Application of optical fibres with reduced normalized frequency for SPR-based refractometry

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ABSTRACT

We present a numerical analysis of surface plasmon resonance (SPR) excitation in a bent metal-coated single mode optical fibre with a low normalized frequency. It is shown that by choosing a proper combination of fibre parameters, such as bend radius and metal film thickness, a direct energy transfer can occur from the fundamental mode, guided by the fibre core, to the surface plasmon wave excited at the metal layer applied to the fibre cladding. The prospects for precision refractive index measurement based on the proposed configuration are discussed, with the spectral sensitivity and resolution estimated at 70 µm/refractive index unit and 3 × 10⁻⁷, respectively.

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Introduction

Biosensing systems based on surface plasmon resonance (SPR), due to their extreme sensitivity and ability to dispense with fluorescent markers, have increasingly been applied in molecular biology and biochemistry, medicine, environmental monitoring, chemical and food industries [1–5]. The sensing elements of such systems use surface plasmon waves excited at a metal-dielectric interface for measuring ultra-small variations in refractive index (RI), with resolutions down to 10⁻⁸–10⁻⁹ refractive index units (RIU) [1,5]. Among various configurations of sensing systems based on surface plasmon excitation, fibre optic SPR-sensors appear particularly attractive due to such advantages as variable gauge length, no requirement for mechanical adjustment of optical elements, miniaturization and remote sensing capabilities, as well as the potential to lower costs of biosensing systems [1,6].

As a rule, fibre optic SPR-sensors are built on either multimode fibres with polymer cladding or all-silica single mode (SM) fibres [6]. In the former case, polymer cladding can easily be removed, and the metal-dielectric interface can be formed by applying a metal film straight onto the fibre core. The fabrication procedure for such sensors is very simple, but multimode operation of the fibre impedes their metrological performance [5]. Much better results are achieved through the use of single mode fibres, but the light guided by the 8-micron core of an SM fibre is separated from the surrounding medium by a 60-micron thick cladding layer. Therefore, to allow the interaction of the core mode with metal, a part of the optical cladding has to be removed either chemically or mechanically, after which the metal layer can be deposited in close proximity to the fibre core [4–6]. These so-called D-type sensors are more difficult to fabricate, and, more importantly, damaging the structural integrity of the fibre may impair the mechanical stability, reliability, and longevity of the sensor.

In Ref. [7,8], a new approach to the development of fibre optic SPR-sensors was proposed, whereby the metal film is deposited straight onto the optical cladding of a standard single mode fibre. The interaction of the fundamental mode (FM) with the metal layer is achieved by bending the fibre through the medium of whispering gallery modes, which propagate in the cladding, and at certain bend radii, can effectively couple to the FM. Such a configuration offers enhanced resolution compared with other fibre optic SPR sensors, without compromising the integrity of the fibre [8]. However, the core mode of a bent SM fibre can interact directly with the metal layer applied to its cladding, provided that the FM field sufficiently penetrates into the cladding due to the bending. This can be

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achieved by either bending the fibre with a small curvature radius, which makes it very fragile, or by decreasing its normalized frequency, \( V \). In the latter case, the fundamental mode is weakly guided by the core, and even moderate bending becomes sufficient for it to directly transfer energy to surface plasmon waves excited in the metal coating of the cladding. Thus, a numerical study of this new approach of the excitation of surface plasmon resonance in a bent single mode fibre with metal-coated optical cladding is the aim of the present paper.

Methodology and results

The waveguide under study, consisting of a silica core (RI = \( n_1 \)), silica cladding (RI = \( n_2 \)), and polymer coating, is schematically presented in Fig. 1. The sensitive section of the fibre is stripped off the polymer jacket, coated with a thin layer of silver, bent at a constant curvature radius \( R \), and placed in a medium with a refractive index to be measured \( n_3 \). The latter is expected to lie within the range 1.33–1.44, which covers the refractive indexes of many solvents used in biosensing. Light is input and output to and from the sensing section through the straight sections of the same fibre (i.e., 1 and 3), which due to preserved polymer jacket 6, are insensitive to refractive index \( n_3 \). As a working wavelength range for our study, we choose \( \lambda = 1.5–1.6 \, \mu m \), which is a standard wavelength for fibre optics.

The eigenmode expansion method (EME) is used for numerically modelling the waveguiding structure under study [9,10]. Numerical analysis shows that the meridional modes of the fibre play a key role in the excitation of surface plasmon resonance, so to simplify the calculations, we use the effective index method (EIM) [11] and replace the cylindrical step-index fibre with an equivalent graded-index slab waveguide, whose modes are a reasonable approximation to the meridional modes of the fibre [10]. To illustrate this approach, Fig. 1, Inset 1 shows the graded RI profile of the slab waveguide calculated for a standard SMF-28-type single mode fibre.

