Comparison of regenerated fiber Bragg gratings properties in standard and B/Ge co-doped single-mode silica fibers

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***Abstract*—This paper compares thermal regeneration process of uniform and tilted fiber Bragg gratings (TFBG) written in standard single-mode silica fiber (Corning SMF-28) and photosensitive B/Ge co-doped optical fiber (fiberCore PS-1250/1500). By monitoring the reflection and transmission spectra of the gratings, we show that TFBG in SMF-28 regenerates at 950 °C with efficiencies of 2.06 % and 1.10 % for the core mode and the cladding modes respectively. On the other hand, in TFBG written in PS fiber, the regeneration temperature is only 500 °C due to doping. Moreover, the regeneration efficiencies are lower to reach 1.27 % and 0.16 % for the core mode and the cladding modes, respectively.**

***Index Terms*—FBG, TFBG, Regeneration, High temperature sensing**

I. Introduction

Fiber Bragg gratings (FBGs) are key components in optical sensors as they possess many important properties such as compact size (mm range), immunity to EM interferences, resistance to corrosion, fast response time, ... Moreover, they can be used for multi-parameter sensing and quasi-distributed sensing. Due to these outstanding features, FBGs have been used in numerous sensing applications for the last decades [1]–[6]. Nevertheless, type I gratings in standard telecommunication optical fibers can only sustain up to 300 °C for short-term applications without degradation in reflectivity [7].

High temperature sensing (up to 1000 °C) is also important for many applications in research and industry [8]–[13], but the decay in reflectivity above 300 °C is a severe limitation in such harsh environments. Several attempts have been done to increase the temperature resistance of FBGs, of which the so-called thermal regeneration of gratings is particularly interesting [14]–[17]. In this process, a seed grating is annealed at high temperature (a plateau between 700 °C-1000 °C) until this seed grating vanishes and a new grating rebuilds from the initial footprint, which is called regenerated grating. Regenerated gratings show all the properties of type-I gratings, and, in addition, can sustain up to the regeneration temperature without any decay in reflectivity [18]. They are thus interesting candidates for harsh environment.

In tilted Bragg gratings (TFBGs), the grating is slanted around the fiber axis. They present all the advantages of FBGs, but they are also able to excite cladding modes resonances that are sensitive to bending and surrounding refractive index (SRI) [19]–[21], which makes them ideal for sensing the species around the fiber. As any grating, TFBGs are sensitive to temperature and strain. So by exploiting this property, the Bragg mode can be used to compensate for the temperature and/or strain effects to create a self compensated bending and/or SRI sensors. Regenerated TFBGs can be used for high temperature applications and also in applications when high temperature treatment is required like chemical CVD processes [22]. There are few studies on high temperature behavior and thermal regeneration of TFBG [13], [17]. In this research, we investigate the thermal regeneration of FBGs and TFBGs inscribed into hydrogenated SMF28 and B/Ge co-doped single-mode silica fibers. According to [12], the regeneration temperature in B/Ge co-doped fiber can be lower for high temperature operation and better mechanical stability.

II. Background Theory

FBG is a longitudinal periodic refractive index modulation in the optical fiber core that can be achieved by exposing a short section of the optical fiber to a UV interferometric pattern. This perturbation leads to reflection of a specific wavelength which is called the Bragg wavelength that fulfills the Bragg condition, Equ. 1.

$$\lambda_{\mathrm{B}} = 2\mathrm{n}_{\mathrm{eff}}\Lambda \tag{1}$$

where λ_B is the Bragg wavelength, $\mathrm{n}_{\mathrm{eff}}$ is effective refractive index of core mode, and Λ is the grating period.

