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Thomas Blanchet, Sylvain Magne, Guillaume Laffont. Packaged sapphire fiber Bragg gratings ability to withstand temperature up to 1500°C. EWOFs 2023 - European Workshop on Optical Fibre Sensors, May 2023, Mons, Belgium. pp.1264320, 10.1117/12.2678533 . cea-04189376

HAL Id: cea-04189376

<https://cea.hal.science/cea-04189376>

Submitted on 28 Aug 2023

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Packaged Sapphire Fiber Bragg Gratings Ability to Withstand Temperature up to 1500°C

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ABSTRACT

A fiber Bragg grating has been inscribed in a 100- μm diameter sapphire optical fiber with the phase mask technique and a fs-laser emitting at 800 nm. The grating was placed inside a sealed alumina capillary to protect the fiber from the environment. Then the fiber was set inside an oven and cycled up 7 times to a maximum temperature of 1500°C during 2 h. We observed that after two cycles, the grating is stabilized and no more hysteresis on the Bragg wavelength is observed. However, the temperature uncertainty is as high as 15°C and is principally due to modal interference. Then the grating is submitted to a 3-day annealing and two successive 4-day annealing – for a total of eleven days – at a temperature of 1500°C. During this treatment, the grating amplitude remained constant and the Bragg wavelength showed no significant drift. As a conclusion, the packaged grating did not exhibit any erasure during these annealing experiments and perform reliable temperature measurement up to 1500°C.

Keywords: Sapphire Fiber Bragg Grating, Optical Fiber Sensors, High Temperature

1. INTRODUCTION

Optical Fiber Sensors (OFSs) can be used to measure different parameters as temperature¹, strain¹, radiation², ... As far as temperature measurements are concerned, distributed sensors based on the light back-scattering can hardly reach temperature higher than 800°C³. Sensors as Fiber Bragg Gratings (FBGs) can reach temperature as high almost as 1300°C⁴. However, at temperature higher than 900°C the FBG sensors exhibit a drift on temperature measurements^{5,6}. One solution to overcome this limit is to change the fiber material, using sapphire rather than silica, since the melting temperature of sapphire crystal is about 2040°C⁷.

However, Sapphire Optical Fiber (S-OF) is only constituted of crystalline sapphire, since no dopant were added during the fabrication process, leading to a cladding-less fiber with the light only guided by the outside environment. Moreover, the S-OF is a highly multimodal guide since the fiber diameter is usually of several tens of micrometers⁸. Due to the multimodal behavior of the S-OF, the FBG inscribed in a sapphire fiber (S-FBG) shows a wide Bragg peak – several nanometers⁹ (Figure 1.a) – and not as reflective as the one inscribed in their counterpart in silica-based fiber as only few dB^{10,11} are reflected in the S-OFs. Moreover, the reflectivity of the S-FBG is higher, when the inscribed fringe area is wider, or the fiber diameter lesser¹⁰.

Considering FBG inscription, the point-by-point (PbP) technique cannot be used directly, but other methods derived from it such as the line-by-line (LbL) technique¹⁰ or the inscription of parallel lines of PbP gratings¹² can be used. Also more classical methods such as the phase mask technique¹¹ or the Talbot interferometer¹³ can create FBGs in sapphire fibers.

S-FBGs inscribed with the LbL technique have been annealed up to 1612°C by Xu *et al.*¹⁰. The authors observed a difference on the grating response between heating and cooldown phases, but no hysteresis was observed. Sapphire gratings inscribed with the phase mask techniques have been cycled between 500°C and 1200°C during 20 min and the cycles were repeated during 4 weeks¹⁴. The authors did not observe any significant Bragg Wavelength Shift (BWS) nor decrease of the peak amplitude. For cycles at temperatures higher than 1200°C¹⁴, the grating showed a hysteresis after an annealing at 1600°C, but the Bragg wavelength was measured at a temperature of 1200°C. This effect is still observable after one cycle at 1200°C, one at 1600°C, one again at 1745°C and three at 1600°C.

