SLM Fiber Laser Stabilized at High Temperature

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***Abstract*— In this letter, an annealing process of UV-written fiber Bragg gratings (FBGs) has been employed to achieve FBGs with narrower reflection spectra to be employed in fiber lasers. These FBGs have been used to design distributed Bragg relfector (DBR) laser sensors working on the single longitudinal mode (SLM) regime even at high temperatures. A fiber laser sensor working on multimode regime has been written into commercial Er-doped fiber before annealing its mirror FBGs, removing the unstable UV-induced modulation part and narrowing the FBGs' combined response. This process obtains a DBR fiber laser sensor working on SLM regime at high temperatures (T = 500 °C), and also exhibiting a remarkably good linearity and stability. The achieved results confirm the empirically adjusted aging model and prove its usefulness to design high precision devices able to work at high temperatures.**

***Index Terms*— Fiber lasers, erbium, single longitudinal mode, fiber Bragg grating, high temperature.**

I. Introduction

DURING the last years, optical fiber devices have played an important role in many different scenarios. Beyond communication networks, Optical Fiber Sensors (OFSs) have been widely developed for many applications such as health monitoring, industrial control, bio-sensors and even environmental applications [1], [2]. Although the term OFS covers a lot of technologies, some of them have stood out for their current (and future) applications. Particularly, Fiber Bragg Gratings have proved to be remarkably stable devices, being even employed as key elements for more complex sensing structures such as Fiber Laser Sensors [3].

Most of these sensors are suitable to operate under environmental scenarios, however, they exhibit several limitations under harsh environments, such as high temperature sensing. Particularly, the success of real time monitoring in different industries (such as oil and gas) relies on obtaining measurements at temperatures around $400°C$, being a research field that has got more attention during the last years. Within these environments, optical fiber technologies are becoming more attractive, trying to develop distributed and quasi-distributed approaches [4] to address market requirements.

Although different OFSs have been reported to measure high temperatures, FBG-based techniques exhibit several benefits depending on their manufacturing process. Several studies have addressed the thermal degradation of UV-induced FBGs [5]–[7] and how it can be overcome employing annealing processes [4], [8]. Besides damage-FBGs (e.g. written using femtosecond lasers), other reported technique is regeneration, that can stabilize FBGs even at higher temperatures [4], [9], [10]. However, the main problem with these methods is that the achieved gratings usually compromise the spectral properties of UV-induced FBGs, reducing their possibilities to be employed in high precision devices (e.g. fiber lasers), in addition to mechanical degradation of silica fibers under very high temperatures. There are several examples that employ FBG regeneration [11] or FBG annealing to obtain fiber lasers working at high temperatures, even reaching the SLM regime [12], [13]. However the frequency selection has been typically achieved by employing ultra-short cavities of highly doped fibers instead of adjusting the spectral shape of their mirror FBGs.

In this work, UV-written FBGs have been annealed, narrowing their spectral response, to obtain a Fiber Laser Sensor working on SLM regime at high temperatures. An *aging factor* has been defined and experimentally characterized to predict the spectral evolution of annealed FBGs before manufacturing a short linear cavity by inscribing two uniform FBGs into a commercial Er-doped fiber. This cavity has been thermally annealed to narrow the response of the equivalent filter, reducing the FBGs index modulation but increasing their thermal stability. With this process, a DBR laser (multimode) has been narrowed to reach the SLM regime at high temperatures ($T = 500°C$). The final device has been tested at high temperatures and the achieved results exhibited a remarkably good linearity and stability.

