Thermal stability of fiber Bragg gratings recorded under different conditions

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Abstract

In this work an experiment was performed to examine the thermal stability of fiber Bragg gratings recorded using both pulsed and continuous-wave ultraviolet radiation. Thermal cycles of 30 minutes at temperatures varying from 25 to 260 ^oC have been applied to the fiber gratings in a dry environment. The changes in grating reflectivity and Bragg wavelength are analyzed as a function of the temperature and inscription condition.

Introduction

Fiber Bragg gratings (FBG) are widely used in optical communication systems, acting as mirrors in fiber lasers, as dispersion compensators and gain flatteners in pulse compression and optical amplification systems, as filters in wavelength-division multiplexing systems. The high sensitivity of the Bragg wavelength to the strain applied to the fiber, as well as to variations in temperature and refractive index of the external environment makes FBG an interesting alternative in several sensing applications. FBG sensors offer a multitude of advantages, as low cost, immunity to electromagnetic interference, good resistance to environmental conditions, low weight and the possibility of multiplexing several sensors along the same fiber.

Fiber Bragg gratings are obtained by exposition of the fiber core to an ultraviolet (UV) radiation interference pattern. The UV radiation, absorbed by the fiber core, creates defects in the core matrix, altering the refractive index of the illuminated regions. This periodic modulation of the core index reflects the propagating light periodically. Constructive interference of the reflected light takes place only for in-phase radiation, with wavelength λ_B determined by the Bragg law: $\lambda_B = 2n_{eff}\Lambda$, where n_{eff} the effective core-cladding refractive index and Λ, the index modulation period [1].

The values of the Bragg wavelength λ_B and the total grating reflectivity, depend directly on the refractive index modulation amplitude. A slow decay of this modulation amplitude is expected from relaxation of some unstable defects created upon UV absorption [2]. In order to guarantee the functionality and reliability of telecommunication devices and sensors based on FBG, it is necessary to determine the grating stability under the operating conditions. Thermal activation of unstable defects is the most important source of grating degradation. The thermal stability of the fiber gratings may also be affected by the inscription method and fiber doping characteristics.

In this work we evaluate the stability of the FBG recorded in our laboratories to thermal cycles. We compare the results obtained in FBG recorded using two different UV sources: short-duration laser pulses and continuous-wave (cw) laser.

Experiment

The FBG were produced using two similar set ups, where the only difference is the inscription radiation [3,4]. The UV sources used for FBG inscription were: a) the forth harmonic of a Q-Switched Nd:YAG laser, which delivers pulses with energies up to 10 mJ at 20 Hz and 266 nm; and b) the second harmonic of a cw Argon laser that furnishes up to 200 mW at 244 nm. The beam diameter of the Nd:YAG laser is about 3 mm and it is focused on the fiber by a cylindrical lens. The Argon laser has a diameter smaller than 1 mm at the fiber position. Adequate phase mask is placed at the exit of the laser source, diffracting the beam into two main orders, +1 and –1. Two high-flatness mirrors reflect the two diffracted beams, which interfere in the bare optical fiber, imprinting the interference pattern on its core. The recorded grating period, Λ, is defined by the angle between the incident beams and the fiber, and can be tuned by rotating the mirrors. Besides the wavelength, the main difference between the two inscription systems is that, due to the high energy delivered by the pulses, the cladding may be burned if too much power is used for the inscription, preventing a proper grating from growing. As a consequence, the average pulsed laser power cannot be raised beyond 20 mW, lengthening the exposition time with respect to the cw system.

In this work, the gratings were recorded in commercially available photosensitive single-mode fibers. To raise the photosensitivity, the fibers were submitted to a pressurized hydrogen environment (150 kg/cm^2), at room temperature, during one week. Reflectivities approaching 100% are commonly recorded in the hydrogenated photosensitive fibers using both inscription sources. Gratings with reflectivities as high as 70% are obtainable in hydrogenated standard telecommunication fibers. It has also been demonstrated the inscription of FBG in standard multimode fibers using the cw system [5]. The typical spectral bandwidth is less than 1 nm for gratings recorded in hydrogenated photosensitive fibers, and less than 0.5 nm for those written in hydrogenated standard telecommunication fibers.