From the coupling mode theory, we can calculate the power reflectivity of the Bragg reflection as R [23]:

$$\mathrm{R} = \tanh^2(\kappa \mathrm{L}) = \tanh^2\left(\frac{\pi}{\lambda_{\max}} v\delta \mathrm{nL}\right) \tag{2}$$

where κ is the coupling constant, L is the grating length, δn is the refractive index modulation, v (between 0 and 1) is the visibility of δn, $\lambda_{\max}$ is the central Bragg reflection wavelength. The reflectivity R and the Bragg wavelength λ_B can be determined from the transmission spectrum of the gratings. It can be shown [24] that the refractive index modulation δn consists of two component: the mean refractive index change δn_{DC} and the refractive index modulation amplitude δn_{AC}.

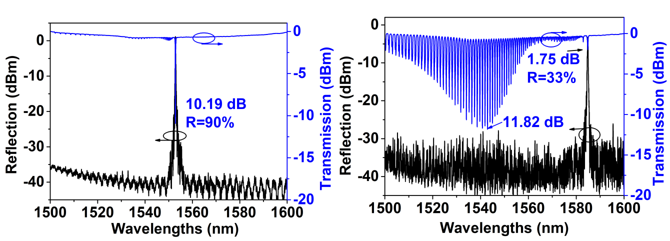
III. Experiments

In this study, FBGs and TFBGs are inscribed in "SMF-28" standard single-mode optical fibers and in photosensitive Boron/Germanium (B/Ge) co-doped "PS-1250/1500" fibers by nanosecond ArF Excimer laser (from NORIA) emitting at 193 nm central wavelength with an energy of 5 mJ and 50 Hz repetition rate. Prior to grating inscription, the optical fibers were hydrogen-loaded under 205 bar and 60 °C for three days.

To perform the regeneration processes, the gratings are placed in a horizontal tubular furnace (Carbolite) that can elevate the temperature up to 1200 °C with controllable temperature ramping rates. An additional thermocouple (type N) is used to control the temperature near the grating position. During the thermal treatment, both reflection and transmission spectra of the gratings are monitored by an optical interrogator (fiber Sensing- FS 2200) with an acquisition rate of 1 Hz.

A. Thermal regeneration of gratings written in SMF-28 fibers

Fig. 1 shows the reflection and transmission spectra of a seed grating (Fig. 1(a)) and a 7°TFBG (Fig. 1(b)) at room temperature (21 °C) before the thermal cycle. The reflectivities of these seed gratings are 90 % and 33 % for the FBG and TFBG respectively, and the maximum cladding mode amplitude of the TFBG is around 10 dB. Fig. 2 presents the reflection power change of the Bragg mode for both FBG and 7°TFBG versus time and temperature. In this experiment, temperature is elevated from room temperature to 1000 °C with a 5 °C/min heating rate. Then the gratings are kept at 1000 °C for one hour after regeneration, and finally heating is stopped so that temperature naturally returns to the room temperature. During this thermal cycle, the reflectivity of both gratings decreases to zero (the seed gratings are erased), then increases after regeneration (regenerated gratings are born). Both gratings regenerate isothermally at temperature between 950 °C and 980 °C, leading to Bragg reflectivities of 6.7 %, and 0.68 % for FBG and TFBG respectively, as can be seen in the inset figure. Therefore, the regeneration efficiency, defined as the ratio of the reflectivity after regeneration to the initial one, is 7.44 % and 2.06 % for FBG and TFBG, respectively.



(a) FBG (b) 7°TFBG

Fig. 1: Seed gratings reflection (black lines) and transmission (blue lines) spectra at room temperature.

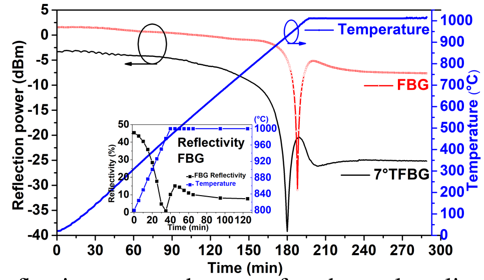


Fig. 2: Reflection power changes after thermal cycling for FBG (red line) and 7°TFBG (black line) versus temperature (blue line). The inset is FBG reflectivity change from 800 °C to 1000 °C.

