Fabrication of Internal Gratings in PDMS Using a Femtosecond Laser

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Abstract

Photo-induced gratings in flexible PDMS (polydimethly siloxane) film are directly written by a high-intensity femtosecond (130fs) Ti: Sapphire laser (λ_p = 800nm). The refractive index modifications with 4 μm diameters were photo-induced after the femtosecond irradiation with peak intensities of more than 1×10^{11} W/cm^2. The graded refractive index profile was fabricated to be a symmetric around the center of the point at which femtosecond laser by controlling both laser power and focused depth. The change on refractive index in the laser-modified regions was estimated to be approximately 10^{-3}. The internal flexible symmetric diffraction gratings in PDMS film was successfully fabricated using a femtosecond laser.

Keywords: Femtosecond Laser, Refractive index change, PDMS, Internal gratings, Diffraction gratings

1. Introduction

Polymeric materials are widely used to fabricate micro-devices and optical elements because of numerous advantageous characteristics, including low cost, ease of manufacture, and high transmission in the visible spectral region. Of many candidate polymer materials, polydimethly siloxane (PDMS) is one of the most widely used flexible polymers for bio-devices and optical components because of its physical flexibility, ease of processing, high chemical resistance and high transmission.[1] It is normally used in nanoimprinting, self-assembling, and soft lithography as an elastic stamp to transfer the desired nano- or micro- patterns.[2]

Much attention has been paid to polymeric waveguides and optical gratings as powerful tools for polymeric optical couplers, polymetric lasers,[3] resonators,[4,5] modulator,[6] and long period gratings.[7] In particular, an optical embedded diffraction grating, which is a fundamental optical component used to periodically modulate the phase or amplitude of incident waves, has been expected to be a useful device for wavelength division of propagated multi-wavelength beams into a single-wavelength beam in a multi-wavelength network system.[8-11]

Although the several methods used to fabricate the structure of transparent diffraction gratings in flexible PDMS is the surface monolithic processing such as photo-lithography and soft-lithography,[7] there has been a technical issue in making a transparent diffraction grating in terms of complex, slow, and high cost, requiring sophisticated facilities and equipment.[12] If refractive index modification using a transparent diffraction grating in an optical preformed flexible PDMS film can easily be accomplished, it can be used at low cost in various applications such as Bragg grating, wavelength interferometers, wavelength converters, and arrayed waveguide gratings in flexible optical systems.

In this paper, we report the use of the direct femtosecond writing technique to inscribe period arrays of refractive index modifications in the

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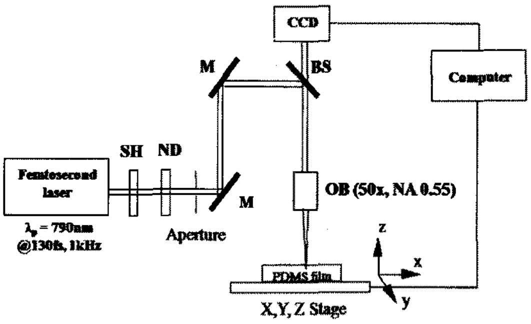
PDMS polymer and observation of diffraction images. This process may be a tool for designing optical transparent embedded components in flexible polymer films with refractive index modification induced by low-intensity femtosecond lasers.

2. Experimental Setup

The schematic diagram of the experimental setup for photo-induced refractive index modification is shown in Fig. 1. The irradiation laser used in the experiment is a Ti: sapphire oscillator amplifier laser system (λ_p = 800nm) based on the chirped pulse amplification technique with a 130fs pulse duration, 3.5W maximum output power, and 1kHz repetition rate. The linearly polarized laser beam with a Gaussian profile is focused tightly onto the planar PDMS film through an objective lens (NA: 0.55). The planar flexible film is commercially available PDMS (Model No. Sylgard 184) provided from the DOW CORNING. Co. USA. The PDMS film was prepared in non-cross-linked form, as a two-part resin and cross linker by mixing the two components in a 10:1 ratio by weight, respectively. The size of PDMS film is 30mm × 30mm × 5mm. The four sides of the PDMS film were cut by a knife. The PDMS film is set on the X-Y-Z stage with space resolution of 50nm to be scanned. The energy of the incident beam irradiating the planar PDMS film is controlled using neutral density (ND) filters that are inserted between laser and focusing objective lens. Optical images of the temporal behavior of plasma formation and photo-induced bulk structure transformations (refractive index modification, optical damage) are observed from a direction perpendicular to the optical axis using an optical microscope with a CCD camera connected to the computer.

