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Impact of CO_2 Laser Pretreatment on the Thermal Endurance of Bragg Gratings

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The thermal endurance of fiber Bragg gratings (FBGs), written with the aid of 193-nm ArF excimer laser irradiation on H_2-loaded Ge/B codoped silica fiber, and pretreated with a CO_2 laser and a subsequent slow cooling process, is investigated. These treated gratings show relatively less degradation of grating strength during the thermal annealing procedure. The thermal decay characteristics of treated and untreated fiber, recorded over a time period of 9 hours, have been compared. The effect on the Bragg transmission depth (BTD) and the center-wavelength shift, as well as the growth of refractive-index change during the grating inscription process for both treated and untreated fiber, are analyzed.

Keywords : CO_2 laser annealing, fiber Bragg grating (FBG), 193 nm ArF excimer laser, thermal stability
OCIS codes : (060.2310) Fiber optics; (060.3735) Fiber Bragg gratings; (140.3470) Lasers, carbon dioxide

I. INTRODUCTION

Temperature sensing in dynamic temperature environments has attracted much interest from many researchers. In particular, temperature monitoring in dynamic environments has always been a challenge, and much research must be carried out to develop temperature sensors that are robust and reliable in the volatile condition. Fiber-based temperature sensors have emerged as competitive substitutes for numerous conventional temperature sensors. Notably, fiber Bragg gratings (FBGs) are one of the most commonly used components in the development of these sensors. The thermal stability of these Bragg gratings relies on several factors, for instance the type of fiber, presence of hydrogen, inscription wavelength [1], and any pretreatment process. Erdogan *et al.* proposed two approaches to predict the thermal stability of the refractive-index change after thermal annealing: a power-law model, and an accelerated-aging model [2]. These models are based on the assumption that UV-induced defects are the reason behind the change in refractive index. These defects are thermally reversible and present a distribution of activation energies. Atkins *et al.* investigated the mechanisms responsible for the increased photoinduced refractive-index changes in germanosilicate glasses soaked in hydrogen at high pressure and low temperature, when exposed to 248-nm UV irradiation. These mechanisms involved both photolytically and thermally driven reactions, leading to the formation of OH radicals and UV-absorbing species [3]. Gunawardena *et al.* demonstrated the thermal degradation of a fiber Bragg grating written on hydrogen-loaded, photosensitive germanium/boron codoped fiber using 193-nm ArF excimer laser irradiation. This investigation demonstrated a significant increase in the Bragg transmission depth during annealing at 425°C, which is referred to as the thermally induced reversible effect [4]. This effect deviates from the general thermal-decay behavior of a Bragg grating. Both stepwise and continuous annealing procedures indicated similar behavior in the accelerated aging characteristics, when analyzed with respect to the demarcation energy E_d [4]. Patrick *et al.* conducted a comparative study to investigate the thermal stability of Bragg gratings inscribed on both hydrogen-loaded and nonloaded germanium-doped fiber [5]. However, the characteristic response to temperature variation of Bragg gratings annealed with a controlled cooling process remains an aspect for further exploration.

In an optical fiber, the thermal stress between the fiber core and the cladding is due to the difference in their thermal

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expansion coefficients (TECs). In a doped fiber, the core has a higher TEC, lower viscosity, and lower glass transition temperature T_g than the fiber cladding. During the fiber-drawing process the cladding glass tends to solidify at a higher temperature than the core glass, resulting in contraction of the core as it cools down from the liquid state. Therefore, after the drawing process a hydrostatic tension develops in the fiber core at room temperature [6-7]. Li *et al.* managed to fabricate FBGs with enhanced thermal stability by using femtosecond pulse exposure on optical fibers with relaxed residual stress, with the aid of high-temperature annealing [8]. The thermal stress between the fiber core and cladding can be modified using CO_2-laser annealing [9, 10]. The CO_2 laser has also been useful in thermal annealing of semiconductors [11] and glass waveguides [12]. Since many applications employing fiber Bragg gratings, such as accurate wavelength-control devices in the telecommunication industry, require Bragg gratings with stabilized optical properties to support long-term usage, it is essential to study the decay characteristics of these Bragg gratings. To date, there have been several reports on the thermal decay characteristics of Bragg gratings inscribed on germanosilicate fiber [2, 13] under different experimental conditions, such as F_2-laser pretreated fiber and KrF-laser pretreated fiber [13]. However, there is very limited literature on the thermal response of fibers annealed under a controlled cooling procedure using a CO_2 laser.