Calculation of the waveguide mode spectrum indicates that, as expected, sections 1 and 3 support only one core mode (Fig. 1, curves 9). The metalized section 2, generally speaking, supports many modes, which is due to the removed polymer jacket and total internal reflection at the outer surface of the cladding, although attenuated by the metal layer. However, the processes of guided light energy transfer from the core to the surface plasmons at the resonant wavelength are governed by only two modes of section 2. The amplitude profiles of those modes are nearly identical, and in the core region, are similar to the straight waveguide fundamental mode, which implies their high excitation efficiency by FM of section 1. At the interface between the metal and the surrounding medium, they have a sharp peak, which is an indication of surface plasmon excitation (Fig. 1, curve 8). Both modes have high attenuation as a consequence of energy losses associated with SPR, similar propagation constants and significantly different phase profiles, which are not shown for the sake of simplicity.

Based on the numerical results, for single mode waveguides with a standard value \( V \)-number (e.g., SMF-28 \( V=2 \) at \( \lambda = 1.55 \, \mu m \)), such modes are not observed in the mode spectrum of section 2, even for bends with small curvature radii \( R = 8 \, \text{mm} \) and less. However, for waveguides with smaller \( V \)-numbers \( V = 0.7–0.8 \), they appear even at rather large bend radii, on the order of several centimetres. Thus, for numerical modelling we use the parameters of the Thorlabs SM800 optical fibre: \( n_1 = 1.449, n_2 = 1.444, \rho = 1.6 \, \mu m, V = 0.7783 \) (at \( \lambda = 1.55 \, \mu m \)), where \( \rho \) denotes the fibre core radius. Fig. 1 (curve 8) depicts a characteristic amplitude profile of one of the modes calculated at the resonant wavelength for fibre SM800 at \( R = 7 \, \text{cm} \). It should be noted that contrary to the case studied in Ref [8], when the fundamental mode energy is coupled to the surface plasmons through the medium of cladding modes, as seen in the figure, the field of the modes of interest is

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**Fig. 1.** The schematic of the waveguide under study: 1 – straight input section, 2 – bent metal-coated sensing section, 3 – straight output section, 4 – waveguide core, 5 – waveguide cladding, 6 – polymer jacket, 7 – silver layer, 8 – amplitude profile of one of the two modes responsible for the transfer of the core mode power to the surface plasmons (the second mode’s profile is nearly identical and not shown), 9 – amplitude profile of the fundamental mode of sections 1 and 3. Inset 1 – RI profile of a standard single mode optical fibre and the effective graded profile of an equivalent slab waveguide (\( n' \)).
mainly localized in the core and the metal layer regions, and not in the cladding of the fibre. This implies the direct nature of the interaction between the core and surface plasmon modes and the slight effect that cladding modes have on SPR excitation in the structure under study. The transmission coefficient of the whole structure under study is calculated as a ratio of the FM power in sections 3 and 1. Because modes of segment 2 feature high ohmic losses, in the same manner as in Ref. [8], an unconjugated form of the orthogonality relation is used for the computation of mode amplitudes when modelling light transmission between different sections [10,12]. The calculated results for wavelength dependence of the transmission coefficient show that, as expected, the transmission spectrum features a resonant dip at the SPR wavelength (Fig. 2a). The width of the dip Δλ (at 3 dB from the maximum attenuation) depends strongly on the length of the sensing section L and metal layer thickness d, and reaches a minimum at L = 2 cm and d = 37 nm, which are therefore chosen as optimal values.

In Fig. 2a, the numerical results are presented for the transmission spectrum calculated for three values of the surrounding medium refractive index: n3 = 1.4312, 1.4314, 1.4316, at the optimal values of d and L. As one can see, the SPR wavelength has a strong and nearly linear dependence on n3, as illustrated in Fig. 2b. The figure also shows that the spectral sensitivity amounts to ~70 um/RIU, which is significantly higher than the typical characteristics of waveguide-based SPR-refractometers, and more than three times exceeds the sensitivity that can be obtained if the coupling between fundamental and surface plasmon modes is realized through the medium of a cladding whispering gallery mode [8]. The resolution of refractive index measurement that can be obtained through the use of the studied structure is estimated at 3 × 10^{-2}.

Conclusions

We have numerically studied the processes of SPR excitation in a bent metal-coated single mode fibre with a low normalized frequency. It is shown that by choosing a proper combination of the normalized frequency, bend radius, and metal film thickness, one can achieve direct energy transfer from the fundamental mode guided by the fibre core to the surface plasmon wave excited at the metal layer applied to the cladding of the fibre. This effect is demonstrated to allow refractive index measurement with a spectral sensitivity of ~70 um/RIU, which is significantly higher than the typical characteristics of waveguide-based SPR-refractometers, and more than three times exceeds the sensitivity that can be attained if the coupling between fundamental and surface plasmon modes is realized through the medium of a cladding whispering gallery mode [8]. The resolution of refractive index measurement that can be obtained through the use of the studied structure is estimated at 3 × 10^{-2}.

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References