Optical diffraction gratings embedded in BK-7 glasses by tightly focused femtosecond laser

Ji Wook Yoon, Won Suk Choi, Hoon Young Kim, Sung-Hak Cho⊠

Department of Nano-Mechatronics, University of Science and Technology (UST)

Nano Machining Laboratory, Korea Institute of Machinery and Materials (KIMM)

Abstract

Optical embedded diffraction gratings with the bulk modification in BK-7 glass plates excited by tightly focused high-intensity femtosecond (130fs) Ti: sapphire laser (peak wavelength = 790nm) were demonstrated. The structural modifications with diameters ranging from 400nm to 4μm were photo-induced after plasma formation occurred upon irradiation with peak intensities of more than $1x1013 W/cm^2$. The graded refractive index profile was fabricated to be a symmetric around from the center of the point at which low-density plasma occurred. The maximum refractive index change was estimated to be 1.5×10^{-2}. The two optical embedded gratings in BK-7 glass plate were demonstrated with refractive index modification induced by the scanning of low-density plasma formation.

Keywords: BK-7 glass plate; Embedded diffraction grating; Refractive index modification; Plasma formation; Femtosecond laser

1. Introduction

The interaction between ultrashort, high-intensity laser light and transparent materials has become of major concern since the advent of high-intensity femtosecond lasers[1,2]. The structural bulk modification of dielectrics by tight focusing of femtosecond laser pulses was demonstrated[3]. Also, a large increase ($>10^{-2}$) in refractive index was obtained in a modified region of silica based glass by irradiation with femtosecond laser pulses[4]. The infrared photosensitivity of transparent materials allows the fabrication of three-dimensional photonic structures or devices through translation of the sample with respect to the focal point. Although the physical mechanisms responsible for infrared photosensitivity are still under investigation, this technique has been applied to three-dimensional optical storage, waveguides in a wide variety of glasses, couplers, and photonic crystals[5-9]. Plasma formation due to the self-focusing of ultrashort laser pulses in transparent materials is closely related to the occurrence of refractive-index change, micro-crack, three-dimensional microstructuring, and internal grating structure[10,11]. Optical damage has occurred in the crystallization of silver nano-particles in silver-doped glass and the bulk modification of optical fibers[12,13]. Periodical arrays with grating structures on the surface of glass were also demonstrated using the holographic interference of two beams[14,15]. However, the related experiments for optical plasma formation and bulk modification using high-intensity femtosecond laser pulses have been reported mostly in silica based glasses.

In the meantime, several types of optical components based on BK-7 (B_2O_3-$3SiO_2$) glass have been developed in the fields of optical communications, laser, medicine, and optical sensors because of their high transmission of UV to near-IR wavelength and low cost[16]. In particular, an optical 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[17,18].

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교신저자 : 조성학 ⊠ E.mail: shcho@kimm.re.kr

The device can be made of a transparent plate with periodically varying thickness or periodically graded refractive index. Although the methods used to fabricate the structure of transparent diffraction gratings in optical planar waveguides are surface processes, i.e., flame hydrolysis deposition (FDH), reactive ion etching (RIE), or vapor-phase axial deposition (VAD), there has been a technical issue in making a transparent diffraction grating on coupled waveguides of limited input in an optical planar plate, in terms of high cost and complicated fabrication technology[19,20].

Although several experiments of plasma formation and bulk modification in transparent glasses using high-intensity femtosecond laser pulses have been reported[21], the relationship between plasma formation and structural change induced in the solid BK-7 glasses has not been explained in detail. To fabricate an optical transparent diffraction grating in a transparent planar BK-7 glass plate, we will use the interaction between plasma formation and a planar plate with BK-7, which enables to fabricate the embedded periodical structural change of the refractive index along the BK-7 glass plate.

In this paper, we report the experimental results of plasma-induced bulk modification in optical planar plates of BK-7 glass using low-density plasma formation excited by a tightly focused femtosecond laser. Temporal behaviors of plasma formation and photo-induced bulk refractive index modification are observed *in situ*. The relationship between plasma formation and induced bulk refractive index modification in the optical planar BK-7 plate is also clarified. In our experiments, optical planar plates composed of BK-7, for use in optical communications, lasers and optical sensors are used to study the optical properties of the area of low-density plasma-induced refractive index modification.

