Analysis of a fibre-optic sensor design based on SPR in nanowire metamaterial films

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ABSTRACT

This paper investigates numerically the performance of a design for an optical sensor of the refractive index of gases and liquids based on smart or functional metamaterial films (smart optical metamembranes).

Keywords: Optical metamaterials, optical metamembranes, nanowires, surface plasmon resonance, fibre-optic sensors.

1. INTRODUCTION

Surface plasmon resonance (SPR) constitutes one of the most sensitive principles used in optical sensors to measure the refractive index of gases and liquids, being able to achieve resolutions down to 10^{-7} RIU.[1] Typically, SPR sensors are based on one of two designs, the Kretschmann and Otto geometries.[2,3] In particular, the Kretschmann configuration has been adapted to fibre-optic sensors by depositing a thin metallic film on a tapered or side-polished fibre.[4,5]

These sensors are based on the possibility of exciting surface plasmon-polaritons (SPPs) on the interface between a thin metallic film and the dielectric medium being measured. At specific wavelengths, which depend on the refractive index of the gas or liquid, the light in the fibre couples to SPPs and is tunneled through the metallic film escaping from the fibre, rendering the metal transparent in practice. This physical process translates into increased losses in the power propagating in the fibre, resulting in the reduction of the transmission coefficient of the sensing section of the fibre. These metallic thin films work as optical membranes, which selectively reflect or transmit certain wavelengths. However, the SPPs require special conditions to be excited. First, the metal must have a negative dielectric constant at those wavelengths and second, the electric field of the light inside the fibre must have a component perpendicular to the surface of the metallic film. As the result of these constraints, the development of this kind of sensors has been somewhat limited by the necessity of using the metals with adequate optical properties to finely tune the SPR to the working wavelength of the fibre and to variations of the Kretschmann sensing configuration, previously mentioned.

Optical metamaterials are artificial nanostructured materials which can exhibit exotic and tailor-made optical properties. Therefore, they constitute an opportunity for SPR sensing in the optical domain by replacing the thin metallic films with

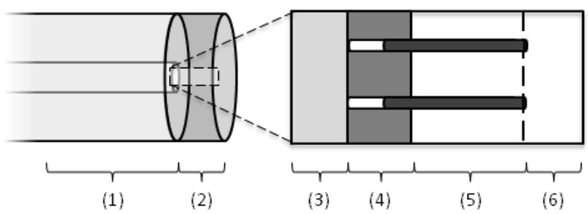

Figure 1. Scheme of the optical sensor design (left): (1) multimode optical fibre tip, and (2) smart metamembrane mounted on the tip of the optical fibre. Detail of the structure of the metamembrane (right): (3) glass corresponding to the tip of the optical fibre where the metamembrane is mounted, (4) anchoring layer comprising a porous aluminum oxide matrix partially filled with silver, (5) exposed silver nanowires embedded in the external medium, and (6) the external medium.

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an optimized metamaterial film, which can also work as an optical membrane. Also, these metamaterials can be composed of metallic nanostructures capable of supporting SPP modes and exhibit SPR even when the electromagnetic field incident on the metamaterial film does not have an electric field component perpendicular to the surface. This paves the way for new configurations of SPR fibre-optic sensors where the metamaterial film may be mounted on the cleaved tip of an optical fibre, and not only on its lateral surface. Recently, we have proposed a new type of metamaterial optical membrane constituted by metallic nanowires anchored in an aluminum oxide (Al_2O_3) matrix which, exposed to an external liquid or gaseous medium, presents an even more exciting possibility for optical sensing.[6-8] The optical response of these materials strongly depends on the optical properties of the external medium filling the space between the nanowires. As a consequence, these metamaterials constitute functional, or smart, optical membranes ("smart metamembranes") with varying or controllable optical properties. This manuscript describes part of the engineering work done in our group to incorporate this type of smart metamembrane in the design of refractometric fibre-optic sensors based on SPR. Unlike the Kretschmann configuration used in most SPR fibre sensors, which rely on the losses introduced in the fibre by the SPR on the metallic film, the configuration presented here considers a smart metamembrane mounted on the cleaved tip of an optical fibre (see Fig. 1). It is based on a judicious and careful control of the transmission, reflection and absorption of light through the interfaces between the fibre, the metamembrane, the different layers of the metamembrane and the external medium. This article is organized as follows: section 2 describes the sensor design, including the main features of the metamembrane, and present the numerical model used in the analysis of the sensor, section 3 discusses the results and section 4 presents our conclusions.

