THERMAL TREATMENT OF FIBER BRAGG GRATINGS RECORDED USING HIGH POWER LASERS

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Abstract

In this work we evaluated the performance, at elevate temperatures, of fiber Bragg gratings recorded using high power UV lasers. The evolution of gratings wavelengths and reflectivities when fibers were submitted to several thermal cycles was determined. The range of thermal stability of the gratings was found to be suitable for telecommunication and sensing applications.

I. INTRODUCTION

Fiber Bragg grating sensors are nowadays becoming a reality for many in-field applications, such as monitoring pressure and temperature in oil plants [1]. Other demonstrated applications include temperature, pressure, strain, and fatigue aircraft monitoring [2], the development of smart civil structures, as well as human-body temperature and flow measurements with medical purposes [3], and biotechnological prospecting [4].

Fiber Bragg gratings (FBG) are small-dimension narrowband reflectors integrated to the optical fiber. It is obtained by recording distributed Bragg reflectors in the fiber core through ultraviolet (UV) exposure. The operation of FBG sensors is based on the Bragg wavelength shift as a consequence of changes in the parameter to be measured, e.g. the environment temperature or the strain submitted to a surface on which the FBG is attached [3].

The main characteristics of FBG sensors are: small weight, low cost, flexibility, low signal loss, and linearity response. They offer a multitude of advantages with respect to electrical sensors, e.g. immunity to electromagnetic interference, good resistance to environmental conditions such as exposure to radiation, and high temperature tolerance. But it is the possibility of multiplexing several sensors along the same fiber, and the simplicity of the interrogating system that have attracted the attention to fiber-sensing technology using FBG. Several techniques have been developed to interrogate both point and distributed FBG sensors [5]. Among the commonly used scheme for point sensor interrogation, the passband

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tunable filter presents good conditions for field applications due to its simplicity and low cost. In this system, a FBG can be used as interrogating filter, transforming the sensor wavelength shift in light intensity variation. The wavelength division multiplexing (WDM), the time division multiplexing (TDM), and optical time-domain reflectometry (OTDR) are techniques employed in distributed FBG sensors. In most of these techniques, wavelength stability is required for proper signal detection.

Besides the sensing industry, important applications of FBG are found in optical communication systems, where they act as mirrors for lasers, filters for dispersion compensators, gain flatteners and wavelength-division multiplexing systems [6].

For all the applications mentioned above, the stability of the FBG under operating conditions has to be well known in order to guarantee the functionality as well as to establish the reliability of the telecommunication devices and sensors based on these gratings. In special, the influence of environment temperature on the grating stability must be well determined. The annealing process, to which the gratings have to be submitted before device manufacturing, shall be adequate to each particular application and operating condition.

The stability of FBG may be affected by fiber doping characteristics [7] as well as by the inscription conditions [8]-[11]. In this work we evaluate the particular performance of FBG recorded in our laboratories using two high power UV lasers, at 266 nm (Nd:YAG laser) and 257 nm (Argon laser) wavelengths. The effect of thermal treatments at temperatures up to 250°C on gratings with different reflectivities is investigated in order to determine the thermal stability of the gratings obtained under our particular fabrication conditions, envisaging oil plants and aeroespacial sensing applications.

II. EXPERIMENTAL PROCEDURE

A. Bragg Grating Fabrication

Fiber Bragg gratings are obtained by exposure of the fiber core to an interference pattern of UV radiation. The absorption of UV radiation by Ge centers generates defects in the core matrix, which alter the refractive index of the illuminated regions. Bragg gratings are commonly recorded in the so-called photosensitive fibers, for which the core is doped with high levels of Ge (typically around 10-20%-mol) or other elements to enhance the UV absorption. In order to increase the photosensitivity, the fibers may be loaded with hydrogen [12]. The refractive index can vary with respect to the core index by a factor up to 10^{-3}, causing a partial reflection on a propagating light. Constructive interference of the reflected light occurs for in-phase radiation, according to the Bragg law: $\lambda_B = 2n_{eff}\,\Lambda$, where n_{eff} is the effective index of the guided mode, Λ is the index modulation period, and λ_B is the Bragg wavelength [3], [6].

The FBG were produced in commercially available photosensitive fibers, previously hydrogenated during one week at room temperature and 150kg/cm^2 hydrogen pressure. The two 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; b) the second harmonic of a continuous wave (CW) Argon laser that delivers up to 200 mW at 257 nm. These UV power levels are about 5 times higher than the employed in [7]. The high inscription power may be responsible for microfissures or fiber damage, and the effect on the grating stability has to be evaluated in this particular case.

Reflectivities as high as 100% are obtained with hydrogen-loaded photosensitive fibers. The spectral bandwidth of the reflectivity spectra stays around 1 nm. Grating inscription has also been demonstrated in standard telecommunication fibers, where a maximum reflectivity of 70% around 0.5 nm of bandwidth can be obtained. Pulsed laser at 213 nm has also been employed with success to record the FBG.

