Plasmon excitation by the Gaussian-like core mode of a photonic crystal waveguide or a fiber

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Abstract: Resonant excitation of a plasmon by the Gaussian-like leaky core mode of a metal covered 1D photonic crystal waveguide or fiber is presented. Application in sensing and comparison with the existing waveguide-based schemes is 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. Typically, these sensors are implemented in the Kretschmann-Raether 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 [1]. 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. Mathematically, phase matching condition is expressed as an equality between a plasmon wavevector and a projection of a wavevector of an incident wave along the interface. Since plasmon excitation condition depends resonantly on the value of the refractive index of an ambient medium within 200-300nm from the interface, the method enables, for example, detection, with unprecedented sensitivity, of biological binding events on the metal surface [2, 3]. The course of a biological reaction can then be followed by monitoring angular [2, 3], spectral [4] or phase [5] characteristics of the reflected light.

To miniaturize SPR biosensors, several waveguide and fiber based implementations have been introduced [4, 6]. 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, which mathematically amounts to the equality between their modal propagation constants. Ideally, one would use a single mode waveguide (SMW) with all the power travelling 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 [6] 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 (for example, for the waveguides[6] angle of modal incidence exceeds 85°).

As follows from the basic SPR theory [7], coupling at such grazing incidence angles leads to an inevitable decrease of sensitivity of an SPR method.

In principle, to increase angle of modal incidence on the interface high index contrast waveguides could be employed. However, quick inspection of a corresponding band diagram (Fig. 1(a)) shows that 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 such a mode is close to the refractive index of a core material, which is typically larger than 1.45 due to the materials limitations. Refractive index of a plasmon is close to the refractive index of the 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 (\( \lambda < 650\text{nm} \)) 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[8] (MMW). As seen from the plot of their dispersion relations (Fig. 1(b)), 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 plasmon.

In what follows, we demonstrate efficient SPR excitation with a Gaussian-like core mode of a PC waveguide. We show that such configuration makes the plasmon excitation possible at steeper angles of modal incidence, and lower frequencies, improving the sensitivity and enlarging the probe depth of a sensor.

![Figure 1](image.png)

**Fig. 1.** Band diagrams of a) a SMW mode (solid thin) and a plasmon (solid thick). Inset - coupler schematic: $|H_\text{y}|^2$ of a plasmon (left) and a SMW mode (right). b) the MMW modes (solid thin) and a plasmon (solid thick). Inset - coupler schematic: $|H_\text{y}|^2$ of a plasmon (left) and a high order MMW mode (right) at the phase matching point (black circle). c) Band diagrams of the core mode of a PC waveguide (solid thin) and a plasmon (solid thick). Two waveguide designs are presented demonstrating that phase matching point (black circles) can be chosen at will. Inset - coupler schematic: $|H_\text{y}|$ of a plasmon (left) and a Gaussian-like core mode of a PC waveguide (right).

2. **Plasmon excitation by a core mode of a Bragg waveguide**

In what follows we consider plasmon excitation by a Gaussian-like TM polarized mode of an anti-guiding photonic crystal waveguide (Fig. 1(c)) where light confinement in a lower refractive index core is achieved by a surrounding multilayer reflector. As incoming laser beam is typically Gaussian-like, power coupling efficiency into the core mode is high due to good spatial mode matching. 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 antiguiding 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 to be well below the value of a core index. Another important aspect of a proposed setup is a freedom of adjusting coupling strength between the core and plasmonic modes. As penetration of a leaky mode reduces exponentially fast into the multilayer reflector, coupling strength between the plasmon and core modes can be controlled by changing the number of reflector layers between the core and a metal film.

We would like to note that although in this paper we consider planar geometries, proposed plasmon excitation setup can be equally well implemented in fiber geometries. For example, metallized Bragg fiber with a filled lower index core can be used to implement radial index distribution of Fig. 1(c). In fact, we have recently succeeded in developing fabrication technique for all-polymer Bragg fiber fabrication [10] and we are currently implementing proposed plasmonic coupling setup using home drawn all-polymer Bragg fibers Fig. 2.

Photonic crystal waveguide under consideration consists of 27 alternating layers with indexes $n_b = 2.0$, $n_l = 1.5$. Core layer is number 12 with index $n_c = n_l$. Analyte (first cladding) is water $n_a = 1.332$ bordering
a 50nm layer of gold. Substrate index is 1.5. Theory of the planar PC waveguides with infinite reflectors where $n_c = n_l$, predicts that for a design wavelength $\lambda_d$ effective refractive index of the fundamental TE and TM modes of a PC waveguide can be designed at will $0 \leq n_{eff} < n_l$ by choosing the reflector layer thicknesses as $d_l \sqrt{n_l^2 - n_{eff}^2} = d_h \sqrt{n_h^2 - n_{eff}^2} = \lambda_d/4$, and a core layer thickness as $d_c = 2d_l$. Moreover, for this choice of $n_c$ field distribution in the core is Gaussian-like both for TE and TM modes [9]. By choosing effective refractive index of a core mode to be that of a plasmon a desired phase matching condition is achieved. For a waveguide with a finite reflector same design principle holds approximately. Thus, for a wavelength of operation $\lambda = 640nm$ phase matching is achieved when PC waveguide above is designed for $n_{eff} = 1.46$ with $\lambda_d = 635nm$.

Near the phase matching point, fields of a core guided mode contain strong plasmon contribution (inset of Fig. 3(a)). As plasmon exhibits very high propagation loss, the loss of a core mode (lines with circles in Fig. 3(a)) will also exhibit sharp increase near the phase matching point. For comparison, dashed line at the bottom of Fig. 3(a) presents the loss of a core guided mode in the absence of a metallic layer on top of a multilayer. When analyte refractive index is varied plasmon dispersion relation changes leading to a shift in the position of the phase matching point with a core guided mode. Thus, at a given frequency, loss of a core guided mode will vary dramatically with changes in the ambient refractive index. Field distribution in a plasmon mode propagating on the top of a PC multilayer shows some penetration into the multilayer and losses almost independent of the analyte refractive index (line with crosses in Fig. 3(a)), for comparison, dashed line at the top of Fig. 3(a) corresponds to the plasmon losses in the absence of a multilayer.

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. 3(b)). 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 0.8$d_c$ centered in the middle of a waveguide core. Reflection from the air-multilayer interface was less than 3%.

In Fig. 3(c) 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. 3(b) we present $S_x$ distribution across a waveguide crosssection 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 $\Delta P/P_{1.332} \approx 60|n_a - 1.332|$; thus, an absolute variation of 0.001 in the ambient refractive index would lead to a $\sim 6\%$ variation in the transmitted power which is readily detectable. Similar calculations can be carried out assuming that refractive index of water stays unchanged, while on the top
of a metal layer one deposits a very thin layer of thickness \( d_{\text{bio}} \) of a biological material with refractive index 1.42. In this case sensitivity of the same design will be \( \Delta P/P_{1.332} \approx 0.05d_{\text{bio}}/1\text{nm} \); thus, adding 1nm of a bio-layer would change the transmitted intensity by \( \sim 5\% \).

3. Conclusion

In conclusion, we have presented a novel approach to design of a waveguide based SPR sensor, where Gaussian-like mode of an effectively single mode PC waveguide can be phase matched at any desirable wavelength to a surface plasmon propagating on the top of such a waveguide. Moreover, in resonance, modal incidence angle onto a metallic layer is not grazing resulting in enhanced sensitivity. Coupling strength between the waveguide core and plasmon modes can be varied by changing the number of intermediate reflector layers, thus enabling design of an overall sensor length.

4. References