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Titre: Surface plasmon resonance-based fiber and planar waveguide sensors
Title:

Auteurs: Raman Kashyap, & Galina Nemova
Authors:

Date: 2009

Type: Article de revue / Article

Référence: Kashyap, R., & Nemova, G. (2009). Surface plasmon resonance-based fiber and planar waveguide sensors. Journal of Sensors, 2009, 645162. https://doi.org/10.1155/2009/645162
Citation:

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Document issued by the official publisher

Titre de la revue: Journal of Sensors (vol. 2009)
Journal Title:

Maison d'édition: Hindawi
Publisher:

URL officiel: https://doi.org/10.1155/2009/645162
Official URL:

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Journal of Sensors
Volume 2009, Article ID 645162, 9 pages
doi:10.1155/2009/645162

Review Article

Surface Plasmon Resonance-Based Fiber and Planar Waveguide Sensors

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Received 29 March 2009; Accepted 26 June 2009

Recommended by Christos Riziotis

Bulk surface Plasmons resonance devices have been researched for several decades. These devices have found a special niche as high-sensitivity refractive index sensor in biomedical applications. Recent advances in guided wave devices are rapidly changing the capabilities of such sensors, not only increasing convenience of use but also opening opportunities due to their versatility. This paper reviews many of these devices and presents some of their salient features.

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1. Introduction

The optical performance of metal or metallic gratings dates back to 1902 when Wood discovered absorption anomalies in the response of such structures illuminated by light [1]. Later these absorption anomalies were understood as being caused by the excitation of surface Plasmon-Polaritons along the metal surface. A surface Plasmon-Polariton (SPP) is an electromagnetic excitation at a metal-dielectric interface, which consists of a surface-charge-density oscillation coupled to the electromagnetic fields [2, 3]. The SPP field components have their maxima at the interfaces and decay exponentially in both surrounding a metal layer (usually a few to 10's nm thick) media. In the case of a planar structure the SPP can exist in the form of p-polarized (TM) wave, when the permittivities of two adjacent media have opposite signs, and in the form of s-polarized (TE) wave, when the permeabilities of two adjacent media have opposite signs [4]. Being localised at the metal-dielectric interface, the SPP can serve as a promising tool for sensor applications to investigate the medium near the interface [5–10]. At the present time there are many of different SPP sensors bulk, planar, and fiber geometries.

All these sensors can be characterised by two important parameters: the sensitivity and operating (or dynamic) range. *Sensitivity* is the derivative of the monitored SPP parameter (e.g., resonant angle, wavelength, intensity) with respect to the parameter to be determined (e.g., refractive index). An *operating* (*dynamic*) *range* is the range of values of the parameter to be determined, which can be measured by the sensor. The third important parameter of the sensor is its resolution. The sensor *resolution* is the minimum change in the parameter to be determined, which can be resolved by the sensor. Contrary to the sensitivity and the operating range, the resolution of the sensor depends not only on the sensor properties itself but also on the accuracy with which the sensor is monitored. It means that increasing the accuracy of the interrogation unit one can increase the resolution of the sensor.

2. Surface Plasmon Sensors

In the late sixties, optical excitation of surface plasmons by the method of the attenuated total reflection was demonstrated by Otto [11] (Figure 1(a)). In this scheme there is a finite gap between prism base and metal layer and it is

