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Additional Information

# Packaged Optical Sensors based on Regenerated Fiber Bragg Gratings for high temperature applications

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*Abstract*— **We report on temperature sensors based on regenerated fiber Bragg gratings (RFBGs) for measurements up to 1100°C. The annealing process required to regenerate such gratings makes the optical fiber too delicate, thus making an adequate packaging necessary. The optical fiber with the RFBG is protected with a ceramic tube which in turn is shielded with a thick metal casing. We have compared the thermo-optical response of both packaged and unpackaged RFBG sensors placing especial attention on possible residual hysteresis after several temperature cycling tests. The response and recovery times of packaged sensors were found to be, respectively, ~9s and ~22s.**

*Index Terms*— **High-temperature, optical fibre sensor, packaging, regenerated fiber Bragg gratings.**

## I. INTRODUCTION

The research of reliable fiber-based temperature sensors capable of operating continuously up to 1000°C is currently a topic that has attracted considerable interest by the sensor community [1-8]. Fiber-based high temperature sensors have applications in important and expanding fields such as turbines, combustors, nuclear reactors, health-monitoring systems for aerospace hot structures, amongst others. To date several high-temperature fiber sensors based on interferometers [1-3], photonic crystal fibers [4], long-period gratings [5], Chiral fiber gratings [6], sapphire gratings [7], etc., have been proposed. All these optical fiber-based temperature sensors have intrinsic advantages such as configurability, miniature size, light weight, immunity to electromagnetic and radio-frequency interference and the possibility to operate in toxic, corrosive or potentially explosive environments. However, the advantageous multiplexing capability, the measurement of the reflected light, the low insertion losses and the use of standard optical fibers points the so called Regenerated Fiber Bragg Grating (RFBG) as one of the most viable option for high temperature sensing [8]. RFBGs are usually created typically by thermal processing of a seed grating at high temperatures. During the annealing process the original FBG is completely erased and a new refractive index modulation is created in the UV exposed zones. It has been demonstrated that these gratings can withstand temperatures as high as 1295°C [9]. However, the exposure of the optical fiber to high temperature makes it brittle and fragile. This imposes a packaging constraint that has to be solved properly before a RFBG is used in real operating conditions. Basically, the packaging must provide good mechanical stability and not compromising the optical response of the grating.

In this work, we report on the performance of RFBG for high temperature measurement. Also, we report on a packaging design for high-temperature sensors based on RFBGs consisting of a combination of ceramic and metal tubes. We have analyzed the sensor performance with and without the packaging in terms of wavelength shift with temperature, refractive index modulation decay, hysteresis in the thermo-optical response and permanent wavelength drift for temperatures up to 1100°C. We also studied the response time of the packaged sensor.

## II. GRATINGS REGENERATION AND DECAY STUDY

Standard FBGs in germanium-doped silica fiber suffer from an important limitation for high temperature measurements. The periodic refractive index modulation created in the core of the optical fiber decay as a function of temperature and time. Several techniques have been developed to increase the refractive index thermal stability such as preirradiation and accelerated aging. However, even applying these techniques the refractive index modulation decays until complete depletion around 600°C - 700°C [10].

Although the use of other fibers is feasible, in this work we have employed a standard telecommunications fiber (Corning SMF-28) to create the RFBGs. The use of standard
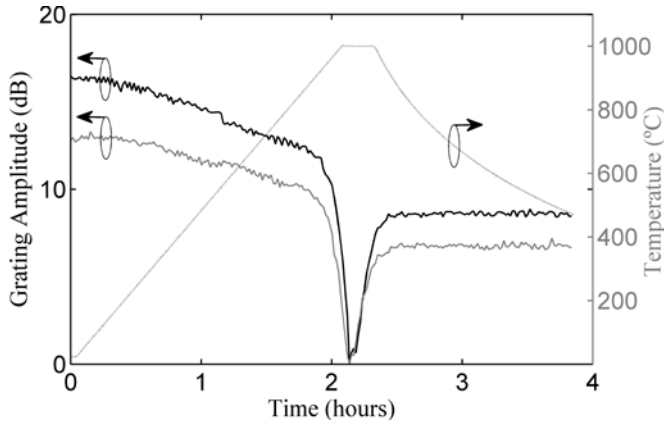
Fig. 1. Regeneration process for two FBGs inscribed into standard germanium doped fibers.

