Fibre Bragg Gratings as Interrogation Elements for Surface Plasmon Resonance Sensors

N. Díaz-Herrera[1], D. Viegas[2,3], P.A.S. Jorge[3], M.C. Navarrete[4], L.A. Ferreira[3], F.M. Araújo[3], J.L. Santos[2,3], A. González-Cano[1]

[1] Departamento de Óptica. Escuela Universitaria de Óptica. Universidad Complutense. Arcos de Jalón 118. 28037 Madrid. Phone: + 34 91 394 5010. E-mail: ndiazher@fis.ucm.es
[2] Department of Physics. FCUP, Rua do Campo Alegre 687, 4169-007 Porto, Portugal.
[3] INESC Porto, Rua do Campo Alegre 687, 4169-007 Porto, Portugal.
[4] Departamento de Óptica. Facultad de CC. Físicas. Universidad Complutense. Ciudad Universitaria s/n. 28040 Madrid.

ABSTRACT

A new interrogation method based on Fibre Bragg Gratings (FBG) for Surface Plamon Resonance (SPR) sensors in the region of refractive indices of aqueous solutions is described. Two FBGs are selected with their Bragg wavelengths at opposite sides of the plasmon resonance peak. The response of the system can be made independent of the fluctuations of the optical power source, and the linearity and the sensitivity of the sensor are improved. The use of the spectral selectivity of gratings for the interrogation of SPR sensors in different configurations is also promising in terms of multiplexing, temperature referencing or multiparameter detection.

Key Words: Fibre-optics sensors, Fibre Bragg Gratings, Surface Plasmon Resonance, Refractometer.

INTRODUCTION

The importance of Surface Plasmon Resonance fibre optic sensors in the field of chemical, biological and environmental sensing has notably increased in the last years, and many different configurations and analytes have been studied in the literature. [1, 2] However, the exigent requirements of this kind of systems impose the necessity of improving the performance of the existing sensors to fully exploit the advantages of optical fibres for these measurements.

One of the best options to improve sensitivity is to use interferometric interrogation schemes. However, this approach requires more complex setups and a careful control of polarization [3, 4]. Alternatively, the high spectral selectivity of the Fibre Bragg Gratings can be applied in a new interrogation scheme that uses in a more efficient way the spectral information provided by the plasmonic transducers. In this scheme, not only the displacement of the plasmon resonance wavelength is used for the measurements, but also the variations in the power associated to different wavelengths, conveniently chosen to provide a linear response, independent of the fluctuations of the optical power source.

Although both SPR and FBG are concepts of great interest in the fields of fibre optic sensors [5], there are not many studies in which they are combined to multiply their potentialities. To demonstrate this new concept SPR transducers based on DL-UWTs (doubly deposited uniform-waist tapered optical fibres) have been used. We have been working in the last years in this kind of elements, that have proved to be very simple, versatile, powerful alternatives to the existing SPR systems. [6, 7] In this work, DL-UWTs have been combined with standard FBG elements to implement a new self-referenced interrogation scheme for SPR based sensors.

SENSOR CONCEPT AND EXPERIMENTAL SET-UP

Two FBGs, used in series with a DL-UWT element, were selected in order to have their Bragg wavelengths in opposite sides of the SPR resonance wavelength. For this resonance a well-defined minimum is observed in the transmittance curve. When the external refractive index varies, this minimum moves to higher values of wavelength.

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This displacement of the transmittance curve also produces a change in the reflected power of the FBGs. Once the shape and behaviour of the SPR minimum is characterized, the refractive index value can be obtained from the variation of the reflected power of the FBGs.

To test this concept, several DL-UWTs were fabricated by depositing in a tapered fibre a double layer asymmetrically, an Aluminium layer 8 nm thick and a Titanium Dioxide layer 45 to 47 nm thick, in a vacuum chamber by sputtering, and fixing them to a glass support with waterproof glue, Araldite epoxy. These DL-UWTs presented a surface plasmon resonance at around 800 nm and were tested previously to determine the shape of the resonance curve and the exact position of the minimum in order to select those with spectral characteristics that better fitted the existing interrogation elements. The FBGs fabricated had their Bragg wavelengths at 809.986 nm and at 834.62 nm.

The DL-UWTs were tested by two methods simultaneously, considering the scheme shown in Fig.1. As we registered at the same time the displacement of the SPR minimum and the variation of the power reflected by the two FBGs, this configuration allowed us to make an exhaustive characterization of the phenomenon. In a real application, however, the SPR sensor followed by the two FBGs can be located remotely, the spectrometer is not necessary and the OSA can be replaced by simple detectors, which is very convenient for this kind of measurements.