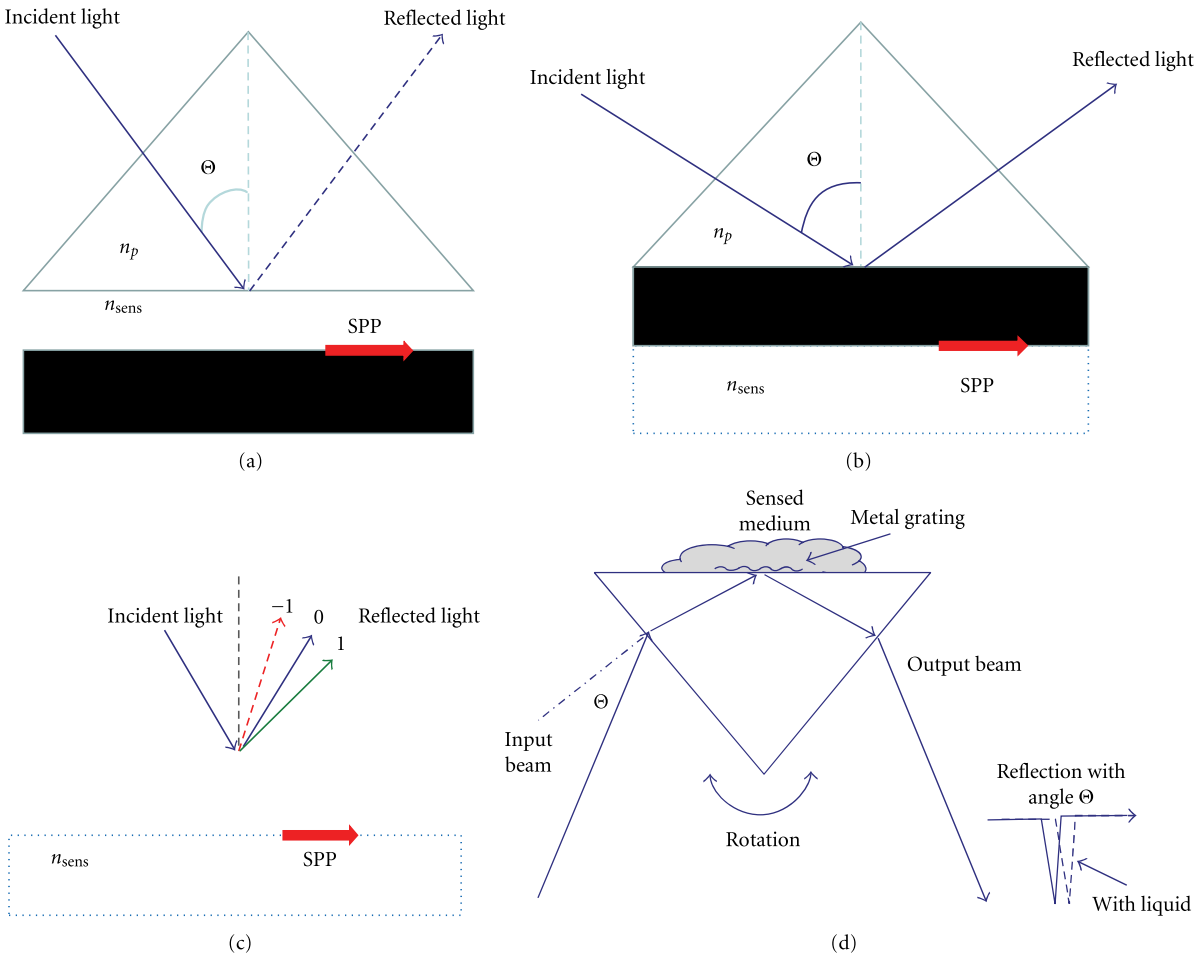

Figure 1: (a) Otto configuration for the SPP excitation. (b) Kretschmann configuration for the SPP excitation. (c) Grating coupled SPP system. (d) Practical implementation of an SPP sensor.

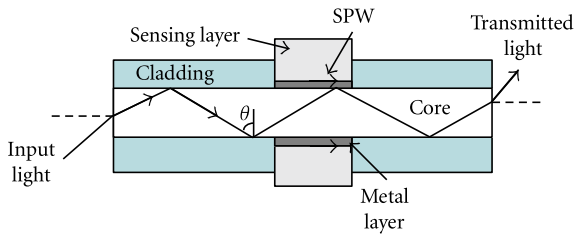

Figure 2: One of the widely used Polariton fiber sensor configurations.

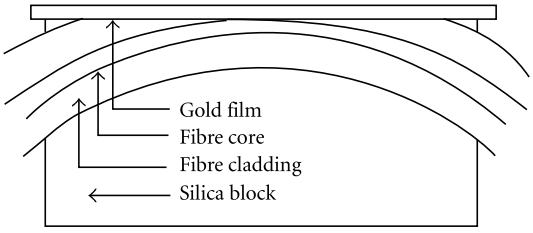

Figure 3: Side-polished Polariton fiber sensor.

suitable for surfaces that need to be changed easily. This scheme was modified by Kretschmann and Raether [12] and Kretschmann [13]. In Kretschmann's scheme, a metal layer contacts the prism base (Figure 1(b)). Kretschmann's scheme is one of the most widely used techniques for SPP excitation till now. A scheme with the grating on the top of the structure was also suggested [14] (Figure 1(c)). All these schemes are widely used in sensor application, and a practical configuration is shown in Figure 1(d). The angle, at which the coupling to the Plasmon occurs, changes when a liquid is placed on the surface of the prism. As is clear from Figure 1(d), the angle has to be measured with precision if a high resolution is required. Thus, most of the well-known schemes have elements with a nonplanar geometry and require moving parts and are rather bulky and cumbersome to adjust with high precision. As one can see in Figure 1

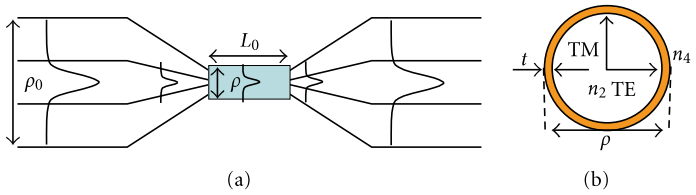

FIGURE 4: (a) Tapered fiber structure with uniform waist. (b) Cross section of the waist of the fiber with the metal coating.