In this paper, we have inscribed S-FBG with the phase mask technique using a fs-laser emitting at 800 nm. The S-FBG was sealed in an alumina capillary and then placed inside a tubular oven. Firstly, the grating was submitted to thermal cycling, up to 1200°C for the first cycle and 1500°C for the 2-hour long six other cycles. Secondly, the grating was annealed up to 1500°C for 3 cycles lasting 3 to 4 days each: one lasting 3 days and two cycles lasting 4 days each.

2. GRATING INSCRIPTION AND PACKAGING

A fs-laser (Ti:Sa – Astrella, Coherent) emitting at 800 nm with a pulse width of 35 fs at a frequency of 1 kHz was used to inscribed the S-FBG. The laser energy was set at 650 mJ during the inscription. A cylindrical lens is placed at few millimeters in front of the phase mask. The sapphire fiber is positioned, on the focal line created by the lens in the interference area produced by the +1/-1 diffraction orders of the phase mask. The lens is mounted on a piezo-electric actuator and moved transversally to the fiber axis, so that the focal line is swept across the fiber. After inscription, the S-FBG reflected amplitude is about 4 dB for a 100 μm diameter sapphire fiber with the interrogation setup described hereunder. The S-OF is produced by Micromaterials (USA) and one side is mounted with a standard FC/APC connector and the other end is polished at 8°. The fiber polishing and the connector were made by IDIL (Lannion, France).

During the annealing at high temperature, the S-OF surface can be polluted by the external environment⁹, thereby modifying the light guidance inside the claddingless fiber. The fiber is inserted inside an alumina capillary, where one extremity is sealed with zirconium glue, which can withstand 2000°C. On the other side, a custom-made plug is used to seal the capillary and to bond with the capillary and the fiber connector, together (figure 1.b).

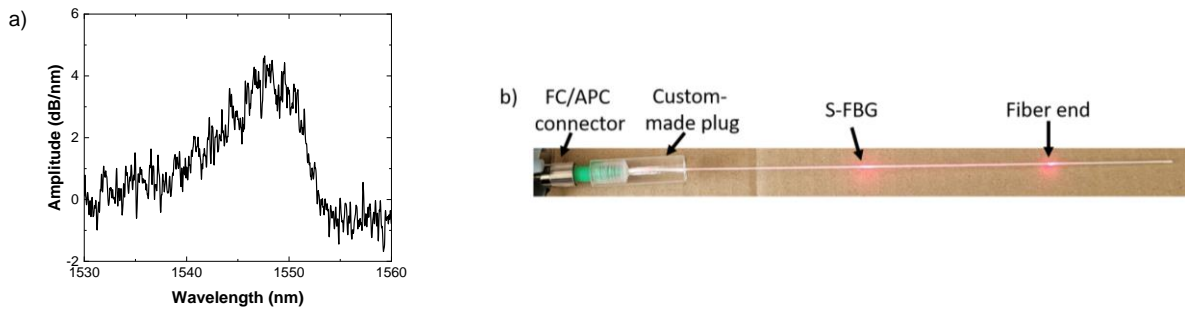


Figure 1.a. S-FBG spectrum just after inscription and b) packaging of a 20 cm long S-OF with a grating inside the capillary

3. EXPERIMENTAL SETUP

The packaged fiber is placed horizontally inside an oven (Carbolite Gero – TF1 16/60/300) which can operate up to 1500°C in air. A S-type thermocouple (TC) is used to control the temperature inside the oven near the grating. The internal TC of the oven was used as a reference instead of the S-type TC that does not support this long term annealing.

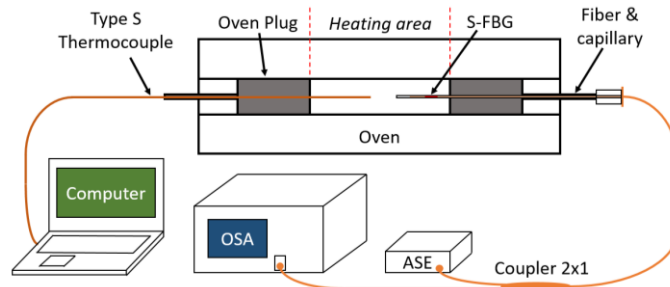


Figure 2. Experimental setup used for the annealing tests.

