Internal modification in transparent materials using plasma formation induced by a femtosecond laser

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Abstract

The fabrication of internal diffraction gratings with photoinduced refractive index modification in transparent materials was demonstrated using low-density plasma formation excited by a femtosecond (130 fs) Ti: sapphire laser (λ_p=800 nm). The refractive index modifications with diameters ranging from 1 μm to 3 μm were photoinduced after plasma formation occurred upon irradiation with peak intensities of more than 2.0×10^{13} W/cm^2. The graded refractive index profile was fabricated to be a symmetric around from the center of the point at which low-density plasma occurred.

Keywords: femtosecond laser, plasma formation, internal diffraction gratings, refractive index modification, transparent materials

1. Introduction

Optical embedded diffraction gratings, a fundamental optical component used to periodically modulate the phase or amplitude of incident waves, is expected to be a useful device for wavelength division of propagated multi-wavelength beams into a single-wavelength beam in multi-wavelength network systems[1,2]. Although several approaches to fabricate the structure of diffraction gratings in transparent materials involve the surface monolithic processing such as photo-lithography and soft-lithography, there are obstacles in making a transparent diffraction grating, including complexity, slowness, and the requirement of sophisticated facilities, and equipment. If refractive index modification using a transparent diffraction grating in an optical preformed transparent plate could be easily accomplished as simple method, it could be used in various applications such as Bragg gratings, wavelength interferometers, wavelength converters, and arrayed waveguide gratings in optical systems[2-6].

Although several experiments of plasma formation and bulk modification in solids using high-intensity femtosecond laser pulses have been reported, the relationship between plasma formation and structural change induced in the solid has not been explained in detail. To fabricate an optical transparent diffraction grating in a transparent planar plate, we will use the interaction between plasma formation and a planar plate with pure silica, which enables to fabricate the periodical structural change of the refractive index along the silica plate.

In this paper, we report the experimental results of plasma-induced bulk modification in optical planar silica plates using low-density plasma formation excited by a tightly focused femtosecond laser.

2. Experimental Setup

The schematic diagram of the experimental setup for plasma-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=800 nm) based on the chirped pulse amplification technique with a 130 fs pulse duration, 1 W average output power, and 1 kHz repetition rate. The linearly polarized laser beam with a Gaussian profile is focused tightly onto

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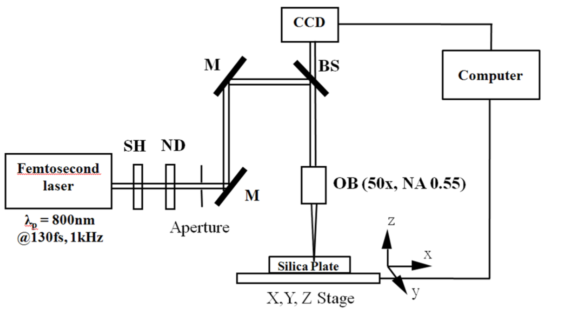
the planar silica plate through an objective lens (×50, N.A.: 0.55). The size of planar silica plate is 10 mm × 20 mm × 4 mm. The six sides of the silica plate were optically polished for in situ observation. The sample (planar silica plate) is set on the X-Y-Z stage with space resolution of 50 nm to be scanned. The energy of the incident beam irradiating the planar silica plate is controlled using neutral density (ND) filters that are inserted between the laser and focusing objective lens. The power transmitted through the planar silica plate is recorded using the optical powermeter.

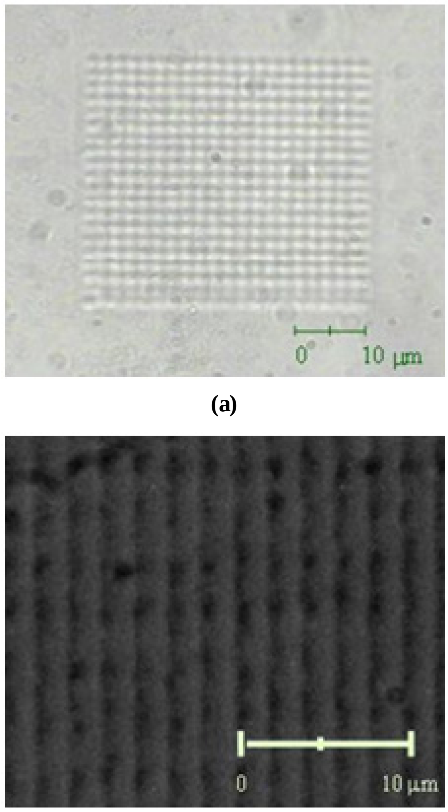


SH: Shutter, ND: Neutral density filter, M: Mirror, BS: Beam splitter, OB: Objective lens

Fig. 1 Schematic of the experimental setup for laser-induced plasma formation and refractive index modification in optical silica plates.