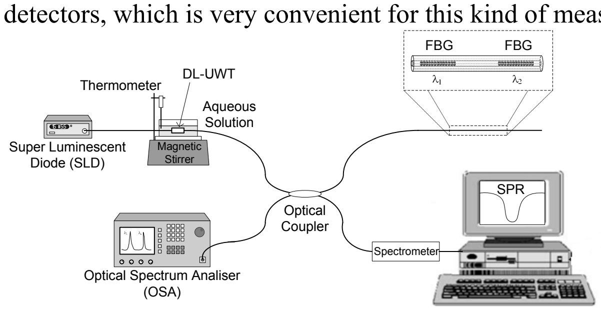


Figure 1: Scheme of the experimental set-up.

The optical power source was a superluminiscent diode (SLD) emitting partially polarized light around 800 nm with a FWHM around 100 nm, directly connected to the sensor. At the output the DL-UWT was connected to a directional coupler. One of the outputs of the coupler was connected to the FBGs, and the other one to an Avantes spectrometer (AvaSpec 2048-2) to register the SPR variation. The optical power reflected by the two FBGs was registered by an Optical Spectrum Analyser (Ando AQ 6315B).

The DL-UWTs sensors are polarization dependent but it has been shown that this dependence is not critical due to the non-flatness of the deposits so it is possible to carry out the measurements with acceptable results using this simple set-up as the sensitivity is the same with or without the presence of polarization-controlling elements (although more accurate measurements can be carried out including an in-line polarizer). [8]

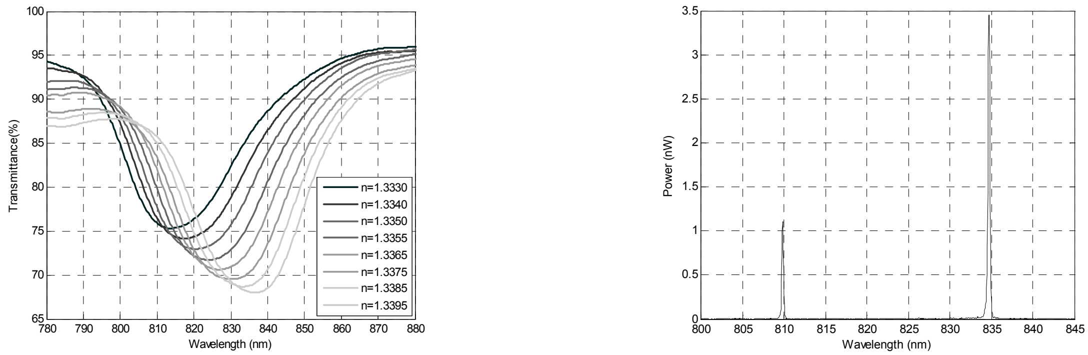
EXPERIMENTAL RESULTS

To carry out the tests, the sensors were immersed in a mixture of ethylene glycol and water whose refractive index was varied from 1.333 to 1.35 and was measured by an Abbe refractometer. For each variation the transmittance of the SPR, and the power reflected by the two FBGs was simultaneously measured. The results obtained can be seen in figure 2. Fig. 2a shows the behaviour obtained (spectral transmittance for several values of outer refractive index) for these DL-UWTs. As expected a well defined minimum that moves towards higher wavelengths as refractive index increases, can be observed. It can be seen that the SPR minimum is located between the Bragg wavelengths of the two FBGs. In the usual method of interrogation of these sensors, the movement of the dip wavelength is tracked, and it can be fitted to a linear function. In Fig.2b the data registered by the OSA for the reflected power of the FBGs for the case where n=1.333 is shown. The FBGs select two narrow slices of the spectrum where the reflected power depends on the resonance position and thus on refractive index. The refractive index information on the FBGs output can then be retrieved, independently of optical power drifts, by considering the normalized power, given by:

$$P_{norm} = \frac{P_1 - P_2}{P_1 + P_2}$$

where P_1 and P_2 are the reflected power values for the two FBGs. The variation of this normalized power as a function of external refractive index can be seen in Fig. 3a. In order to see the effect of the optical power level, two tests were carried out for two different amounts of light inserted in the fibre by means of the inclusion of a piece of glass between source and fibre that differed in 8 %. The dependence is not linear but the behaviour is very stable and a polynomial function can be used as calibration curve to obtain the refractive index value from the data of the FBGs. The two curves are coincident, being the largest difference around 0.05 % so in fact the results are independent of the power fluctuations, which is a really interesting feature for field application.

