Regeneration of Tilted Fiber Bragg Gratings

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ABSTRACT

The regeneration of Tilted Fiber Bragg Gratings photowritten in a singlemode SMF-28e fiber is investigated. Three tilted FBGs, with respectively 0°, 4° and 8° external tilt angles are annealed according to a conventional high temperature regeneration protocol. We monitor the evolution of distinct spectral features during the thermal annealing process. We also propose a method in order to follow the regeneration process of tilted FBG, without focusing on individual spectral resonances. Regeneration of tilted FBGs presents numerous interests for the realization of high temperature sensors and devices, but also to improve their resistance to preliminary manufacturing processes requiring high temperature steps.

Keywords: Optical Fiber Sensors, Fiber Bragg Grating, Tilted Fiber Bragg Grating, Regeneration, High temperature

1. INTRODUCTION

The regeneration process of Fiber Bragg Gratings is highly attractive in order to develop high temperature resistant FBG sensors, especially for monitoring applications in harsh environment [1, 2]. While not fully understood yet and raising interesting issues on the glass transformation at high temperature, the process of regeneration within silica optical fibers is a practical solution to develop high temperature resistant FBGs while preserving their spectral shape for accurate metrology in severe environment. Tilted FBGs (TFBGs) have been shown, in the past, as interesting transducers and sensors able to address metrological parameters such as outer refractive index [3] or bending, but also in order to realize spectral devices for the monitoring of standard FBGs (edge filter and all-fiber diffractive element within compact spectrometer) [4, 5]. In this paper, we investigate the use of the regeneration process applied to TFBGs in order to transpose their main sensing applications to high temperature environments.

2. "SEED" TILTED FBG FABRICATION

2.1 Cladding mode coupling and criteria for tilt angle selection

Tilted FBGs consist in a periodic modulation of the core's refractive index, which is tilted with respect to the propagation axis (see Fig. 1). This is easily achieved with conventional photo-writing setups such as those involving phase masks or Lloyd mirror interferometers by introducing an angle between the fiber and the UV-light fringe pattern. Even small tilt angles drastically change the spectral response of such a grating. Due to the limited radial extension of the periodic pattern of standard FBGs, cladding resonances are also observed in non-tilted FBGs. One way to reduce the presence of cladding resonances consists to radially extend the periodic pattern, for instance using a photosensitive cladding singlemode fiber. The reverse, which consists in maximizing coupling coefficients between the fundamental mode and backward propagating cladding modes, may be obtained with highly localized or tilted FBGs. The transmission spectrum of a tilted FBG is related to the fiber index profile and to the tilt angle. Increasing this angle induces coupling to higher order cladding modes. For discrete tilt angle values, the coupling coefficient to the fundamental backward propagating mode tends to zero. Moreover, low tilt angles may also induce the forming of a so-called ghost mode associated to low order cladding modes, with a radial field distribution reaching zero near the core-cladding interface.

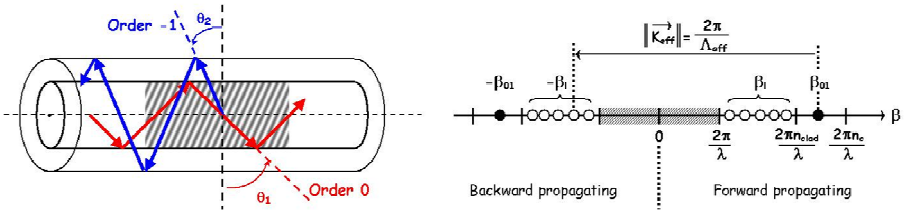


Figure 1. Tilted FBG coupling diagram.

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All these characteristics are helpful to determine whether the cladding resonances observed during the regeneration of a "seed" TFBGs are due to a regenerated tilted pattern or to a localized grating. The "external" tilt angles (angle between the fiber propagation axis and the fringe pattern) selected in this experiment are respectively 0°, 4° and 8°. The 8° tilt angle corresponds to a grating characterized by a hardly distinguishable Bragg peak, a pronounced ghost mode and a lot of cladding resonances. The 4° TFBG presents the same spectral features with the addition of a Bragg peak. 0° TFBG, *i.e.* non-tilted FBG, is routinely regenerated: thus it is used in this study as a way to track and estimate the efficiency of the regeneration process and to be sure that the temperature thresholds have correctly been chosen. The spectral offset between the Bragg resonance and the first cladding mode remains the same whatever the tilt angle: it is related only to the optical fiber numerical aperture.