telecommunications optical fibers in the RFBGs has an important advantage in terms of sensor simplicity and compatibility over other high-temperature Bragg gratings such as Chiral fiber gratings [6] or sapphire gratings [7].

To create the RFBGs the fiber was first placed into a hydrogenation chamber at room temperature for 14 days at a pressure of 25bar. The presence of hydrogen is necessary for regeneration in the latter annealing process. The FBGs were inscribed into the hydrogen loaded fiber using the phase mask technique and an Argon CW laser with an emission wavelength of 244 nm. The RFBGs are regenerated in a subsequent annealing process performed inserting the fibers into a tubular furnace where a quartz tube help us to place the RFBGs in the center of the oven and maintain the temperature uniform along the entire length of the gratings. Fig. 1 shows one of the annealing processes used for the regeneration of the FBGs. The temperature during the annealing process is depicted in the right ordinate of Fig. 1 and consists of a heating ramp of 10°C/min up to 1000°C, a 30 minutes long dwell, followed by a passive cool-down to room temperature. Fig. 1 also shows in the left ordinate the amplitude evolution for two FBGs during the annealing process. As the temperature increases, the original FBGs are progressively extinguished, until full erasure and subsequent appearance of the regenerated grating at a temperature of approximately 950°C.

Fig. 2 shows the spectra of two FBGs with different apodization and their respective regenerated gratings. Fig. 2(a) refers to 1 cm long uniform FBG, whereas Fig. 2(b) to 2 cm long Gaussian apodized FBG. The fact that in both cases the apodization is maintained after regeneration suggests that the regeneration process only affect those areas of the fiber that were exposed to the UV laser while the seed FBG was inscribed. The preservation of the original apodization can be very important for some applications where special gratings are needed. After the regeneration process we have observed a permanent wavelength shift towards longer wavelengths. This wavelength shift is due to stress relaxations of the fiber during the annealing process. Because the center wavelength regenerated grating is shifted to compare the spectra of this
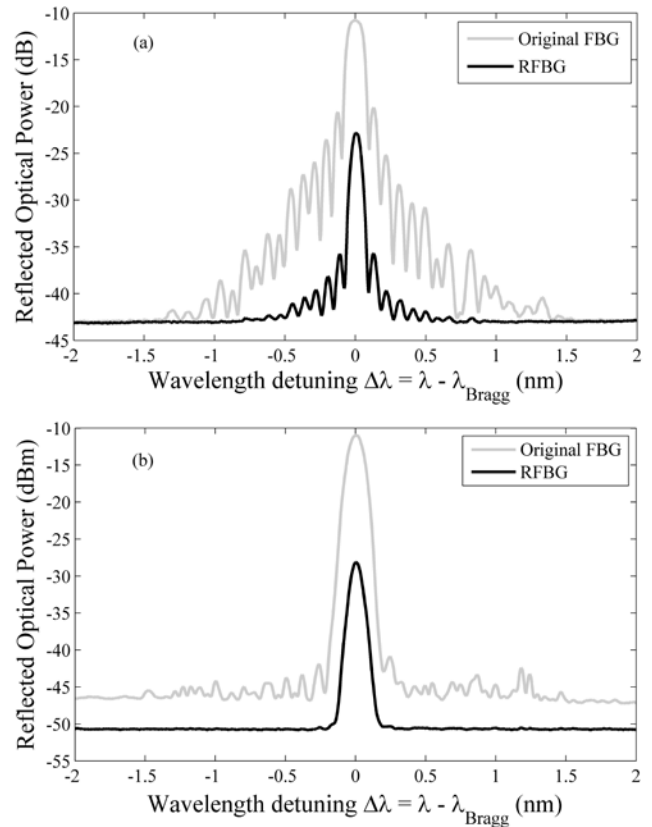


