Direct laser writing of thermally stabilized channel waveguides with Bragg gratings

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Abstract: Thermally stabilized photo-induced channel waveguides with Bragg gratings were fabricated in Ge-B-SiO_2 thin glass films by exposure with KrF excimer laser and successive annealing at 600°C. The annealing reversed the photo-induced refractive index pattern and also enhanced its thermal stability. The stabilized channel waveguide with a Bragg grating showed diffraction efficiency of 18.0 dB and 18.7 dB for TE- and TM-like modes, respectively. The diffraction efficiencies and wavelengths for both modes never changed after heat treatment at 500°C, whereas the conventional photo-induced grating decayed even at 200°C.

OCIS codes: (160.2750) Glass and other amorphous materials; (220.4610) Optical fabrication; (230.1950) Diffraction gratings; (230.7370) Waveguides.

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1. Introduction

Photo-induced refractive index change in oxide glasses is used widely to fabricate optical elements such as channel waveguides and gratings by the use of direct laser writing. This technique presents advantages compared to other complicated fabrication process including lithography and dry etching. So far, optical elements written using KrF excimer laser, femtosecond laser, and others have been reported [1-5]. Nevertheless, the thermal stability of elements that are fabricated using direct laser writing techniques is much lower than that by the conventional lithography and etching techniques [4,6-9]. For example, the thermal decay in photo-induced refractive index change in Ge-B-SiO_2 core fibers using a pulse light source at 244 nm wavelength reportedly started even at temperatures below 150°C [9]. Moreover, photo-induced refractive index change in hydrogen-loaded fibers began to be erased at much lower temperatures than that in non-loaded ones [10,11]. Such thermal decay limits the application of devices fabricated by the direct laser writing technique.

We have presented a novel approach for thermally stabilized photo-induced refractive index change in Ge-B-SiO_2 thin glass films [12,13]. A photo-induced grating (PG) in the film, which used the increase in refractive index in the irradiated region, decayed remarkably after annealing at temperatures below 500°C. However, subsequent annealing at 600°C reversed the photo-induced refractive index pattern of the PG, namely, refractive index in the unirradiated region became higher than that in the irradiated one after annealing, yielding a new type of grating with higher diffraction efficiency and thermal stability than that before annealing. We named such a grating, which is induced by the annealing, a thermally stabilized grating (TG). In this study, we fabricated the thermally stabilized channel waveguides with TGs by laser irradiation and successive annealing. Diffraction efficiencies and diffraction wavelengths of the TG in the channel waveguide never changed after heat treatment at 500°C for 1 h.

2. Experimental

2.1. Preparation of Ge-B-SiO_2 thin glass films and photo-induced gratings

Ge-B-SiO_2 thin glass films of 4 μm thickness were deposited on silica glass substrates using the plasma enhanced chemical vapor deposition method (PD-10C; Samco International Co. Ltd.). Liquid sources of $Si(OC_2H_5)_4$, $Ge(OCH_3)_4$, and $B(OC_2H_5)_3$ were used as raw materials for SiO_2, GeO_2, and B_2O_3, respectively. Vapors of source materials were introduced with oxygen gas into a chamber and then decomposed using oxygen plasma. The plasma was enhanced using a radio frequency of 13.56 MHz with 250 W. The inner pressure was 53 Pa; the temperature was kept at 400°C. Compositions of thin films were analyzed using electron probe microanalysis (EPMA: JCMA-733; JEOL). The refractive index, thickness, and propagation loss were measured using the prism coupling method (Model 2010; Metricon Corp.). Photo-induced gratings with a period of 530 nm were written by irradiation with a KrF excimer laser (COMPex102; Lambda Physik) of 248 nm wavelength through a phase mask at room temperature without hydrogen loading. The photon density and shot number for the grating writing were fixed at 80 mJ/cm^2/pulse and 12 000 shots, respectively.

2.2. Fabrication of a channel waveguide with a Bragg grating

Channel waveguides with TGs were fabricated using irradiation with a KrF excimer laser and subsequent annealing. First, a 5-mm-long PG was written in a thin film. Then, irradiation through a Cr mask with a straight line pattern of 6 μm width on a silica glass substrate was carried out under the condition of the photon density of 180 mJ/cm^2/pulse and a shot number of 27 000. Finally, this specimen was annealed at 600°C for 20 min.Thermal annealing was performed in a tube furnace with a nitrogen atmosphere. Transmission spectra of channel waveguides were measured with an optical spectrum analyzer using a wavelength tunable laser diode as a light source. The incident beam was butt-coupled into channel waveguides using a commercial single-mode optical fiber with a numerical aperture of 0.15.

