Narrow-band interrogation of tilted fiber Bragg grating refractometers

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A real-time interrogation method for tilted fiber Bragg grating refractometers is described. A tunable laser is set up to work at the corresponding wavelength of the most sensitive mode of the sensor under test. Tiny variations in the refractive index of the medium surrounding the sensor produce local amplitude changes in the transmitted amplitude spectrum. The transmitted optical power is then monitored in real-time with a photodiode connected to an analog-to-digital converter. Some results in terms of bandwidth use and sensitivity are reported.

Introduction

A tilted fiber Bragg grating (TFBG) is a periodic pattern photo-inscribed in the core of an optical fiber that is slightly angled with respect to the perpendicular to the fiber longitudinal axis. Compared to uniform Bragg gratings, the tilt angle allows not only the reflection of a mode confined in the fiber core, known as Bragg mode, but the additional coupling of multiple modes to the fiber cladding [1].
Each of the cladding modes possesses its own effective refractive index value. When the refractive index of the medium surrounding the grating reaches a value close to the one of a cladding mode, the mode is not longer totally internally reflected at the cladding outer interface and tends to propagate to the outer medium, producing a change on its transmitted spectrum. This phenomenon has allowed the use of TFBGs as highly sensitive refractometers to develop several optical fiber sensing approaches [2].
In this work, we study an interrogation method based on the local monitoring of the TFBG transmitted optical power variation due to changes in the surrounding medium. This technique constitutes a narrow-band alternative for refractive index measurements and is also characterized by its ease of development and integration.

Previous characterization

The work we report in this paper was carried out on a 6° TFBG with a length of 1 cm. The pattern was photo-inscribed in the core of a hydrogen-loaded photosensitive optical fiber exposing a 1070 nm pitch phase mask to the continuous UV radiation produced by a frequency-doubled Ar laser emitting at 244 nm. After the inscription, the grating was

kept inside an oven at a temperature of 85 °C for about 12 hours in order to remove the hydrogen left in the fiber and stabilize its behavior.
First measurements were aimed to characterize the refractometric response of the TFBG. A grating manufactured with the parameters described above typically presents a set of cladding mode resonances whose corresponding effective refractive index values are around the one of the water. We immersed the grating in a solution consisting of distilled water mixed with lithium chloride (LiCl) using a magnetic stirrer. The resulting refractive index was measured with a Reichert AR200 digital refractometer. The procedure consisted of adding more distilled water to the mixture in order to decrease the LiCl concentration and hence slightly decrease the refractive index of the solution. At the same time we recorded the TFBG transmitted spectrum corresponding to each step with an optical vector analyzer from Luna Technologies, obtaining the results shown in figure 1.

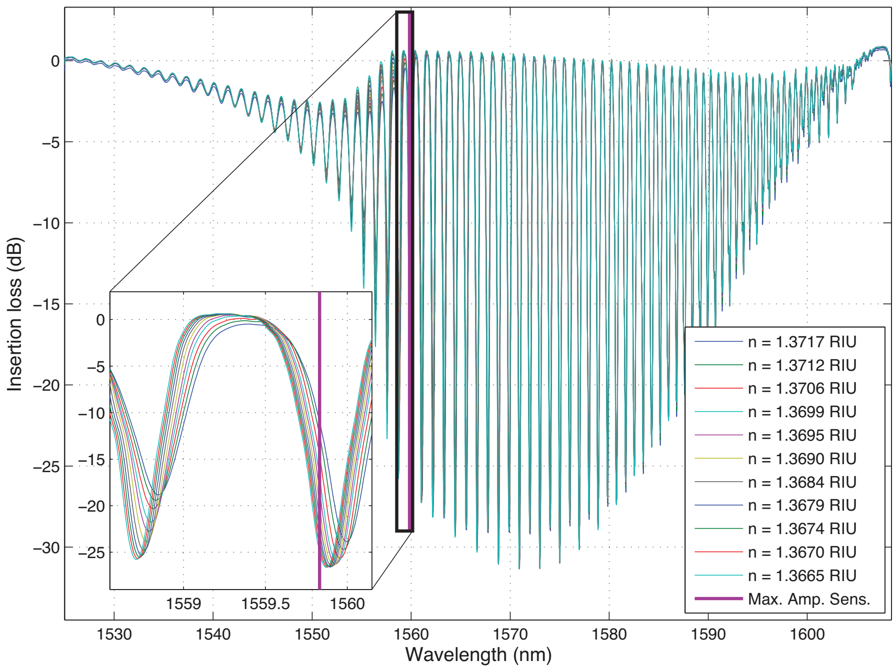

Fig. 1: TFBG under different surrounding refractive index conditions, with a zoom to the most sensitive mode in terms of wavelength shift (left) and insertion loss (right).

At first sight we can observe a coupling to the outer medium of the upper part of the spectrum between 1530 nm and 1560 nm. From this fact we can deduct that for the refractive index range we have used, the most sensitive cladding modes will be located in this region of the spectrum. Apart from demonstrating experimentally that the TFBG we manufactured behaves as expected, this experiment is interesting for the purpose of identifying the most sensitive cladding modes for this particular refractive index conditions.
After analyzing each mode separately we have highlighted in the zoomed window of figure 1 that the most sensitive mode in terms of wavelength shift is the one located around 1558.8 nm and the mode that presents the greatest insertion loss variations is its neighbor, located around 1559.9 nm.

