Sensors and Actuators B 268 (2018) 150–156

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Signal processing in SPR fiber sensors: Some remarks and a new method

E. Rodríguez-Schwendtner [a], A. González-Cano [b,*], N. Díaz-Herrera [b], M.C. Navarrete [c], Ó. Esteban [a]

[a] Photonics Engineering Group, Universidad de Alcalá, Alcalá de Henares, 28871 Madrid, Spain
[b] Applied Optics Complutense Group, Facultad de Óptica y Optometría, Universidad Complutense, Av. Arcos de Jalón 118, 28037 Madrid, Spain
[c] Applied Optics Complutense Group, Facultad de CC Físicas, Universidad Complutense, Ciudad Universitaria s/n, 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 19 July 2017
Received in revised form 19 March 2018
Accepted 16 April 2018
Available online 22 April 2018

Keywords:
Optical fiber
Surface Plasmon Resonance
Fiber-optic sensors
Signal processing

ABSTRACT

The importance of Surface Plasmon Resonance (SPR)-based devices in the field of chemical and biological sensing and the expectations created in terms of sensitivity and resolution impose the necessity of developing an adequate methodology for the processing of the signals obtained and for the evaluation of the performance of the sensing systems. We discuss in depth and clarify the problem of the analysis of data acquiring and processing in SPR fiber sensors, show how in many cases this analysis could and must be improved and propose a new method of SPR curve shaping, apt for sensors encapsulated or inaccesible. We illustrate the use of the method with real experimental examples.

1. Introduction

There is no longer need of remembering how important and ubiquitous SPR-based devices have become in many fields, but especially in chemical and biological sensing. The performance of these systems is so remarkable in terms of sensitivity and resolution that SPR spectroscopy has established itself as a reference technique in these fields [1,2]. Usually, the mechanism for the excitation of surface plasmon is attenuated total reflection (ATR) in the so-called Kretschmann configuration [3], for which angular interrogation is the most common measurement method. Fiber-optic SPR sensors offer quite evident advantages compared to Kretschmann configuration, which requires mobile parts and bulky arrangements, while fibers provide accesibility to far regions for remote sensing, more compact and versatile sensors, possibility of multiplexing, etc. For those reasons, in the last decades many SPR-based fiber sensors, spectrally interrogated, have been proposed and tested [4,5].

All those systems follow, with little variations, a basic scheme: an experimental arrangement (optical and eventually mechanic) provides a light beam apt to fulfill the phase-matching conditions necessary to excite a surface plasma wave in the interface between a metallic and a dielectric medium. This is a resonant mechanism that implies a very efficient absorption of the incident light. Light collected from the sensing region shows, then, a well-defined dip in the transmission curve. This is what we usually identify as “a plasmon”, and in most cases what we measure is the displacement of that minimum when the conditions are changed, usually by changing the refractive index of the outer medium. SPR sensors are, then, primarily refractometers. They become chemical sensors or biosensors when we associate the change in the refractive index of the medium in the near proximity of the sensing region to the presence or the variation of the concentration of the analyte by the introduction of some recognizing agents attached to that region that react to that analyte [6,7].

Having been proven so many times the extremely good performance of the systems that follow that scheme, one might think that nothing more is to be said about the problem of the acquiring and processing of data. But, as we will show in this paper, this is a rather delicate matter and must be discussed carefully, especially when optical fibers are used. Somehow SPR sensors are so well-known that what we usually find in the papers nowadays are only sophisticated developments of the above depicted standard scheme or fine details on the particular transduction process for a given analyte. In general we find little information about the exact experimental procedures and in many papers the authors directly deal with the SPR curves.

* Corresponding author.
E-mail address: agugonza@ucm.es (A. González-Cano).

https://doi.org/10.1016/j.snb.2018.04.083
0925-4005/

At the same time, we find many non-experimental papers in which the authors perform numerous simulations starting from that "canonical" scheme, generally with quasi-geometrical, matricial methods, and assuming perfect conditions in the surfaces or the deposited materials. In this way, they produce figures for the resolution and sensitivity of the systems that are very far from those which can be really reached in real systems [8,9]. In almost all these simulations the authors directly compute "transmittance" o "reflectance", which are, as we will show later, rather objectable concepts when dealing with real world sensors, so the problem of the comparison between theoretical predictions and experimental results becomes complicated.

Finally, there exist some sensors for which the standard processing scheme is directly impossible, because the normalization or referencing process implicit in the SPR curve shaping cannot be performed, the sensor being encapsulated, inaccesible, etc.

For all those reasons, we propose in this paper, first, an in-depth discussion on signal processing in SPR sensors and the establishment of the procedures involved in the usual protocols, frequently implicit, and then a new, alternative method of SPR curve shaping, especifically apt for what we may call "closed" fiber sensors, based on evanescent field coupling, for which it is almost the only realistic possibility.

