Interrogation technique for plasmonic optical fiber biosensors using orthogonal cladding modes

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Tilted fiber Bragg gratings covered by a nanoscale layer of gold allow the generation of surface Plasmon resonances, which are strongly dependent on the polarization state of the transmission light. This dependency can be advantageously used to demodulate the amplitude spectrum and retrieve the surrounding refractive index (SRI). We present an automated demodulation technique that measures the SRI by comparing the differential amplitude of resonance peaks near the plasmon attenuation for two orthogonal amplitude spectra. A mean sensitivity of more than 500 nm per refractive index unit is reported. This SPR platform is used to characterize and quantify macromolecular interactions based on the affinity avidin/biotin.

Introduction

Tilted fiber Bragg grating (TFBG) transmission spectra are characterized by both a core-mode resonance called the Bragg wavelength (λ_{Bragg}) and several cladding-mode resonances. Thanks to a nano-scale gold coating deposited on the TFBG, the generation of surface plasmon resonances (SPRs) was demonstrated for accurate refractometric purposes [1]. Indeed, the cladding modes have non zero evanescent fields extending outside the cladding and hence into the metal film. There is a transfer of energy to a plasmon wave across the metallic surface if the effective refractive index and the polarization state of the cladding modes are equal to those of the plasmon wave. Light polarization plays a crucial role not only in the generation of SPRs but also in the subsequent amplitude spectrum demodulation [2]. Today, we know that the use of two particular orthogonal polarization light states (maximizing and minimizing the SPR signature in the amplitude spectrum) automates the demodulation technique and improves its sensitivity to the surrounding refractive index (SRI). In [3], the unique signature of the TFBG polarization dependent loss (PDL) spectrum was exploited. We propose here a complementary methodology that computes the difference between corresponding resonance peaks of both orthogonal amplitude spectra [4].

Experiments and Results

For our experiments, we use the set-up presented in Fig.1(a). The sensor is composed of a 1 cm-long TFBG characterized by an internal tilt angle equal to 10° and written into hydrogen-loaded singlemode fiber using a pulsed excimer laser emiting at 248 nm. The TFBG is covered by a 50 nm gold coating deposited by a sputtering process to create a TFBG-SPR refractometer.

The amplitude spectrum of the TFBG is collected by an optical vector analyzer (OVA) from *Luna Technologies* offering a measurement resolution of 1.25 pm. A linear polarizer

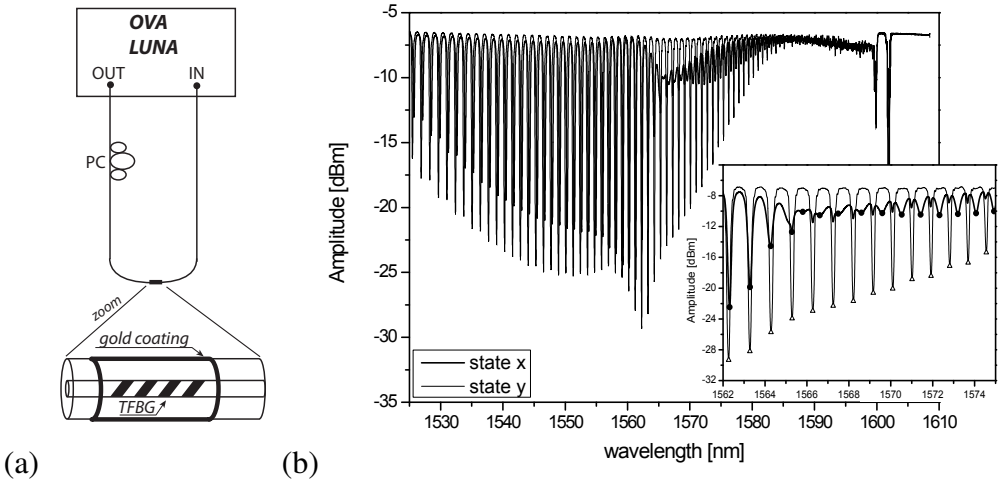

Figure 1: (a) Sketch of the demodulation technique used to interrogate SPR sensors. (b) Orthogonal transmitted amplitude spectra with SPR signature maximized (state x) and minimized (state y) for the refractive index of ~ 1.39 (n_{ref}) and zoom on the plasmon resonance.

is placed between the OVA optical source (OUT) and the TFBG-SPR sensor to modify the polarization state of the incident light launched into the refractometer. The TFBG-SPR sensor was immersed in a water-salt mixture that we dilute during the experiment to modify its refractive index. The changes in SRI value are calculated on the basis of the added volume and the temperature of the mixture with an accuracy of 0.1 ml and 0.1 °C respectively. By consequence, we obtain a nominal refractive index uncertainty equal to 1.2×10^{-5} RIU.