In this study, the thermal response of fiber Bragg gratings inscribed on H_2-loaded Ge/B codoped fiber, pretreated with a CO_2 laser followed by a controlled cooling process, is investigated along with H_2-loaded untreated Ge/B codoped fiber. Since this type of fiber shows enhanced photosensitivity compared to standard telecommunication fiber, higher refractive-index changes can be obtained at low UV fluence levels, increasing the possibility to fabricate a wide range of devices suitable for different applications. The Bragg transmission depth (BTD) and the center-wavelength shift with increased isothermal annealing temperature are explored in the current work. Accelerated aging curves are plotted to investigate and characterize the thermal stability of both CO_2-treated and untreated fiber in the long run.

II. EXPERIMENTAL PROCEDURE

The fabrication procedure begins with CO_2-laser treatment of Ge/B codoped photosensitive fiber (Fibercore PS1250/1500), on a region 15 mm long. The fan-cooled CO_2 laser (SYNRAD 48-2 SAM) is placed on a stainless steel optical table in an air-conditioned laboratory. It has a maximum output power of 35 W (± 2%, maximum). A vertical beam 15 mm long was produced by initially expanding the laser beam with the aid of two convex lenses, and subsequently compressing it using a cylindrical lens with a focal length of 50.8 mm. During the CO_2-laser treatment, the irradiated laser power on the fiber was increased from 0 to 14.4 W (80% of the maximum laser power) at a rate of 0.18 W/s, with a hold time of 5 minutes after the ramping procedure. A slow cooling process followed, where the laser power was reduced at a rate of 0.009 W/s. Subsequently the treated fiber, along with an untreated fiber, was kept in a pressurized hydrogen chamber at 1800 psi for 10 days. Afterward the FBG inscription procedure was carried out on both types of fiber, and 10-mm Bragg gratings were inscribed using a 193-nm ArF excimer laser with pulse duration, pulse energy, and repetition rate of ~10 ns, 8 mJ, and 1 Hz respectively, until similar reflectivity levels were achieved for each fiber. During the FBG writing process, the UV beam size was expanded using a beam expander, the beam width being maintained at 10 mm using an adjustable vertical slit. The reflectivity of each fiber amounted to approximately 40 dB. The transmission spectra of the two types of fiber were monitored using an Optical Spectrum Analyzer (OSA). Prior to annealing, both the treated and untreated PS fibers were placed in an oven at 80°C for 8 hours, to achieve out-diffusion of the residual H_2 trapped inside the fiber core.

The annealing process was carried out on both CO_2-laser-treated and untreated fibers under similar temperature conditions, for accurate measurement. The fibers were placed inside a tube furnace, where the temperature increment was controlled using a built-in program. During annealing the temperature was initially increased from room temperature (25°C) to 100°C in a ramping time of 5 minutes, then incremented to 200°C and 300°C, dwelling at each temperature for 3 hours. During the treatment, transmission spectra were recorded every minute for each fiber with the aid of an OSA controlled by a LabVIEW program via a general purpose interface bus (GPIB) interface. The experiment was repeated at 100°C, 150°C, and 250°C to analyze the accelerated aging curves of the treated fiber, and to verify the validity of this study.

III. RESULTS AND DISCUSSION

Figure 1 shows the refractive-index changes of the CO_2-laser-treated and untreated fiber during the grating inscription procedure with 193-nm ArF laser irradiation. From Fig. 1 it is seen that with increasing UV fluence, the CO_2-laser-treated fiber experiences a higher refractive-index change, up to ~1.7×10^{-4}, compared to that of the untreated fiber. This Δn_{mod} can be calculated using the following expression [14, 15]

$$\Delta n_{\mathrm{mod}} = \frac{\lambda_C(F)\tanh^{-1}(\sqrt{R})}{\eta\pi L} \tag{1}$$

where $\lambda_c(F)$ is the center wavelength (a function of cumulative UV fluence), R the reflectivity of the grating, λ_D the designed Bragg wavelength, η the mode overlap parameter, and L

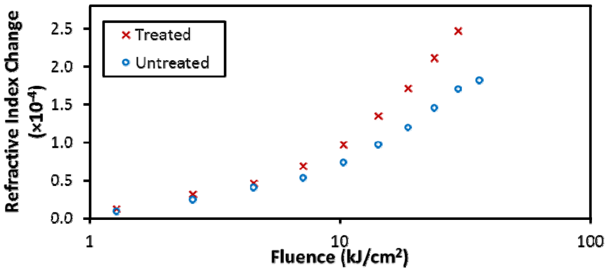

FIG. 1. Growth of refractive-index change of CO_2-laser-treated, slow-cooled fiber and untreated fiber during grating inscription with exposure to an 193-nm ArF excimer laser.

the grating length. The mode overlap parameter can be represented as

$$\eta = \frac{\pi^2 d^2 k^2}{\lambda^2 + \pi^2 d^2 k^2} \tag{2}$$

where d, k, and λ indicate respectively the fiber core diameter, the numerical aperture (NA) of the fiber, and the center wavelength. Brambilla *et al.* demonstrated enhancement of grating refractive-index modulation and average refractive index in a fiber after CO_2-laser annealing [16], which can be attributed to the change in germanium oxygen deficient center (GODC) population after CO_2-laser treatment. Their study also demonstrated that the defects responsible for the enhancement in UV photosensitivity can be bleached only at high UV intensities, which further suggests multiphoton absorption [16].

