Temperature and RH response of polymer CYTOP FBG treated by gamma radiation

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ABSTRACT

Polymer fiber Bragg grating (FBGs) demonstrate a wider strain range and stronger temperature sensitivity compared to standard silica FBGs. Besides, their advantageous feature is sensitivity to humidity that enables FBG-based relative humidity (RH) sensing. However, practical realization of RH sensors requires temperature cross-sensitivity elimination. A certain optimal fiber pre-strain and gamma irradiation of perfluorinated (CYTOP) FBGs up to certain optimal dose are potential recently proposed solutions for this problem. In this work, we investigate temperature and RH response of FBGs inscribed line-by-line in a few-mode polymer fiber with 20-μm CYTOP core and 250-μm XYLEX overclad. We compare the cases of the pristine FBG sample and the sample received 200 kGy irradiation dose. The 200-kGy dose was previously confirmed to provide temperature sensitivity minimization at 40%RH. Here, we show the close-to-zero temperature sensitivity (≈1pm/°C) for 200-kGy dose at high RH value of 89%. Besides, we briefly analyze the stabilization process of FBGs response to strong and quick RH changes.

Keywords: Polymer optical fiber, fiber Bragg gratings, CYTOP, perfluorinated polymer, fiber optic sensors

1. INTRODUCTION

Polymer optical fibers (POFs) have a number of beneficial properties, such as low Young’s modulus, high strain range and flexibility, biomedical compatibility and safety. Among other POFs, fiber made of perfluorinated (CYTOP®) polymer exhibit minimal attenuation in telecom transparency windows, and, therefore, it is under significant attention from a research community [1-3]. The advantageous feature of POFs is sensitivity to humidity that enables FBG-based relative humidity (RH) and moisture sensing [4-5]. However, practical realization of RH sensors requires temperature cross-sensitivity elimination. A certain optimal fiber pre-strain [6] and gamma irradiation of FBGs of up to optimal dose [7-9] are potential solutions recently proposed for CYTOP® FBGs.

In our previous works [7-9], we demonstrated that gamma radiation treatment changes the climatic properties of CYTOP FBGs: we observed a rise of the RH sensitivity with received dose and a decrease of temperature sensitivity with subsequent change of sign from positive to negative. Among irradiation doses, which we applied in the experiment, the dose of 200 kGy provided the closest to zero temperature sensitivity of the irradiated FBGs [7,8]. This case is prospective for RH sensing since temperature cross-sensitivity can be eliminated. However, we previously performed the temperature characterization only at a single RH value of 40%.

In this work, we show the results of temperature characterization of pristine and irradiated (200 kGy gamma radiation dose) CYTOP® FBGs at high RH value (89%). We confirm the close-to-zero temperature sensitivity (≈1pm/°C) for the irradiated FBG sample at 89 %RH. Besides, we briefly analyze the stabilization process of FBGs response when the RH quickly changes from high value (89%) to moderate (40.5%) and back. The latter is important to take into account for practical applications of CYTOP FBGs as RH sensors and for temperature characterization experiments at high RH values.

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2. EXPERIMENTAL SETUP

For FBGs inscription, we used a POF of custom design produced by Chromis Technologies with a few-mode 20-µm CYTOP® core and a 250-µm protective overclad. The fiber core had a gradient refractive index profile with effective refractive index of 1.34. A protective overclad was made of XYLEX® material, which is a blend of polycarbonate and amorphous polyester. FBGs were inscribed using a plane-by-plane direct inscription method by femtosecond laser [10, 11]. We used HighQ laser femtoREGEN source at λ=517 nm with 220 femtoseconds pulse duration and 1 kHz repetition rate. The fiber samples with FBGs were centered and connected with standard silica SMF pigtails using a UV-curing glue.

Irradiation was conducted using a calibrated γ-radiation setup (Brigitte facility, SCK-CEN, Belgium) based on ^{60}Co irradiation sources located at a depth of seven meters in a water pool and provided a dose-rate of 5.3 kGy/h (Figure 1). The irradiation sources formed a cylindrical volume where the stainless steel hermetic container with the fiber sample was placed for a specified time according to the required dose of 200 kGy. Irradiation was conducted at a temperature of 41-44 °C. Temperature was stabilized by an oven located at the hermetic contained and controlled by the Eurotherm 2408 temperature controller.

Climatic experiments were conducted using an environment chamber Weiss SB22/300 (Figure 1). Temperature and RH were measured by internal sensors of the chamber and by the Thorlabs TSP01 sensor for additional control. Temperature annealing was performed for three hours (65°C, 40 %RH) prior to experiments to enhance the stability of the results and reduce possible hysteresis. We used a standard commercial interrogator (FiberSensing FS2200) operating in the 1500-1600 nm wavelength range for the monitoring of FBGs reflection spectra.