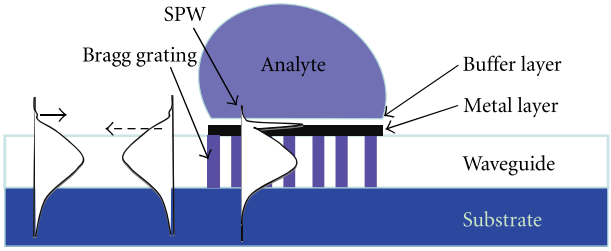

FIGURE 5: Surface Plasmon resonance sensing structure with Bragg grating.

in these schemes the SPP excitation is based on resonant transfer of the incident photon energy from the free space in the form of *p*-polarized light to a SPP. All these schemes provide the wave-vector matching condition for the incident free space radiation to the SPP with the attenuated total reflection configuration.

3. Guided Wave Surface Plasmon Sensors

Since the SPP excitation with a prism is based on total internal reflection, the coupling prism can be replaced by a waveguide layer of the planar structure of a fiber core to get a compact device easily integrated in any planar or fiber schemes. Indeed propagation of the guided modes in the waveguide layer or in the fiber core is based on total internal reflection. The development of sensors based on the planar and fiber structures began in the early of nineties of last century. During the last two decades, the SPP sensor technique has been widely used for detection of physical, chemical, and biological parameters. We will now present and discuss the most popular, widely used sensor schemes based on fiber or planar structures and review some of the latest ideas in literature.

In the scheme presented in Figure 2 the cladding of the fiber is removed and it is coated with a metal layer, which is surrounded by the sensed medium. However, the radius of the core is very small, and this structure is difficult to fabricate. As an alternative solution a side-polished fiber sensor has also been suggested [15]. This scheme is illustrated in Figure 3. In [16]; a fiber sensor with an asymmetric metal coating on a uniform waist of a single-mode tapered fiber was suggested (a detail is shown in Figure 4). In all these fiber sensors the transmitted guided mode is used in the interrogation process, and a recent review of these fiber sensors can be found in [17].

Planar structures are also widely used for sensor applications. A review of some of these sensors can be found in [18]. In 1999, Ctyroky et al. suggested the use of the reflected guided mode for the monitoring of a sensor [19]. In all these fiber and planar schemes, the sensor element or sensor tool is a surface Plasmon wave (SPW), which has a *hybrid nature*. It consists of the guided mode *coupled* to a surface Plasmon-Polariton as can be seen in Figure 5 [19]. An SPW oscillates in the fiber core or a waveguide layer of the planar structure. Its effective refractive index is only *slightly* different from the effective refractive index of the guided mode supported by the structure without the metal layer. This is because most of the energy is associated with the guided mode and only slightly weighted by Plasmon-Polariton's effective index. This condition means that the hybrid mode is only weakly sensitive to any change in the effective index of the Plasmon, should it be altered by the presence or absence of a surrounding layer.

In 2006, the authors of this paper suggested an improved sensor by the use the "pure" SPP as opposed to the hybrid mode [20]. Contrary to SPW, in this "pure" SPP, almost all the energy is concentrated at the metal-dielectric interfaces.

The "pure" SPP decays exponentially away from the metal surface, including a waveguide layer of the sensor structure. The difference between effective refractive index of the guided mode and effective refractive index of the "pure" SPP is thus large and requires a special scheme to excite the "pure" SPP. This is done with a grating, which allows the wave-vector matching condition to be met. The advantage of using the grating is that it decouples the coupling scheme from the second important parameter—the overlap integral between the guided exciting mode and the "pure" SPP. Since almost all energy of the "pure" SPP is concentrated at the metal-dielectric interface, this scheme is extremely sensitive to small changes in the refractive index of the sensed medium. The value of the change in the effective refractive index of the "pure" SPP caused by the change in the refractive index of the sensed medium depends on the parameters of the structure. A full theoretical model of a hollow core fiber with the Bragg grating imprinted in its waveguide layer (Figure 6) may be found in [21].

Other planar structures with Bragg gratings imprinted into the waveguide layer or the use of a corrugated Bragg grating engraved on the top of the metal layer have also been considered [22, 23]. In these structures the Bragg grating excites a counter-propagating SPP, that is, in the opposite direction to the incident guided mode (Figure 7).

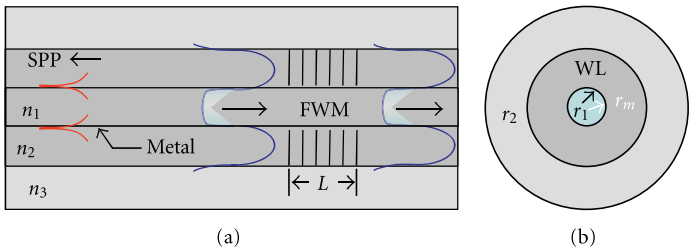

FIGURE 6: (a) Hollow core sensing structure with Bragg grating. (b) Cross section of the sensor.

