Characteristics of Deuterium-Loaded Fiber Bragg Gratings

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Fiber Bragg gratings with controllable reflectance and bandwidth were fabricated by employing high-pressure deuterium loading for photosensitivity enhancement and by utilizing a phase mask for holographic exposure. The absorption peak near $1.71\ \mu\text{m}$ was used as an indicator to monitor the evolution of deuterium diffusion into and out of the fiber, and it was noted that the measured results were consistent with the simulated ones. Thermal hysteresis of the fiber Bragg grating was markedly reduced and reliability was therefore increased, following annealing. The difference between hydrogen and deuterium loadings is also discussed.

KEYWORDS: fiber Bragg gratings, deuterium, photosensitivity, thermal reliability

1. Introduction

Recently there has been a considerable interest in the UV-written fiber Bragg gratings due to their applicability as building blocks of devices employed in optical fiber communication and optical fiber sensing such as wavelength division multiplexers (WDMs),¹⁾ fiber lasers,^{2,3)} dispersion compensators⁴⁾ and smart sensors.⁵⁾ The strength of each fiber Bragg grating has to be designed so as to fit its application. It is known that grating strength is strongly related to the UV-induced refractive index change. The fiber to be exposed should, therefore, have enough photosensitivity which generally increases with the amount of GeO_2 in a common silica fiber. In 1993, Lemaire and coworkers first reported an effective method of enhancing photosensitivity by hydrogen loading on the silica fibers, which resulted in typically two orders of magnitude improvement compared to ones without loading.^{6,7)} In this work, we use deuterium loading on high germanium-doped silica fibers to study the induced photosensitivity enhancement and compare it with the result obtained by hydrogen loading.

In addition, Bragg wavelength stability is an important consideration to obtain a reliable and accurate operation of a fiber Bragg grating. In optical fiber communication devices employing WDM technologies, Bragg wavelength drift may induce severe crosstalk and even total failure in a given channel. In optical fiber sensing, the Bragg wavelength shift amount is proportional to the physical parameter being measured such as strain, pressure, and temperature. It is therefore apparent that the reliability of fiber Bragg gratings plays an important role, particularly for those imprinted on hydrogen- or deuterium-loaded fibers because hydrogen or deuterium may gradually diffuse out, causing Bragg wavelength drift.

In this paper, we also discuss the characteristics of a fiber Bragg grating which is imprinted on a deuterium-loaded dispersion-shifted fiber by UV light exposure. The evolution of deuterium when diffused into and out of the fiber, and the Bragg wavelength shift after a grating is imprinted, are characterized both numerically and experimentally. The effect of annealing and the thermal reliability of deuterium-loaded fiber Bragg gratings are also discussed.

2. Photosensitivity of Deuterium-Loaded Optical Fibers

2.1 Loss spectra of deuterium-loaded optical fibers

We used dispersion-shifted fibers for deuterium loading which had a core diameter of $\sim 5.7\ \mu\text{m}$, and had a quasitriangular index profile. The maximum index difference between the core and cladding layer of fiber measured in its preform was ~ 0.017 . These fibers had been loaded in a deuterium chamber at the pressure of $102\ \text{kg}/\text{cm}^2$ and temperature of 28°C for more than 30 days before they were measured. These 4-meter-long fibers were completely saturated with deuterium. The loss spectra of the optical fiber before and after deuterium loading are shown in Fig. 1. Subtracting these two curves, we find a significant magnitude change at the wavelength of $1715\ \text{nm}$ as shown in Fig. 2, which is associated with deuterium.⁸⁾ Therefore, the relative loss magnitude at this wavelength can be used as an indicator for monitoring the deuterium concentration in the core. In addition, the required time constant for reaching the saturation level can be obtained by characterizing the evolution of deuterium diffusion.

2.2 Modeling of deuterium-diffusion behavior in fibers

Figure 3 shows the evolution of deuterium concentration when the optical fibers were immersed in deuterium under the same conditions as described previously. The solid circles in the figure represent the measured deuterium-induced losses at $1715\ \text{nm}$ normalized to the saturated value. The line

Fig. 1. Loss spectra of an optical fiber before and after deuterium loading.

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Fig. 2. Difference between the loss spectra of Fig. 1.

Fig. 3. Simulation and experiment results of deuterium diffusion into optical fibers at 28°C.

curve represents the simulation result obtained by employing the diffusion model described below. The good agreement between the measured and simulation results clearly suggests a strong correlation between the deuterium-induced loss and deuterium concentration.

