Photon crystal waveguide-based surface plasmon resonance biosensor

Maksim Skorobogatiy[a] and Andrei V. Kabashin
Department of Engineering Physics, Ecole Polytechnique de Montreal, Case Postale 6079, Succ. Centre-ville, Montreal, Quebec H3C 3A7, Canada

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The concept of a photonic crystal waveguide-based surface plasmon resonance sensor is proposed, in which plasmons on a surface of a thin metal film are excited by a Gaussian-like leaky mode of an effectively single mode photonic crystal waveguide. The authors demonstrate that effective refractive index of a waveguide core mode can be designed to be considerably smaller than that of a core material, enabling efficient phase matching with plasmons at any wavelength of choice, while retaining highly sensitive response to changes in the refractive index of an analyte layer. This is attractive for the development of portable surface plasmon resonance biochemical sensors. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2360186]

Surface plasmon resonance (SPR) is a prominent optical phenomenon, which involves the resonant excitation of plasmon or electromagnetic waves coupled with collective oscillations of free electrons in metal, over a metal/dielectric interface.[1] When excited over a metal/liquid interface, the plasmons offer attractive applications in biosensing. In bulk sensor geometry, SPR is produced with the help of a prism in the Kretschmann-Raether arrangement[2] by launching *p*-polarized light into a glass prism and reflecting it from a gold covered prism facet in contact with liquid ambient. The phase matching of a pumping photon with a plasmon causes a dip of reflectivity at a specific combination of the angle of incidence and wavelength. Since this combination is resonantly dependent on the refractive index of the adjacent medium within distances of about 200–300 nm from gold,[1] the method enables to detect extremely small variations of the thickness of biological films on the metal by following angular,[3,4] spectral,[5] or phase[6,7] characteristics of the reflected light. Due to resonant nature of SPR transduction and the absence of a labeling step, this method has quickly become a technology of choice for the direct detection of binding events between a target analyte and its corresponding receptor and is used for a plethora of bioanalytical applications.[8] However, the high cost and large size of all commercially available systems make them useful only in a laboratory setting, while many important applications requiring the compactness and portability remain out of reach of the method.

To miniaturize SPR biosensors and reduce their cost, several waveguide-based systems have been introduced.[9–14] In these sensors, one launches light into a waveguide core and then uses the coupling of a fundamental core mode with a plasmon propagating over the metal film deposited onto the waveguide. However, phase matching between the fundamental core mode and the plasmon is not easy to achieve, since the effective refractive index of a plasmon is close to that of the ambient medium ($n \sim 1$ for air and $n \sim 1.33$ for water), while the effective refractive index of the mode is close to the one of the core material, which is typically larger than 1.45. This forces the use of waveguide materials with low core refractive indices of $n < 1.45$ (which, in practice, are not easy to find and process) and results in high operation frequencies ($\lambda < 650$ nm), at which effective refractive index of a plasmon increases considerably above that of an analyte. At such high frequencies, however, plasmon probing depth and, hence, the sensitivity is reduced. Moreover, in a single mode waveguide, where the mode excitation by an external Gaussian-like source is very efficient, the effective angle of light incidence onto a metal layer becomes shallow, greatly reducing the resultant sensitivity of SPR sensing transduction.[1] In principle, the problems of phase matching and loss of sensitivity due to shallow incident angles could be alleviated by using multimode waveguides.[15–19] If launched properly, effective beam propagation angles in such waveguides can be much steeper, resulting in smaller effective refractive indices of the propagating beam, thus, better phase matching with the plasmon and potentially better sensitivity to a refractive index change. However, in multimode waveguides only a certain number of higher order modes can be phase matched with the plasmon. This causes a strong dependence of the sensitivity and stability of such sensors on launch conditions. Moreover, since the spatial field distribution in a Gaussian-like laser source is typically not well matched with the field distributions in the higher order modes of a multimode waveguide, only a small fraction of energy can be launched into such plasmon-matched modes resulting again in a decreased sensitivity.