It should be pointed out that the Bragg wavelengths of the FBGs chosen affect the shape of the normalized power curve. In that sense it is possible to optimize the set of FBGs to simplify the analysis. We are working in the adaptation of algorithms to automatically determine the optimal wavelengths to be chosen. In this particular case, for instance, if the FBG at 809.986 nm is maintained but the other is shifted to 850.08 nm, the resulting curve is shown in Fig. 3b. In



this case the behaviour is linear and again the difference between both of them is less than 0.05 %.

Figure 2: (a) Variation of the wavelength of the SPR minimum when the refractive index of the external medium changes; (b) Spectrum of the optical power returned from the sensing head for water as external medium.

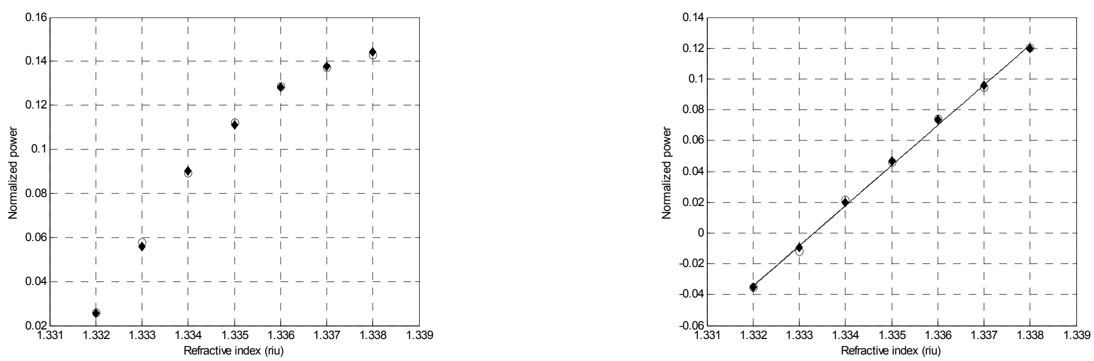


Figure 3: Variation of the normalized signal as a function of the refractive index of the external medium for two distinct emitted powers of the optical source considering two pairs of FBGs with different wavelengths (the circles correspond to the higher value of the source power and the solid diamonds to the lower one).

A final test was carried out to investigate the resolution achieved with this method. Ten measurements were registered for each refractive index value using one single FBG and for several values of the refractive index (see Fig.4). So the dispersion on the value of the maxima for a single value of refractive index together with the known steps permits to calculate the resolution of the sensor as:

$$\frac{\delta n}{\left(\dfrac{\Delta P_{res}}{\delta P_{noise}}\right)}$$

where δn is the refractive index variation, ΔP_{res} is the power variation that corresponds to that index variation and δP_{noise} is the standard deviation of the power for the ten measurements at each refractive index value.

The value of the resolution varies slightly from one step to the other, due to the non uniformity in the shape of the transmittance curve, values between $2 \cdot 10^{-5}$ to $9 \cdot 10^{-5}$ were obtained. This reveals again the importance of choosing an optimum set of FBGs because when they are confined in the region of the SPR curve in which the shape can be fitted to a linear function the resolution achieved can be as good as $2\cdot10^{-5}$. In any case, this result comprises an improvement of an order of magnitude with respect to the obtained with the traditional interrogation method.

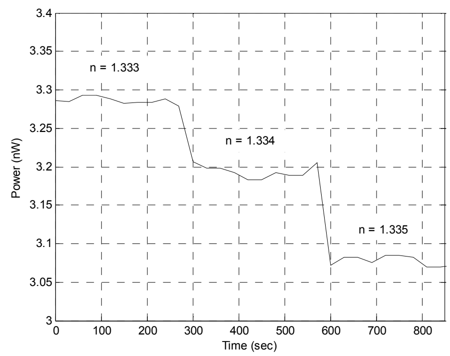


Figure 4: Variation of the FBG reflected power as a function of time for three different values of the refractive index.

CONCLUSIONS

We have presented a new interrogation scheme based on FBG as interrogation elements for a refractometric SPR sensor for aqueous solutions. It is shown that registering the normalized output from the reflected power of two FBGs chosen for having the SPR minimum between their Bragg wavelengths, it is possible to determine the refractive index of the external medium independently of power source fluctuations resulting in a more reliable data. The sensitivity and resolution achieved in this case is also an improvement compared with the ones obtained with the traditional method. This method is able to be extended to any SPR sensor configuration.

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