2.2 Tilted FBGs and regeneration protocol

Tilted FBGs used in this experiment are photowritten with an argon laser emitting at 244 nm (100 mW output power) and a Lloyd mirror interferometer equipped with an accurate rotation stage. The Lloyd mirror being cut at 45° on one edge makes it possible to rotate the fiber *versus* the fringe pattern. This rotation angle is called "external" tilt angle throughout this paper. The effective tilt angle of the refractive index modulation within the fiber's core is slightly different due to light refraction at the fiber's optical cladding. Three 5 mm long TFBGs are photo-written in an SMF-28e optical fiber. Long exposure times ranging from 2 to 3 hours are used to maximize the attenuation that can be reached for each grating. A non-tilted FBG is used as a reference for the regeneration process of two TFBGs having respectively 4° and 8° external tilt angles. The 8° TFBG is located on the same piece of fiber, but 5 mm away from the non-tilted FBG in order to be regenerated simultaneously with the same experimental conditions than the reference grating. Temperature inhomogeneity along the regeneration area is lower than 1°C.

The regeneration process used in our experiment consists in a two steps heating sequence. An intermediate annealing is performed at 700°C for 1 to 2 hours, and then the regeneration step occurs at 900°C. Between each step, the furnace heating rate is fixed at 5°C/min. The tubular furnace itself is 85 cm long and equipped with three heating zones in order to minimize the temperature gradient. Our gratings are slightly decentered by 5 cm with respect to the furnace central heater in order to avoid any central temperature overshoot observed during heating ramps. Tilted FBG transmission spectra are acquired every 25 s using a tunable laser source scanning 200 nm from 1440 nm to 1640 nm and with a spectral sampling every 1 pm. The gratings are slightly pre-strained thanks to fiber clamps carefully positioned at the furnace's extremities.

3. REGENERATION EXPERIMENT

3.1 Comparison of Tilted FBG spectra before and after regeneration

Figure 2 shows transmission spectra of the three Tilted FBGs at key instants of their regeneration process. A first group of graphs, on Line I, correspond to the grating spectra at the early beginning of the experiment. For the 0° TFBG, a strong Bragg resonance of roughly 50 dB is obtained. For the 4° and 8° seed TFBGs, cladding resonances with attenuation up to 10 dB and 20 dB are respectively obtained. The 4° TFBG exhibits a strong and distinctive ghost mode like spectral feature. Its amplitude is greater than that of the Bragg peak. For the 8° TFBG, the ghost mode is also observed together with a hardly distinguishable Bragg resonance. Decrease of the Bragg resonance from 0° TFBG to 8° TFBG is consistent with the decrease of the fundamental to the backward propagating guided mode coupling coefficient with the tilt angle. Annealing of the three TFBGs at 700°C partially erase the gratings, while almost preserving the spectral shapes of their respective spectra. For the 4° TFBG, the ghost mode erasing is more pronounced than that of the Bragg peak, although the initial ghost mode attenuation is stronger.
On Figure 2, Line II shows spectra acquired on the 900°C step used during the regeneration. For each grating, we extracted a spectrum just before the complete erasing of the seed TFBG and a spectrum after regeneration corresponding to the optimal attenuation of the cladding resonances. One can clearly observe that the spectra before and after regeneration are almost identical from shape point of view. Identical resonances (*e.g*; the Bragg peaks) are slightly different in term of wavelength, before and after the regeneration. This is not due to temperature discrepancies but to a constant load applied to each TFBG during the process. Such a load induces wavelength shift during the regeneration as described by Wang *et al*. [6]. The identical spectral shape of each TFBG spectrum before and after regeneration is consistent with the fact that the tilted pattern is preserved during the process.