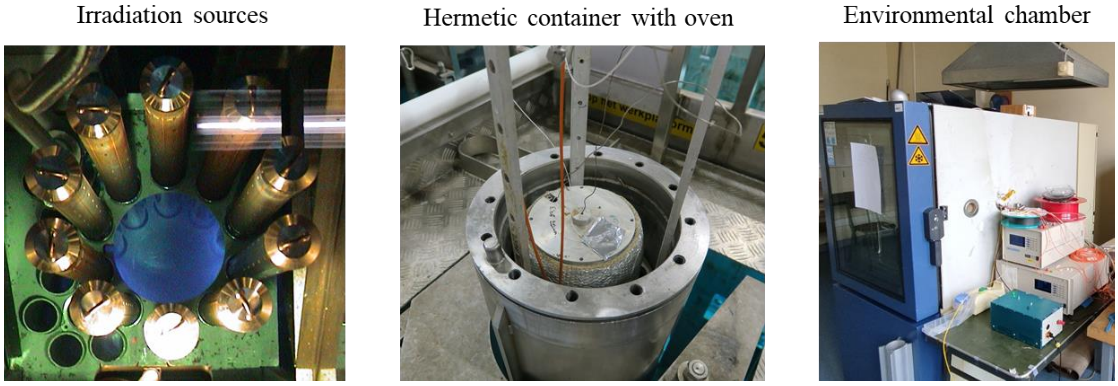

Figure 1. Photographs of the experimental facilities: the irradiation sources (left), the hermetic container for irradiation of the sample (center), and the environmental chamber for climatic experiments (right).

3. EXPERIMENTAL RESULTS

In the first experiment, we performed a temperature cycle at 40 %RH (Figure 2, lower part of the graph, right scale). The temperature was programmed to increase and then decrease stepwise with the values of 25, 35, 45, and 50 °C. The stabilization time at each temperature was 4 hours and the duration of temperature changes was 30 minutes. Figure 2 also shows the evolution of the Bragg wavelength (BW) shift of both pristine and irradiated FBGs during the temperature cycle (upper part of the graph, left scale). The pristine sample demonstrates positive temperature sensitivity that was measured to be 19.6 pm/°C. The irradiated FBG shows close-to-zero temperature response estimated as ≈1 pm/°C. As it was mentioned in the introduction, the last case is advantageous for RH sensing due to eliminated temperature cross-sensitivity. It should be noted that the climatic chamber did not provide ideal RH stabilization during the temperature cycle, especially during temperature changes parts: the RH spikes with the magnitude up to 3 %RH can be observed. This stimulated parasitic spikes of the BW at the beginning of each temperature level. Thus, these spikes are attributed to the RH instabilities but not to the BW reaction to temperature changes.

Performing the second temperature cycle at high RH (89%) straight after the cycle at 40 %RH, we faced a difficulty with temperature sensitivity precise calculation, because the BW slowly increased during the entire experiment. From our previously performed experiments with RH cycles [8], we found that the BW requires longer stabilization time in case of high RH levels and when the FBG was treated by gamma radiation. Taking this into account, we developed a program of the experiment allowing to analyze the FBG response when the RH quickly changes from high value to moderate and back, and allowing to perform the temperature cycle at stable BW (Figure 3). The RH initially stabilized at 89% quickly dropped to the 40.5% value which than was kept stable during almost 8 hours. After that, the RH quickly increased back to the value of 89%. This RH value was then kept stable during 50 hours, i.e. until the end of the experiment. After the first 20 hours of RH stabilization, we started the temperature cycle. Comparing to the first cycle, we added an additional temperature of 15 °C at the end of the cycle to extend the investigated temperature range. The long-term stabilization allowed us to perform the experiment, when the BW change was caused only by temperature changes but not by slow water saturation of the FBGs.