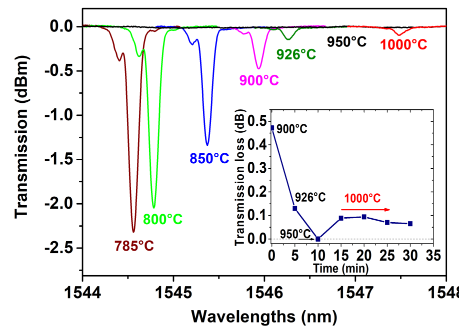


Fig. 3: Following one cladding mode in thermal cycle from 785 °C to 1000 °C when it removes and regenerates, the inset presents this mode transmission loss after 900 °C.

Fig. 3 shows the evolution of the maximum cladding mode of the TFBG from 785 °C to 1000 °C. The transmission loss of this mode decreases from 2.3 dB at 785 °C to zero at 950 °C, then regenerates and increases to 0.11 dB, as it can be seen in inset figure. The efficiency of the regeneration for the maximum cladding mode, defined as the ratio of transmission loss after (0.11 dB) and before (10 dB) the regeneration, is 1.10 %.

The modification in the transmission loss is zoomed for some cladding modes in Fig. 4, where it can be seen that the transmission loss decreased from around 0.15 dB at 926 °C (dashed blue line) to zero at 950 °C (solid black line), and

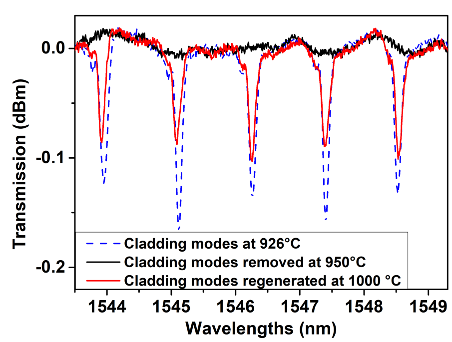
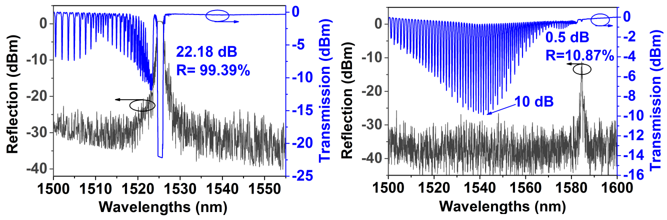


Fig. 4: Part of cladding modes of 7°TFBG before removing (dashed blue line) and after regeneration of grating (red solid line), black solid line shows the moment that grating is removed.



(a) FBG (b) TFBG

Fig. 5: Reflection and transmission of seed gratings inscribed in PS fiber.

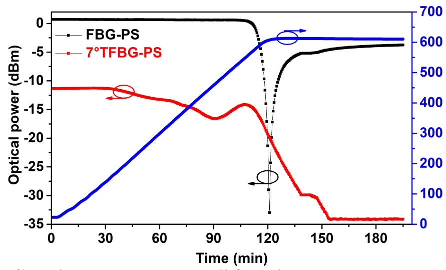


Fig. 6: Reflection power modification versus temperature and time of FBG and 7°TFBG written in PS fiber.

was followed by regeneration to around 0.11 dB at 1000 °C (solid red line).

After the thermal cycle, both gratings return to room temperature, and permanent blue shifts of the Bragg wavelengths are observed around 1.50 nm for FBG and 2.78 nm for TFBG.

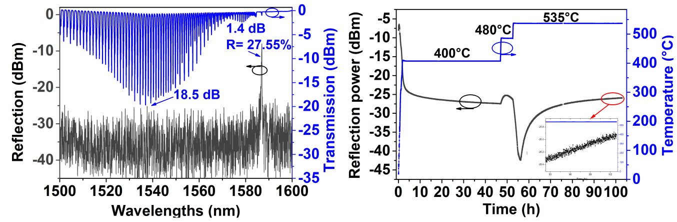
B. Thermal regeneration of gratings written in PS fibers

The same procedure was applied for FBG (Fig. 5(a), initial reflectivity of 99.34 %) and 7°TFBG (Fig. 5(b), initial reflectivity of 10.87 %) written in PS fiber. The gratings were heated up to 600 °C isochronally with temperature increase of 5 °C/min as shown in Fig. 6.