Narrow-band measurements

In addition to the computation of the area delimited by the cladding mode resonance [3], the most used interrogation method for TFBG sensors has typically been the measurement of the wavelength shift induced on the most sensitive mode by the surrounding refractive index changes. However, we have seen in the previous section that there is a mode that maximizes the difference of insertion losses, being this mode the most sensitive in terms of amplitude changes. We propose to benefit from this mode sensitivity in order to carry out an alternative measurement method and establish a comparison between both of them. A tunable laser source from Luna Technologies has been configured to emit around 1559.8 nm, which is the wavelength where the mentioned mode is most amplitude-sensitive. One side of the previously used TFBG has been connected to the source and the other to a dBm Optics Model 4100 optical power meter that integrates a photodiode together with an analog-to-digital converter to finally display the measured values. Once again, the grating has been immersed into a solution of distilled water and LiCl and the experience has consisted on repeating the same procedure we developed with the optical vector analyzer, but monitoring the change on the transmitted optical power.

Results and discussion

We have been able to monitor the wavelength shift of the cladding mode located around 1558.8 nm and the amplitude variation around the wavelength of 1559.8 nm, both phenomena produced by the change of the refractive index value of the medium surrounding the grating. In figure 2 we can observe the experimental data we measured, as well as a fit showing the behavior of each interrogation method.

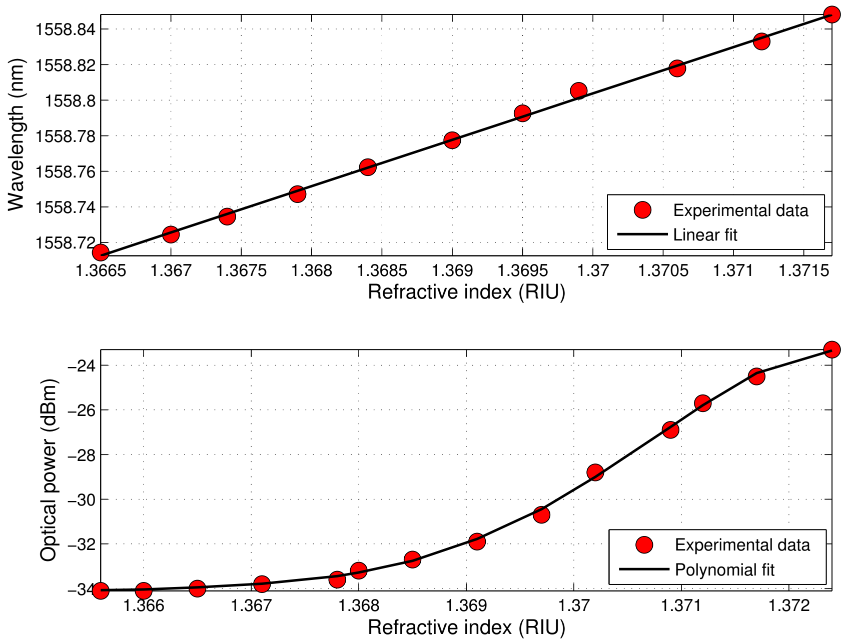

Fig. 2: Wavelength shift of the cladding mode around 1558.8 nm (up) and optical power change around 1559.8 nm (down).

As we can see in the upper part of the figure, the first procedure presents a linear behavior, a desirable fact for sensor interrogation. On the other hand, in the lower part of the figure the monitoring of the amplitude changes exhibits a more typical response of a polynomial curve, or even a sigmoid function. In both sides of the refractive index range with which we have worked during the experiments the transmitted optical power tends to stabilize, while the region in which we observe a linear response is limited to a region of the spectrum between 1.3695 and 1.3715 RIU. This is a similar behavior as the previously reported one for the wavelength shift of plasmonic sensors [4] and is due to the fact that the mode we are analyzing is the most sensitive one only for this refractive index range. Out of this range, we should select another cladding mode with a closer effective refractive index to the ones we want to work with.
Finally, the quantitative comparison of both interrogation methods has been summarized in table 1. Offering both of them a very high sensitivity and resolution, the main differences arise in terms of the refractive index range in which they present a linear response and the required bandwidth.

	Sensitivity $\pm$ Resolution	Linear Range	Bandwidth
Wavelength shift	$26.055 \pm 3 \times 10^{-5}$ nm/RIU	$> 5 \times 10^{-3}$ RIU	> 1 nm
Amplitude change	$3094 \pm 4 \times 10^{-5}$ dBm/RIU	$\approx 2 \times 10^{-3}$ RIU	< 1 pm

Table 1: Quantitative comparison of both interrogation methods.

Conclusion

The local transmitted optical power measurement is an interrogation method suitable for applications such as bio-sensing, where the changes in the surrounding refractive index are of the order of ppm (parts per million), and are located around a region of the spectrum known *a priori*. It is also an interesting approach when integrating sensing platforms to work in the field, through the replacement of the tunable laser by a fixed one.

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