We have studied two sets of FBG recorded using the two different UV lasers, respectively. Each set contain three gratings with different Bragg wavelengths, grown in the same piece of fiber under the same conditions. The gratings A, B, and C, obtained with UV pulses, presented reflectivities around 100% before treatment. The reflectivities of the gratings D, E and F, written through cw exposure were of 40% for D and E, and of 15% for F, before thermal treatment.

The thermal treatment of the fibers was carried out several days after the grating inscription. We suppose that, by that moment, all the residual hydrogen present in the fiber matrix had already escaped. The FBG have been put into an oven and submitted to temperatures of 50, 80, 130, 140, 160, 180 and 200^{o}C, during 30 minutes at each temperature, and to 260^{o}C during 1 hour. Afterwards, the gratings were cooled to room temperature and re-heated to 250^{o}C for a period of 6 hours.

Results and Discussions

The reflectivity spectra have been monitored during the process. Typical results obtained at high temperatures with the gratings A, B and C can be observed in Figure 1 (a). The temperature induces a modification on the Bragg wavelength, as expected, due to the fiber refractive index variation with temperature. In Figure 1(b), we plot this wavelength variation as a function of the temperature. The experimental data (symbols) are compared with the expected values [1] showing a good agreement. Besides, as discussed below, one observes a decrease of the reflectivity as the temperature increases.

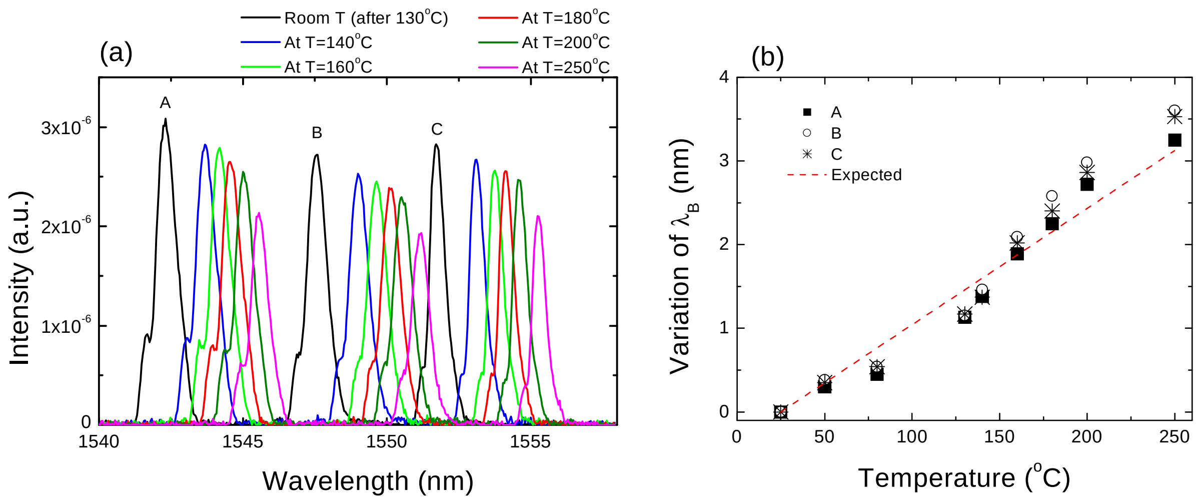

Figure 1: (a) Reflectivity spectra, at high temperatures, for the FBG recorded with pulsed laser; (b) variation of the Bragg wavelengths at high temperature: points are experimental data and the dotted line is the theoretical curve.