With this set-up, we are able to change the light states and we obtain both specific orthogonal amplitude spectra required for the demodulation step. These two orthogonal states of polarization are the ones for which the SPR is maximized (polarization state x) and minimized (polarization state y). An example is given in Fig.1(b). An algorithm has been implemented to automatically detect the cladding mode resonances in both spectra. The resonance peaks detected in the x and y amplitude spectra are respectively indicated by dots and triangles in the inset of Fig.1(b). From this detection, we compute the differential wavelength ($\Delta\lambda_{x,y}$) and amplitude ($\Delta A_{x,y}$) between two corresponding minima of the x and y amplitude spectra (a dot and a neighbouring triangle). The computational results are given as a function of the wavelength and for different SRI values in Fig. 2.

The differential wavelength evolution is discontinuous near the SPR. The position of the discontinuity reflects the SPR signature, so it changes with SRI. For an SRI variation of 10^{-2}, we get a total shift of ~ 5 nm. However, this shift is not linear because there is a superposition of several differential wavelength curves obtained for different SRI changes of the order of 10^{-3}. This particular behaviour could be attributed to the fact that resonances at the SPR peak are too attenuated and broadened to allow a measurement of the resonance position that has the necessary accuracy to resolve picometer level wavelength shifts as previously indicated in some of early experimental investigations [2,3]. By consequence, we are not able to retrieve the surrounding refractive index with an efficient accuracy using only $\Delta\lambda_{x,y}$. In contrast, the differential amplitude curves shift linearly and smoothly with the SRI. For an SRI variation of 10^{-2}, we observe a total shift of about 6 nm. Fig. 3(a) is a zoom on the evolution of $\Delta A_{x,y}$ for different SRI changes around

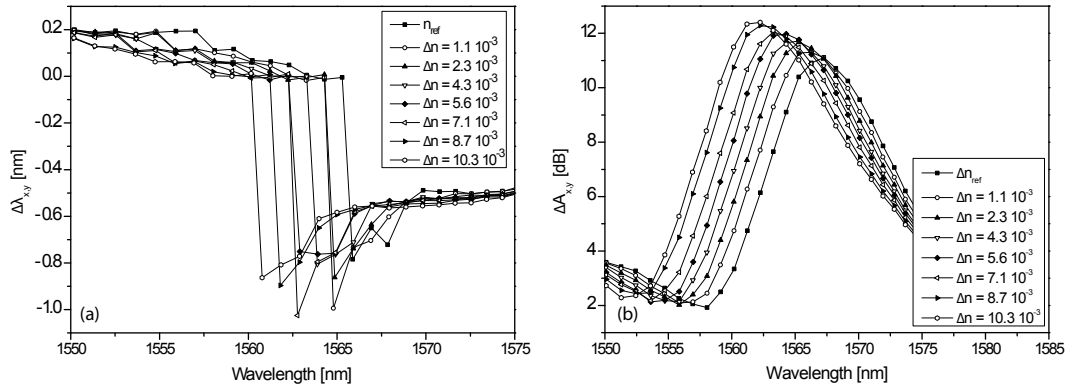

Figure 2: Differential wavelength (a) and differential amplitude (b) of corresponding cladding mode resonances for two orthogonal polarization states as a function of the wavelength.