II. Spectral Response of Annealed FBGs

Aging of UV-written FBGs have been typically employed to reach more stable devices, being able to estimate their lifetime under different conditions [5], [6]. The UV-induced FBG annealing process usually removes the unstable part of the induced index change, obtaining a very stable device at lower temperatures. With the reduction on the FBG index change, both its reflectivity and spectral shape are modified, which can be employed to adjust high precision devices (e.g. fiber lasers) while their thermal stability is also improved. Based on this idea, an aging factor has been defined to model the annealing process. This aging factor (α_ν) can be defined as an efficiency that multiplies the fringe visibility (ν) of the theoretical model of FBGs [14]:

$$\delta n_{eff}(z) = \overline{\delta n_{eff}}(z) \left\{ 1 + \alpha_\nu \cdot \nu \cdot \cos\left[\frac{2\pi}{\Lambda}z + \phi z\right]\right\} \quad (1)$$

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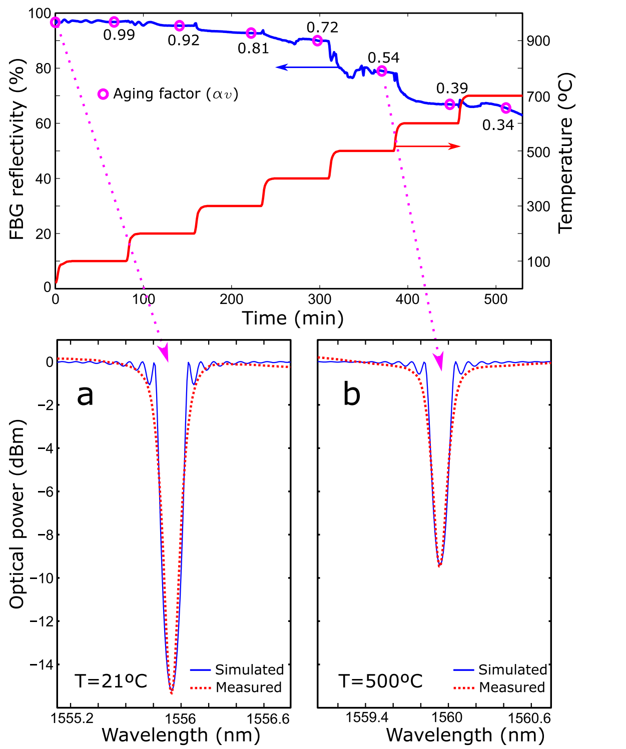

Fig. 1. Isochronal annealing of a 8mm length FBG written into Er-doped fiber. FBG reflectivity has been compared to the applied temperature sweep (top). Measured spectra (using an Agilent 86142A with a resolution of 60 pm) have been fitted to estimate their UV-induced index changes (bottom) at room temperature (a) and at $T_a = 500°C$ (b).

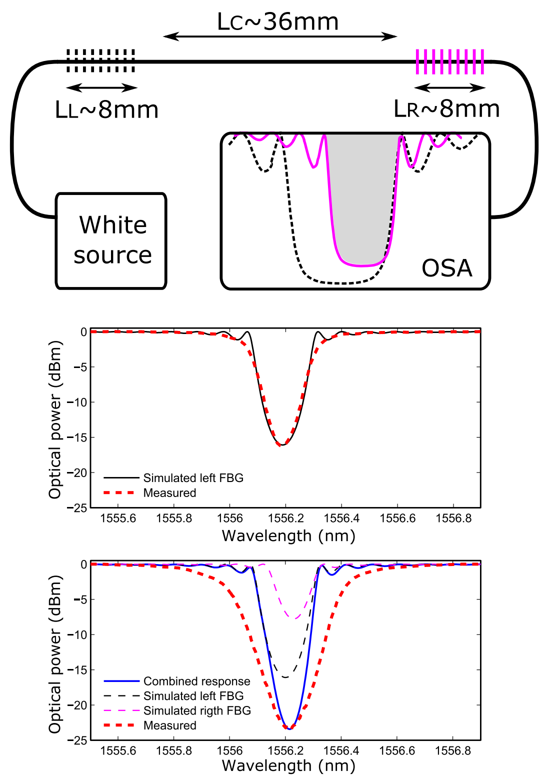

Fig. 2. Scheme of the DBR structure (top). Simulated left FBG parameters compared to its measured spectrum (middle). Simulated combined FBGs' response compared to their measured spectra (bottom).

Despite the amount of parameters that have influence on the FBG annealing process [4]–[6], [8] (UV wavelength, fiber dopants, seed FBGs, H_2 presence, thermal history…), this process is repeatable when the initial parameters are maintained. Without going into details regarding the physical effects that take place during FBGs annealing, this process can be empirically characterized for a specific procedure (fiber, UV-written FBG, annealing ramp…) before designing new devices that take advantage of the spectral modification of annealed FBGs.