The grating spectra have been analyzed after some of the thermal cycles. The results, summarized in Figures 2 and 3, give us information about the thermal stability of the FBG fabricated under the conditions described before.

Figure 2 (a) shows the reflectivity decay as a function of the temperature for the gratings recorded by pulsed laser. Decay around 30% on the reflectivities has been observed. For the set grown upon cw irradiation, the reflectivities measured at the treatment temperatures are presented in Fig. 2(b). Decay of 45% has been found for the gratings D and E, originally 40% reflective; the grating F, originally 15% reflective, has lost about 55% of its reflectivity.

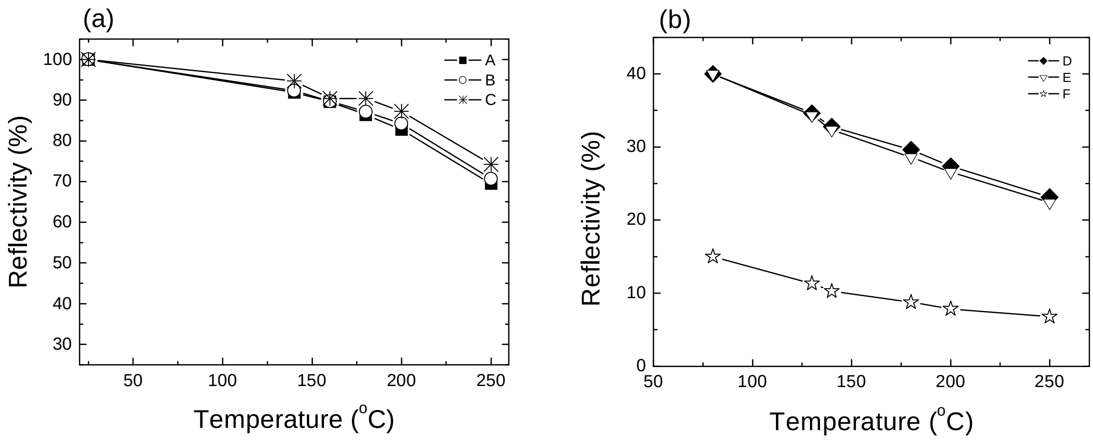

Figure 2: Reflectivities as a function of treatment temperature for the FBG: (a) recorded with pulsed laser; (b) recorded through cw laser exposure.

The Bragg wavelengths of the gratings have been measured at room temperature after annealing. As can be observed in Figure 3, the values of λ_B for all FBG decrease as a consequence of the thermal treatment previously performed at the temperatures indicated. A decrease up to 1.2 nm has been observed for the set fabricated with laser pulses. The shift in λ_B is slightly smaller for the set fabricated through cw laser exposure, about 0.6 nm. It is known that, for the hydrogenated fibers, the escape of the hydrogen from the fiber matrix, either at room temperature or induced by heat, leads to a modification in the effective core-cladding index, n_{eff}, and to a shift in λ_B towards shorter wavelengths. In the present work, the thermal treatment was performed after hydrogen escape from the fibers at room temperature, which means that the shifts in Fig.3 occurred due to the thermal treatment. A decrease of approximately 0.5 nm in λ_B due to hydrogen escape at room temperature was observed before the thermal treatment.

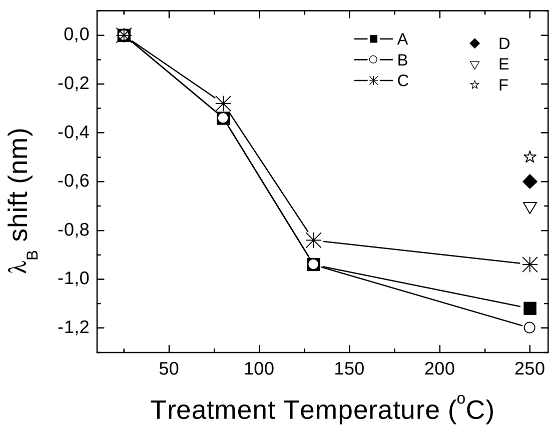

Figure 3: Bragg wavelength shifts, measured at room temperature, after thermal treatment at the indicated temperatures. Lines plus symbols: FBG recorded with pulsed laser. Symbols: FBG obtained and through cw laser exposure.