The goal of this letter is to build upon a great body of ideas developed by the waveguide-based SPR sensing community and to demonstrate that the phase matching and coupling issues can be efficiently resolved using photonic crystal (PC) waveguides operating in the effectively single mode regime. In particular, we propose a concept of a photonic crystal waveguide-based surface plasmon resonance sensor, combining one-dimensional (1D) PC planar waveguides with metal layers.

Figure 1 (inset) shows a schematic of a proposed configuration of the photonic crystal waveguide-based (PCW) SPR biosensor. Here, the photonic crystal waveguide consists of 27 alternating layers with indices $n_h=2.0$ and $n_l=1.5$. The core layer is number 12 with the index of $n_c=n_l$ supporting a Gaussian-like TM mode (magnetic field is parallel to the plane of layers). The analyte (first cladding) is water ($n_s=1.332$) bordering a thin layer of gold. We assume that the refractive index of the substrate is 1.5. The light

[a]Electronic mail: maksim.skorobogatiy@polymtl.ca

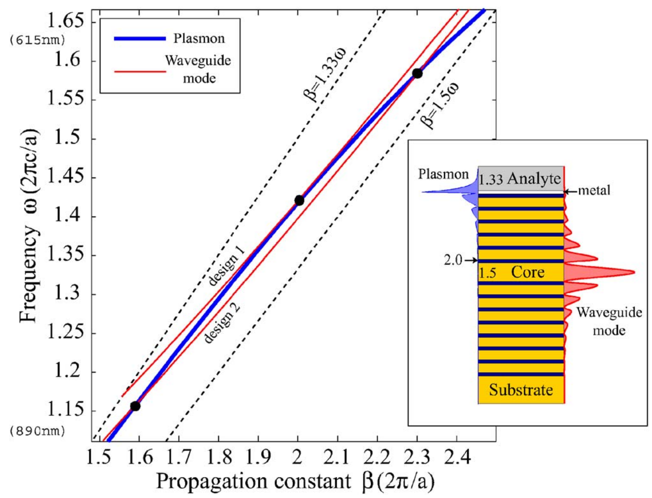

FIG. 1. (Color online) (a) Band diagrams of a Gaussian like core mode of a PC waveguide (red) and a plasmonic mode (blue). Two waveguide designs are presented demonstrating that phase matching point (black circles) can be chosen at will. In the inset—sensor structure; $|H_y|^2$ of the TM modes of a metallic layer (left) and a Gaussian-like core mode of a PC waveguide (right).

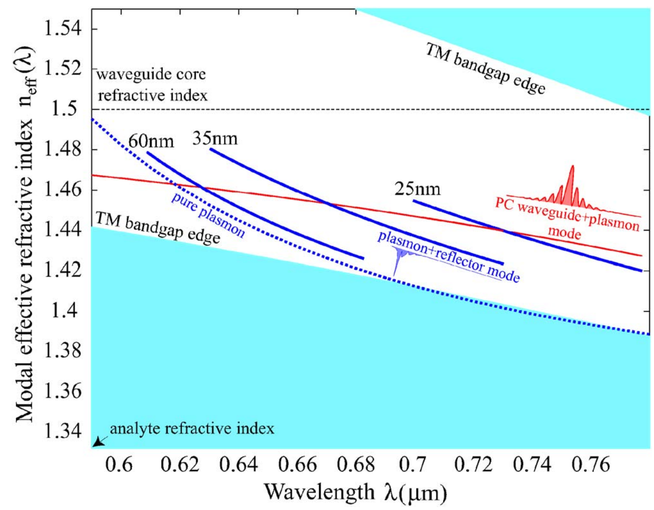

FIG. 2. (Color online) Dispersion relations of the core guided (thin red line) and plasmon (thick blue lines) modes. Filled light blue regions define the TM polarized bulk states of a periodic reflector, while clear region defines a TM band gap. By design, effective refractive index of a core guided mode can be made significantly smaller than that of a waveguide core material.