Fig. 2. Original and regenerated fiber Bragg gratings spectra in Germanium doped fibers. (a) 1 cm long uniform FBG. (b) 2 cm long Gaussian apodized FBG.

wavelength detuning $\Delta\lambda$ with respect of each grating Bragg wavelength $\Delta\lambda = \lambda - \lambda_B$.

The regeneration process strongly depends on the optical fiber used but it is very repetitive for the same fiber. The presence of different dopant concentrations in the optical fiber can severely change the regeneration process for example reducing the minimum temperature at which regeneration occurs and the decay behavior of the RFBG. It can also change the optical thermo-optical coefficient [11-12]. The mechanisms that cause the regeneration of the FBG have been widely discussed in the literature and several models have been proposed [9, 13, 14].

After the regeneration the RFBGs have been tested at temperatures up to 1100°C. The right ordinate of Fig. 3 shows the temperature evolution used for this test. We have used a temperature ramp with a temperature rate of 8°C/min up to 900°C and an increasing isothermal temperature pattern between 900°C and 1100°C in 50°C steps. Each temperature step lasts five hours. Fig.3 also shows in the left ordinate the reflected optical power variation during this test for two RFBGs. It can be seen that the behavior of the two RFBGs is almost the same. The results show a maximum reflected optical power variation around 0.5dB and no significant decay has been found.
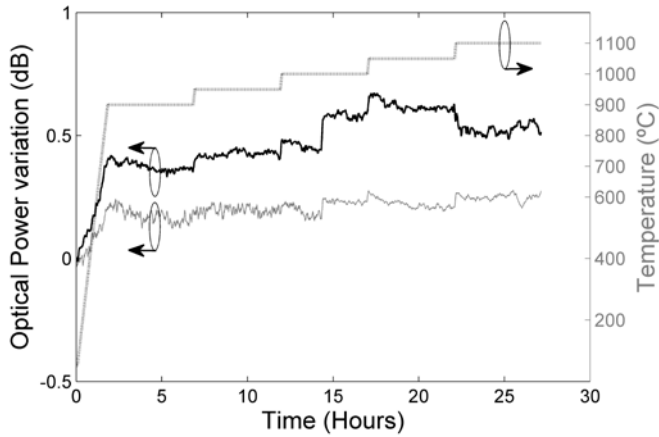
Fig. 3. RFBG in standard telecommunications fiber (SMF-28). Temperature evolution inside the oven and reflected and optical power variation at high temperatures for two RFBGs.

## III. GRATINGS PACKAGING AND CHARACTERIZATION

The high temperatures needed to regenerate the FBG make it essential to remove all the standard fiber coatings (acrylate and polymer coatings). The lack of a protective coating causes the optical fiber to become extremely fragile. Thus, a packaging solution needs to be implemented to allow safe handling of the fiber sensor. We have designed a packaging concept composed by a two-bore ceramic (alumina) tube which holds the fiber grating straight and an external metal (INCONEL 600 nickel alloy) casing. The bore diameter of the ceramic tube is ~130 µm and its external diameter is ~1.2 mm. The internal/external diameters of the metal casing are equal to ~1.3/1.5 mm. Fig. 4 shows a photograph of ready-to-use RFBG temperature sensor. The fiber grating is located at the tip of the metal casing, as indicated by the arrow. To secure the fiber, the ceramic tube and the metal casing are bonded using a high temperature ceramic adhesive in the packaging end opposed to the RFBG. This guarantees that the RFBG is sensitive to temperature only. To assure the mechanical of
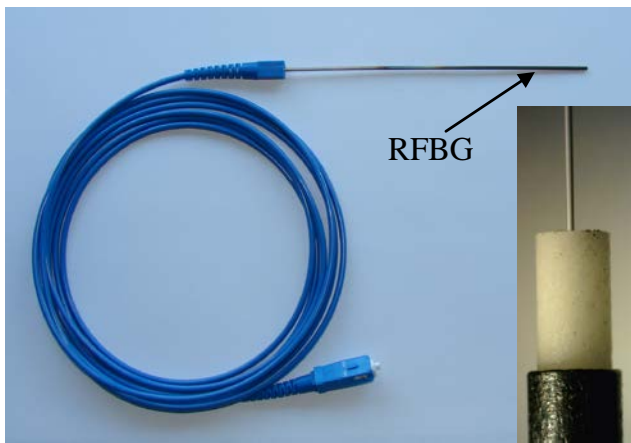