It is observed from Fig. 2 that with increasing annealing temperature, the Bragg transmission depth (BTD) gradually decreases. At 100°C and 200°C, BTDs of both CO_2 – laser-treated and untreated fibers show a similar kind of progression, whereas this behavior subsequently differs when the fiber has reached 300°C. After isothermal annealing at 300°C for 3 hours, a BTD of 25 dB can be observed for treated fiber, compared to increased decay in the grating strength of untreated fiber. Davis *et al.* have demonstrated that CO_2-laser-induced long-period fiber gratings are highly stable, even when subjected to temperatures as high as 1200°C for longer time intervals [17]. The BTD of the treated fiber indicates a stabilized grating strength, which would be very useful in the production of temperature sensors for long-term usage, where the decay of grating strength should be quite low. Furthermore, Fig. 2 demonstrates redshift of center wavelength with increased annealing temperature, for both types of fiber. Throughout the annealing process, a center-wavelength difference of ~1 nm is observed between the treated and untreated fibers. The reason for this redshift of the treated, slow-cooled fiber is the sufficient time available for structural relaxation in the fiber glass in a low-viscosity state, when subject to slow cooling during CO_2-laser annealing.

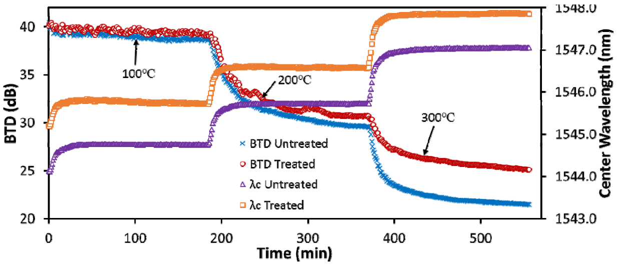

FIG. 2. The evolution of the Bragg transmission depth and center wavelength of treated and untreated fiber at 100°C, 200°C and 300°C.

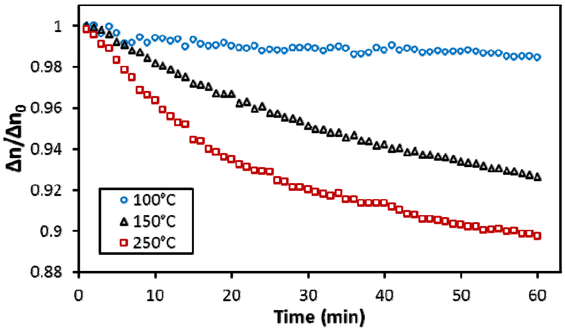

FIG. 3. Accelerated aging curves for gratings in CO_2-laser-treated, slow-cooled fiber at 100°C, 150°C, and 250°C.

As a result of this structural relaxation, the T_g of the fiber-core glass has been reduced, which leads to reduction in thermal stress between fiber core and cladding, and thus the redshift in Bragg wavelength [9]. A negligible effect on Bragg-wavelength response is observed between the treated and untreated fibers when comparing the progression of the BTD, due to the similar temperature sensitivities of both fibers.

Figure 3 shows the normalized decay of the ac index modulation ratio $\eta = \Delta n(t)/\Delta n_0$ of CO_2-laser-treated, slow-cooled fiber at three different annealing temperatures (with a dwelling time of 1 hour). The highest stability is observed at 100°C, followed by 150°C and 250°C, where the ratio is least stable. A monotonic decrease of η is observed, leading to an overall decay of 1%, 8%, and 10% in the FBGs at these three temperatures. However, a different thermal response, resulting in different thermal degradation, is expected when conducting accelerated aging tests, depending on the temperature and duration of the annealing procedure.

IV. CONCLUSION

The thermal endurance of Bragg gratings inscribed on hydrogen loaded Ge/B codoped silica fiber, pretreated with a CO_2 laser followed by a slow cooling process, are investigated over a period of 9 hours at different temperatures. The wavelength response and growth of the refractive-index change of the fiber were explored, and a comparative study has been carried out using untreated fiber. The treated fiber showed less degradation in Bragg transmission depth, compared to the untreated fiber. The prolonged thermal endurance of these gratings inscribed on CO_2-laser-treated fiber increases the interest in using them as temperature sensors in high-temperature environments.

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