Study of the grating length, the UV energy, and the heating rate on the FBGs regeneration process

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High-temperature sensing is a need for industrial and research applications. Regenerated fiber Bragg grating (RFBG) is an attractive candidate for temperature sensing in harsh environments up to 1000 °C. The regeneration process depends on numerous parameters. This research shows the effect of the grating length, the UV energy used for photo-inscription, and the heating ramp rate on regeneration efficiency. The results show that the regeneration efficiency increases when increasing the length of grating and the number of UV pulses when applying identical thermal profiles. However, when the heating rate increases, the regeneration efficiency decreases.

Introduction

Fiber Bragg grating (FBG) sensors have received huge attention in recent decades in the optical engineering field, telecommunication and sensing applications due to their outstanding features such as compact size, passive and immunity to electromagnetic interferences [1]. FBGs can be used for multi-parameter sensing and quasi-distributed sensing to monitor different parameters such as strain, temperature, humidity, external refractive index [2–5], and are appropriate for sensing applications in harsh environments [6, 7]. FBG is a periodic and permanent modulation of the refractive index of the optical fiber core. This modulation is achieved by exposing the optical fiber core to the interference pattern of ultraviolet light [8] and leads to reflection of specific wavelength, referred to as the Bragg wavelength λ_B, that satisfies the Bragg condition. UV-inscribed gratings (Type I) can operate at 80 °C for 25 years or even more, within standard telecommunications applications. This type of gratings only sustain up to 300 °C, without degradation in reflectivity for a short time application. Higher temperature causes a thermally induced decay in the reflectivity of gratings or complete vanishes of the grating. Thermal regeneration of Bragg gratings is a technique of producing high-temperature resistant gratings sensors [9]. In this technique, an initial FBG (seed) is exposed to heating cycle (generally between 700 °C and 1100 °C) which leads to erasure of the seed grating and regeneration of a new grating on its footsteps, so-called regenerated fiber Bragg grating (RFBG). RFBG retains the best features of seed grating and can operate at high temperatures up to 1295 °C [10]. The regeneration process depends on numerous parameters. In this study, we investigate the effect of the heating rate, the length of the seed grating, and the number of UV pulses used to inscribe gratings.

Seed gratings and experimental setup

To study thermal regeneration process, we fabricate gratings using nanosecond laser pulses ArF Excimer laser from NORIA system emitting at 193 nm with a repetition rate of 50 Hz and 5 mJ pulses energy. The gratings are inscribed by phase mask technique in hydrogen-loaded standard single mode telecommunications fibers, SMF-28e+. After the

inscription, FBGs were kept in the fridge (at $\sim -6\,°C$, or cooler at $\sim -18\,°C$) to have the exact condition of hydrogen-loading for experiments.
Thermal treatments for the gratings regeneration are performed in a horizontal tube furnace (Carbolite STF 15/180). The working temperature of the furnace is up to 1200 °C. During the thermal treatment, both reflection and transmission spectra of the grating are monitored with a standard commercial interrogator (FiberSensing FS2200). In addition, for precise temperature measurement in adjacent position of the grating, a type N thermocouple is placed in the ceramic tube inside the furnace.

Experimental results

The reflectivity of a regenerated grating (uniform FBG) depends on the thermal profile used for the regeneration and the strength of initial (seed) gratings. The strength of grating depends on the length of the seed grating and its initial induced index modulation. The initial induced index modulation depends on the UV pulse laser energy, and consequently to the number of pulses that is used for inscription of the grating.