confinement in such a waveguide is achieved by a multilayer reflector on both sides of the waveguide core. As the incoming laser beam is typically Gaussian-like, the power coupling efficiency into the core mode is high due to a spatial mode matching. Moreover, the coupling to such waveguides can be further simplified by choosing the waveguide core size larger than the wavelength of operation. This is possible since the photonic crystal waveguides with low refractive index core can operate in an effectively single mode regime regardless of the core size. As follows from the theory[20] of infinite periodic reflectors with $n_c=n_l$ operating at a wavelength λ_d, effective refractive index of the fundamental TE and TM modes of a corresponding PC waveguide can be designed at will in the range of $0 \leq n_{\text{eff}} < n_l$ by choosing the reflector layer thicknesses as $d_l=\lambda_d/4\sqrt{n_l^2-n_{\text{eff}}^2}$, $d_h=\lambda_d/4\sqrt{n_h^2-n_{\text{eff}}^2}$, and the core layer thickness as $d_c=2pd_l$, (where p is any integer). Moreover, in such waveguides, the field distribution in the core is Gaussian-like for both the TE and TM modes. Thus, by designing the effective refractive index of the fundamental core mode to be equal to that of a plasmon, we can achieve the desired phase matching condition. It should be noted that the proposed design principle holds only approximately in the case of waveguides with a finite reflector. For example, for a wavelength of resonant plasmon excitation $\lambda=640$ nm, the phase matching is achieved when PC waveguide with above mentioned parameters is designed for $n_{\text{eff}}=n_{\text{plasmon}}=1.46$ and $\lambda_d=635$ nm. In what follows we consider this design in detail.

In Fig. 1 in thin red lines we show the dispersion relations of the core guided Gaussian-like modes for two different waveguide designs corresponding to somewhat different effective refractive indexes of the core modes. One can see that at any wavelength of choice the leaky core mode can be easily phase matched by design (black circles) with the plasmon mode (thick blue line) as the effective refractive index of a core mode can be readily tuned and made well below the value of a core refractive index. Intensity of the leaky core mode intensity decreases exponentially fast into the multilayer reflector due to the band gap confinement. Thus, coupling strength between the plasmon and the core mode can be readily controlled by changing the number of reflector layers separating the core from the metal layer. Ultimately, the coupling strength defines the overall length of a sensor device. Finally, if metal film is deposited onto a layer of refractive index n, the effective angle of incidence of the mode onto a metallic layer will be $\arctan(n_{\text{eff}}/\sqrt{n^2-n_{\text{eff}}^2})$ (with respect to a normal to the multilayer), which can be significantly smaller than 90° when the modal effective refractive index n_{eff} is significantly different from both n_l and n_h.

In Fig. 2 we present the band structure of a PCW SPR sensor. All simulations are performed on a complete system that includes both a PC waveguide and a metal layer. Blue regions signify TM polarized bulk states of an infinitely periodic PC reflector. The clear region corresponds to a reflector TM band gap. The thin red line, marked as a PC waveguide+plasmon mode in Fig. 2, is a dispersion relation of a Gaussian-like core mode of the PC waveguide with most of its energy concentrated in the low refractive index core. We have varied the thickness of a gold layer in the range of 25–60 nm and noticed almost no change in the real part of the dispersion relation of the core guided mode. By thick blue lines, marked as plasmon+reflector modes, we show the dispersion relation of the plasmon modes for various thicknesses of the metallic layer. Here, most of the plasmon modal energy is concentrated on the metal-ambient interface, while some of it is present in the reflector. Due to a partial penetration of the plasmon evanescent wave into the reflector, the plasmon dispersion relation appears to be very sensitive to the thickness of the metallic layer. For comparison, by a dotted blue line we show the dispersion relation of a pure plasmon corresponding to an infinitely thick metal layer. Notice that the coupling between the leaky Gaussian-like core mode and the plasmon is evanescent inside of the reflector band gap with the coupling strength decreasing exponentially fast as the number of reflector layers increases.