3. Results and discussion

Figure 1 shows changes of refractive indices at 632.8 nm in wavelength of the unirradiated film and the homogeneously irradiated film against an annealing time at 600°C. The film composition was $15GeO_2$-$5B_2O_3$-$80SiO_2$ (mol%). The photon density and shot number for preparation of the irradiated film were 180 mJ/cm^2/pulse and 27 000 shots, respectively. The photo-induced refractive index increase was as large as 3.1×10^{-3}. After annealing for 10 min, the photo-induced refractive index difference between the films rapidly decreased to 0.5×10^{-3} with accompanying reduction of the refractive indices of both films. One cause for thermal decay in the photo-induced refractive index change is the thermal excitation of the electrons that are trapped at defects during irradiation [6]. Refractive indices of both films increased after annealing periods longer than 10 min. However, the rate of the refractive index increase of the irradiated film was much lower than that of the unirradiated one. Consequently, the refractive index of the unirradiated film became higher than that of the irradiated one after annealing for longer than 10 min, in contrast with the case before annealing. It was considered that such uncommon phenomena was closely related to the predominant formation of B_2O_3-rich phase in the irradiated region followed by the precipitation of crystalline Ge nanoparticles

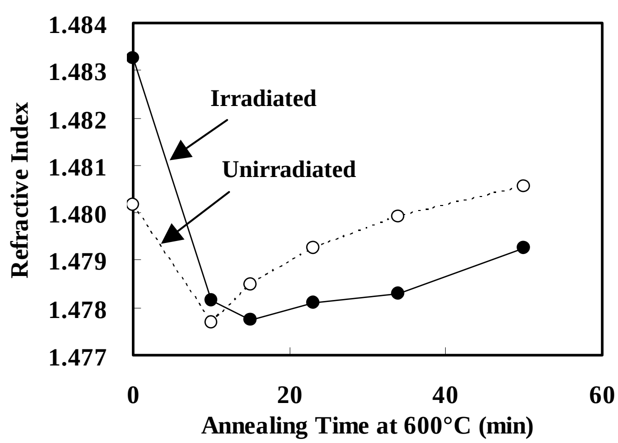

Fig. 1. Changes in refractive indices at 632.8 nm wavelength of the unirradiated film and the homogeneously irradiated film as a function of an annealing time at 600°C. Irradiation was performed with KrF excimer laser under the condition of the photon density of 180 mJ/cm^2/pulse and a shot number of 27 000.

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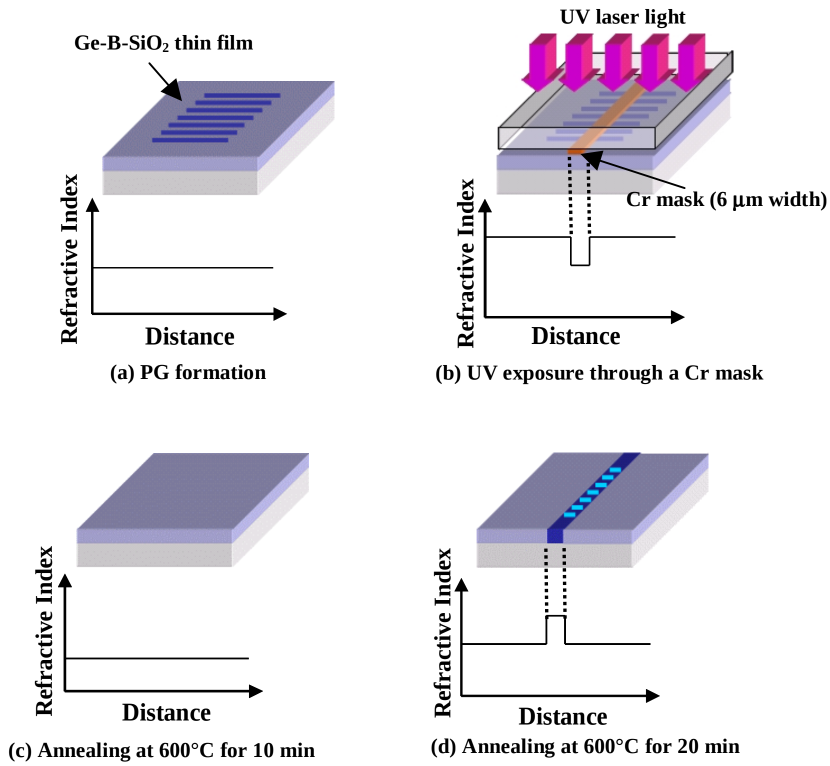

Fig. 2. Schematic fabrication processes of a thermally stabilized channel waveguide with TG by irradiation with KrF excimer laser and thermal annealing. The refractive index distribution in Ge-B-SiO_2 thin film at each process is also shown. The refractive index in the unirradiated region became higher than that of the irradiated one after annealing for longer than 10 min, in contrast with the case before annealing.