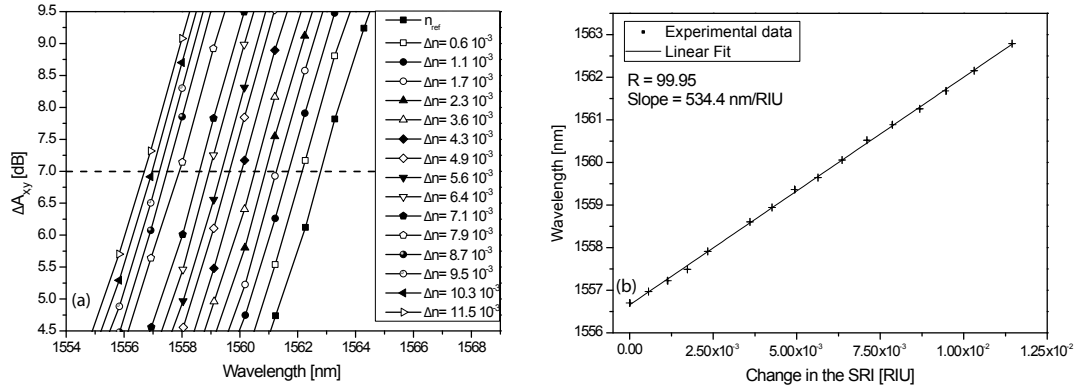

Figure 3: (a) Evolution of $\Delta A_{x,y}$ around 1560 nm as a function of the SRI (Δn) and its detection threshold ($\Delta A_{x,y}$ = 7 dB).(b) Wavelength shift of $\Delta A_{x,y}$ as a function of the SRI (Δn) with threshold $\Delta A_{x,y}$ = 7 dB.

1560 nm. To retrieve SRI, we track the wavelength for which $\Delta A_{x,y}$ is equal to 7 dB (value in the middle of the transition zone). These corresponding wavelengths are presented as a function of SRI changes in Fig. 3(b). The response is linear and the mean SRI sensitivity is of 534 nm/RIU (refractive index unit) with a high correlation (99.95%). Other detection thresholds from 4.5 dB to 9.5 dB were tested and gave similar SRI sensitivity comprised in a range of about 538 nm/RIU $\pm$ 4 nm/RIU. The vertical deviations from each data point to the fitted line are measured to define the root mean square (rms) of the error on the wavelength and thus define the SRI uncertainty. The results give an rms refractive index uncertainty of 5×10^{-5}. The measurement errors on the SRI (1.2×10^{-5}) and on the wavelength (1.25 pm) are reported in Fig. 3(b) but do not appear clearly because the errors are very small in comparison to the full range of SRI.

The possibility of automation, thanks to the algorithm developed to treat the raw data, remains the main feature of this demodulation technique, with the added benefit that a single algorithm is used to identify both the absolute value of the SRI over a wide range (1.32 - 1.39 RIU) and very small changes around that value. To improve further the degree of automation and so the processing speed, a modification of the set-up described could be to use a polarizing beam splitter (PBS) and a two port detector behind the SPR sensor.

In doing so, we would be able to collect rapidly both orthogonal amplitude spectra and to obtain the deduced SRI in less than a few seconds.

Affinity Biotin/Avidin

In addition to bulk refractometry, we have tested the SPR-TFBG sensor for detection of biomolecular interactions like in [5]. For this purpose, we have used the strong affinity between the biotin/avidin couple (dissociation constant $K_d \cong 10^{-15}M$). In a first step, biotin was grafted on the gold-coating by covalent bond. Then, the grating was immersed in PBS (phosphate buffer solution). In Fig.4, we compare the SPR signature, before and after being in contact with avidin solution (avidin in PBS, 25 μg/ml). As we can see, the interaction between biotin and avidin impacts the transmitted spectrum of TFBG around the SPR signature. There is a pronounced decrease of the amplitude of the peaks (3 dB for the peak indicated by an arrow) especially at wavelengths below 1532 nm. This preliminary result confirms that the developped sensing platform can be used for biodetection.

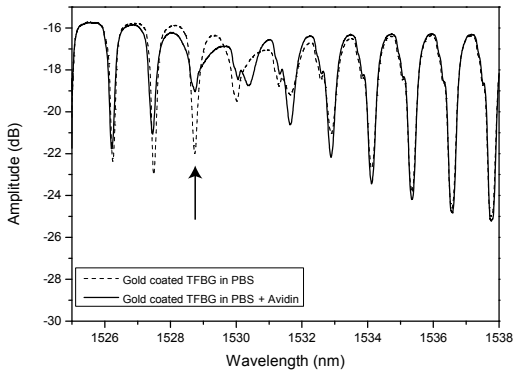

Figure 4: Comparison of the transmitted spectrum before and after biotin/avidin interactions.

Conclusions

In this paper, we have demonstrated the operating principle of an automated demodulation technique for a TFBG-SPR refractometer. The SRI value is deduced from the differential amplitude of corresponding resonance peaks near the plasmon attenuation for two orthogonal amplitude spectra. The method is automated, easy to implement and provides an absolute measurement of SRI over a full range of 1.32 to 1.39 RIU with a demonstrated uncertainty of at least 5×10^{-5}. Finally, we demonstrated the detection of biomolecular interactions thanks to a biotin/avidin system.

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