The annealing process of FBG written into H_2 loaded commercial Ed-doped fiber (I-25 of Fibercore) has been empirically studied for different temperatures, to employ annealed FBGs as reflecting mirrors of DBR fiber lasers. In Fig. 1 (top), the isochronal annealing of a FBG of $L = 8\ mm$ length written with a continuum UV laser emitting at 244 nm using the phase mask technique is depicted. Each temperature has been maintained for 60 minutes employing a muffle furnace (Hobersal 12PR/300). After the fast decay associated with each annealing temperature, a measured FBG spectrum has been fit using the T-matrix method to estimate its index change visibility, determining its aging factor. Two fits have been compared in Fig. 1 (a, b) to measured spectra at room temperature (a) and at $T_a = 500°C$ (b), exhibiting estimated visibilities of $\nu_{21} \approx 0.355$ and $\nu_{500} \approx 0.255$ respectively. The remaining visibilities have been normalized to the highest (estimated at room temperature) to obtain the aging factor and are shown in Fig. 1 (top). These experimental results quantify the reduction in the UV-index modulation at different temperatures. This aging factor can be employed to determine the final FBG spectrum from a seed FBG.

III. Laser Structure Implementation

A DBR laser structure has been manufactured by inscribing two $L = 8\ mm$ length FBGs into commercial Er-doped fiber (I-25 of Fibercore) with an intermediate spacing of $L_C \approx 36\ mm$ (Fig. 2, top). The first (left) FBG has been inscribed with similar parameters to the one employed for annealing test (Fig. 1). The same fitting model has been employed to estimate its index change visibility (Fig. 2, middle), obtaining a similar value to the test FBG $\nu_L \approx 0.370$. A second FBG has been also written into the same fiber reducing the UV-laser exposition a 30% factor to decrease the FBG reflectivity, favoring the structure to lasing in this direction. The combined response of both FBGs has been also fitted, determining the visibility of the right FBG to $\nu_R \approx 0.255$, suggesting a lower UV-induced index change. A central wavelength offset of $\Delta\lambda \approx 30\ pm$ has been applied to the second (right) FBG, trying to model the asymmetry of the combined FBG spectrum. Both spectra and their combined response have been depicted in (Fig. 2, bottom).

IV. Annealing Process

After manufacturing the laser structure, a pre-annealing step (20 hours at $T = 120°C$) has been carried out to reduce the amount of hydrogen remaining within the fiber from

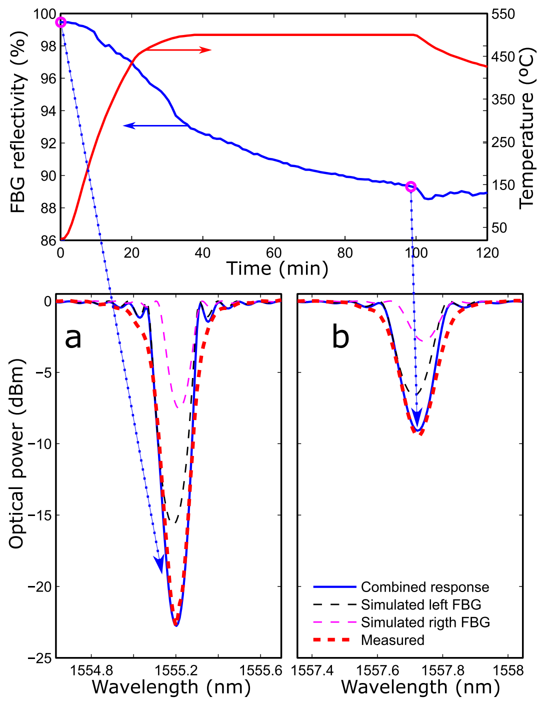

Fig. 3. Evolution of FBGs' combined response during the annealing (top). Simulated model of FBGs' response compared to their measured spectra before (a, aging $\alpha_\nu = 0.98$) and after the annealing (b, aging $\alpha_\nu = 0.54$).