The concentration of deuterium diffused into the fiber can be obtained by solving the following diffusion equation⁹⁾

$$\frac{C(r, t)}{C_0} = 1 - 2 \sum_{n=1}^{\infty} \frac{\exp(-D\alpha_n^2 t) J_0(r\alpha_n)}{a\alpha_n J_1(a\alpha_n)}, \quad (1)$$

where a is radius of the fiber, α_n 's are the roots of $J_0(a\alpha_n)$, and $J_0(x)$ and $J_1(x)$ are the Bessel functions of the first kind of the orders zero and one, respectively. Similarly, the concentration of out-diffusing deuterium can be expressed as¹⁰⁾

$$\frac{C(r, t)}{C_0} = 2 \sum_{n=1}^{\infty} \frac{\exp(-D\alpha_n^2 t) J_0(r\alpha_n)}{a\alpha_n J_1(a\alpha_n)}. \quad (2)$$

In both cases, the diffusion coefficient of deuterium, D , is given by⁸⁾

$$D = 5 \times 10^{-4} \exp\left(\frac{-10.5 \text{ kcal/mol}}{RT}\right) \text{ cm}^2/\text{s} \quad (3)$$

Fig. 4. Simulation and experiment results of deuterium diffusion out of saturated optical fibers at 20°C and -22°C.

where R is the molar gas constant, and T is the temperature in Kelvin. The deuterium concentration obtained from eq. (1) is therefore equivalent to the degree of photosensitivity in a deuterium-loaded fiber.

The theoretical curve shown in Fig. 3 is obtained by employing the diffusion coefficient $D = 1.1709 \times 10^{-11} \text{ cm}^2/\text{s}$ to fit the measured deuterium-induced losses, and the radius of the cylinder is set at $62.5 \mu\text{m}$. From eq. (2), it can be noted that the deuterium concentration along the cylinder axis would reach 95% of the saturation value in a time, defined as time constant, given by

$$t_{0.95} = \frac{0.6a^2}{D_{D_2}}. \quad (4)$$

Conversely, the amount of time, $t_{0.05}$, taken for the out-diffusing deuterium concentration to reach 5% of its final value in the fiber axis has the same expression as eq. (4).

As shown in Fig. 3, 95% of its saturation value was reached after about 23 days. The evolution of deuterium diffused out of the fibers that are initially saturated at two different temperatures is shown in Fig. 4. The results show that it takes longer time for deuterium in the fibers at lower temperatures to diffuse out, suggesting that in order to maintain its photosensitivity a deuterium-treated fiber needs to be preserved at low temperatures. For example, the photosensitivity of a deuterium-loaded optical fiber can last for more than one month when kept at -22°C.

3. Fabrication of Fiber Bragg Grating

A KrF excimer laser (248 nm) operating at a repetition rate of 5 Hz was used to expose the fibers described in §2.1 through a phase mask. The reflected or transmitted light spectra were monitored *in situ* using a broad-band light source and a 3 dB coupler. The output ends were dipped with index oil to minimize Fresnel reflection when measuring reflection spectra. The reflectance of a fiber Bragg grating was obtained by taking the splitting ratio of coupler in the spectral region of interest into account. The transmission spectrum of fiber Bragg grating that we fabricated through a zero-order-nulled phase mask (period=1053 nm) at the fluence of $270 \text{ mJ}/\text{cm}^2/\text{pulse}$ is shown in Fig. 5. The Bragg grating was 7 mm long, and the exposure duration was 5 min. The Bragg wavelength was

Fig. 5. Transmission spectrum of a typical fiber Bragg grating, with Bragg wavelength λ_B centered at 1525.28 nm.

centered at 1525.28 nm, and its bandwidth measured at full-width at half maximum (FWHM) was 0.53 nm. Since the period of the phase mask is known, the effective mode index is estimated to be 1.4485 according to the following Bragg condition

$$\lambda_B = 2n_{\text{eff}}\Lambda, \quad (5)$$

where λ_B is the Bragg wavelength, n_{eff} is the effective mode index, and Λ is the fiber grating period. For a uniform grating, the maximum reflectance can be expressed as¹¹⁾

$$R_{\text{max}} = \tanh^2(\kappa L) \quad (6)$$

$$\kappa = \frac{\pi \Delta n \eta}{\lambda_B} \quad (7)$$

where κ is the coupling coefficient, Δn is the refractive index change, L is the grating length and η is the fraction of light propagating in the core. The cut-off wavelength of our fiber was 1199 nm; therefore, the normalized frequency V was equal to 1.8904 at 1525 nm. By applying eqs. (6) and (7) and the calculated $\eta = 0.674$ for the dispersion-shifted fiber at the normalized frequency, the refractive index change in the optical fiber was estimated to be 3.38×10^{-4} .

