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Narrowband interrogation of plasmonic optical fiber biosensors based on spectral combs

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ABSTRACT

Gold-coated tilted fiber Bragg gratings can probe surface Plasmon polaritons with high resolution and sensitivity. In this work, we report two configurations to interrogate such plasmonic biosensors, with the aim of providing more efficient alternatives to the widespread spectrometer-based techniques. To this aim, the interrogation is based on measuring the optical power evolution of the cladding modes with respect to surrounding refractive index changes instead of computing their wavelength shift. Both setups are composed of a broadband source and a photodiode and enable a narrowband interrogation around the cladding mode that excites the surface Plasmon resonance. The first configuration makes use of a uniform fiber Bragg grating to filter the broadband response of the source in a way that the final interrogation is based on an intensity modulation measured in transmission. The second setup uses a uniform fiber grating too, but located beyond the sensor and acting as a selective optical mirror, so the interrogation is carried out in reflection. Both configurations are compared, showing interesting differential features. The first one exhibits a very high sensitivity while the second one has an almost temperature-insensitive behavior. Hence, the choice of the most appropriate method will be driven by the requirements of the target application.

1. Introduction

Since the rise of fiber Bragg grating (FBG) sensors over the last decades, many configurations have been proposed to study a wide set of phenomena. Temperature, strain, pressure, magnetic field or acoustic sensing are just some examples of achievable platforms in which these devices provide some improvements or advantages. Aside from physical phenomena, FBGs have also been used as chemical sensors, especially for detecting hazardous compounds in harsh environments [1]. Within this group, refractometric sensors remain one of the most extended solutions to sense the characteristics of both gaseous and liquid media. Refractometry can be defined as the technique that measures the speed of light in a given substance with respect to the speed of light in air, a ratio known as refractive index, mathematically represented by the letter n, that gives information about the composition or purity of the medium. Several optical refractometric platforms exist [2,3]. Those based on fiber gratings can be obtained with etched FBGs [4–6] or long period gratings (LPGs) [7,8] due to the possibility of coupling light to an external medium.

Tilted fiber Bragg gratings (TFBGs) constitute an additional platform to couple light to the medium surrounding the fiber [9], featuring some advantages as keeping the fiber physical integrity and providing a high Q-factor interrogation. A TFBG is a periodic modulation of the refractive index of an optical fiber core that is slightly tilted with respect to the perpendicular to the fiber longitudinal axis. Similarly to FBGs, the part of the light that satisfies the Bragg condition gets reflected backwards when it reaches a TFBG. However, the tilt angle of the grating planes causes the coupling of a whole set of modes into the cladding of the optical fiber, each of them propagating with a corresponding effective refractive index. These modes are confined in the cladding while the total internal reflection condition is satisfied (i.e. while the refractive index of the surrounding medium is lower than the refractive index of the modes). But in the reverse case, the modes tend to couple to the external medium, producing a distinctive response on the TFBG transmitted spectrum [10], which has been used for the development of lots of different sensors [11–15].

Another feature of TFBGs is their ability to excite a surface Plasmon wave when being coated with a thin metallic film. A surface Plasmon is a collective oscillation of electrons at the interface between a metal and a dielectric, widely studied in the well-known Krestchmann prism configuration [16]. In the case of TFBGs,

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when properly polarized modes propagating through the fiber cladding reach the metal coating, some of them are propagated to the surrounding medium and this propagation can be appreciated on the transmitted spectrum as a characteristic surface Plasmon resonance (SPR) signature [17]. Due to the optical properties of biological tissues in terms of refractive index [18] and to the high sensitivity obtained with these configurations, plasmonic TFBG sensors have been specially applied for biosensing applications [19,20].

The change in the transmitted spectrum due to a change in the refractive index of the medium surrounding a plasmonic TFBG sensor can be demodulated by different means. The tracking of the wavelength shift of the most sensitive cladding mode or the interrogation based on the polarization properties of the sensor are techniques that have proven to exhibit high sensitivity and resolution [21]. However, they both rely on spectral measurements (most often over a wavelength range of a few tens of nanometers) that imply the use of quite expensive and cumbersome optical equipment. As this can be a handicap when using these sensors in practical situations such as in clinical settings [22], the aim of this work is to study cost-effective configurations to interrogate plasmonic TFBG biosensors. The shift exhibited by the cladding mode resonances implies that at a fixed wavelength the optical power also changes as a function of the external refractive index. That is why the following interrogation setups will be based on optical power measurements, which will allow to significantly reduce the cost of the required equipment.

