Reflected power-based interrogation of plasmonic tilted fiber Bragg grating sensors

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In this work an interrogation technique for plasmonic tilted fiber Bragg grating (TFBG) sensors is reported. The sensor under test is followed by a uniform FBG whose central wavelength matches the one of a surface plasmon resonance sensitive mode. Light reflected backwards by the grating gets partially attenuated due to the coupling of the plasmon wave to the external medium. Thus, tiny changes in the refractive index of the medium around the sensor are translated into a power variation. This method provides an interrogation schema based on the use of the reflected spectrum, especially suitable for remote or in-vivo measurements.

Introduction

Plasmonic tilted fiber Bragg grating sensors provide an excellent platform to accurately measure tiny changes in the refractive index of the medium in which they are located. Originally conceived as an adaptation of the bulky Kretschmann prism, they act as miniaturized in-fiber refractometers especially suitable for *in-vivo* and real-time applications [1]. The first stage in their fabrication is the photo-inscription of a TFBG in the core of a photo-sensitive optical fiber. This consists of a periodic modulation in the refractive index of the core that is slightly angled with respect to the perpendicular to the fiber longitudinal axis. It causes part of the light being transmitted through the core to be coupled to the cladding of the optical fiber in the form of multiple modes that subsequently reach the interface between the cladding and the outer medium. Each of these modes propagate with a corresponding effective refractive index value and if it matches the one of the surrounding medium they get coupled out of the fiber, producing a change in the optical transmitted spectrum [2]. After the TFBG photo-inscription, a thin metallic film is deposited upon the fiber circumference at the location of the grating in order to create a metal-dielectric interface with the outer medium. This permits part of the cladding modes to be able to excite a plasmon wave on the surface of the sensor.

Bare TFBGs provide a refractometric sensing solution by themselves, however, the metallic coating and the ensuing surface plasmon excitation enhance their typical sensitivity by an order of magnitude [3]. This sensitivity also depends on the employed method of interrogation, usually based on tracking the wavelength of the most sensitive mode. This involves the use of expensive equipment and sometimes limits the system to be interrogated in transmission. In this work, a cost-effective interrogation technique based on the reflected optical power is proposed. Light reflected by a uniform FBG passes through the sensor under test, enabling to interrogate its transmitted response backwards. It is intended to be applied outside of the laboratory environment, in situations where sensors are accessible from only one side of the optical path.

Experimental setup

In order to evaluate the performance of the proposed interrogation technique, a plasmonic sensor was subject to a refractometric experiment. The sensor consisted of a 6° TFBG photo-inscribed through continuous UV radiation and the well known phase mask technique [4] before being coated with a 50 nm thick gold film [3] by means of a sputtering process (Leica EM SCD 500). It was then immersed into a solution consisting of distilled water and lithium chloride (LiCl) so that the refractive index of the surrounding medium changed with the concentration of the solution.

This sensor is able to excite a surface plasmon wave in the interface composed by the gold film and the dielectric solution when the input light is linearly polarized in the plane of the grating tilt direction. However, both the mode that excites the plasmon wave and the adjacent modes that exhibit the highest sensitivity to changes in the outer medium are propagated along the cladding of the optical fiber. Hence, their direct monitoring can just be carried out through the sensor transmitted spectrum if no additional element is added to the system.

The suggested approach to perform a set of measurements relying on the reflected optical power is illustrated in figure 1. As can be seen, light from a LED source (Amonics ALS-CL-17-B-FA) is linearly polarized as described above and reaches the sensor under test through an optical circulator. The sensor excites a plasmon wave and the most sensitive cladding mode resonance for the specific refractive index of the solution is chosen by analyzing its optical transmitted spectrum [5]. A uniform FBG is then fabricated using a Lloyd's mirror setup [6] to finely define its central wavelength and match it to the one of the mentioned resonance, creating a wavelength-gated scheme [7]. Light reflected backwards by the FBG passes through the plasmonic sensor again, being partially attenuated by the sensitive resonance. Finally, it is transmitted to the third port of the circulator, where an optical power meter (dBm Optics Model 4100) monitors the power variation due to the changes in the refractive index of the solution the sensor is immersed in.

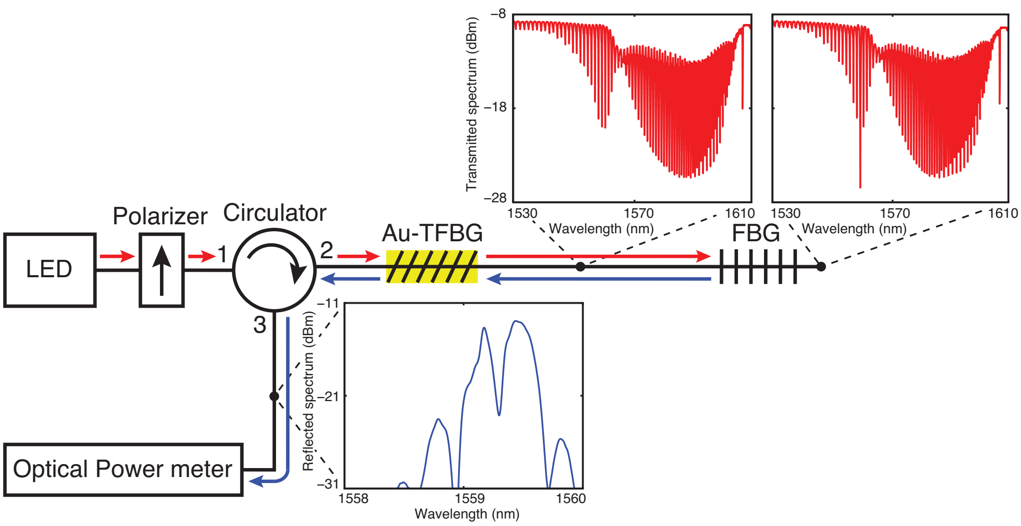

Fig. 1: Experimental setup of the proposed interrogation technique, with details of the corresponding spectra in different locations along the optical path.