Fig. 4. Photograph of a ready-to-used device. The inset picture shows the metal casing, ceramic tube and the fiber.
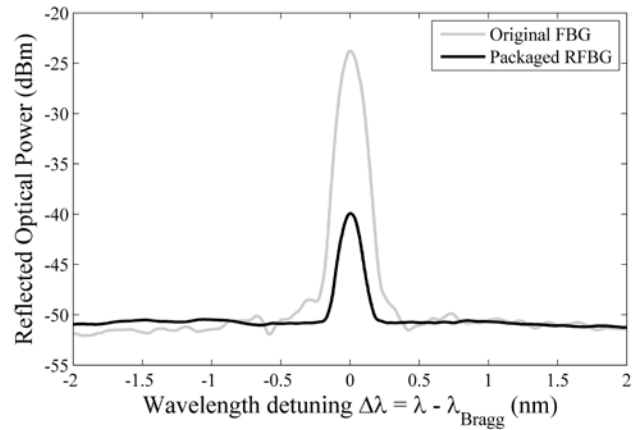


Fig. 5. Original FBG and Packaged RFBG sensor spectra as function of wavelength detuning.

the RFBG it is important to point out that the annealing process was carried out after packaging the FBGs.

After the packaging and the annealing process we have compared the spectra of the original FBG and the packaged RFBG sensor, see Fig. 5. The similitude between the FBG spectra and the packaged regenerated gratings indicates that the packaging does not interfere in the regeneration process and does not introduce additional stresses into the FBG.

The packaging should also not interfere with the sensing properties of the RFBG. For this reason we have performed several tests to analyze the influence of the packaging. We have measured the wavelength shift versus temperature, the repeatability of the thermal response at high temperatures and the time response. These entire tests have been performed for both unpackaged and packaged sensors and we have compared the results.

The wavelength shift versus temperature has been obtained for temperatures between 25°C to 1025°C. Fig. 6 shows the thermo-optical response for the unpackaged (crosses) and the packaged RFBG sensor (squares). It can be seen that both gratings exhibit almost identical thermo-optical response. The fitting to these two curves corresponds to a second-order polynomial fit. In fact, the difference between both fittings is less than 1% for the second order coefficient and 0.5% for the
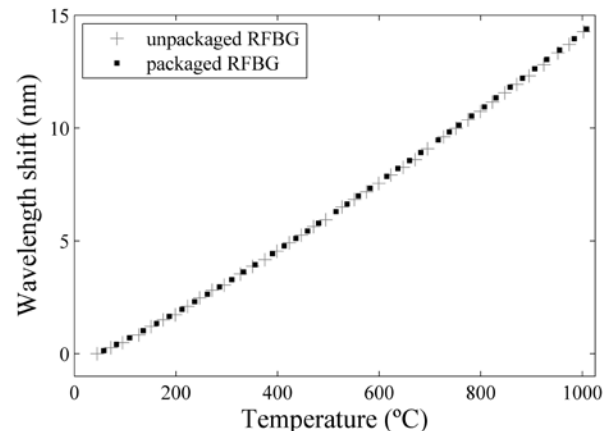