2. Study into the modes behavior

To start analyzing the response of plamonic TFBG sensors in terms of the optical variation in their modes, several samples were produced and a special attention was paid to obtain good conditions for surface Plasmon excitation by measuring their transmitted spectrum. As the centerpieces of the sensors, TFBGs were photo-inscribed in the core of a hydrogen-loaded PS-1250 photosensitive optical fiber from FiberCore. Light emitted by a continuous-wave (CW) frequency-doubled fiber laser at 244 nm was properly guided to reach a 1063 nm pitch silica phase-mask. Given the period of the phase-mask, a tilt angle of 6° for the grating planes was chosen. In doing so, it was possible to get a Plasmon signature in the spectral region around 1550 nm when immersing the sensor in aqueous media exhibiting similar refractive index values to the ones of biological tissues. On the photo-inscription setup, the phase-mask was tilted within the plane perpendicular to the laser beam to obtain the aforementioned angle. The TFBGs were then introduced in an oven set to 85 °C for about 18 h to remove the residual hydrogen molecules still present in the fiber and after that, a gold coating with a thickness of 50 nm was deposited by a sputtering process [23].

The sensors were immersed into a solution to perform the first characterization shown in Fig. 1A, obtained by interrogating them in transmission with an optical vector analyzer (OVA). Between the optical source and the sensor, a polarizer was introduced to select a radial (P) polarization and thus be able to excite a surface Plasmon resonance at the interface between the gold and the surrounding dielectric medium [24]. The arrows in the figure point to the regions of interest for the present study. Beginning from the right, the Bragg mode is the one that propagates confined in the core of the optical fiber, also known as core mode and that can serve as a temperature reference for spectral measurements. Next to it the ghost mode is the cladding mode featuring the highest effective refractive index and the entire resonance comb located on the lower part of the spectrum propagate along the fiber cladding. The SPR excitation involves a characteristic signature that is also highlighted and that is produced by the set of cladding modes that satisfy the conditions to be transferred to the outer medium as an evanescent wave. Finally, the rest of the cladding modes remain confined into the fiber cladding due to their reflection against the gold film. The modes that exhibit the highest sensitivity for refractive index sensing are the ones located near the SPR signature on the left part of the spectrum. Following the convention implemented on previous studies [17], these modes are numbered taking the one with the highest peak-to-peak amplitude as the “mode 0” and subsequently assigning incremental indices towards the right. The analysis of the modes behavior will be carried out on the modes ranging from the indices +1 and +7, both included.

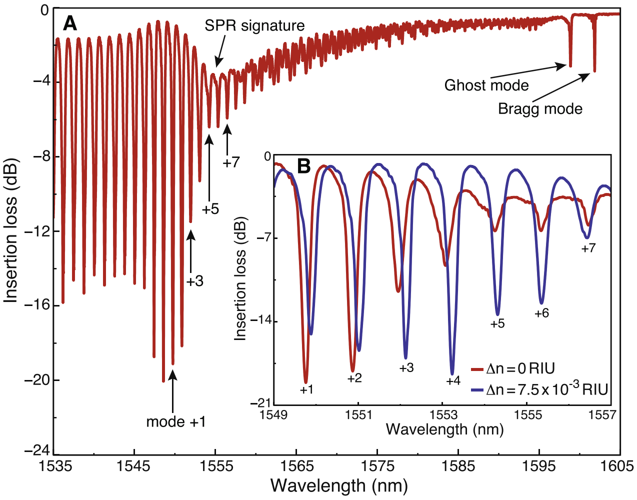

Fig. 1. (A) Transmitted spectrum of a gold-coated TFBG immersed in solution with arrows pointing to its resonances of interest and (B) wavelength shift due to a variation in the surrounding refractive index.

The refractive index of the solution in which the sensors were immersed was increased by 7.5×10^{-3} refractive index unit (RIU) in a controlled manner and the spectra before and after this modification can be seen in Fig. 1B. The wavelength shift of the modes can be easily appreciated and at the same time a difference in insertion loss occurs at fixed wavelengths. Thus, the most relevant information comes from studying the evolution of the optical power along the whole refractive index range. To do so, the previously used broadband source was substituted by a tunable laser source (TLS) set to emit at the specific wavelengths of the cladding modes of interest [25]. The optical detector consisted of a photodiode and the refractive index of the solution was measured by a digital refractometer with a resolution of 10^{-4} RIU. With this schema, the corresponding cladding mode modulates the optical power from the source in a similar way as in edge filtering interrogation [26–30]. As a result, a graphical evolution of the optical power of the seven modes can be obtained, as depicted in Fig. 2. It is worth mentioning that the optical power changes do not correspond to the optical power differences of the modes peaks, but to the actual difference at fixed wavelengths, due to the nature of the TLS. According to the graph, it is easy to determine that the evolution of the transmitted power is not linear but follows the characteristic shape of a negative sigmoid function. This means that the response can be considered linear but just in reduced refractive index regions. In other words, for each refractive index region a different mode should be chosen in order to perform a linear refractometric measurement. As an example, the“mode + 2” exhibits a linear behavior for relative increments until 1.5×10^{-3} RIU but it is clear that this mode is not appropriate at all to measure changes higher than 4.5×10^{-3} RIU.

The investigated refractive index relative variation was divided into five different increments of 1.5×10^{-3} RIU and a numerical