The FBG (black line) regenerated at 600 °C and reached a reflectivity of 36.9 % (37.14 % regeneration efficiency), while the TFBG (red line) showed almost no regeneration at this temperature, meaning that this temperature is too high for an efficient regeneration mechanism in PS-TFBG. Hence, we operated a different thermal treatment at slightly lower temperature. A similar TFBG, with 27.5 % reflectivity, was placed in the furnace and heated up to 550 °C in multi-step process. As shown in Fig. 7, the temperature was first ramped to 400 °C isochronally with 5 °C/min, then kept constant for 45 h. The thermal cycle was followed by a first temperature increase to 480 °C for 4 h, and a second temperature increase to 535 °C for 60 h. Regeneration took place at the last temperature step, 535 °C, leading to a regenerated grating of 0.35 % (regeneration efficiency of 1.27 %), and with permanent blue shift of the Bragg wavelength of 1.86 nm (Fig. 8(a)). Moreover, the cladding modes after regeneration are quite noisy (Fig. 8(b)) with an amplitude around 0.03 dB that leads to a regeneration efficiency of only 0.16 %.

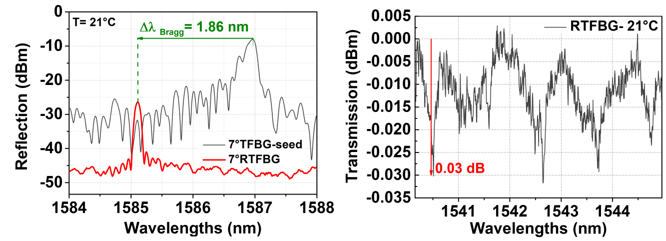
IV. Discussion and Conclusion

The regeneration processes induce a decrease in DC and AC components of the refractive index modulation, which



(a) Seed TFBG (b) Reflection power modification

Fig. 7: Behavior of a 7°TFBG written in PS fiber versus temperature and time.



(a) Full spectrum (b) Zoom on the cladding modes

Fig. 8: Regenerated tilted grating in PS fiber after thermal regeneration.

can be linked to thermal induced periodic structural changes of the glass material and relaxation effects [23], [25], [26]. Indeed, the drastic decrease in amplitude of the resonance modes after regeneration is explained by the δn_{AC} and δn_{DC} contributions, whereas the permanent wavelength blue shift after annealing is linked to the δn_{DC} contribution. This latter shift is due to the decay of UV-induced defect annealing (negative contribution), and to the thermal annealing of doping especially Boron (positive contribution) [27]–[30].

In conclusion, thermal regeneration of FBGs and TFBGs inscribed by nanosecond ArF UV laser (193 nm) shows a behavior depending on the fiber chemical composition. Gratings inscribed in SMF-28 fibers regenerated at around 950 °C with a regeneration efficiency of 7.44 % for FBG and 2.06 % and 1.10 % for TFBG core mode and cladding modes, respectively. Gratings in B/Ge co-doped PS fibers showed a lower regeneration temperature around 600 °C, with a regeneration efficiency of 37.14 % for FBG and 1.27 % and 0.16 % for TFBG core mode and cladding modes, respectively. Therefore, regenerated FBG can be operated for high temperature sensing applications up to 900 °C with both PS ([12]) and SMF-28 fibers, and up to 1000 °C with SMF-28. For chemical/physical sensing at high temperatures, regenerated TFBGs in SMF-28, despite small cladding mode amplitudes, are possible candidates, whereas regenerated TFBGs in PS fibers are not usable.

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