2. Experimental Setup

The irradiation laser used in the experiment is a Ti:sapphire oscillator-amplifier laser system (λ_p = 790nm) 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 BK-7 plate through an objective lens (X60, N.A. = 0.85). A commercially available planar BK-7 (CVI, product number: 04-06-627, n = 1.51) is used. The size of BK-7 plate is 15mm × 25mm × 4mm. The six sides of the BK-7 glass plate were optically polished for *in situ* observation. The sample (planar BK-7 plate) 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 BK-7 plate is controlled using neutral density (ND) filters that are inserted between the laser and focusing objective lens. The power transmitted through the planar BK-7 plate is recorded using the optical powermeter connected to the computer. 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 a trans-illuminated optical microscope (Leica M420) with a CCD camera (Pixera PVC 100C) connected to the computer.

3. Experimental Results and Discussion

Microscopic side views of plasma formation in a planar BK-7 plate upon irradiation of single pulses of various intensities are shown in Fig. 1. Side views of plasma formation were observed using a microscope with a CCD camera and recorded into the computer. When the laser pulse was irradiated on the planar BK-7 plate, the BK-7 plate was scanned at a speed of 500μm/s using the optical X-Y–Z stage to avoid multi-irradiation on the same area of bulk BK-7 glass. Therefore, optical images of the temporal behavior of plasma formation and photo-induced bulk modification induced by the irradiation of single laser pulse could be observed *in situ*. The peak intensity at the tightly focused point was calculated using *Kirchhoff's* diffraction theory[22]. The nonlinear effect due to self-focusing was not considered in the calculation of the peak intensity because of tight focusing by the high-NA objective lens (X60, N.A. = 0.85). No plasma formation was observed when the intensity of the incident beam was 5 × 10^{12}W/cm^2 (Fig. 1(a)). When the intensity of the incident beam reached 1 × 10^{13}W/cm^2, the formation of plasma with the diameter of 400nm in a planar BK-7 plate was first observed (Fig. 1(b)). When the intensity of the incident beam was 8x10^{13}W/cm^2, plasma formation was observed more clearly and the plasma was of a larger size (Fig. 1(c)). The diameter of the induced plasma formation was 2.5μm. In the case of irradiation of 4 × 10^{14}W/cm^2, plasma with a diameter of 8μm was formed. The depth of plasma formation was 1 mm from the irradiated input surface of the sample. In the view of the theory of the cutoff frequency, the low-density plasma excited by a femtosecond laser is lower than the critical density of plasma electrons that can induce the optical damages[23].

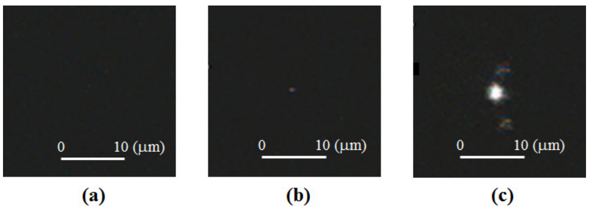

Fig. 1 Microscopic side views of photo-induced plasma formation in a planar BK-7 glass plate upon irradiation of single pulses with various input intensities: (a) 5 × 10^{12}W/cm^2, (b) 1 × 10^{13}W/cm^2, and (c) 8 × 10^{13}W/cm^2. The pictures, which were recorded using a CCD camera and a microscope, were taken with the exposure time of 1second.

Fig. 2 shows the microscopic side views of areas of induced bulk modification after plasma formation occurred. No bulk modification was observed when a plasma formation did not occur (Fig. 2 (a)). However, modification was visible when plasma formation occurred (Fig. 2 (b),(c)). Refractive index modification areas with diameter in the range of 400nm-4μm were induced (Fig. 2 (b),(c)). The depth of induced refractive index modification was 1 mm from the irradiated input surface of the sample. With an irradiation intensity lower than 1 × 10^{14}W/cm^2, the power of the transmitted incident beam decreased to 96% that of the incident beam because of the plasma formation. Refractive index modifications were induced by plasma formation upon irradiation of the incident laser beam. No cracks were observed in the region of refractive index modification. However, when the intensity exceeded 1 × 10^{14}W/cm^2, some cracks, i.e., optical damage, were deserved. In this case, the transmitted beam power was decreased to 40% of that of the incident beam because of scattering or diffraction losses from the induced plasma. The beam intensity of -1.5 × 10^{14}W/cm^2 was reported as the damage threshold for transparent silica glasses, in the recent studies of damage with femtosecond laser pulses[9,18,24]. It was inferred that the optical damage of cracks was induced by plasma formation in the breakdown region.