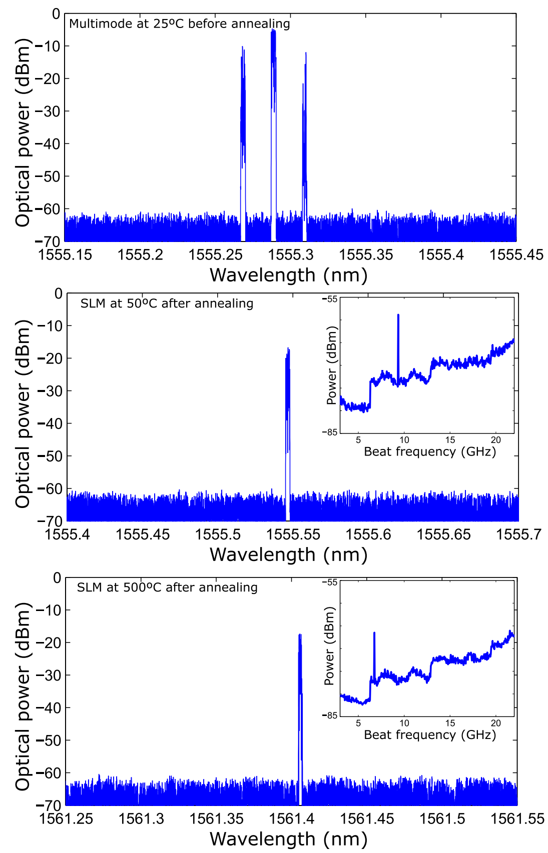

Fig. 4. Achieved longitudinal modes when pumped at 980 nm (150 mA) before the annealing (top), after the annealing (middle) and after the annealing but at high temperature (bottom). Captures with a heterodyne detection system to isolate the SLM regime at high and low temperatures.

the H_2 loading process. The chosen temperature has been kept low, to avoid interference with the following annealing process but also preventing wavelength drifts at high temperatures provoked by different hydrogen concentrations. As suggested by the preliminary tests, a low-temperature pre-annealing process did not have a remarkable influence on FBGs response, but reduces the amount of hydrogen present within the fiber (it can be noticed by the reduction on the FBG central wavelength). The fitted model of the combined FBG response with an aging factor of $\alpha_\nu = 0.98$ multiplying the visibility of both FBGs has been compared to the measured spectrum after the pre-annealing step (Fig. 3, a). This aging factor has been estimated from the measurements and confirms the visibility reduction estimated on the preliminary test, which exhibited a $\alpha_\nu = 0.99$ during the $T = 100°C$ annealing step.

Based on preliminary experiments, an annealing temperature of $T = 500°C$ has been determined to perform the laser stabilization. With an estimated aging factor of $\alpha_\nu = 0.54$, the final FBGs reflectivities should be suitable to maintain the laser cavity active. A single step temperature stabilization has been performed by applying $T = 500°C$ during 60 min to the laser structure (Fig. 3, top), improving the stability of this device at lower temperatures [5].

The estimated aging factor $\alpha_\nu = 0.54$ measured at $T = 500°C$ on the initial tests, has been applied to the simulated model of both FBGs. Their measured spectra have been compared to the simulated ones (which included the aging factor) in Fig. 3 (b), exhibiting a remarkable good agreement, and confirming the index change reduction quantified during the initial tests.

V. Experimental Characterization

After completing the annealing process, both reflectivity and spectral shape of the written FBGs have been changed, reducing the laser power but narrowing the equivalent filter response [3]. The laser structure has been pumped using a 980 nm laser and, as expected, laser threshold increased after the annealing process to achieve a stable output ($\Delta P_{Pump} \approx 30\%$); however, the employed cavity length provides enough gain to deal with this reduction.

A. Single Longitudinal Mode Regime

Thermal annealing of FBGs has been employed to narrow the combined filter response of the DBR structure. Since its passive spectral response is difficult to obtain [15], the laser output has been characterized. Particularly, longitudinal modes have been measured using a high resolution Optical Spectrum Analyzed (BOSA from Aragon Photonics, with a resolution of 0.08 pm). All the measurements have been performed maintaining the same pump power: a 980 nm laser diode fed with 150 mA.