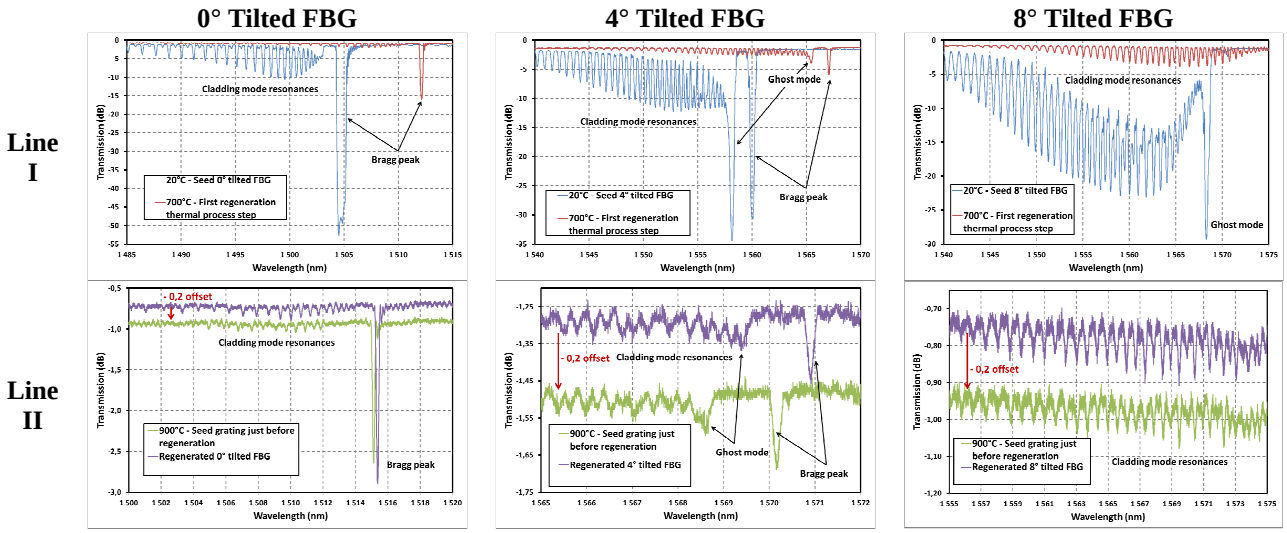


Figure 2. Transmission spectra of the three Tilted FBGs investigated (0°, 4° and 8° external tilt angles). Line I: before the regeneration process (in blue) and at the end of the first annealing step at 700°C (in red). Line II: at the 900°C annealing step (regeneration phase), few minutes before the complete erasing of the seed grating (in violet) and once regenerated (in green).

3.2 Evolution of several cladding modes peaks during the regeneration

Regeneration of the 0° TFBG leads to a regenerated Bragg peak with an attenuation of 2.7 dB. This strong regeneration ratio is typical from what can be obtained is SMF-28-like fiber. This is the reason for the choice of such a fiber in this experiment. We have anticipated that regenerated cladding resonances would correspond to low level attenuation peak. Thus, we have selected an optical fiber that enables strong regenerated grating. Even with such a fiber and strong seed TFBGs, tracking the cladding resonances during the regeneration process is quite challenging. Typical evolution of several cladding resonances are given on Figure 3. On these curves, obtained for the Bragg peaks, the ghost mode and cladding mode resonances are similar to what is expected during grating regeneration. The spectral resonances are simultaneously erased and reappear with similar growing rates.

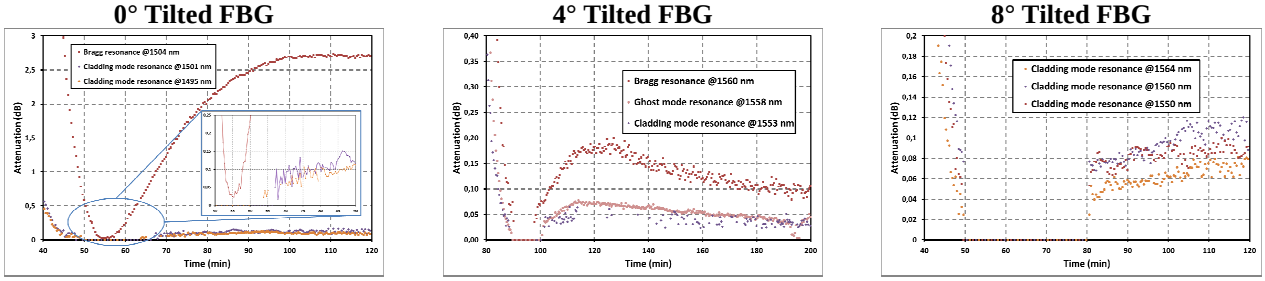


Figure 3. Evolution of distinctive spectral resoncances for each Tilted FBG during the regeneration process.