The S-FBG is interrogated with a broadband light source (Amplified Spontaneous Emission – ASE) emitting from 1520 nm to 1620 nm (figure 2). The signal is injected into a 2x1 multimode coupler which output is connected to the sapphire fiber and the other input is connected to an Optical Spectrum Analyzer (OSA, AQ6376D, Yokogawa). The acquisition time per spectrum is around 5 min and during the long-term annealing, the recording rate was fixed to 30 min. To extract the Bragg wavelength, a sliding average is used to smooth the peak and either X-bandwidth¹⁵ or polynomial¹⁵ fits are used to estimate the Bragg wavelength. The two methods showed similar results. During the 3rd cycle, the BWS was calibrated in temperature, by applying a 3rd order polynomial fit to obtain a law between the Bragg wavelength and the temperature measured by the reference TC. For the following results, the S-FBG measurements are given in temperature (°C).

4. THERMAL CYCLING

Firstly, a S-FBG is submitted to several thermal cycles, where the first cycle is up to 1200°C during 2 h and the six other cycles are up to 1500°C during 2 h. During the first cycle, a strong hysteresis, in excess of 100°C is observed (figure 3.a). Moreover, the grating amplitude increases from 2.5 dB to almost 5 dB (figure 3.b, red circle). During the second annealing at 1500°C another hysteresis is observed and the difference between the beginning and the end of the treatment is almost 50°C. And, as for the first cycle, the grating amplitude increases from 0.5 dB to 5.5 dB.

An increase in amplitude of similar S-FBG has already been observed by Busch *et al.*¹⁴ for their first cycles at temperature below 1400°C, but for the cycles at higher temperature, the grating amplitude started to decrease. This is not the case with our S-FBG, where the grating amplitude remains constant for the rest of the cycles at 1500°C.

For the cycles from the 3rd to the 7th, no more noticeable hysteresis is observed: the S-FBG follows the thermocouple measurements. Moreover, excepting during heating and cooldown phases, where the temperature inside the oven is not homogeneous, the deviation between the TC and the S-FBG measurements are less than 15°C. This measurement error is principally due to the amplitude fluctuations on the Bragg peak spectrum, coming from modal interferences (speckle).

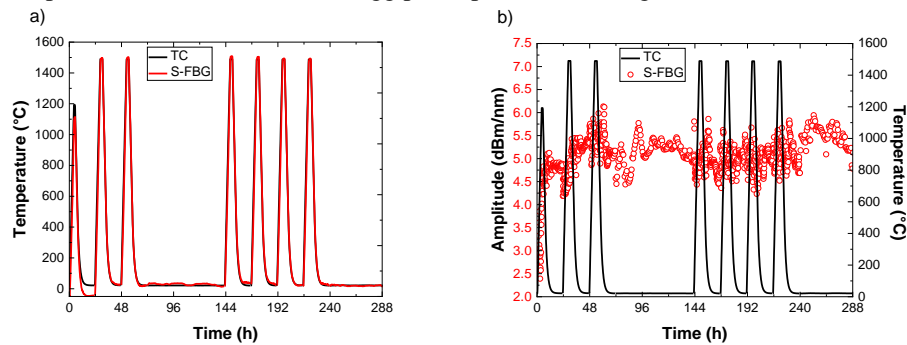


Figure 3. a) Temperature measured by the thermocouple (TC- black) and a S-FBG (red) and b) amplitude of the S-FBG (red circle) and temperature measured by the TC (Black) during the seven treatments up to a temperature of 1500°C during 2 h.