Different heating rates The 6 mm long gratings were inscribed by exposing the fiber core to 5000 UV pulses. A two-step thermal profile was used with an intermediate step at 700 °C, Fig. 1 (left). The isochronal heating rate of $20\,°C\,min^{-1}$ up to 700 °C, then in the second step, isochronal heating with different heating rates up to 900 °C. Gratings are kept at constant temperature 900 °C for almost 2 h. The different heating rates α set to the furnace were 1, 5, 7, 10.5, 11 and $13\,°C\,min^{-1}$, Fig. 1 (left). The maximum

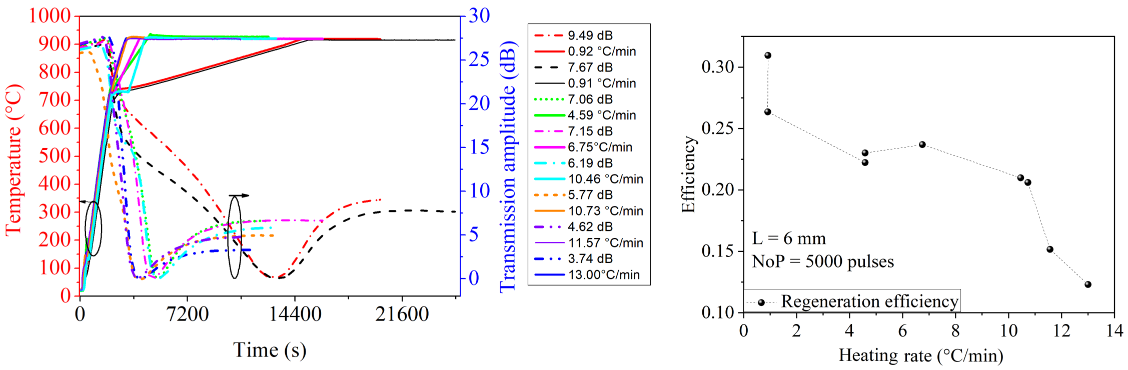

Figure 1 - *(left) Two-step thermal profile with different ramp rates at step two, (right) Comparison of regeneration efficiency of gratings with different heating ramp rates* α.

transmission amplitude, T_f, of 9.49 dB, belongs to the grating that regenerated with lowest heating ramp rate $\alpha = 0.92\,°C\,min^{-1} \cong 1\,°C\,min^{-1}$, and the lowest T_f of 3.74 dB is for the grating that regenerated with highest heating ramp rate $\alpha = 13.00\,°C\,min^{-1}$. Fig. 1 (right) presents the regeneration efficiency versus the heating rate. The regeneration efficiency is calculated by ratio of the transmission amplitude after and before the regeneration. From these results, it can be concluded that with increasing the heating ramp rate (α), the regeneration efficiency of RFBG becomes weaker. Therefore, to obtain a stronger RFBG, low α (less than $7\,°C\,min^{-1}$) should be chosen, and optimum result is achieved by $\alpha = 1\,°C\,min^{-1}$.

Different numbers of UV pulses 9 mm gratings were inscribed using different numbers of UV laser pulses in the range of 100 pulses to 15 000 pulses, and regenerated using optimum heating rate ($\alpha = 1\,°\mathrm{C\,min^{-1}}$). Fig. 2 (left) shows the transmission amplitude changes with temperature and time in this experiment. Fig. 2(right) shows the regenera-

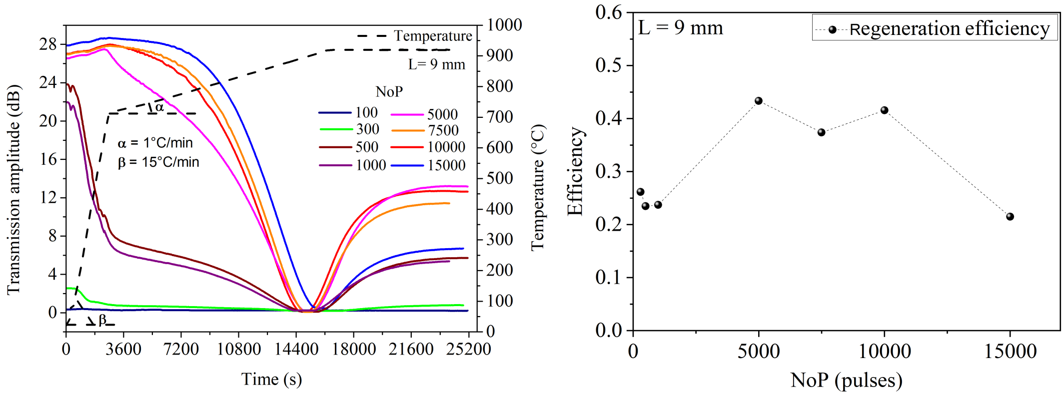

Figure 2 - *(left) Transmission amplitude versus temperature in regeneration process of the gratings inscribed with different numbers of UV pulses (NoP), (right) Regeneration efficiency versus NoP.*

tion efficiency versus NoP changes. The efficiency of RFBG is saturated when the NoP exceeds 5000, and then is decreased by increasing the NoP.