Fig. 6. Wavelength shift versus temperature for the unpackaged RFBG and the packaged sensor.
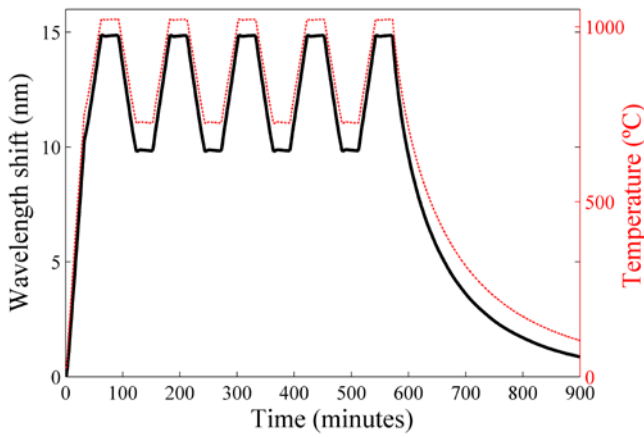
Fig. 7. Temperature cycling test used to evaluate the repeatability of the thermal response. Temperature inside the furnace (dotted red line) and wavelength shift (solid black line).

first order coefficient.

The repeatability of the thermal response at high temperatures has been analyzed to find any hysteresis or permanent wavelength drift. The test consists in five consecutive temperature cycles between 720°C and 1020°C. Each temperature cycle lasts 120 minutes and is comprise of a heating up phase followed by a 30 minutes long temperature dwell and a cooling down phase followed by another 30 minutes long temperature dwell. Similar plots have been obtained with unpackaged devices. We show one of these tests performed on a packaged RFBG sensor in Fig. 7. The dotted red line represents the temperature inside of the furnace and the solid black line the wavelength shift of the device. The results have been analyzed looking for any hysteresis or a permanent wavelength drift. Fig. 8 represents the repeatability of the thermo-optical response for the packaged sensor. The red line is the reference fitting of the thermal response between 720°C and 1020°C (corresponding to the first heating up and shown in Fig. 6), the black bars are the maximum deviation from this value measured at different temperatures between 750°C and 1000°C. Our results indicate that the maximum deviation is less than 1% (±5°C). These results coincide with those previously reported for the unpackaged RFBGs [12]. More importantly, there is no evidence of substantial hysteresis or drift in the grating wavelength shift in both unpackaged and packaged RFBG sensor. This suggests that there is no sensor degradation due to repeated exposure to high temperatures.

A critical factor in a temperature sensor is its time response. We have measured the heating up time response and the cooling down time response. To measure the heating up time response the tubular oven is heated up to 1000°C and maintained at such temperature for 30 minutes prior to start the test. Then, a packaged RFBG sensor is introduced into the oven and the optical sensor response is acquired using a commercial FBG interrogator (Ibsen Photonics I-MON 512E) with a sampling rate of 3 samples/s. The experimental data are shown in the Fig. 9(a). The time response (evaluated from the
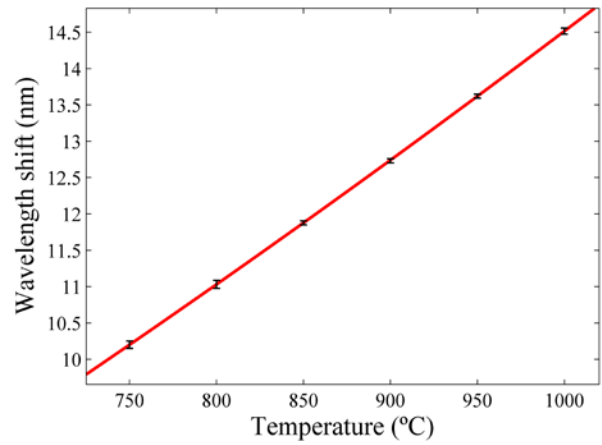


Fig. 8. Repeatability of the thermo-optical response for the packaged RFBG sensor. Wavelength shift versus temperature fitting for the first temperature cycle (red line) and wavelength shift variation for all the cycles (solid black bars).