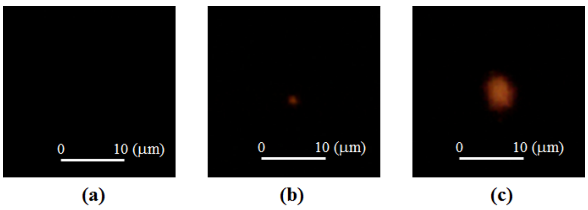

Fig. 2 Microscopic side views of bulk refractive index modification induced by plasma formation upon irradiation at different intensities: (a) 5 × 10^{12}W/cm^2, (b) 1 × 10^{13}W/cm^2, and (c) 8 × 10^{13}W/cm^2.

Fig. 3 shows the profiles of induced bulk refractive index modification after plasma formation occurred. 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[25].

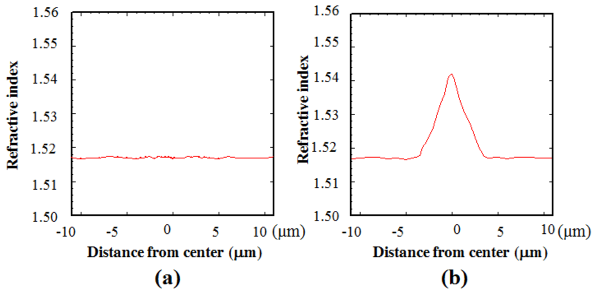

Fig. 3 The refractive index profiles of areas of plasma-induced bulk modification: (a) before irradiation and (b) after irradiation of 10^4 pulses at the intensity of 8.0×10^{13}W/cm^2.

At normal incidence we have the Fresnel reflection

$$R = \left(\frac{n_{modification} - n_{air}}{n_{modification} + n_{air}} \right)^2 \quad (1)$$

A linearly polarized He-Ne laser is incident upon a 10x beam expander and is focused onto the surface of the area of bulk refractive index modification on a polished BK-7 plate by a 20x microscope objective. The minimum spot diameter of the focused beam on the surface of the optical BK-7 plate was approximately 2μm. The opposite surface of the planar BK-7 plate was coupled with the matching oil (n = 1.51) to prevent Fresnel reflection from the opposite surface of the optical BK-7 plate. The thickness of the optical BK-7 plate does not affect the incorporated measurement of the refractive index modification. The 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[26]. 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 obtained by parabolic fitting is shown in Fig. 3[27]. The refractive index profile of the area of bulk modification induced by 10,000 irradiation shots at 8×10^{13}W/cm^2 clearly shows that bulk modification resulted in a graded refractive index profile in an optical BK-7 plate (Fig. 3(b)), in comparison with the refractive index profile of the unmodified area of optical BK-7 plate (Fig. 3(a)). But He-Ne laser, BK-7 plate and sensor are not 0° perfectly, measurement data can be have error slightly. 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.

By scanning the planar BK-7 plate, using the optical X-Y-Z stages during laser irradiation, periodically arrayed structures of modified bulk were fabricated with irradiation at different intensities. Based on the diffraction efficiency of *Kogelnik's* coupled mode theory[28], photo-induced refractive index changes ($\triangle n$) upon irradiation at various intensities were measured (Fig. 4). The measured minimum value of refractive index change ($\triangle n$) was 2×10^{-3} for irradiation at 1×10^{13}W/cm^2. The maximum value of refractive index change ($\triangle n$) was estimated to be 1.5×10^{-2}. As the irradiated intensity was increased, the value of refractive index change($\triangle n$) increased linearly within the range from 2x10^{-3} to 1.5×10^{-2} at intensities higher than 1.0×10^{13}W/cm^2. The measured error of refractive index change was less than ±15%.