Results and discussion

It is important to highlight that this technique is intended to be applied for measuring refractive index changes of the order of 10^{-4} RIU (refractive index units) within a predefined range of values. In fact, the wavelength in which the surface plasmon excitation occurs directly depends on the refractive index value of the medium where the sensor is located. Hence, if the external refractive index changed, the plasmon wave would be excited by a different mode and the previously described setup would not be valid. This phenomenon is graphically explained in the left part of figure 2. Both traces were obtained by measuring the optical spectrum transmitted from the third port of the circulator, that is, the light that would enter the power meter. The red trace corresponds to a refractive index value for which the most sensitive mode of the sensor matches the central wavelength of the FBG. In this way, the variations in the solution concentration will cause both a wavelength shift and a power change on this resonance. As it is located in the main lobe of the FBG, where most of the optical power is contained, the power meter will be able to measure the induced power variation. However, the opposite case is the one illustrated by the black trace, corresponding to a refractive index value out of the range of measurement. Here, the sensitive resonance of the plasmonic sensor is out of the FBG shape, so the changes in the surrounding medium do not affect the optical power measured by the power meter. This is the reason why a previous characterization of the sensor under test is essential.

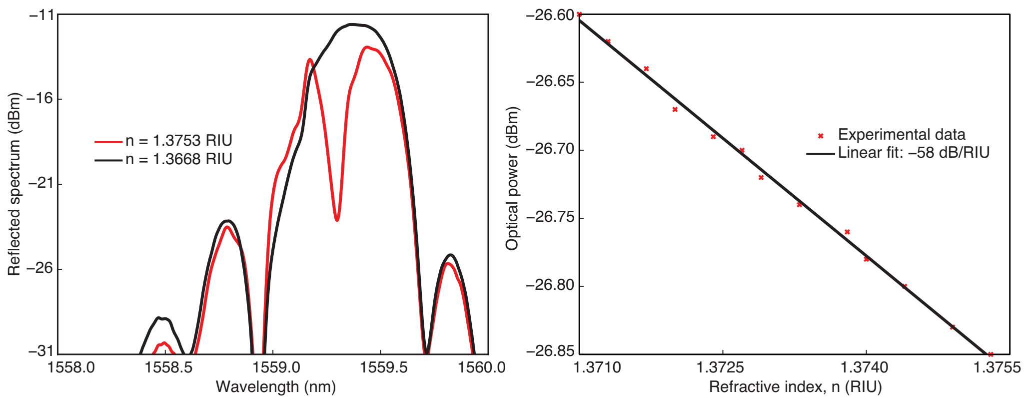

Fig. 2: Reflected spectrum of the setup for two different refractive index values of the surrounding solution (left) and computation of the measured optical power changes (right).

The interrogation technique was tested by making small modifications to the concentration of the solution and monitoring the optical power integrated and displayed by the power meter. To control the refractive index of the solution at every step a Reichert AR200 digital refractometer was used. The obtained results are displayed on the right side of figure 2, in which a fit of the experimental data was also included. As can be seen, in the refractive index range of values for which this technique is suitable, the change in power is clearly linear. In addition, the sensitivity was computed, obtaining a value of -58 dB/RIU, that is lower than the one obtained by other amplitude-based interrogation methods [8]. However, this technique provides several advantages worth mentioning. First, the couple formed by the plasmonic sensor and the FBG can be located far away from the rest of the system. When it is taken into account that the interrogation is carried out from one side of the optical path, remote operation is possible. Secondly, the use of a LED source and an optical power meter involves a cost-effective solution. The price of the equipment could even be reduced by substituting the latter by a photo-diode and an analog-to-digital converter, without modifing the basis of the technique. Finally, its behaviour is intrinsically temperature-insensitive. Both the plasmonic sensor and the FBG are equally sensitive to temperature changes, so they would register an identical wavelength shift and therefore the measurements taken by the power meter would be unaffected.

Conclusion

A cost-effective interrogation technique for plasmonic tilted fiber Bragg grating sensors based on the reflected optical power has been proposed and tested. The input light is linearly polarized and reaches the sensor under test, exciting a surface plasmon wave on the interface between its gold coating and the dielectric medium in which it is immersed. Part of the light is then reflected backwards by a uniform FBG whose central wavelength matches the one of the most sensitive resonance of the plasmonic sensor. This light thus suffers a power variation that is directly linked to the changes produced in the refractive index of the surrounding medium. The sensitivity of this methodology has been calculated to be -58 dB/RIU for the range of refractive index values in which the sensor is intended to work. Among its features, this technique allows sensor interrogation from a single side of the optical path and exhibits temperature-insensitive behavior.

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