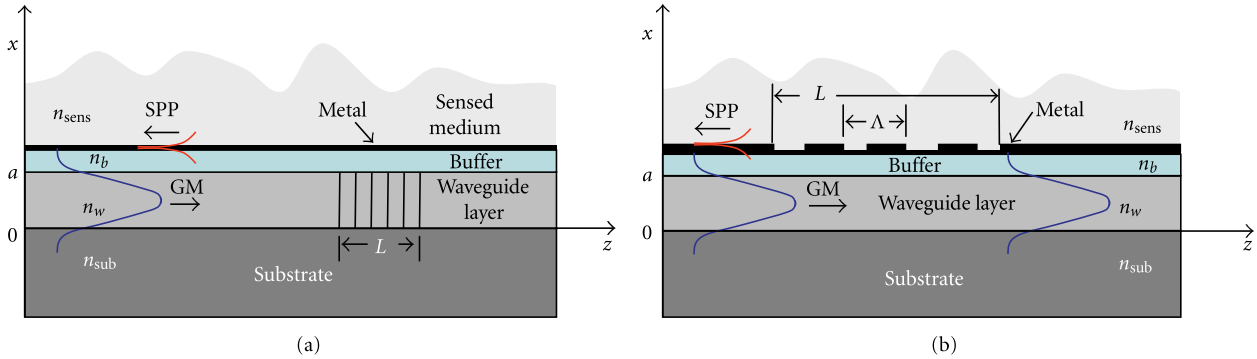

FIGURE 7: Planar SPP sensor with (a) Bragg grating imprinted into the waveguide layer and (b) Bragg grating engraved on the top of the metal layer.

The guided mode transmitted through the Bragg grating can then be used in the interrogation process. The sensitivity of the structure is characterized by the shift in the wavelength of the grating transmission dip versus the refractive index of sensed medium. The sensitivity of these sensors is ~250 nm/RIU (refractive index units) for optimised structures. This sensitivity does not depend on the Bragg grating (imprinted in the waveguide layer or engraved on the top of the metal layer) used for exciting the counter-propagating SPP.

To increase the sensitivity of the sensor, the Bragg grating may be replaced by a long period grating (LPG) (Figure 8). In these sensor structures the guided mode propagating in the waveguide layer of the structure excites a copropagating SPP. The LPG may be imprinted into the waveguide layer or engraved on the top of the metal layer. The guided mode transmitted through the LPG is then used to interrogate the sensor. The sensitivity of these structures is ~1100 nm/RIU.

The increase in the sensor's sensitivity may be easily explained, by comparing the LPG to the Bragg grating. Indeed, the larger grating period of the LPG is a result of the *difference* between the propagation constants of the guided and SPP modes. On the other hand the shorter period Bragg grating for exciting the counter-propagating SPP is a result of the *sum* of the propagation constants of the guided and SPP modes, since the SPP and the guided modes propagate in opposite directions. Any small change in the refractive index of the surrounding medium (n_{sens}) induces a larger fractional change in the LPG-based sensor as it changes the SPP's propagation constant; that is, if δn is the change in the SPP's effective refractive index for a change in n_{sens}, then the fractional change in the mismatch is

$$\frac{\delta n}{(n^p - n^g)}, \tag{1}$$

where n^p and n^g are the effective indexes of the SPP and guided modes, respectively. In the counter propagating scheme with the Bragg grating, a small change in the propagation constant of the SPP has a smaller fractional influence on the sum of the propagation constants of the SPP and the guided mode as

$$\frac{\delta n}{(n^p + n^g)}. \tag{2}$$

The ratio of the sensitivities of the LPG and the SPG sensors is therefore

$$r \approx \frac{n^p + n^g}{n^p - n^g}. \tag{3}$$

In (3), the ratio r is greater than unity, indicating an enhanced sensitivity for the LPG (copropagating) compared to the SPG-based sensor (counter-propagating).

In all schemes presented in Figures 6, 7, and 8, the intensity of the guided mode transmitted through the grating is used to acquire the information concerning the sensed medium. A novel approach to monitor a planar refractive index sensor with the "pure" SPP used as a sensor tool was suggested in [24]. A variation of this type of sensor may