10% to 90% of the maximum wavelength shift) has been found to be ~9 s. This value is comparable to that of commercial thermometers based on thermocouples (e.g. 1.5 and 3 mm thick type N thermocouple). The time response of an unpackaged RFBG has also been measured with the same technique and is approximately 8 seconds [12]. This indicates
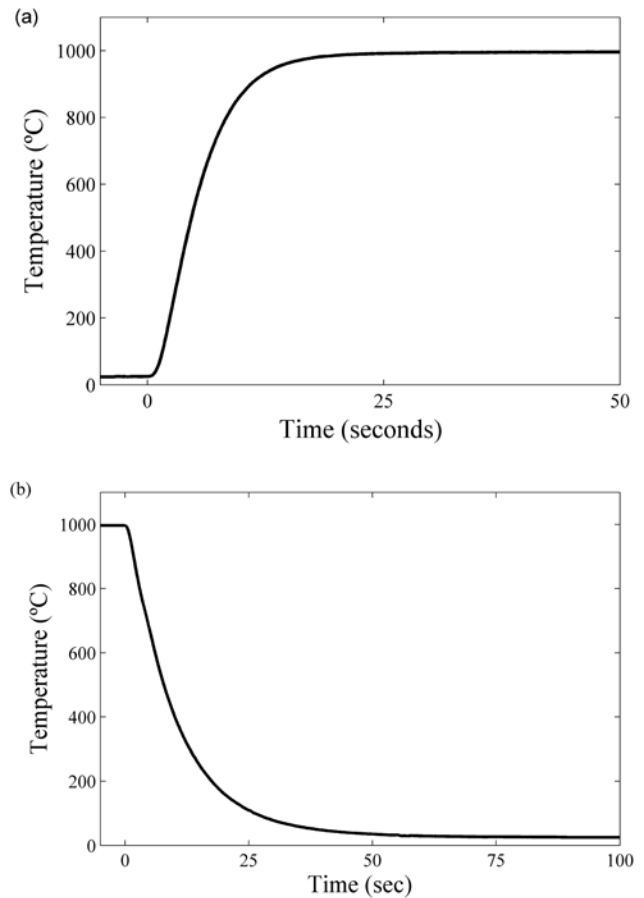


Fig. 9. (a) Heating up time response for the packaged RFBG sensor. (b) Cooling down time response.

that the time response performance of the packaged sensor can be further improved by reducing the dimension of the ceramic and metallic tubes (less thermal mass load).

We also measured the cooling down time response removing the RFBG sensor from the oven and let it cool-down to room temperature. As shown in Fig. 9(b) the cooling down time response is ~22 s.

## IV. CONCLUSION

We have successfully regenerated fiber Bragg gratings for high-temperature applications up to 1100°C. We have studied the regeneration and the high temperature decay of these gratings. We have shown that is possible to preserve the apodization of the initial FBG. No decay has been found for temperatures up to 1100°C. A high temperature package has been designed for mechanically protect the regenerated gratings. The packaging effect has been studied comparing the thermo optical characteristics of the unpackaged RFBGs and the packaged sensor. The results show that the packaging does not affect the sensor performances, while providing support for the otherwise fragile fiber. The packaged sensor shows a high repeatability with a maximum deviation of the 1% and does not exhibit any hysteresis or wavelength drift. The heating up time response and the cooling down time response have been measured. The packaged sensor has a heating up time response of the order of 9 s and a cooling down time response of the order of 22 s, which is comparable to that of commercial high temperature sensors based on thermocouples.

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