2. SENSOR DESIGN AND MODEL

The sensor is basically composed of a cleaved fibre-optic tip in which is mounted a metamembrane similar to the configuration discussed in a previous work,[7] as shown Fig. 1. This membrane can be prepared using a standard bottom-up fabrication technique where silver (Ag) is chemically electrodeposited inside a nanoporous anodic aluminum oxide (AAO) template.[8,9] The nanowires may be partially exposed using a selective chemical etching to remove part of the Al_2O_3 matrix. The resulting membrane can be described as being composed of three overlaying effective media: one layer where the pores of the alumina matrix have not been completely filled with silver and are empty (i.e. filled with air), the second where the pores are filled with silver, constituting the anchoring layer of the wires, and finally a layer composed of the exposed silver nanowires immersed in the external medium. It is necessary to adjust the characteristics of the metamembrane to allow the light shining from optical fibre to propagate through, reach the layer of exposed nanowires, and then be reflected back into the fibre. The overall reflectivity of the sensing head will be strongly dependent on the effective refractive index of the anchoring layer and the layer with the exposed nanowires. In the following section we discuss the model used to simulate the sensing operation of the proposed structure. We consider the system to be based in a multimode optical fibre which can support a wide spectral range, e.g. from 400-2200 nm.[10]
The effective permittivity of the different layers of the metamembrane was obtained from the Maxwell-Garnett model:[11]

$$\varepsilon_{eff} = \varepsilon_h \frac{1+\eta\Sigma}{1-\Sigma}, \Sigma = f_1 \frac{\varepsilon_1 - \varepsilon_h}{\varepsilon_1 + \eta\varepsilon_h} + f_2 \frac{\varepsilon_2 - \varepsilon_h}{\varepsilon_2 + \eta\varepsilon_h} \quad (1)$$

where ε_h is the dielectric constant of the host medium, $\varepsilon_{1,2}$ are the electric permittivities of the two types of inclusions, with volume filling-ratios of f_1 and $f_2 = 1 - f_1$, respectively. In addition, η is the screening factor of the inclusions which takes into account their shape and orientation with respect to the interacting electric field. In the particular case considered here, the inclusions have a cylindrical geometry and are oriented perpendicular to the electric field since we consider propagation along the cylinders, and therefore $\eta = 1$.[12] The values for the permittivities of the optical materials were fitted from experimental data taken from the literature.[13,14] The propagation of light through the optical system depicted in Fig.1 was then calculated using a transfer-matrix approach to stratified optical media. Using this technique, each layer is replaced by an equivalent homogenous slab, described by a 2×2 transfer-matrix given by (normal incidence is assumed):

$$[m_{ij}] = \begin{bmatrix} \cos(k_0 \tilde{n}_{eff} d) & -i\tilde{n}_{eff}^{-1} \sin(k_0 \tilde{n}_{eff} d) \\ -i\tilde{n}_{eff} \sin(k_0 \tilde{n}_{eff} d) & \cos(k_0 \tilde{n}_{eff} d) \end{bmatrix} \quad (2)$$

where $\tilde{n}_{eff} = n_{eff} + i\kappa_{eff} = (\varepsilon_{eff})^{1/2}$ is the (complex) effective refractive index of the layer, calculated using Eq. (1), d its thickness, and $k_0 = 2\pi/\lambda$ is the free-space wavenumber (λ is the wavelength in vacuum).