2. An analysis of signal processing in SPR sensors

2.1. Standard protocol for ATR-based systems

When we are dealing with Kretschmann configuration, light travels from the source and through the prism to the interface where a metal layer is deposited. Gratings are sometimes used, but it makes no difference for the following discussion. In any case, no waveguides are used. The angle of incidence of the beam on the metal layer is varied and the reflected light is collected, again with no waveguide involved. This is called angular interrogation and plasmons reveal themselves as minima of reflectance. The only possibility of exciting a plasmon is with a TM polarized beam, so many authors proposed as a way of normalizing the output signal to divide this signal by the output obtained with TE polarization, for which no plasmon should be excited [10].

This implies that, added to the elements that permit the rotation of the beam, we need to incorporate operable polarization controlling elements, so that each measurement is twofold and sequential. Assuming that the "no-plasmon" output signal thus obtained is basically equivalent to the input signal on the metallic surface deposited on the prism (that is, the light coming from the source through the free propagation of the beam within the prism), these authors compute a so-called "reflectance" as the quotient from the two ouput signals (plasmon/no plasmon). This is the way they obtain an "SPR curve", a curve in which plasmons are represented as well-defined *dips*. These dips move when the refractive index of the outer medium in contact with the metallic layer is changed. It is this SPR curve that we are usually presented with, and the emphasis is then placed in the extraction of the information of the refractive index starting from that SPR curve, and the way that this variation of the index can be related to the presence or concentration of given analytes [11].

In other situations, the "no-plasmon" condition can be achieved by taking a reference measurement (usually called "air reference"), with the system not exposed to the liquids in the range of refractive indices able to excite plasmons. In those cases, the reference is commonly taken only once, at the beginning of the series of variations of the index in the characterization process. Of course, it is not necessary that we literally have "air" as the outer medium: any medium with a refractive index outside the region for which the particular configuration of layers employed is the right one to excite plasmons will do.

Some authors, starting from this "standard" protocol, have analysed the potential contributions of several noise sources to the resolution of the system, concentrating themselves in the noises in the detector, mostly [12]. In general, an averaging process is routinely performed in the detector, as well as a "dark signal" subtraction, so a smoothing of the output signal curve is always present, and not necessarily declared, before any normalization is made.

Also, as it can be seen from our previous discussion, the sequential nature inherent to the referencing procedure, especially when only one reference signal is measured at the beginning, implies that any subsequent variation in the input power is not taken into account. The possibility of an inaccurate polarization change in the incident beam when taking a TE reference, or any misadjustments or misalignments are also an issue, for we cannot always assume that these are just compensated by the normalization. All these facts are most relevant when determining the resolution and the sensitivity of the sensors, making any comparison with the "optimistic" simulations of the literature really difficult.

2.2. Spectral interrogation in optical fiber sensors

Angular interrogation is not the only option in SPR sensors, and intensity or phase measurements can be considered. However, when using optical fiber sensors, where we cannot manipulate the angle of incidence, spectral interrogation (which is also used sometimes in Kretschmann configuration) is by far the most common technique. A major difference between Kretschmann configuration and fiber sensors is, obviously, the use of waveguides. This is advantageous from many points of view, as shown in many occasions, especially for the possibility of remote sensing, but complicates the analysis of the measurement and signal processing.

In the first place, TE referencing is no longer a possibility, especially when realistic lengths of fiber are considered. We can, of course, inject in the fiber a given polarization, but in general we cannot keep that polarization unless the fiber is perfectly straight all the way down to the sensing region and then to the spectrometer. We can use a polarization-maintaining fiber and introduce polarization controlling elements, but this overcomplicates a fiber sensor of this kind. Also, in many SPR fiber sensors (namely, those based on tapered and etched fibers) we have no longer a well-defined polarization plane, being the transducing region curve. We have shown in the past how we can even eliminate all polarization dependence by a 360° deposit on a taper [13].

We are then obliged to "air" referencing, that is, to take a first measure in "no-plasmon" condition, with the sensor exposed to an outer medium whose refractive index is not in the appropriate range to excite plasmons. This reference signal is no longer equivalent to the "input" signal: it is a kind of "zero" signal depending on the transmission of light through the whole fiber path. The spectrum of the light incident on the sensing region is not exactly the source spectrum, because light has traveled within the fiber, which has its own transmission window and acts as a filter. Then, light must go through the sensing region. We are dealing with "closed sensors", so, even if no plasmon is excited, light passes through the taper or the etched area and reflects itself on the deposited layers, etc. Then, again, lights travel through the collecting part of the system until the spectrometer.

As we can see, there are many factors, not only the power fluctuations of the source, that can influence this zero-signal. Also, in general, sequential measurements are made and the zero-signal is only taken at the beginning. All this must be taken into account when evaluating the performance of the sensors in terms of limits of resolution.