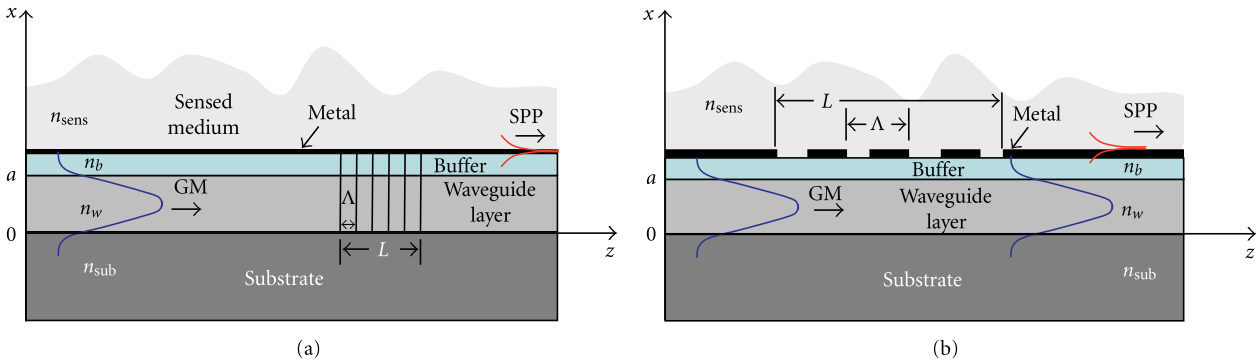

FIGURE 8: Planar SPP sensor with (a) LPG imprinted into the waveguide layer and (b) LPG engraved on the top of the metal layer.

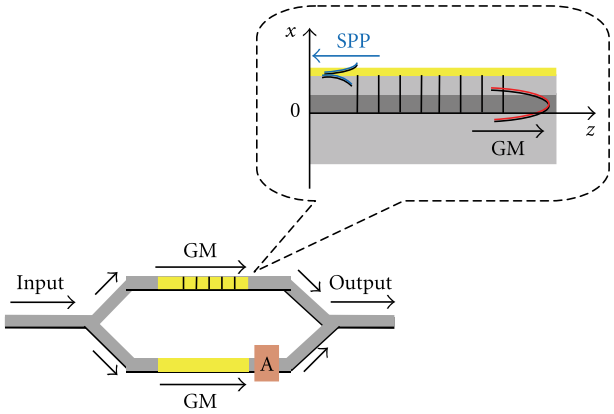

FIGURE 9: GM is the guided mode, and **A** is an attenuator. Insertion illustrates the MZI branch with the Bragg grating. The other MZI branch is identical to the shown one, but without the grating. The SPP travels in the opposite direction if an LPG is used.

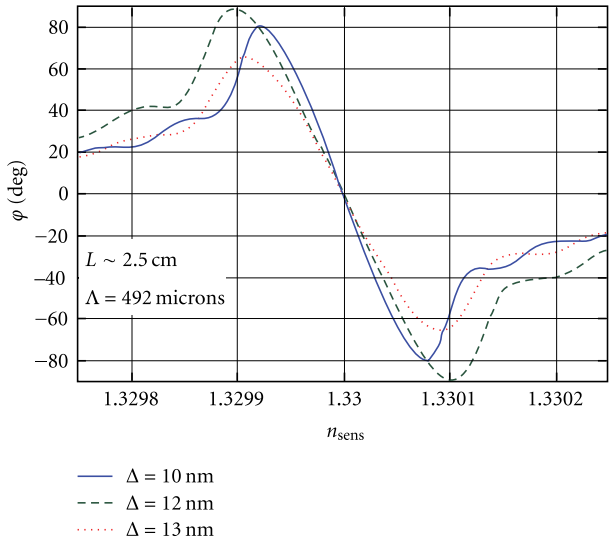

FIGURE 10: Dependence between the refractive index of the sensed medium (n_{sens}) and the phase of the guided mode transmitted through the grating (φ) for three structures with the thickness of the metal layer $\Delta = 10$ nm, $\Delta = 12$ nm, and $\Delta = 13$ nm.

also be found in [25] but is based on the *hybrid* SPP mode. This new interferometric approach is based on the detection of the *phase* of the guided mode transmitted through the grating (Figure 9). Close to the resonance condition, which corresponds to the excitation of the "pure" SPP, a very small changes in the refractive index of the sensed medium causes a dramatic change in the phase of the guided mode transmitted through the grating. The phase detection of the guided mode is performed by a simple integrated optical Mach-Zehnder interferometer (MZI). The sensitivity of the sensor can be characterised by $dn_{sen}/d\varphi$ (RIU/°), where $d\varphi$ is the change in the phase of the guided mode transmitted through the grating, and dn_{sen} is the change in the refractive index of the sensed medium causing the phase change.

The sensitivity of the optimised sensor is $\sim 8 \times 10^{-7}$RIU/° with a linear slope for a refractive index change of 10×10^{-4}, at the operating refractive index of, $n_{sen} = 1.33$ (Figure 10), common for many biological applications. It is important to note that if parameters of the planar structure used in the sensor structure presented in Figure 7(a) are identical to the parameters of the planar structure presented in Figure 9, the sensitivity of the sensor is ~250 nm/RIU. If the Optical Spectrum Analyzer (OSA), used as an interrogation unit, has a resolution 0.01 nm, the resolution of the sensor presented in Figure 7(a) is $\Delta n_{sen}^{min} \approx 4 \times 10^{-5}$. The value of the transmission dip in the guided mode transmission spectrum changes with the change in the refractive index of the sensed medium restricting the dynamic range of this device. The dynamic range of this sensor is defined as the range within which the value of the transmission dip changes in the interval ±0.1 around the chosen value of the transmission dip equal to 0.3 (i.e., 30% dip in transmission) for $n_{sen} = 1.33$. Roughly estimated, this dynamic range turns out to be an interval $\Delta n_{sen} \sim 0.01$.