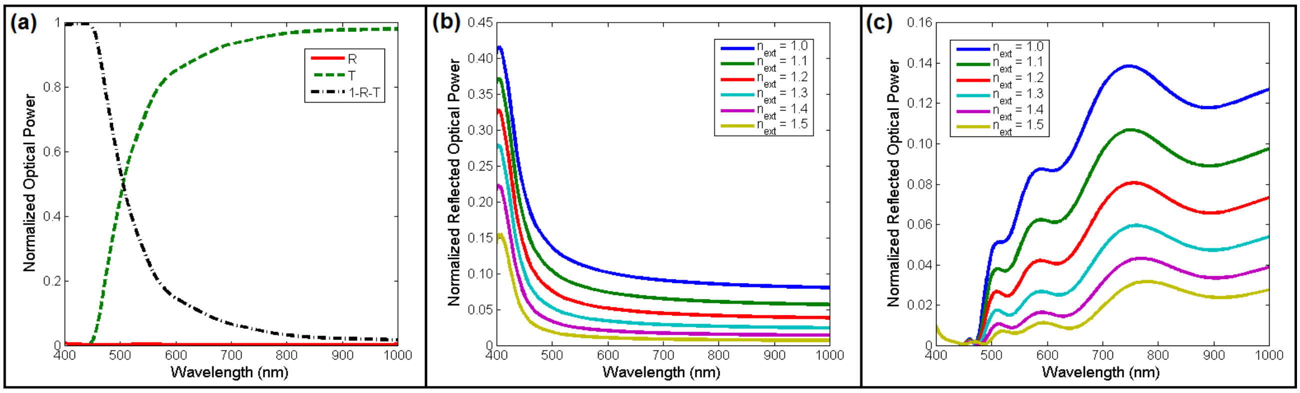

Figure 2. (a) Reflected (solid-red), transmitted (dashed-green) and absorbed (dash-dotted-black) optical power from the fibre up to the interface between the anchoring layer and the layer with exposed nanowires considering a thickness of the anchoring later of 200 nm; (b) Reflectivity of the interface with exposed nanowires for different external refractive indices; (c) Reflectivity of the overall sensing head for different values of external refractive index.

3. DISCUSSION AND RESULTS

We assume typical values for the structural parameters of the metallic nanowires produced by the techniques described in a previous work.[8] In particular, we assume a filling-ratio of $f = 0.20$, corresponding to nanowires of radius $D = 47$ nm and interwire spacing of $a = 100$ nm. The plots in Fig. 2(a) present the transmitted and absorbed optical power from the fibre up to the interface between the anchoring layer and the layer with exposed nanowires, for a thickness of the anchoring layer of 200 nm (a conservative value to guarantee a good anchoring of the nanowires). From this plot, we notice that absorption dominates for wavelengths below 600 nm, which constrains the spectral range of operation of this sensor, since no light actually reaches the exposed nanowires. Therefore, the range of operation of the potential sensor must lay in wavelengths above 600 nm. In Fig. 2(b) we present the reflectivity of the interface with exposed nanowires, for different external refractive indices. In Fig. 2(c) we show the reflectivity of the overall sensing head for different values of external refractive index, obtained from the combination of the previous results, which also shows a strong dependence on the refractive index of the external medium. This result shows that only a small percentage (up to 15%) is reflected back into the fiber however, the intensity of such signal can be strongly altered by the external medium.