B. Thermal Treatment

The Bragg wavelength λ_B and the total grating reflectivity depend directly on the modulation amplitude of the refractive index induced in the fiber core by the UV writing. A slow decay of this modulation amplitude is expected from relaxation of some unstable defects. Thermal activation of these defects is the most important source of grating degradation [13]-[15]. Therefore, the dependence of the thermal processes on the particular grating fabrication conditions must be evaluated.

Several sets of gratings, with different Bragg wavelengths and reflectivities, were recorded using the two different UV lasers, in photosensitive and standard telecommunication fibers. The gratings with different reflectivities have been obtained under the same inscription conditions, except for the interval of exposure to the UV pattern. Here we present results obtained with gratings recorded in hydrogenated photosensitive and standard fibers with reflectivities of 100%, 70%, 40%, and 15% before thermal treatment.

The thermal treatment was carried out in a dry environment, several days after the grating inscription. Therefore, we suppose that all the residual hydrogen present in the fiber matrix had already escaped. After that procedure, the FBG were put into an oven and submitted to temperatures of 50, 80, 130, 140, 160, 180 and 200°C, during 30 minutes at each temperature, and to 250°C during 1 hour. This range of temperature largely covers the (over-zero) expected operating temperatures for our particular applications in oil wells and aircraft. Some of the gratings were submitted to the entire thermal treatment without cooling. Others were cooled to room temperature after each thermal cycle. Afterwards, the gratings were cooled to room temperature and re-heated to 250°C for a period of 6 hours.

III. RESULTS AND DISCUSSIONS

The evolution of the grating spectra was monitored during the thermal treatment. The broadband radiation of a light emitting diode (LED) was launched into the fiber containing the FBG and an optical spectrum analyzer recorded either the reflected or the transmitted portion of the spectrum. Fig.1 (a) shows transmission spectra for two gratings at several temperatures. The reflected portions of the grating spectra appear as pronounced dips in the transmission spectra. The small amplitude oscillations between the two dips are due to residual Fabry-Pérot features. The decreasing overall intensity for increasing wavelengths is due to the LED spectral profile at that wavelength range. The temperature induces a modification on the Bragg wavelength, as expected, due to the fiber refractive index variation with temperature [3], [6]. Good agreement has been found between expected and observed Bragg wavelength shift as a function of temperature. A decrease of the reflectivity by increasing the temperature is remarkable in this figure, and will be discussed in the sequence.

Fig. 1 (b) shows the transmission spectra, measured at room temperature, for the gratings after the thermal cycles at the indicated temperatures. As one observes, the reflectivity of the gratings are not recovered after thermal treatment, and the Bragg wavelength values decrease as a consequence of thermal treatment.

This overall behavior has been found for all the gratings, with saturated and non-saturated reflectivities, recorded in photosensitive and standard telecommunication fibers, upon CW as well as pulsed UV exposure. Nevertheless, the dependence of reflectivity decays and wavelength decreases with respect to the treatment temperature employed appeared to be particular of each the recording condition. In Figs. 2 and 3, we compare results obtained for saturated gratings recorded in photosensitive and standard fibers with those found for photosensitive non-saturated fiber gratings. The results give us information about the thermal stability of the FBG fabricated with high power, pulsed and CW, lasers.