3. Results and discussions

Fig. 2 shows a sample of planar PDMS film and its flexibility before femtosecond laser irradiation. The irradiation used a Ti: Sapphire femtosecond laser delivering 5μJ pulses with 1 kHz repetition rate and pulse width of 130fs. Energy focused into the sample was varied using a combination of neutral density filters. We used three dimensional stages together to move polymer substrate in x-, y- and z- directions and 50× (NA: 0.55) microscopic objectives to focus the laser into the PDMS substrate. The depth of plasma formation was 500μm from the irradiated under the surface of PDMS film. Initially line structures were written at same energies with scanning speed of 1 mm/s. It was confirmed that refractive index modification structures have increasing diameter as the energy of input laser pulses is increased and decreasing diameter as the focused plasma depth is increased. In this experiment, Clean and symmetric structures from the center of focused beam can be obtained by controlling laser peak intensity and focused depth.



SH: Shutter, ND: Neutral density filter, M: Mirror, BS: Beam splitter, OB: Objective lens

Fig. 1 Schematic of the experimental setup for femtosecond laser-induced refractive index modification embedded in PDMS film.

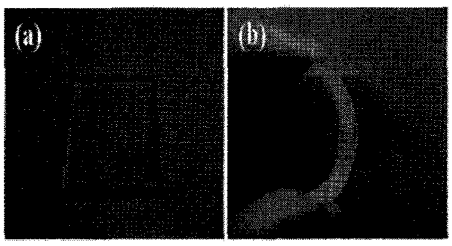


Fig. 2 Sample view of planar flexible PDMS film before femtosecond laser irradiation; front view (a) and side view (b).

The embedded diffraction gratings with refractive index modification up to 500μm below the surface of transparent PDMS film were fabricated by scanning of flexible PDMS films at 1mm/s scanning speed and a sequence of 800 nm, 130fs pulse focused at 0.55-NA and pulse energy of 5μJ. Fig. 3(a) shows optical microscopic image of internal grating structures with refractive index modification. The diameter of structures with induced refractive index modification was approximately 4μm. The pitch between such structures was 10μm.

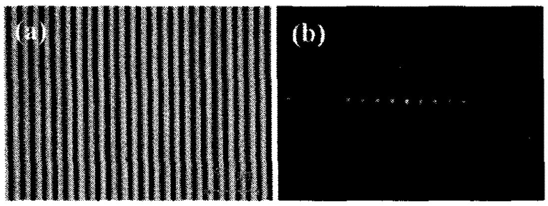


Fig. 3 (a) Optical microscopic image of internal grating structures with refractive index modification and (b) a diffraction image of internal grating structures with refractive index modification.

Fig. 3(b) shows the diffraction images of internal grating with refractive index modification fabricated using a single-wavelength light source (He-Ne laser, λ = 633nm). A 590μW He-Ne laser was incident normally on the written grating and formed an impressive far-field diffraction pattern with more 8 orders as shown in Fig. 3(b). The fraction of incident He-Ne light intensity diffracted into each order was measured using a silicon detector mounted on a translation stage to form a measure of the diffraction efficiency, η. The linear structure with refractive index modification was employed. The photo-induced grating was used as shown in Fig. 3(a). A diffraction image of more ±8 order was observed. Efficiency rates (%) of diffraction were 1.6% (±1 order), 1.4% (±2 order), and 1.2% (±3 order). The value of refractive index change can be calculated by measuring the efficiency rate of diffraction order as shown in Fig. 4.

