Photon Crystal Waveguide-based Surface Plasmon Resonance Biosensor

M. Skorobogatiy , A.V. Kabashin
Géne Physique, École Polytechnique de Montréal, H3C 3A7, Canada
www.photonics.phys.polymtl.ca

Abstract: Resonant excitation of a plasmon by the Gaussian-like leaky core mode of a metal covered 1D photonic crystal waveguide is presented. Applications in sensing and major advantages over the existing waveguide-based schemes are discussed.

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1. Introduction

Propagating at the metal/dielectric interface, surface plasmons are extremely sensitive to changes in the refractive index of the dielectric. This feature constitutes the core of many Surface Plasmon Resonance (SPR) sensors [1]. Typically, these sensors are implemented in the prism geometry to direct p-polarized light through a glass prism and reflect it from a thin metal (Au, Ag) film deposited on the prism facet. The presence of a prism allows phase matching of an incident electromagnetic wave with a plasmonic wave at the metal/ambient dielectric interface at a specific combination of the angle of incidence and wavelength, which is resonantly dependent on the refractive index of an ambient medium. In SPR biosensors, refractive index changes due to biological reactions are controlled by monitoring angular [1], spectral [2] or phase [3] characteristics of the reflected light.

To miniaturize SPR biosensors, several waveguide-based implementations have been introduced [4,5]. In these sensors, one launches the light into a waveguide core and then uses coupling of a guided mode with a plasmonic mode to probe for the changes in the ambient environment. To excite efficiently a surface plasmon the phase matching condition between the plasmon and waveguide modes has to be satisfied. Ideally, one would use a single mode waveguide with all the power traveling in a single Gaussian-like core mode operating near the point of resonant excitation of a plasmon. Near such a point most of the energy launched into the waveguide core could be efficiently transferred into a plasmon mode. Wilkinson [4] used such an approach to provide several compact designs of SPR biosensors based on planar waveguides. However, for such single mode, low index-contrast waveguides the SPR coupling is realized at essentially grazing angles of modal incidence on the metal layer. As follows from the SPR theory, coupling at such grazing incidence angles leads to an inevitable decrease of sensitivity.

To increase angle of modal incidence on the interface high index contrast waveguides could be employed. However, in such waveguides phase matching between plasmon mode and a fundamental waveguide mode is not easy to realize. This is related to the fact that effective refractive index of a waveguide mode is close to that of a core material, which is typically larger than 1.45 due to the materials limitations. Refractive index of a plasmon is close to that of an ambient medium which is typically air n=1 or water n=1.3. Thus, large discrepancy in the effective refractive indexes makes it hard to achieve phase matching between the two modes, with an exception of higher frequencies $\lambda<650$nm where plasmon dispersion relation deviated substantially from that of an analyte material.

Another solution to the phase matching and incidence angle problem is coupling to a plasmon via the high order modes of a multimoded waveguide [5]. Such modes can have significantly lower effective refractive indexes than a waveguide core index. In such a set-up light has to be launched into a waveguide as to excite high order modes some of which will be phase matched with a plasmon mode. As only a fraction of higher order modes are phase matched to a plasmon, then only a fraction of total launched power will be coupled to a plasmon, again reducing sensitivity.

2. Plasmon excitation by the anti-guiding core mode of a photonic crystal waveguide

We consider novel plasmon excitation mechanism using Gaussian-like anti-guiding mode of a Photonic Crystal waveguide. Compared to other waveguide schemes, phase matching of such a mode with a plasmon is possible at any frequency and at steeper angles of incidence, improving the sensitivity and enlarging the sensor probe depth.

In particular, we consider plasmon excitation by a Gaussian-like TM polarized mode of an anti-guiding photonic crystal waveguide (Fig. 1) where light confinement in a lower refractive index core n=1.5 is achieved by the surrounding multilayer reflector (n_h=2.0/n_l=1.5) [6]. As incoming laser beam is typically Gaussian-like, power coupling efficiency into the core mode is high due to good spatial overlap. Moreover, coupling to such waveguides can be further simplified by choosing waveguide core size to be significantly larger than the wavelength of operation. This is possible as anti-guiding waveguides operate in the effectively single mode regime regardless of the core size. Leaky core mode can be easily phase matched with a plasmon mode by design, as effective refractive index of such a mode can be readily tuned between 0 and that of a core. Another interesting aspect of a proposed setup is a possibility of adjusting coupling strength between the core and plasmonic modes, thus designing a sensor length. As penetration of a core mode reduces rapidly into the multilayer reflector, coupling strength between the plasmon and a core mode can be controlled by the number of reflector periods between the core and a metal film.