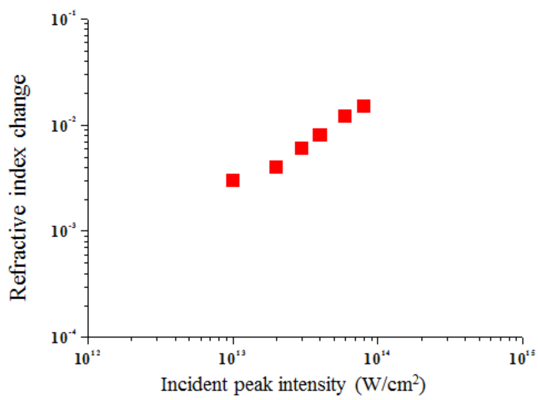

Fig. 4 Variation of refractive index change ($\triangle n$) induced by single pulse irradiation at various peak intensities.

Periodically arrayed structures of modified bulk were demonstrated with irradiation at different intensities (Fig. 5). The depth of such periodically arrayed structures was 1mm from the irradiated surface of the BK-7 substrate. Periodic structures with refractive index modification were fabricated due to low-density plasma formation upon single-shot irradiation. Fig. 5 showed the microscopic side views of internal grating patterns in BK-7 glass with different pitches; (a) 3μm, (b) 2.5μm, (c) 2 μm, and (d) 1.5μm at the irradiation of different intensities. Periodic structures with refractive index modification were fabricated due to plasma formation upon single-shot irradiation. The diameter of structures with refractive index modification was approximately 600nm-1.3μm.

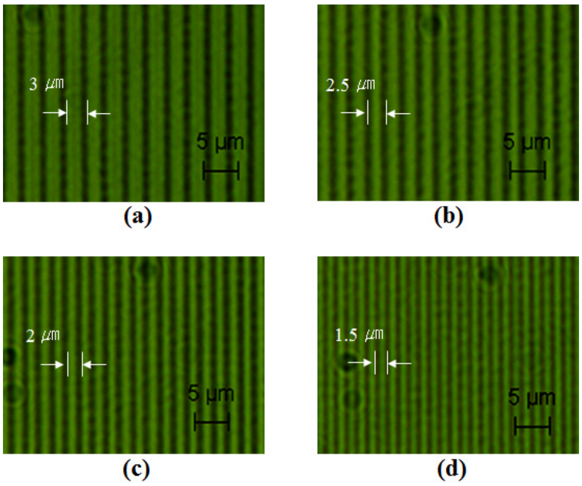

Fig. 5 Microscopic side views of internal grating patterns in BK7(under 1mm from surface) with different pitch; (a) 3μm at 5 × 10^{13}W/cm^2, (b) 2.5μm at 4 × 10^{13}W/cm^2, (c)2μm at 2 × 10^{13}W/cm^2, and (d) 1.5μm at 1 × 10^{13}W/cm^2

By scanning planar BK-7 plates using the optical X-Y-Z stage during laser irradiation, two types of structures of the internal grating in planar BK-7 plates were obtained, as shown in Fig. 6. Both line structure (Fig. 6(a)) and cross line structure (Fig. 6(b)) 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. The planar BK-7 plate was scanned at the speed of 1 mm/s using the optical X-Y-Z stage. The laser pulse of 5μJ/pulse was irradiated onto the BK-7 plate. Fig. 6 (c),(d) showed the diffraction images from internal grating with refractive index modification fabricated using single-wavelength light source (He-Ne laser, @ 632.8nm). The refractive index change ($\triangle n$) of the areas of induced bulk modification was 4.0 × 10^{-3}, which is a relatively low change of the refractive index. The maximum value of refractive index change ($\triangle n$) could be controlled by the irradiation conditions of the incident beam. A diffraction image of -±4 order was observed. Efficiency rates (%) of diffraction were 7.7% (±1 order), 2.7% (±2 order), and 0.5% (±3 order). In the case of a relatively high refractive index change ($\triangle n$), e.g., 1 × 10^{-2}, the diffraction image of -±8 order was observed. The efficiency rates of the diffraction were 10.6% (±1 order), 3.1% (±2 order), and 1.2% (±3 order). The adjustment of the refractive index change could control efficiency rate of diffraction order (Fig. 6 (c)). 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 BK-7 glass plates.