In order to analyze the potential of this design for optical sensing, we introduce the parameter γ as a figure of merit, defined by $\gamma \equiv \partial \ln R / \partial \ln n_{ext} \approx (\Delta R . n_{\mathrm{ext}})/(\Delta n_{\mathrm{ext}} . R)$. This parameter corresponds to the scaling power between the reflectivity R and the refractive index of the external medium n_{ext}, say $R = (n_{\mathrm{ext}})^{\gamma}$. This implies that a change in the external refractive index Δn_{ext} results in a change of reflectivity of $\Delta R = \gamma (n_{\mathrm{ext}})^{\gamma} . (\Delta n_{\mathrm{ext}}/n_{\mathrm{ext}}) \approx \gamma (\Delta n_{\mathrm{ext}}/n_{\mathrm{ext}})$. For example, for $\gamma = 1$ we have that a change of 1% in the refractive index of the external medium results in a change off 1% in the reflectivity R, since $\Delta R = (\Delta n_{\mathrm{ext}}/n_{\mathrm{ext}})$. Whereas, for $\gamma = 10$ we have that a change of 1% in the refractive index of the external medium results in a change of 10% in the reflectivity R, since $\Delta R = 10(\Delta n_{\mathrm{ext}}/n_{\mathrm{ext}})$. In Fig. 3(a), (b) and (c) we present respectively the results for the reflectivity R, transmissivity T, and the parameter γ as a function of the wavelength and the external refractive index. We notice that this sensor design presents very interesting results for n_{ext} between 1.3 and 1.5 and

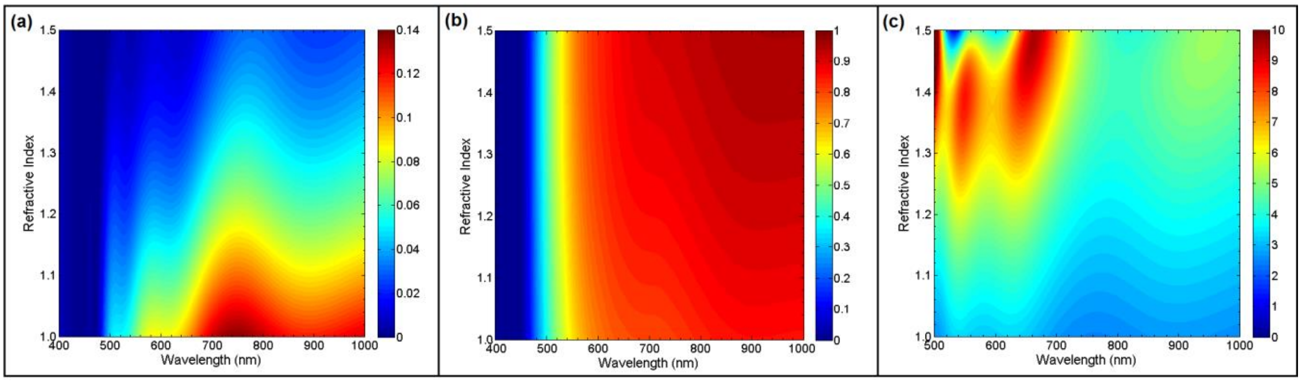

Figure 3. (a) Reflectivity R, (b) transmissivity T and (c) scaling parameter γ as function of the wavelength and n_{ext}.

operation wavelength between 650 nm and 700 nm, where the parameter γ has values well above 8, reaching even a value of 10. This is very promising since this range of Δn_{ext} includes external media such as water and other liquids of interest. For Δn_{ext} around 1 (corresponding to the refractive index of most gases), the results are not as interesting since the parameter γ takes values of only around 4. It should be noticed that in this work we have not optimized the structural parameters of the metamembrane to increase the values of γ for specific liquids or gases. Instead, we considered only typical parameters from the metamembranes currently produced in our group. Therefore, the results presented are only exploratory but demonstrate the potential of smart metamembranes for optical sensing.

4. CONCLUSIONS

In this paper we discuss a SPR fibre-optic sensor based on a smart metamembrane composed by a thin film of an array of metallic nanowires exposed to the fluid (liquid or gas) which we aim to characterize in terms of refractive index. We discuss how the change in the optical properties of the metamembrane induced by variations of the refractive index of the external medium can alter substantially the reflectivity of the structure, and work as a refractometric optical sensor. As mentioned, these are only exploratory results and much work needs to follow. A problem that needs to be addressed is to increase the typical reflectivity of the sensing head to values above 0.5, to allow a sensor with lower input power requirements.

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