Different lengths of the grating The grating length is an important parameter on the grating strength, and consequently, on the regeneration process. To study the effect of the length, we inscribe different FBGs with grating's length from 1 mm to 11 mm. The fiber is exposed to the 5000 UV pulses and the thermal profile is the same as the previous experiment. Fig. 3 (left) presents the transmission amplitude modification during the

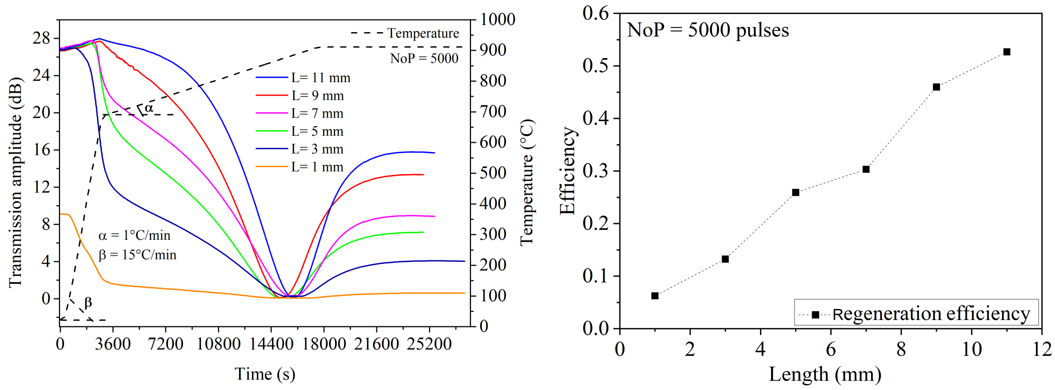

Figure 3 - *(left) Transmission amplitude versus temperature in regeneration process of the gratings inscribed with different lengths, (right) Regeneration efficiency versus the length of grating.*

regeneration process. As it can be seen, with increasing the length of the grating, the transmission amplitude of the RFBG increases. The regeneration efficiency of RFBG is increased when the seed grating length increases and maximum efficiency of 53 % obtained with L = 11 mm as shown in Fig. 3 (right).

Conclusion

In conclusion, we studied the effect of heating rate, seed grating length, and the number of UV pulses on the regeneration process of FBGs. The results are summarized in Table 1. The two-step thermal profiles with different thermal ramp rates (at the second step), were tested for the regeneration of uniform gratings inscribed in hydrogen-loaded SMF−28e+ fiber. The optimum result, with 31 % efficiency, is obtained for the lowest heating ramp rate ($\alpha \sim 1\,°\mathrm{C\,min^{-1}}$). The effect of the grating strength in the regeneration was tested using an identical thermal profile ($\alpha = 1\,°\mathrm{C\,min^{-1}}$), while the gratings were inscribed in two groups: (1) uniform gratings inscribed with different UV laser pulses (NoP), and identical length of 9 mm, (2) the regeneration process in uniform gratings inscribed with different lengths and the identical NoP (5000). The regeneration efficiency of RFBG is increased when the seed grating length increases, and maximum efficiency of 53 % obtained with L = 11 mm, whereas it shows a saturation behavior up to 10000 NoP, with maximum efficiency of 43 % obtained with NoP = 5000 and decrease at NoP= 15000.

Table 1 - *Summary of the optimum results of FBG regeneration.*

Parameter	Range	Optimum	Efficiency (%)
α (degreeCelsius/min)	1–13	1	31
NoP (pulses)	100–1500	5000	43
L (mm)	1–11	11	53

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