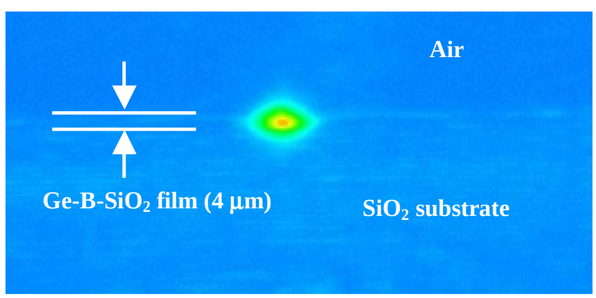

Fig. 3. Near-field pattern of the output beam from a thermally stabilized channel waveguide when the light of 1550 nm in wavelength was coupled. The height and width of the core were 4 µm and 6 µm, respectively.

in the unirradiated region, which were described in our last reports [14,15]. The size of the nanoparticles was 20–40 nm in diameter. Therefore, the origin of the refractive index increase in the unirradiated region after annealing should be the precipitation of Ge nanoparticles because of the much higher refractive index than oxide glasses. The refractive index difference between the films induced by annealing of periods longer than 10 min never

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changed after further annealing up to 500°C. Then, we tried to form such grating in the channel waveguide.

Thermally stabilized channel waveguides with TGs were fabricated using irradiation with a KrF excimer laser and subsequent annealing in a $15GeO_2$-$5B_2O_3$-$80SiO_2$ (mol%) thin film. The fabrication processes mentioned in the section 2.2 and the expected refractive index distribution at each process are shown schematically in Fig. 2. These processes induced a channel waveguide structure with a 4-μm-high and 6-μm-wide core because annealing at 600°C removed the photo-induced refractive index increase and then rendered the refractive index of the unirradiated region higher than that of the irradiated one, as shown in Fig. 1. The identical waveguide structure will be obtained if the step (b) was performed prior to the step (a) in Fig. 2. Annealing at 600°C increased the propagation loss. The propagation loss of the film before and after annealing for 1 h was 0.4 and 1.4 dB/cm at 1545 nm in wavelength, respectively. The increase in loss should be attributed to the precipitation of Ge nanoparticles.

Figure 3 shows the near-field image of the output beam when the light at 1550 nm wavelength was coupled to the channel waveguide. The elliptical shape of the output beam was mainly responsible for the asymmetrical core structure because the refractive index difference between core and cladding regions for the vertical direction was larger than that for the in-plane direction. In addition, the anisotropic stresses in the channel waveguide may be one of the causes for the asymmetrical shape of the output beam. It was inferred from Fig. 1 that the refractive index difference between core and cladding regions for the in-plane direction was approximately 1.2×10^{-3} at 632.8 nm in wavelength.

Figure 4 shows transmission spectra of the channel waveguide. Diffraction peaks of 18.0 dB and 18.7 dB for the TE-like mode and TM-like mode were clearly visible: they were located at 1532.7 nm and 1533.1 nm in wavelength, respectively. These peaks indicate that annealing at 600°C induced not only a channel structure, but also TG. Only one peak was observed for each polarization mode, meaning that a single-mode channel waveguide was attained. Polarization dependence of the diffracted wavelengths is probably attributable to the asymmetrical core structure. It is considered that annealing at 600°C induced the TG only in the channel structure because the homogeneous irradiation in Fig. 2(b) was continued until the PG in the cladding area was completely erased.

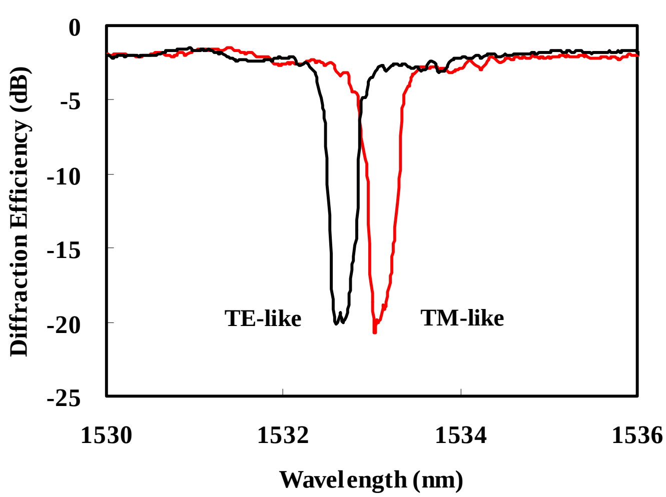

Fig. 4. Transmission spectra of a thermally stabilized channel waveguide with TG for TE- and TM-like modes. Diffraction peaks of 18.0 dB and 18.7 dB for TE-like and TM-like modes were observed, which were located at 1532.7 nm and 1533.1 nm, respectively.