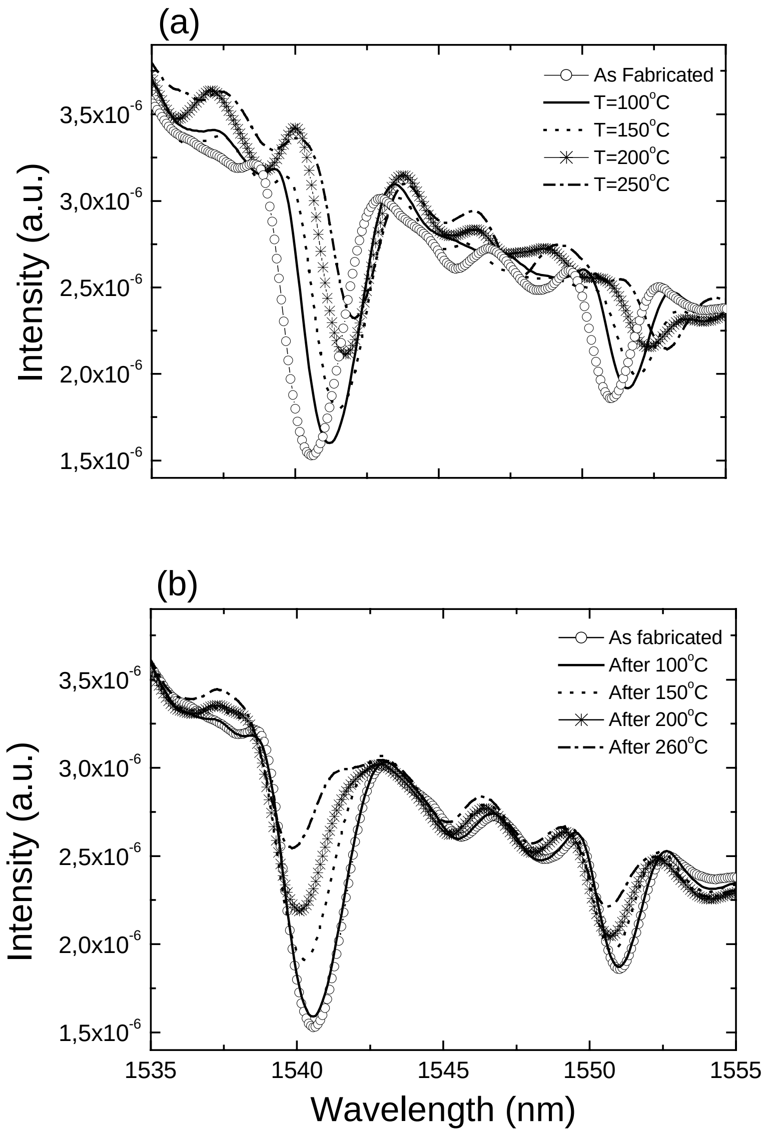

Fig. 1. Transmission spectra of two FBG: (a) measured at high temperatures; (b) measured at room temperature, after the thermal cycles indicated.

Fig. 2 presents the relative reflectivity changes for saturated (FBG-1, originally 100% reflective) and non-saturated gratings (FBG-2, FBG-3, and FBG-4, originally 40%, 15%, and 50% reflective) in hydrogenated photosensitive fibers, as well as for a saturated grating recorded in a standard fiber (FBG-S, originally 70% reflective). FBG-1 and FBG-S were obtained by pulsed UV irradiation, whereas the others, by CW laser illumination. Data in Fig. 2 were obtained at the annealing temperatures, except for FBG-4, which was cooled down to room temperature, after each thermal cycle, before measuring.

For treatment temperatures up to 100°C, it was not observed any appreciable change in the reflectivities of all gratings. For higher temperatures, differentiate behavior of the reflectivity decay could be seen among the several gratings tested. This result is consistent with those reported for gratings obtained with low UV power in hydrogen-loaded fibers [7]. Total relative reflectivity decay around 30% was observed for the originally saturated FBG-1. For the non-saturated FBG-2 and FBG-4, there is a significant change in their reflectivity, around 40%. On the other hand, for the low-reflectivity FBG-3, an important relative loss of

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reflectivity is observed (around 55%). Standard telecommunication fiber gratings seem to be as stable as the non-saturated photosensitive fiber gratings, with about 35% decrease on its original 70% reflectivity.

Comparing FBG-2 with FBG-4, that have approximately the same original reflectivities, one concludes that the relative change in the reflectivity is independent of the thermal treatment history, as pointed out by Patrick et al. in the case of low writing UV power.

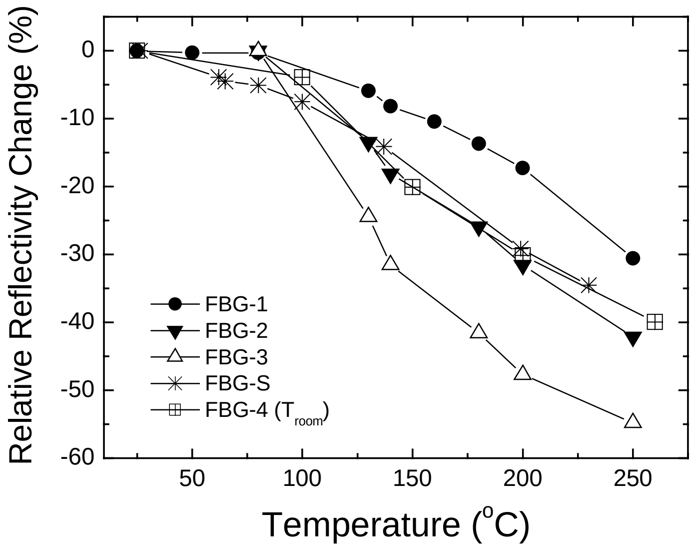

Fig. 2. Relative reflectivity change as a function of treatment temperature. FBG-1: recorded with pulsed laser, originally 100% reflective; FBG-2 and FBG-3: 40% and 15% original reflectivities, respectively, recorded through CW laser exposure. FBG-4 was originally 50% reflective. FBG-4 (T_{room}) data were obtained at room temperature after the thermal cycles at the indicated temperatures. FBG-S is a grating recorded in standard telecommunication fiber, with 70% reflectivity before treatment.