The small multiple peaks which appear in the short-wavelength side of the Bragg wavelength are also shown in Fig. 5. This radiation loss is considered to be due to light leaving the core edge as a result of the grating inscription, because no significant variation of UV-induced loss in this spectral range is observed. When the fiber containing the fiber Bragg grating was surrounded by air, great dips associated with coupling to distinct cladding modes appeared. However, when the fiber was immersed in index oil with index slightly larger than that of cladding, only small residual Fabry-Perot resonance fringes in the short-wavelength side of the Bragg wavelength were observed, and were associated with the imperfect reflection of the radiation mode off the cladding-index oil interface.^{12,13)} Figure 6 shows the transmission spectra of fiber Bragg grating with and without index oil treatment. The multiple peaks are markedly reduced, leaving only the true radiation-mode coupling, when dipping this fiber Bragg grating in an index oil ($n = 1.516$). It should be noted, however, that the wavelength of the main Bragg peak does not shift.

Fig. 6. Transmission spectra of a fiber grating with and without index oil treatment.

4. Shifting of Bragg Wavelength and Thermal Reliability

4.1 Shifting of Bragg wavelength

Due to the presence of the DC term of the interference intensity inside an optical fiber, the effective mode index increased with UV exposure. The Bragg wavelength shifted towards the longer-wavelength side during UV exposure as shown in Fig. 7. With increasing exposure time, the amount of Bragg wavelength shift increased linearly, and the Bragg reflection growth saturated after a certain exposure time. In addition, it can be deduced from some experiments that the Bragg wavelength shift rate was related to the phase mask used for exposure. Thus the optical quality of phase mask might contribute to the controllability of Bragg wavelength.

After the formation of fiber grating, its Bragg wavelength was found to shift gradually toward the short-wavelength side as shown in Fig. 8. The amount of wavelength shift depends on grating reflectance, deuterium concentration in the fiber, and exposure dosage of UV irradiation. The variation of the absorption peak with time at $1.715 \mu\text{m}$, i.e., the indicator of deuterium concentration is also shown. Note that such a shift will have a serious impact on those devices which require a stable Bragg wavelength operation, for example, fiber lasers and fiber sensors. This problem of Bragg wavelength shift can be solved by annealing fiber Bragg grating to force deuterium to diffuse out of the fiber.

The temperature change of a fiber Bragg grating results in its Bragg wavelength shift because of the thermal expansion effects on refractive index and grating period. Following the temperature cycling application in the range from 25°C to 200°C , a discrepancy in the two curves of Bragg wavelength, as shown in Fig. 9(a), was found. In addition, the shift direction of the thermal hysteresis in fiber Bragg grating is related to the deuterium out-diffusion in an optical fiber after UV light exposure as previously described. After annealing this fiber grating, for example at 160°C for 3 h, this thermal hysteresis disappeared as shown in Fig. 9(b), and these annealed fiber gratings could thus have stable optical properties for a long-term operation when used below the annealing temperature. The annealing condition was employed to ensure that

Fig. 7. Growth of fiber Bragg grating with exposure time.

Fig. 8. Variations of Bragg wavelength and residual deuterium with time after a grating is imprinted.

deuterium in the fiber core was forced to diffuse out quickly.

4.2 Thermal reliability

In order to ensure long-term performance stability, thermal reliability of a fiber Bragg grating is an important consideration for practical applications. We measured the photoinduced index variation with time by annealing fiber gratings in an oven at both 100°C, and 200°C, after the gratings were imprinted. We calculated their corresponding coupling coefficients κ according to eq. (6) by taking the reflectance of a fiber grating as $R = 1 - T$ from the measurement of its transmission spectrum. The time dependence of κ/κ_0 at two different temperatures is shown in Fig. 10(a) where κ_0 is the coupling coefficient measured immediately before annealing. These three fiber gratings had reflectance of around 90%. We also measured the other two types of fiber Bragg gratings having 70% and near 100% reflectances as weak and saturated gratings, respectively. The result is shown in Fig. 10(b). For the saturated gratings we alternatively evaluated the refractive index change by taking the bandwidth of -20 dB down from