Interferometric methods enable detection of phase changes below $2\pi \times 10^{-3}$ radians [26]. Using this value as a limit, the resolution of the SPP-interferometer of the sensor, based on phase interrogation and presented in Figure 9, is calculated to be $\Delta n_{sen}^{min} \approx 3 \times 10^{-7}$. The resolution of this sensor is thus extremely high, but the dynamic range, which can be characterised by the linear dependence in Figure 10, is small $\Delta n_{sen} \sim 0.0005$. It is therefore important to remember

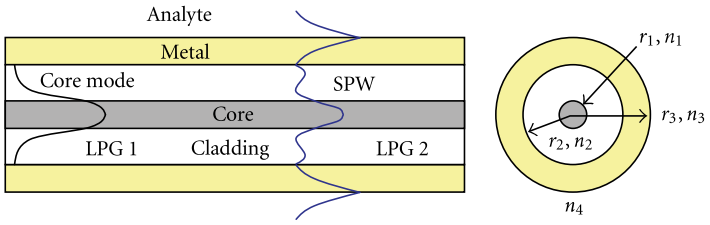

Figure 11: A dual LPG-based SPR sensor. The first LPG couples a guided mode to a particular cladding mode which has a small SPP component (the hybrid mode). The second step is the recoupling of the hybrid surface Plasmon wave back to the guided mode at the output of the fibre. A phase change is imparted by the introduction of the analyte, which detunes the coupling at the second LPG, resulting in an amplitude change at the output [27].

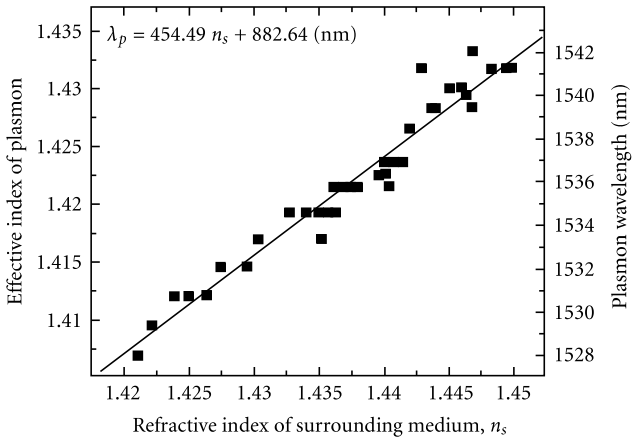

Figure 12: The tilted grating assisted SPR sensor. The guided mode is scattered into a set of counter-propagating cladding modes via the tilted grating. Some are coupled to the SPP in the thin gold layer deposited on the fiber. The introduction on the analyte on the surface of the metal coating changes the details of the resonances spectra at the output [28, 29].

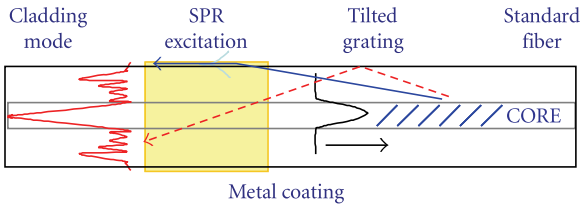

Figure 13: Refractive index of an analyte determined from the changes in the intensities of the cladding mode resonances (Adapted from [28]).

that in the suggested scheme, the Bragg grating is used for exciting the SPP. This means that the excited SPP propagates in an opposite direction to the guided mode (Figure 9). If the Bragg grating is replaced by an LPG, the SPP will copropagate with the guided mode. In the latter case the sensitivity of the sensor can be increased by approximately an order of magnitude; however the dynamic range will be correspondingly reduced by a factor of ten.

Another type of waveguide SPP sensor based on the hybrid mode is shown in Figure 11 [27]. Part of the guided mode is first excited into a cladding mode which then couples to a surface Plasmon-Polariton in the metal layer surrounding the fiber. Any change in the SPP via a refractive index change in the sensed analyte is translated into a phase shift in the propagating cladding hybrid mode, detuning the coupling back into the fundamental guided mode in the core at the second LPG. Thus, the transmitted signal suffers a change in the amplitude through interference of the guided and cladding modes. The overlap of the excited cladding mode with the SPP is small, as seen in Figure 11: the surface Plasmon hybrid-mode has a substantial amount of its energy associated with the guided mode and is therefore intrinsically less sensitive to the surrounding liquid than the "pure" SPP scheme proposed in [20–24]. The second LPG couples the cladding hybrid mode back into the core mode for direct detection.