3. Experimental Results and Discussion

By scanning the planar silica plate, using the optical X-Y-Z stage during laser irradiation, periodically arrayed structures of modified bulk were fabricated with irradiation at different intensities (Fig. 2). The depth of such periodically arrayed structures was 1 mm from the irradiated surface of the silica substrate (sample). Periodic structures with refractive index modification were fabricated due to low-density plasma formation upon single-shot irradiation at 5.0×10^{13} W/cm^2 (Fig. 2 (a)). The diameter of structures with induced refractive index modification was approximately 1 μm. The pitch between such structures was 2 μm. Periodic structures with optical cracks were also fabricated due to solid-density plasma formation upon single-shot irradiation at 4.0×10^{14} W/cm^2 (Fig. 2 (b)). The diameter of structures with cracks was approximately 0.8-1.3 μm. The pitch between optical cracks was 2 μm. Neither optical damage nor laser ablation on the surface of the silica substrate after laser irradiation was observed in Fig. 2 (a) and (b). It was inferred that low-density plasma formation by tightly focused femtosecond beams would be useful for fabricating internal gratings with refractive index modification in silica plates.

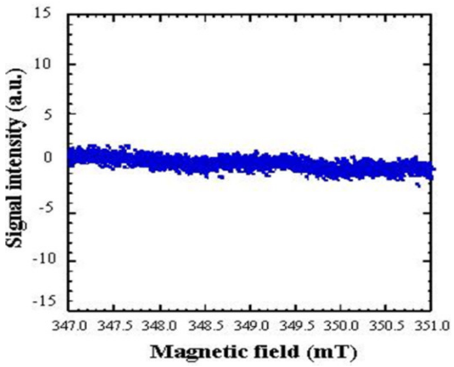


(b)

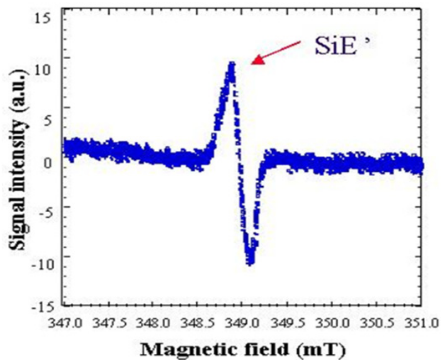
Fig. 2 Two types of internal gratings with refractive index modification by scanning the planar silica plate using an optical stage: (a) dot structure, (b) linear structure.

From the electron spin resonance (ESR) spectroscopic measurement[7,8], the variation of the concentration of induced defects was measured in modified regions (Fig. 3). No defect was observed in the region of no plasma formation upon irradiation at 6.0×10^{12} W/cm^2 (Fig. 3(a)). However, the defect of SiE' was first observed in the region of plasma formation upon irradiation at 2.0×10^{13} W/cm^2 (Fig. 3(b)). These results indicated that defects of SiE' were induced where plasma formation occurred.

At high intensities, the concentrations of SiE' were significantly increased in refractive index modification areas. As a result of plasma formation, the concentration of SiE' (E' center) was significantly increased in refractive-index modified regions (Fig. 3(b)). The measured ESR signal in the modified regions agreed well with the absorption spectrum of SiE', which indicates unpaired electron in a dangling, tetrahedral (sp^3) orbit of a single silicon bound to three oxygens atoms in the glass. Defects other than E' centers were not observed in refractive index modification.



(a) Before irradiation



(b) After irradiation

Fig. 3 ESR spectroscopic measurement in a planar silica plate after laser irradiation of single pulses with various input intensities: (a) 6.0×10^{12} W/cm^2 and (b) 2.0×10^{13} W/cm^2 in plasma-induced refractive index modification. SiE' center was paramagnetic defects.

In order to measure the profile of refractive-index change by bulk modification induced by low-density plasma formation, perpendicular Fresnel reflection was employed. This technique, as developed by Eickhoff and Weidel, relies on the Fresnel relation between the refractive index and reflectivity of the materials[9].