3.3 "Collective" analysis of the Tilted FBG regeneration

As the spectral tracking of cladding resonances during the whole grating regeneration is quite difficult, we have considered another approach. Rather than considering individual resonances, we take benefit from the pseudo-periodic behavior of the cladding resonances and perform an FFT analysis. For a given TFBG transmission spectrum, the cladding resonances spectral pattern is usually associated to a broad peak on the power spectrum (see Fig. 4). Tracking of this peak is easier than that of individual resonances and provides a regeneration curve being easier to analyze. By performing such a "collective" analysis of the cladding resonances, we easily follow the regeneration process.

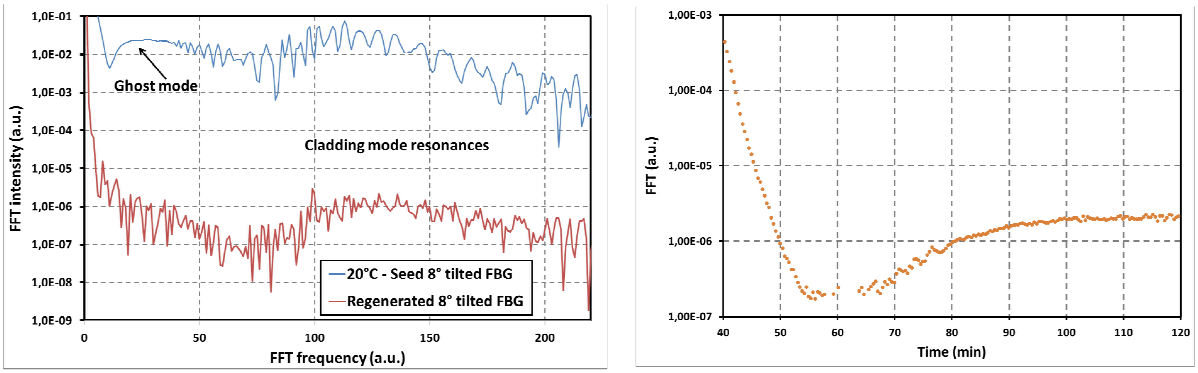


Figure 4. Power spectra for the 8° TFBG before and after regeneration (left). Tracking of the broad peak (located around frequency 140 on the power spectrum graph) attributed to the cladding mode resonances of the 8° TFBG during the regeneration process (right).

4. DISCUSSION

Tilted FBGs photowritten in SMF-28e optical fiber are regenerated using a two steps heating sequence. The attenuation of several cladding mode resonances is followed during the regeneration process and is compared to that of a Bragg peak. Several TFBGs are used in order to get typical spectral signatures of TFBGs (Bragg peak, ghost mode and cladding resonances) in singlemode fibers. Following very accurately the attenuation of low amplitudes cladding mode resonances during the whole regeneration process remains a difficult task even with accurate spectral analyzing tools. Thus a "collective" approach is investigated through the analysis of the FFT power spectrum of the whole transmission spectrum of a given TFBG. This method takes benefit from the pseudo-periodical behavior of the cladding mode resonances and bypasses the difficulty to accurately track low amplitude individual resonances. This study demonstrates that Tilted FBGs can be regenerated in the same way than standard grating. This might give some insight into the regeneration process itself, suggesting that the regeneration process causes a periodic glass structuration across the fiber's core. Using the regeneration approach, we have demonstrated that high temperature resistant Tilted FBGs can be manufactured. While improved spectral characteristics of regenerated TFBG could be obtained through the photo-writing of stronger "seed" grating, usual applications of TFBGs may now be transferred to the case of high temperature environments such as: high temperature refractive index (RI) monitoring, RI monitoring at conventional temperature but with preliminary process such as coating deposition involving high temperature processes, bend sensing, high temperature edge filters for high speed FBG demultiplexing and high temperature operated all-fiber spectrometer.

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