The use of a tilted grating to excite an SPP in a standard telecommunications fiber has some advantages as the system is quite robust. This has been demonstrated [28] and is shown in Figure 12. The scheme relies on the detailed spectra in transmission of the series of counter-propagating cladding modes scattered by the tilted grating, some of which are coupled to the SPP in a thin gold metal layer on the surface of the fiber. The resonance peaks are predominantly defined by the geometric dimensions of the fiber [30] and *not* by the refractive index of an analyte in contact with the metal layer. This makes the interpretation of the data a bit complicated as there is no *shift* in the resonance peaks, but a redistribution of the energy amongst the peaks, as the phase-matching to the SPR shifts to a different wavelength, and there is no "allowed" mode for the geometry of the fiber. In practice, each cladding mode has some bandwidth, and therefore the amplitude of the coupled mode changes. Using this scheme, it is possible to determine the refractive index of the analyte. Figure 13 shows a measurement result [30], with a resolution of 466 nm/RIU. Allsop et al. [29] demonstrated a similar sensor with a germanium-silver metal layer and tilted Bragg grating but with a much lower resolution (3.4 nm/RIU) compared to the results presented in [27].

More recently, a "holey" fibre was proposed as an SPR gas sensor in the THz frequency regime [31]. This scheme,

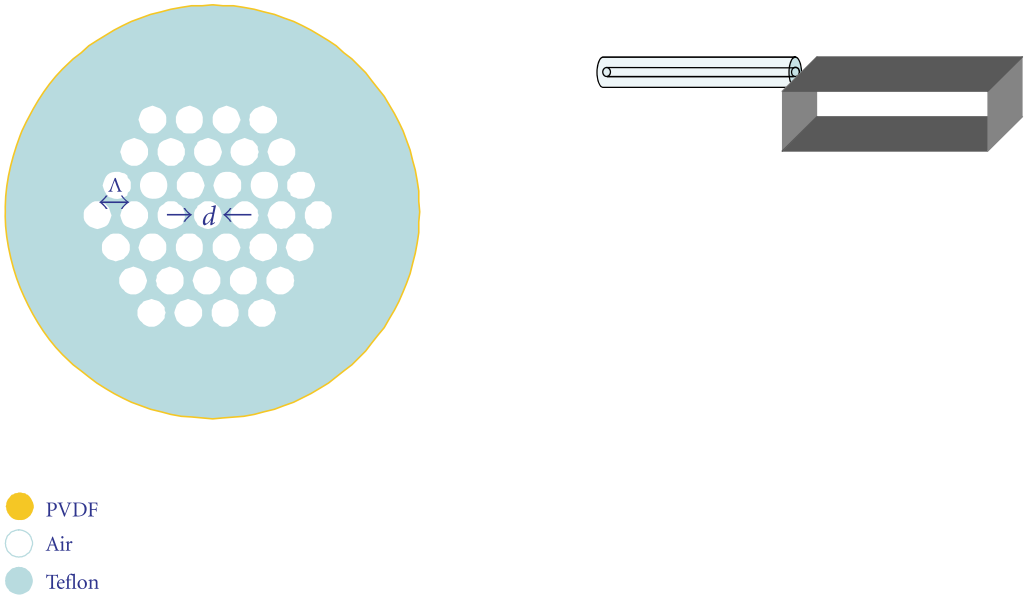

Figure 14: A proposal for a PVDF coated Teflon fibre SPR gas sensor (Adapted from [31]).

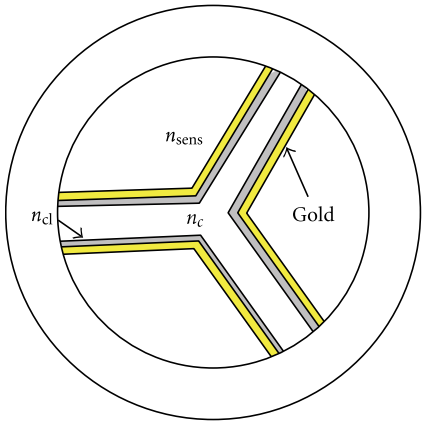

Figure 15: The cross-section of a proposed three section *hybrid mode* SPR sensor [32] in silica glass fiber.

shown in Figure 14, uses a Teflon fibre with a series of holes to introduce a gas into the sensor. The THz guided mode in the Teflon is coupled to the SPP in a ferroelectric outer layer (polyvinylidene: PVDF). The gas introduced into the holes shifts the resonance between the guided mode and the SPP in the THz regime and is thus detected.

Hautakorpi et al. [32] have recently proposed an alternative scheme based on a modified microstructured fiber used by Huy et al. [33]. In this proposal, a *hybrid* SPP mode is excited in the gold layer. The waveguide is a fiber nanowire of refractive index, n_c, supported by three, 120 degree separated strands of glass wires in a multistructured optical fibre. The nanowire mode is thus exposed to three gold-coated surfaces separated from the core by a thin layer of lower refractive index n_{cl}. The liquid to be sensed with a refractive index, n_{sens} is introduced into the three hollow sections as

example, on the highly reliable Kretchmann technique, and therefore should be available commercially in the near future.