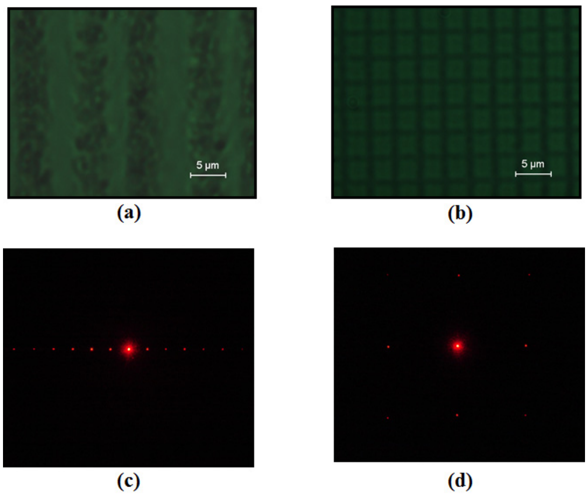

Fig. 6 Two types of internal gratings with refractive index modification by scanning the planar BK-7 glass plate using an optical x-y-z stage: (a) line structure, (b) cross line structure. Diffraction images of the fabricated internal diffraction grating using He-Ne laser (632.8 nm) through (c) line structure and (d) cross line structure.

Fig. 7 showed the diffraction images of the fabricated internal diffraction grating with refractive index modification using white light source. The internal diffraction grating was demonstrated. The irradiated laser pulse of 5μJ/pulse was irradiated onto the BK-7 plate and the pitch of the internal grating was 2μm.

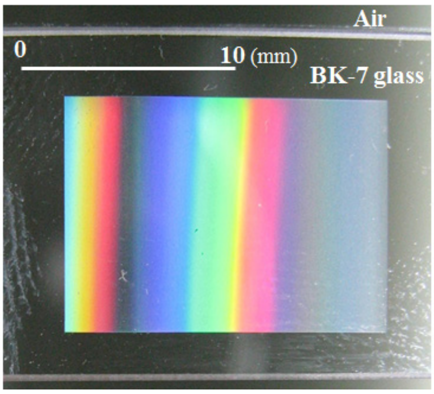

Fig. 7 Diffraction images of the fabricated internal diffraction grating with refractive index modification using white light source.

In this experiment, we demonstrated plasma formation and structural transformation in the regime of refractive index modification in optical transparent planar BK-7 glass plates at irradiation intensities lower than the threshold of optical breakdown, 1×10^{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 photo-induced structural transformations. The formation of color centers changes both the absorption coefficient and density of the medium, leading to the increase of the refractive index[29]. Similar procedures of positive variation of the refractive index due to the generation of conduction electrons were reported in studies of plasma in solids.

Although the details of the physical mechanisms responsible for infrared photosensitivity in the femtosecond regime are still under investigation, low-density plasma formation can easily induce refractive index modification with defects in transparent material. The diffraction images of the output beam transmitted through the periodically arrayed internal structures showed that refractive index modification resulted in an embedded optical grating structure. 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 near infrared optical communications. In comparison with conventional fabrication methods based on surface processing, the fabrication of internal diffraction gratings using low-density plasma induced by a compact femtosecond laser has the merits of low cost and simple fabrication technology. The fabrication method of the internal diffraction grating in planar BK-7 glass plates using low-density plasma can be a useful tool in a variety of applications such as the arrayed-waveguide grating (AWG) and the single-wavelength beam divider in wavelength division multiplexing (WDM) systems in near infrared optical communications and optical sensors.

4. Conclusions

A fabrication method of embedded optical diffraction gratings with bulk refractive index modification was demonstrated in planar BK-7 glass plates using plasma formation induced by a tightly focused femtosecond laser. The bulk refractive index modification resulted in a graded refractive index profile, and the value of refractive index change ($\triangle n$) varied within the range from 2×10^{-3} to 1.5×10^{-2} at intensities higher than 1.0×10^{13}W/cm^2. By scanning a planar BK-7 glass plate, the embedded diffraction gratings with refractive index modification were demonstrated.

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