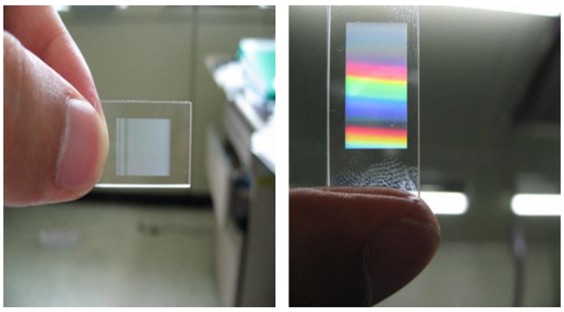
A He-Ne laser is widely used as the probe light source in the measurement of refractive index by the Fresnel reflection method, because of the stability of its mode and frequency. A linearly polarized He-Ne laser is incident upon a ×10 beam expander and is focused onto the surface of the area of bulk refractive index modification on a polished silica plate by a ×20 microscope objective. The minimum spot diameter of the focused beam on the surface of the optical silica plate was approximately 1 μm. The opposite surface of the planar silica plate was coupled with the matching oil (n=1.457) to prevent Fresnel reflection from the opposite surface of the optical silica plate. The thickness of the optical silica plate does not affect the incorporated measurement of the refractive index modification. The reflected beam was detected by a photodiode and its signal was recorded in the computer through a lock-in amplifier. The refractive index profile was obtained by parabolic fitting. The refractive index profile of the area of bulk modification at the intensity of 8×10^{13} W/cm^2 clearly shows that bulk modification resulted in a graded refractive index profile in an optical silica plate, in comparison with the refractive index profile of the unmodified area of optical silica plate. From the measured refractive index profile of induced modification, it was found that the induced refractive index modification exhibited a graded refractive index profile symmetric about point at which the low-density plasma occurred.

Based on the diffraction efficiency of Kogelnik's coupled mode theory, photoinduced refractive index changes upon irradiation at various intensities were measured[10]. The measured minimum value of refractive index change was 3.5×10^{-3} for irradiation at 2.0×10^{13} W/cm^2. The maximum value of refractive index change was estimated to be 1.6×10^{-2}. As the irradiated intensity was increased, the value of refractive index change increased linearly within the range from 3.5×10^{-3} to 1.6×10^{-2} at intensities higher than

2.0×10^{13} W/cm^2. The measured error of refractive index change was less than 15%.

By scanning planar silica plates using the optical X-Y-Z stage during laser irradiation, two types of structures of the internal grating in planar silica plates were obtained. Both a dot structure and a linear structure were fabricated using low-density plasma formation induced by irradiation of a tightly focused femtosecond laser pulse. The structure of the internal grating could be controlled using both the shutter and optical X-Y-Z stage during laser irradiation.

By scanning a planar silica plate using the optical X-Y-Z stage, the internal diffraction grating in a planar silica plate was induced by irradiation of tightly focused femtosecond laser. The linear periodically arrayed structure with refractive index modification was employed. Figure 4 shows the diffraction images of internal grating with refractive index modification fabricated using a white light source. The planar silica plate was scanned at the speed of 1 mm/s using the optical X-Y-Z stage. The laser pulse of 5 μJ/pulse was irradiated onto the silica plate. The pitch of the internal grating was 2 μm (500/mm). The refractive index change of the areas of induced bulk modification was 4.0×10^{-3}, which is a relatively low change of the refractive index.



(a) **(b)**

Fig. 4 Diffraction images of the fabricated internal diffraction grating with refractive index modification using (a) no reference light and (b) white light source.

4. Conclusion

In summary, we demonstrated plasma formation and structural transformation in the regime of refractive index modification in optical transparent planar plates composed of pure silica at irradiation intensities lower than the threshold of optical breakdown, 1.5×10^{14} W/cm^2. The underlying process of refractive index modification has been explained in related studies as the thermalization of the excited electrons due to multiphonon emission, leading to permanent photoinduced structural transformations. The results of ESR spectroscopic measurement showed that the concentration of defects is increased around the modified regions. The formation of color centers changes both the absorption coefficient and density of the medium, leading to the increase of the refractive index. Similar procedures of positive variation of the refractive index due to the generation of conduction electrons were reported in studies of plasma in solids.

Plasma-induced refractive index modification in transparent bulk materials will be a useful technique for the design of optical devices with limited refractive index change for applications, such as optical sensors and optical communications. Low-density plasma-induced refractive index modification would be a useful technique for the design of optical transmission diffraction gratings for such application as optical sensors and optical communications.

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