At the point of the phase matching between dispersion relations of the plasmon and core guide modes, a significant increase in the losses of a core guided mode takes place due

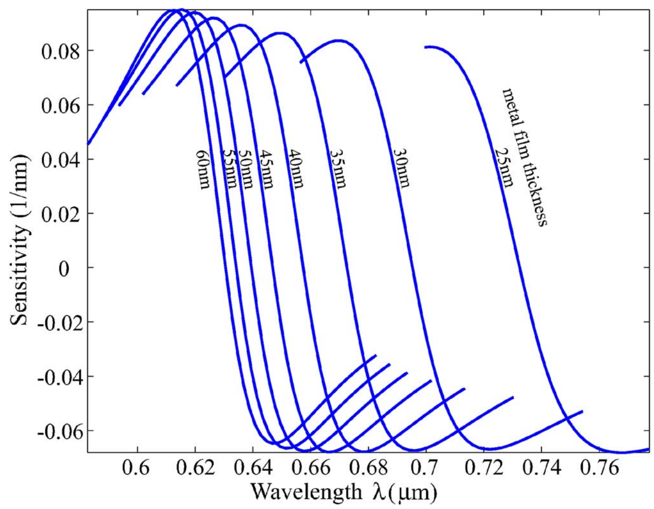

FIG. 3. (Color online) Sensitivity (relative change in the transmitted power) of a proposed PCW SPR sensor to the thickness of a thin biolayer of n_s =1.42 deposited on the top of a gold film.

to plasmon excitation. Since the real part of a plasmon dispersion relation is strongly linked to the dielectric constant of the ambient, the wavelength of phase matching between the waveguide and plasmon modes appears to be very sensitive to changes of ambient conditions. This, in turn, leads to the sensitivity of the waveguide losses at a fixed wavelength near the point of phase matching. In biosensing applications, one uses a sensitivity of the SPR sensor with respect to the ability to detect changes in the thickness (d_s) of a thin biolayer of index n_s (n_s is generally between 1.4 and 1.42 for most biomaterials) deposited on top of a metal film. Such layer might, for example, consist of antigens $(n_s=1.42)$ captured by the antibody-activated metal surface. We define core mode losses as a function of the wavelength and thickness of a biolayer as $\alpha(\lambda,d_s)$. Assuming P_0 to be the power coupled into the core mode of the waveguide, the detected power after the propagation length L will be $P(L,\lambda,d_s) = P_0\exp(-\alpha(\lambda,d_s)L)$. A relative sensitivity can then be defined as $S(\lambda)=[P(L,\lambda,d_s)-P(L,\lambda,0)]/P(L,\lambda,0)/d_s$ (1/nm). Here, the length of an optimally designed sensor is determined by waveguide modal loss. If we choose $L = 1/\alpha(\lambda,d_s)$, the sensitivity for small changes of d_s will be $S(\lambda)=-(\partial\alpha(\lambda,d_s)/\partial d_s)/\alpha(\lambda,d_s)$. In Fig. 3 we present the sensitivity of the proposed PCW SPR sensor for various thicknesses of the metal layer assuming deposition of a nm thick biolayer on a pristine metal surface. In all the implementations sensor length is around 1 cm. As shown in the figure, sensitivity is almost independent of a metal layer thickness. The maximum of sensitivity shifts to shorter wavelengths for thicker metal films following the position of a phase matching point (Fig. 2). Here, the attachment of a 1 nm thick biolayer results in almost 10% change in the transmitted intensity at the wavelength of maximal sensitivity, which is already comparable to what is obtained in bulk SPR biosensing configurations.[2–4] Thus, the proposed PCW SPR biosensor enables to preserve highly sensitive response of a SPR method in essentially compact design. Although the determination of sensor sensitivity requires a detailed consideration of noises, which is not easy in purely theoretical study, our first estimations indicate that even for nonoptimized PCW SPR design these characteristics can be several times greater than that of the traditional waveguide-based SPR schemes with otherwise comparable performance characteristics. The instrumental implementation of PCW SPR, which is now in progress, will enable to perform a direct comparison of sensitivities.

In summary, we introduced the concept of a PCW SPR biosensor, combining a 1D PC planar waveguide with a metal layer. We described conditions of phase matching with a plasmon and showed that they provide highly sensitive response to changes of the thickness of biological films on SPR-supporting metal.

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