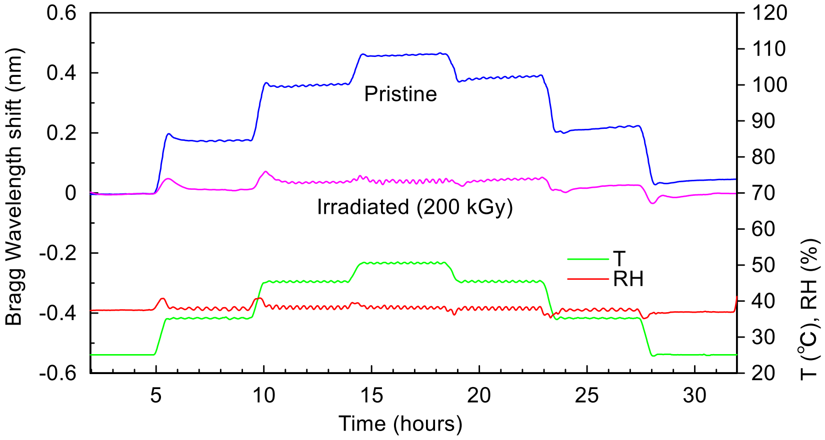

Figure 2. The BW evolution of the pristine and the irradiated (200 kGy) FBGs during the temperature experiment at 40% RH.

Figure 3 shows that the BW stabilized relatively quickly after the RH drop: the delay between the RH and the BW stabilization was ≈ 1.5 and 2 hours for the pristine and the irradiated FBGs correspondingly. However, after the RH rise, the complete BW stabilization for the irradiated FBG required approximately 20 hours. Very slow water saturation process at high RH complicates precise determination of the stabilization time. To compare it for the two FBGs, we calculated the time delay between the moment of RH stabilization and the time when the BW reaches 90% of the stabilized value. It was 1.2 hours for the pristine FBG and 2.75 hours for irradiated FBG. As it is seen, the irradiated FBG requires more than 2 times longer time to reach 90% of the stabilized BW value.

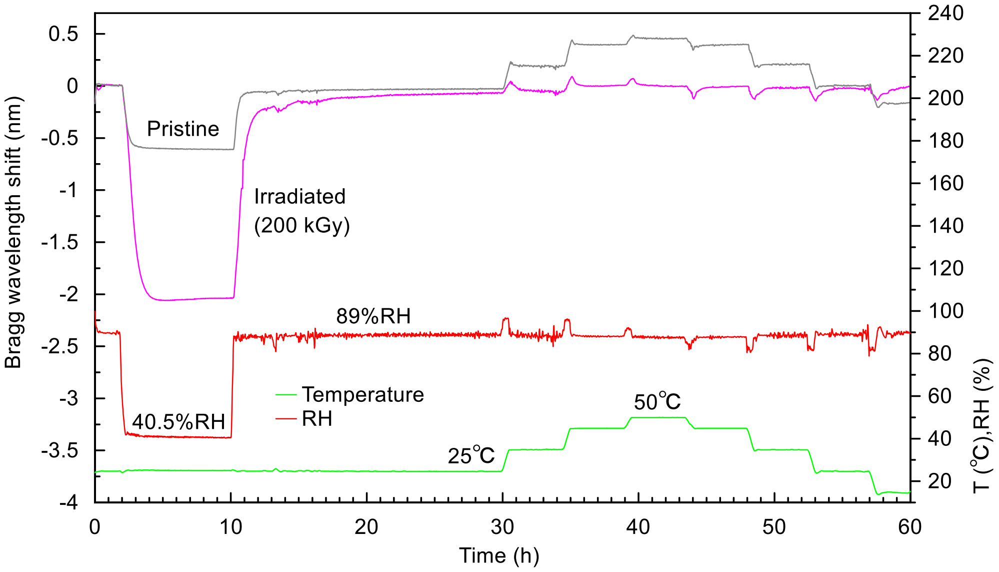

Figure 3. The BW evolution of the pristine and the irradiated (200 kGy) FBGs during the second experiment.

Analyzing the temperature cycle performed at 89 %RH when the BW was stabilized, we calculated the temperature sensitivity to be 20 pm/°C for the pristine FBG and ≈1 pm/°C for the irradiated FBG. Note that the BW spikes at the beginning of each temperature level are caused by the RH instabilities but not by the BW reaction to temperature changes, as it was discussed previously. It is seen that the sensitivity values are very close to those obtained at 40.5 %RH. Thus, the temperature response obtained earlier at moderate RH value (40.5%) is also confirmed at high RH (89%).

4. CONCLUSION

In this work, we performed temperature characterization of pristine and irradiated (200 kGy dose of gamma radiation) FBGs inscribed in a few-mode graded-index polymer fiber made of CYTOP® core/cladding structure and XYLEX® overclad. We showed a close-to-zero temperature sensitivity of the irradiated FBG at 40.5 %RH and then we confirmed it at high RH value of 89%. We also briefly analyzed the FBGs stabilization process when the RH quickly changes from high value (89%) to moderate (40.5%) and back. Longer stabilization time was observed at high RH and when the FBG was previously irradiated. This is important to take into account for practical applications of CYTOP FBGs as RH sensors and for temperature characterization experiments at high RH values.

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