The annealed gratings were submitted to a second thermal cycle at 250°C for 6 hours. No more change in the Bragg wavelengths was observed, attesting that the gratings have attained stability for operation under temperatures up to 250°C. Similar results have also been obtained with FBG recorded in hydrogen-loaded standard telecommunication fibers by the pulsed laser method.

The reflectivity of a grating is related to the index modulation of the fiber core in the grating region, created by exposure to the UV pattern. The elevated temperature activates some of the unstable defects generated during grating inscription [2, 6-10]. This can strongly diminish the index modulation amplitude, leading to reduction on the grating reflectivity. Bragg wavelength decrease as a consequence of thermal treatment is also related to the index modulation decay. Modeling the reflectivity decay and Bragg wavelength shift in our gratings is beyond the scope of the present work. Nevertheless, one can note, from Figs. 2 and 3, that the gratings of each set present similar trends for reflectivity decay and Bragg wavelength shift upon annealing, although, for gratings 100% reflective, made with pulsed laser, significant less decay of reflectivity is found.

Conclusions

We have investigated experimentally the thermal stability of fiber Bragg gratings recorded in our laboratories using pulsed as well as cw ultraviolet lasers for the grating inscription. We observed a decrease of about 0.5 nm in the Bragg wavelength due to hydrogen escape from the fiber matrix, when it rested at room temperature for a few days. Further decrease in λ_B was observed when the gratings were submitted to thermal cycles at temperatures varying from 50 to 250^{o}C. The stability of the Bragg wavelength upon further thermal cycles at temperatures under 250^{o}C has been stated. The gratings also undergo important loss of reflectivity when submitted to the thermal treatment. However, our gratings proved to be resistant enough for most applications in telecommunication and for a wide range of sensing applications.

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References

[1] R. Kashyap, *"Fiber Bragg Gratings"*, Academic Press (1999).
[2] T. Erdogan, J. Appl. Phys. **76**, 73 (1994).
[3] C. J. S. Matos, P. I. Torres, L. C. G. Valente, I. C. S. Carvalho, W. Margulis, Proc. SPIE Vol. **3572**, pp. 400, 3rd Ibero-American Optics Meeting and 6th Latin American Meeting on Optics, Lasers, and Their Applications; Angela M. Guzman ed. (1999).
[4] C. L. Barbosa, H. T. Hattori, O. Lisboa, R. C. Rabelo, V. R. Almeida, R. M. Cazo, V. M. Schneider, Suplemento Especial da Revista Marítima Brasileira, n^o. 13, pp. 249 (2000).
[5] R. M. Cazo, O. Lisboa, H. T. Hattori, V. M. Schneider, C. L. Barbosa, R. C. Rabelo, J. L. S. Ferreira, Microw. Opt. Techn. Let. **28**, 4 (2001).
[6] H. Patrick, S. L. Gilbert, A. Lidgard, M. D. Gallagher, J. Appl. Phys. **78**, 2940 (1995).
[7] S. Kannan, J. Z. Y. Guo, P. J. Lemaire, IEEE J. Lightwave Technol. **15**, 1478 (1997).
[8] I. Riant, B. Poumellec, Electron. Lett. **34**, 1603 (1998).
[9] D. Razafimahatratra, P. Niay, M. Douay, B. Poumellec, I. Riant, Appl. Optics **39**, 1924 (2000).
[10] A. Hidayat, Q. L. Wang, P. Niay, M. Douay, B. Poumellec, F. Kherbouche, I. Riant, Appl. Optics **40**, 2632 (2001).