The Bragg wavelengths of the gratings have been measured at room temperature after some of the thermal cycles. In Fig. 3, the shift of λ_B with respect to its value before annealing is plotted as a function of the temperature to which the grating was submitted. As pointed out before, the value of λ_B diminishes for all FBG. From this figure, however, the remarkable dependence of the wavelength shift on the original grating reflectivity becomes clear. A decrease up to 1.2 nm was found for the originally saturated FBG-1. Similar result has been obtained for the grating recorded in standard telecommunication fiber (asterisk symbol). A smaller shift, of 0.7 nm, on λ_B is observed for the non-saturated FBG-2, and a smaller variation, of about 0.4 nm, is encountered for the low-reflective FBG-3.

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 [3]. In Fig. 3, the effect of hydrogen escape from the fiber is also illustrated. The solid star represents the variation of λ_B, with respect to the Bragg wavelength at the moment of grating inscription, for the FBG-S, which rested out of the hydrogenation for 25 days at room temperature before the measurement. A decrease around 0.9 nm on λ_B was found for this grating. Typical wavelength shifts of 0.7 and 0.5 nm have been observed for gratings we have recorded in photosensitive fibers upon exposure to the laser pulses and to the CW radiation, respectively. In the present work, the thermal treatment was performed after the hydrogen molecules had escaped from the fibers at room temperature, which means that the shifts in Fig.3 occurred due to the thermal treatment.

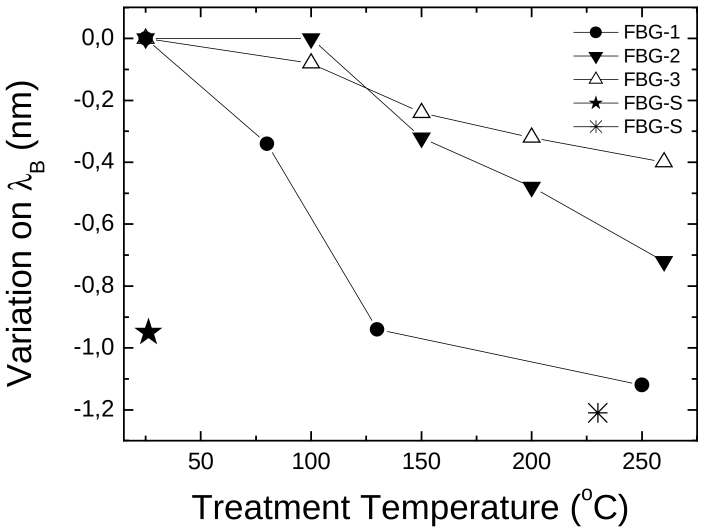

Fig. 3. Bragg wavelength shifts, measured at room temperature, after thermal treatment at the indicated temperatures. FBG-1: recorded with pulsed laser, originally 100% reflective; FBG-2 and FBG-3: 40% and 15% original reflectivities, respectively, recorded through CW laser exposure. FBG-S: recorded in standard telecommunication fiber, with original 70% reflectivity.

The annealed gratings were submitted to a second thermal cycle at 250°C for 6 hours. Any other change in the Bragg wavelengths was not observed, attesting that the gratings have attained mechanical stability for operation under temperatures up to 250°C.

IV. CONCLUDING REMARKS

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 [7], [13]-[17]. This can strongly diminish the index modulation amplitude, leading to a significant reduction on the grating reflectivity. On the other hand, the decrease on the Bragg wavelength as a consequence of thermal treatment is related to average index decay. Figures 2 and 3 revealed that gratings with high and low original reflectivity present opposite trends for reflectivity decay, and λ_B decreases as a function of annealing temperature. For saturated gratings, the refractive index change upon heating is less effective in diminishing the reflectivity as a consequence of defect saturation. Pre- and post-illumination of gratings with patterned and fringeless patterned UV radiation has proven to enhance grating stability to thermal cycles [8]-[11]. On the other hand, the average refractive index change is appreciable for Bragg wavelength shift.

We have established experimentally the thermal evolution of fiber Bragg gratings recorded using high power, pulsed and CW, lasers, at 266 nm and 257 nm, respectively. The

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gratings undergo important loss of reflectivity and Bragg wavelength shift when submitted to the thermal cycles up to 250°C. The results for saturated fibers are similar to those obtained with gratings fabricated upon low power laser exposition [7], [13]-[14]. We also found a clear dependence of the reflectivity decay as well as of the Bragg wavelength shift on the original grating strength.

Although microfissures or fiber damage may be induced by the here employed high inscription power, the gratings offer good resistance to temperature and strain conditions required for most telecommunication and for a wide range of aeroespacial and oil plants sensing applications.

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