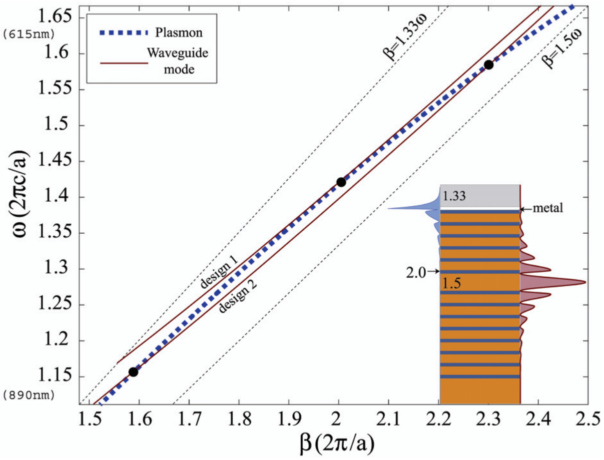

Fig. 1 Band diagrams of the core mode of a PC waveguide (solid) and plasmon (dotted). Two waveguide designs are presented demonstrating that phase matching point (circles) can be chosen at will. Inset – coupler schematic; $/H_y/$ of a plasmon (left) and a core mode of a PC waveguide (right).

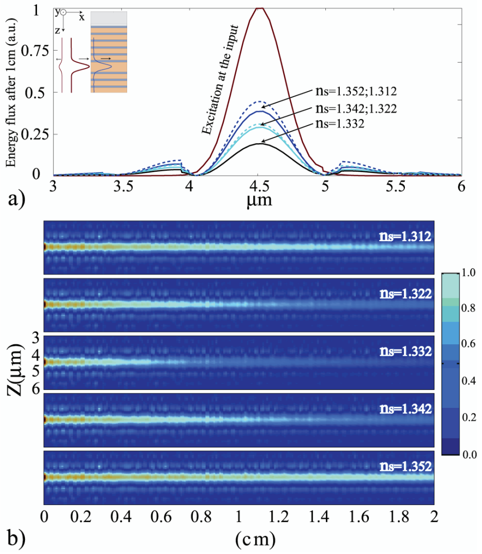

Fig. 2 *Sx* energy flux in a multilayer waveguide for various values of the ambient refractive index: a) distribution across waveguide cross section after 1cm of propagation b) distribution over 2 cm of propagation

To verify mode analysis predictions field propagation was performed. A TM polarized 2D Gaussian beam (H field along Y direction) was launched into a waveguide core from air (inset in Fig. 2(a)). At the air-multilayer interface incoming Gaussian was expanded into the fields of all the guided and leaky, and some evanescent multilayer modes (60 altogether), plus the field of a reflected Gaussian by imposing continuity of the Z and Y field components at the interface. Optimal coupling of 71% of an incoming power into the Gaussian-like core mode was achieved with a Gaussian beam of waist $0.8d_c$ centered in the middle of a waveguide core. Reflection from the air-multilayer interface was less than 3%. In Fig. 2(b) distribution of an X component of the energy flux S_x in a propagating beam is shown for various values of an ambient refractive index. From the figure it is clear that beam propagation loss is very sensitive to the changes in the ambient refractive index. To quantify sensitivity of our design in Fig. 2(a) we present S_x distribution across a waveguide cross section after 1cm of beam propagation. From this figure we calculate that change in the integrated energy flux as a function of the ambient index deviation from 1.332 of a pure water can be approximated as $\Delta P/P_{1.332} \sim 60 \cdot (n_a - 1.332)$; thus, an absolute variation of 10^{-4} in the ambient refractive index would lead to ~1% variation in the transmitted power which is readily detectable.

Another set of simulations, especially useful for biodetection, assumes that refractive index of water stays unchanged, while on the top of a metal layer one deposits a very thin layer of thickness d_{bio} of a biological material with refractive index n=1.42. In this case proposed setup exhibits sub-nm sensitivity in the change of d_{bio}.

3. References

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