The magnitude of the refractive index modification (Δn) can be determined from the diffraction efficiency using equation.[12] Here θ is the incident angle from the normal in the media, η the diffraction fraction into the first order and d the depth of the refractive index modification. λ is a wavelength of incident He-Ne laser.

$$\Delta n = \frac{\lambda \cos\theta \tanh^{-1}(\sqrt{\eta})}{\pi d}$$

Equation indicates that the induced refractive index change, Δn, can be related to the diffraction efficiency, η. The angle of incidence from the normal, θ, is 0°, since the He-Ne laser is incident normally on the grating. To determine the depth d of the refractive index modification, samples were cut with cross-sections through the grating by a knife. The refractive index modification depth *d* could then be viewed and measured using an optical microscope.

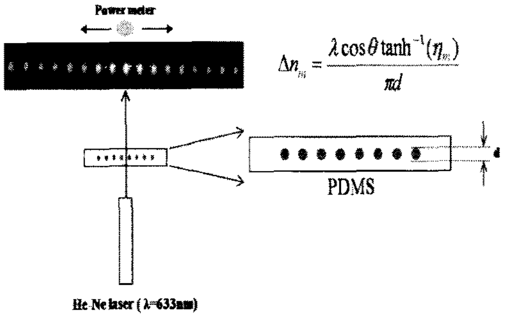


Fig. 4 Schematic of the refractive index change measurement for femtosecond laser-induced refractive index modification embedded in PDMS film.

Efficiency rates (%) of diffraction were 1.6% (±1 order), 1.4% (±2 order), and 1.2% (±3 order) respectively. The refractive index modification resulted in the value of refractive index change (Δn) of 3.17×10^{-3} at intensities higher than 1.0×10^{11}W/cm^2.

4. Conclusions

This research is that the femtosecond laser grating inscription method has been applied to flexible PDMS films. The irradiation laser used in the experiment is a Ti: sapphire oscillator amplifier laser system (λ_p = 800nm) based on the chirped pulse amplification technique with a 130fs pulse duration, 3.5W maximum output power, and 1kHz repetition rate. The linearly polarized laser beam with a Gaussian profile is focused tightly onto the planar PDMS film through an objective lens. The embedded diffraction gratings with refractive index modification up to 500μm below the surface of transparent PDMS film were fabricated by scanning of flexible PDMS films at 1mm/s scanning speed and a sequence of 800nm, 130fs pulses focused at 0.55-NA and pulse energy of 5μJ. The diameter of structures with induced refractive index modification was approximately 4 μm. The pitch between such structures was 10μm. The refractive index structures have sufficient contrast to be observable using an optical microscope. When illuminated normally with a He-Ne laser, the gratings produce a highly ordered far-field diffraction pattern from a refractive index grating, as shown in figure. Efficiency rates (%) of diffraction were 1.6% (±1 order), 1.4% (±2 order), and 1.2% (±3 order) respectively. The refractive index modification resulted in the value of refractive index change ($\triangle n$) of 3.17×10^{-3} at intensities higher than $1.0 \times 10^{11} W/cm^2$.

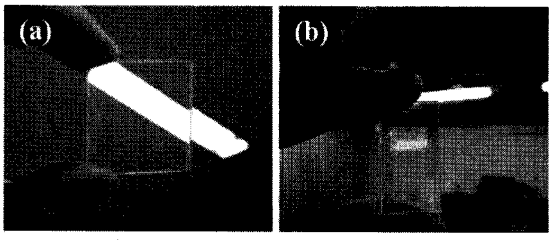


Fig. 5 Diffraction images of PDMS film before femtosecond laser irradiation (a) and the fabricated diffraction grating with refractive index modification using white light source after femtosecond laser irradiation (b).

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