(a)

(b)

Fig. 9. When a fiber Bragg grating is temperature-cycled, thermal hysteresis (a) exists before annealing; (b) is greatly reduced after annealing.

the floor level of the transmission spectrum into the following equation

$$\frac{\Delta\lambda_B}{\lambda_B} = 2 \frac{\Delta n}{n_{\text{eff}}} \quad (8)$$

$\Delta\lambda_B$ and λ_B are the measured bandwidth and Bragg wavelength, respectively. The bandwidth of the saturated gratings, thus measured, was about 0.5 nm. The results of the thermal decay curves for the weak and strong gratings are quite similar, which is consistent with the results reported by Egan *et al.*¹⁴⁾ It was noted that there were no significant thermal index variations between fresh fiber gratings measured within 24 h after UV light inscription and those measured within 2 weeks. From these results, we believe that annealing of a fiber grating of deuterium loading is a good way to enhance its performance stability, so as to retain only the stable portion of the UV-induced refractive index change.

5. Discussion

In this section, we compare the difference between hydrogen- and deuterium-loaded fibers. With both hydrogen-

Fig. 10. Thermal reliability at 100°C and 200°C for fiber gratings with (a) $\sim 90\%$ reflectance; (b) three different reflectances.

and deuterium-loaded techniques, the photosensitivity of an optical fiber can be enhanced. However, the hydrogen loading causes an additional OH absorption loss at $1.38\ \mu\text{m}$ which is within the second window of fiber communication interest. In order to reduce this loss, one can use deuterium instead of hydrogen. The additional OD absorption loss occurs around the wavelengths of $1.9\text{--}2.0\ \mu\text{m}$,¹⁵⁾ far from all windows of fiber communication interest. The measured loss spectra of three 2-m-long fibers are shown in Fig. 11. The fibers were loaded in hydrogen and deuterium chambers at pressures of 77 and 81 kg/cm², respectively, for more than one month at room temperature. From Fig. 11, the OH loss of a deuterium-loaded fiber near $1.38\ \mu\text{m}$ can be seen to be approximately 0.81 dB/m smaller than that of a hydrogen-loaded fiber. Although the loss in the $1.55\ \mu\text{m}$ region is 0.5 dB/m higher for a deuterium-loaded fiber compared to a hydrogen-loaded one, such loss can be compensated since most optical links operating in this region employ erbium-doped fiber amplifiers.

When loaded fibers are taken from a hydrogen or deuterium chamber, hydrogen or deuterium will gradually diffuse out. Therefore, we can not keep the loaded fibers in ambience for a long time. Since the diffusion coefficient of deuterium is smaller than that of hydrogen, it takes a significantly longer time for deuterium to diffuse out as shown in Fig. 12. Therefore, the photosensitivity of a deuterium-loaded fiber can last

Fig. 11. Transmission spectra of fibers with no loading, hydrogen loading and deuterium loading.

Fig. 12. Comparison of out-diffusion evolution between hydrogen- and deuterium-loaded fibers.

longer than that of a hydrogenated fiber i.e., up to 23 days at 20°C.

6. Concluding Remarks

By utilizing both phase-mask technique and deuterium loading we have successfully fabricated fiber Bragg gratings. We have established that deuterium loading is an effective method to enhance optical fiber photosensitivity. A diffusion model was employed to describe the behavior of deuterium diffusion into and out of optical fibers. Using the absorption peak at 1715 nm as an indicator, the measurement results show good agreement with the simulation results. The Bragg wavelength of a deuterium-loaded fiber grating is found to shift during UV light exposure and after grating inscription. Following annealing of the fiber Bragg grating, a permanent thermal hysteresis in the evolution of Bragg wavelength of a fiber grating disappears when temperature cycling is applied. The thermal stabilities of deuterium-loaded fiber gratings of three different strengths are characterized. One solution to solve the problem of Bragg wavelength shift after imprinting

a fiber grating, and thus increase the grating's reliability, is to anneal, quickly forcing the residual deuterium out of the optical fiber. Additionally, it is found that a deuterium-loaded fiber is more desirable than a hydrogen-loaded fiber to imprint a Bragg grating because it has a low OH-induced loss and a longer photosensitivity-maintaining lifetime.

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