Acknowledgments

The first author acknowledges support from the Government of Canada's Canada Research Chairs Program as well as the Canadian Natural Science and Engineering Research Council's Strategic Grants program.

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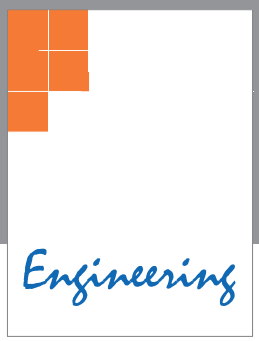

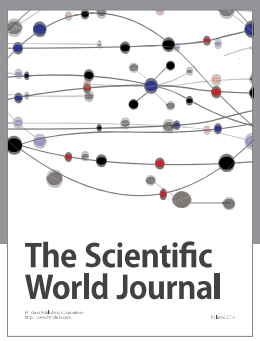

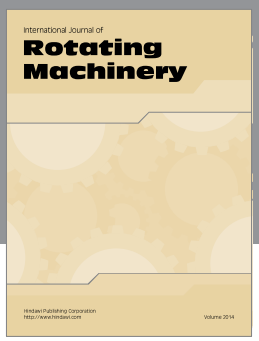

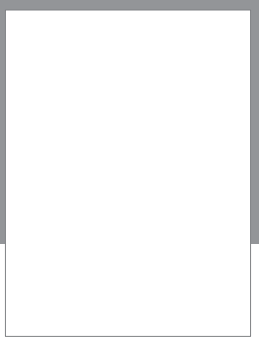

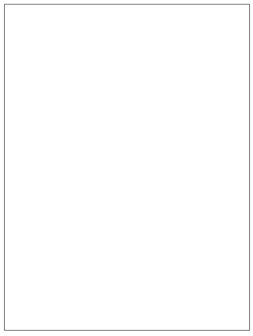

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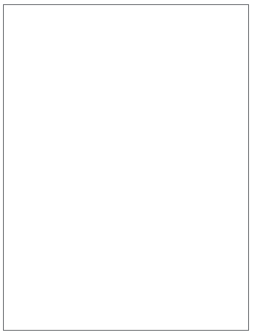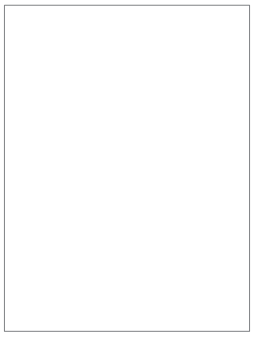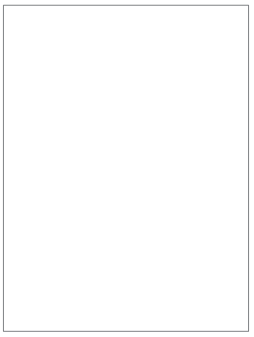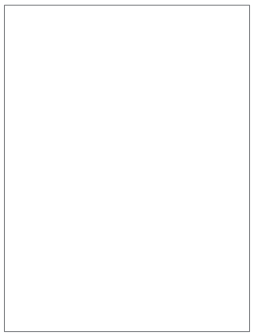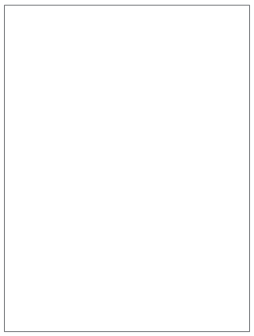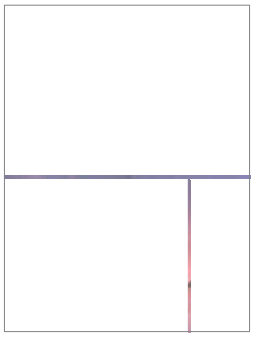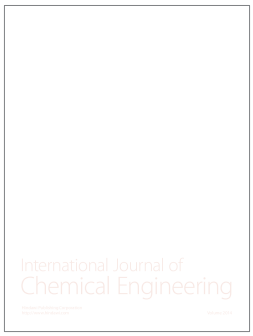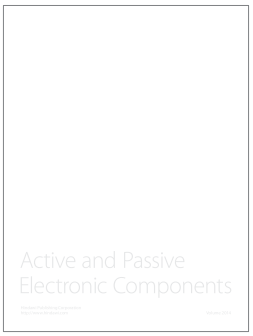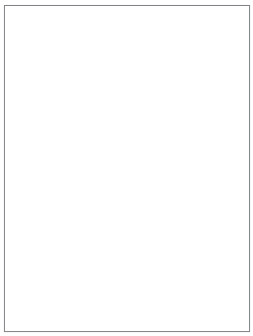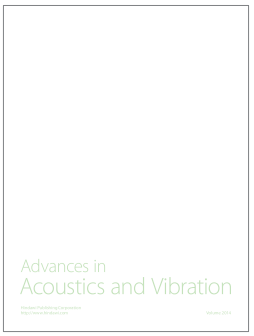
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