In the article from Busch *et al.*¹⁴, for the cycles at temperatures upper than 1500°C, a hysteresis is observed for each cycles. This difference with our results can be due to an insufficient annealing, (not long enough and/or performed at a too low temperature), whereas in our case, two annealing cycles at 1500°C maximum during 2 h seem to prove sufficient to stabilize the S-FBG, i.e. the temperature measured by the S-FBG did not drift anymore along the experiment. However, more tests must be performed to understand clearly the annealing effects and determine the optimal annealing conditions in time and temperature.

5. LONG TERM ANNEALING

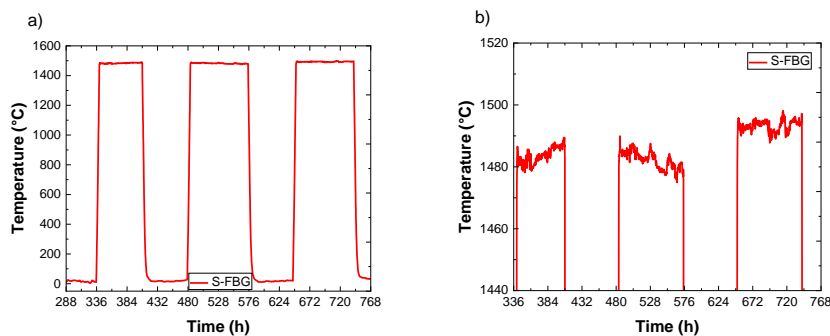


Figure 4. (a) Temperature measured by the S-FBG (red) during the full cycles and (b) zoom on the high temperature measurement

Secondly, the same S-FBG is submitted to longer annealing cycles at 1500°C (figure 4.a) of at least 3 days. During the first cycle of 3 days, the temperature measured by the S-FBG increases by less than 5°C changing from about 1480°C to 1485°C (figure 4.b). The temperature provided by the oven remains stable at 1500°C, but the S-type TC did not withstand

the cycles and started to drift, so no TC measurement are shown. The difference of about 20°C between the oven TC and the S-FBG is due to the thermal inhomogeneity as the position of the two sensors are different: the S-FBG is placed inside the oven tube while the oven TC is placed outside the tube.

During the second annealing of 4 days, the temperature measured by the grating decrease by less than 6°C. The temperature monitored by the oven did not change during this cycle. For the last 4-day long cycle, the temperature measured by the grating remains stable with a temperature variation of less than 5°C. Again, the oven temperature did not change. During these three long-term annealing cycles, no modification on the grating amplitude is observed.

During these cycles, no clear behavior of the S-FBG was observed since during the three cycles, the temperature measured by the S-FBG is roughly stable. We assume that these temperature variations are due to the speckle present on the S-FBG reflection spectrum.

6. CONCLUSION

We have inscribed a fiber Bragg grating inside a sapphire optical fiber with the phase mask technique and a Ti:Sa fs-laser. The obtained sapphire FBG shown a broad Bragg peak with a lot of speckle-induced oscillations on its spectrum. The sapphire fiber was sealed in an alumina capillary to protect the fiber surface from the environment. Then the packaged fiber was inserted inside an oven and was annealed at different temperatures up to 1500°C. For the first cycle at a temperature of 1200°C during 2 h and a second one at 1500°C for the same duration, the grating amplitude increased by almost 3 dB. Moreover, the Bragg wavelength presented a hysteresis of several tens of degrees during the two treatments. Afterward, no more hysteresis is observed and the Bragg peak amplitude remained constant for the five additional cycles at 1500°C. Long-term thermal treatments were applied on the same grating cumulating a total of 11 days at 1500°C. No sign of erasure nor Bragg peak shift were observed.

We can conclude that during the annealing no variation of the amplitude nor temperature drift were observed. These results is due to the fiber packaging inside a sealed alumina capillary, which protect the fiber and the grating from the environment and the two cycles at a temperature up to 1500°C during 2 h. Our further investigations will focus on reducing the influence of the modal interferences in order to improve the Bragg wavelength estimation.

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