grating sample. During the stretching process, the elongations generated are functions of the spatial position on the trapezoid-shaped grating. The elongation of the grating on the elastomeric film surface is determined based on the local thickness of the elastomeric film, the stress, and the Young's modulus of the elastomeric material. The groove density distribution of PDMS grating sample C, when stretched with a force of 2 N, covered a 523.9–411.7 gr/mm range over a distance of 40 mm. The shape-tailored PDMS grating has the ability to tune its groove density along the stretching direction. But the maximum tunability of the optical response is restrained by the ultimated ability of PDMS reversible elastic deformation. The resulting tailorable elastomeric grating can be used in the fabrication of optical position sensors and tunable optical filters.

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