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Figures 5(a) and 5(b) show changes in diffraction efficiencies and diffraction wavelengths, respectively, of the channel waveguide with TG after heat treatment up to 500°C. For comparison, experimental results were also plotted for a PG in a channel waveguide with $3GeO_2$-$11B_2O_3$-$86SiO_2$ (mol%) core and SiO_2 cladding fabricated by the photolithography and dry etching processes. The annealing time was 1 h at each temperature. Diffraction efficiencies for the PG decreased and the peak positions shifted to a shorter wavelength with temperature increase, which is caused by thermal decay in photo-induced refractive index change [14]. In particular, the PG was erased completely after heat treatment up to 400°C. It is noteworthy that no remarkable changes in diffraction efficiencies and peak positions of the TG were observed even after heat treatment at 500°C. Several researchers so far have reported thermal stabilization treatments on fiber Bragg gratings with various glass compositions [14-16]. Although such stabilization treatments reduced the rate of decay, the amplitude of photo-induced refractive index change became much lower than that before heat treatment. Therefore, the laser irradiation followed by the annealing to Ge-B-SiO_2 films is an effective means to form a highly thermally stabilized photo-induced channel waveguide with a grating. Optimization of irradiation and annealing conditions will realize a channel waveguide with a grating with more intense confinement of the guided light, higher diffraction efficiency, and thermal stability.

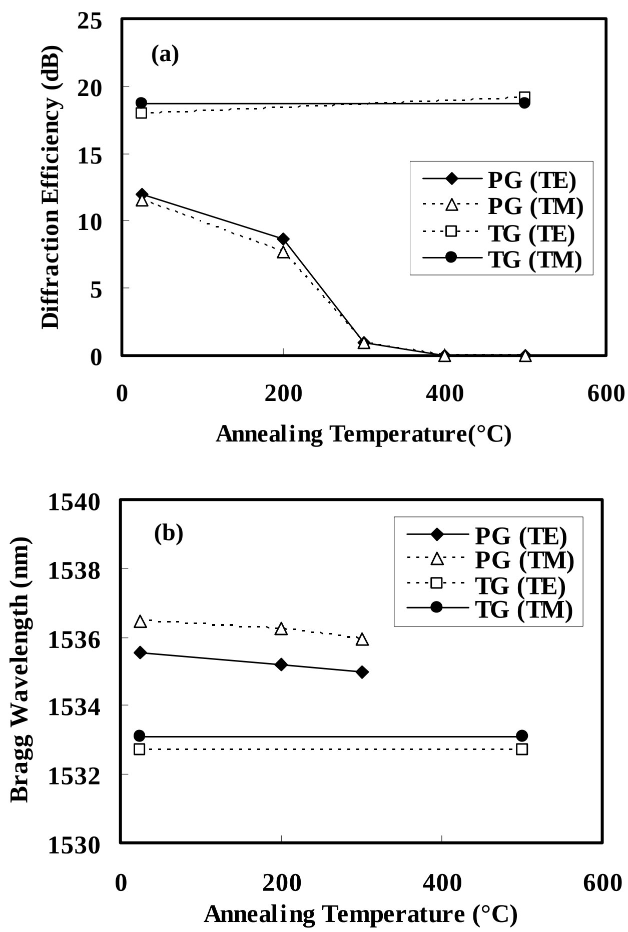

Fig. 5. Changes in (a) diffraction efficiencies and (b) diffraction wavelengths for TE- and TM-like modes of a thermally stabilized channel waveguide with TG after heat treatment up to 500°C. For comparison, the experimental results for a channel waveguide with a PG are also plotted. Annealing time was 1 h at each temperature.

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4. Conclusions

Thermally stabilized photo-induced channel waveguides with Bragg gratings were formed using irradiation and successive annealing at 600°C. The stabilized waveguide with a grating showed diffraction peaks of 18.0 dB for the TE-like mode and 18.7 dB for the TM-like mode, respectively. Neither diffraction peaks nor diffraction wavelengths changed after heat treatment up to 500°C, whereas diffraction efficiencies of the conventional PG decayed after heat treatment at temperatures as low as 200°C. The fabrication process described in this paper, while the long time irradiation or high laser dose may be required for the large scale optical waveguide, is much advantageous compared with the conventional process using photolithography and dry etching. Thermally stabilized photo-induced optical elements in Ge-B-SiO_2 thin films should be applicable to optical devices such as sensors operating at high temperature.

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