In Fig. 4 (top), the laser output has been held for several minutes (at room temperature) exhibiting three longitudinal modes spaced $\Delta\lambda \approx 22\ pm$. This spectrum has been obtained after the pre-annealing step but before the $T_a = 500°C$ annealing process, thus the combined filter response provided

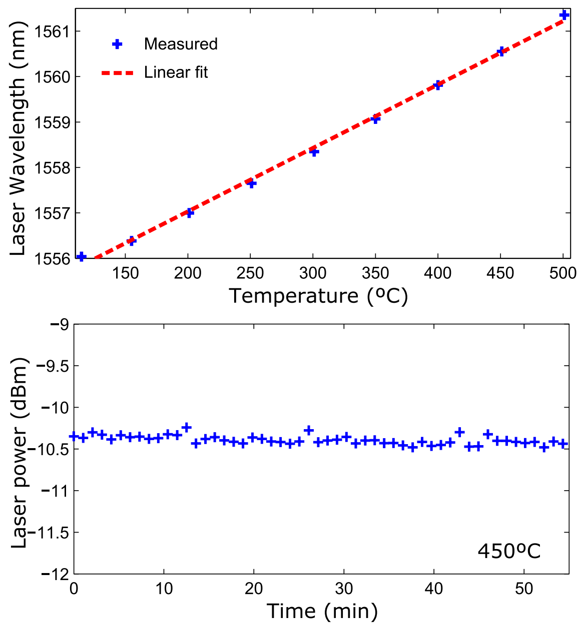

Fig. 5. Wavelength evolution of the annealed laser pumped at 980 nm (150 mA) during a temperature sweep (top). Power stability measured at $T_w = 450°C$ for 50 min (bottom).

for both FBGs is not narrow enough to achieve SLM operation. After the annealing process, the laser output has also been held for several minutes at low temperature (Fig 4, middle) exhibiting a single longitudinal mode. This suggest that the narrowing effect (by making the FBG reflection peak sharper) expected by decreasing the FBG index changes, has been enough to reduce the laser bandwidth [15], thus being able to achieve a stable SLM regime. Finally, in Fig. 4 (bottom), the laser output has been held for several minutes while the top annealing temperature ($T_a = 500°C$) has been applied. The achieved results also show a SLM regime (isolated with a heterodyne detection system [3]) that suggests that the spectral properties of the annealed FBGs have been preserved after the process.

B. Wavelength Response and Stability

After finishing the annealing process, a temperature sweep to the limit of the stabilized laser ($T_a = 500°C$) has been performed while the laser spectra were captured using an Agilent 86142A OSA (Fig. 5). As the spectral properties of the laser output depend on its mirrors (FBGs), a remarkable linear response has been obtained (Fig. 5, top).

The expected long term working temperature for annealed FBGs must be set below the annealing temperature [5], thus, the stability of the tested device, annealed at $T_a = 500°C$ has been studied at a high temperature, but reducing it to $T_w = 450°C$. A spectrum has been captured each minute for 50 minutes using the OSA and maintaining the laser pump power. The achieved results suggest a stable operation because the trend is maintained flat during the measurements.

VI. Conclusions

In this work, annealing of UV-written FBGs has been employed to narrow the spectral response of a DBR fiber laser sensor (reaching the SLM regime) and to stabilize its properties at high temperatures ($T = 500°C$). An empirically adjusted aging model has been employed to determine the reduction of the UV-induced index modulation of two FBGs written into commercial Er-doped fiber, creating a DBR cavity. The manufactured laser has been thermally stabilized at ($T = 500°C$), reducing its active longitudinal modes to reach the SLM regime that has been maintained for the whole temperature range. The achieved results exhibit a remarkably linear response of the laser wavelength even at high temperatures (as expected of FBGs) while their spectral properties are also maintained. The developed annealing model can be employed to design new high precision devices with a remarkably good thermal stabilization.

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