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

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Abstract: We describe resonant excitation of a plasmon by the Gaussian-like leaky mode of an effectively single mode photonic crystal (PC) waveguide. Plasmon is phase matched by design with a waveguide mode, and travels in a metallic layer on the top of a PC waveguide. We observe that small changes in the ambient refractive index just outside the metal film lead to strong variations in the losses of a waveguide core mode, making such a device a good candidate for compact sensor applications. Using low refractive index core PC waveguides makes phase matching between the plasmon and PC core mode relatively easy to enforce at any wavelength of operation as modal effective refractive index in such waveguides can be readily varied in a wide range.

OCIS codes: (130.6010) Sensors; (240.6680) Surface plasmons; (230.1480) Bragg reflectors; (230.4170) Multilayers.

References and links

1. V.M. Agranovich, D.L. Mills. Surface Polaritons - Electromagnetic Waves at Surfaces and Interfaces, (North-Holland, Amsterdam, 1982).
2. E. Kretschmann, H. Raether, “Radiative decay of non radiative surface plasmons excited by light,” Naturforschung A **23**, 2135 (1968).
3. B. Liedberg, C. Nylander, I. Lundstrom, “Surface plasmon resonance for gas detection and biosensing,” Sens. Actuators B **4**, 299 (1983).
4. J.L. Melendez, R. Carr, D.U. Bartholomew, K.A. Kukanskis, J. Elkind, S.S. Yee, C.E. Furlong, R.G. Woodbury, “A commercial solution for surface plasmon sensing,” Sens. Actuators B **35**, 212 (1996).
5. L.M. Zhang and D. Uttamchandani, “Optical chemical sensing employing surface plasmon resonance,” Electron. Lett. **23**, 1469 (1988).
6. A.V. Kabashin and P. Nikitin, “Surface plasmon resonance interferometer for bio- and chemical-sensors,” Opt. Commun. **150**, 5 (1998).
7. A.N. Grigorenko, P. Nikitin, and A.V. Kabashin, “Phase jumps and interferometric surface plasmon resonance imaging,” Appl. Phys. Lett. **75**, 3917 (1999).
8. P. Schuck, “Use of surface plasmon resonance to probe the equilibrium and dynamic aspects of interactions between biological macromolecules,” Annu. Rev. Biophys. Biomol. Struct. **26**, 541 (1997).
9. C.P. Lavers, J.S. Wilkinson, “A waveguide-coupled surface-plasmon sensor for an aqueous environment,” Sens. Actuators B **22**, 75 (1994).
10. R. Harris and J.S. Wilkinson, “Waveguide surface plasmon resonance sensors,” Sens. Actuators B **29**, 261 (1995).
11. M.N. Weiss, R. Srivastava, and H. Grogner, “Experimental investigation of a surface plasmon-based integrated-optic humidity sensor,” Electron. Lett. **32**, 842 (1996).
12. J. Homola, J. Ctyroky, M. Skalky, J. Hradiliva, and P. Kolarova, “A surface plasmon resonance based integrated optical sensor,” Sens. Actuators B **39**, 286 (1997).

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13. J. Dostalek, J. Ctyroky, J. Homola, E. Brynda, M. Skalsky, P. Nekvindova, J. Spirkova, J. Skvor, and J. Schrofel, "Surface plasmon resonance biosensor based on integrated optical waveguide," Sens. Actuators B **76**, 8 (2001).
14. A.K. Sheridan, R.D. Harris, P.N. Bartlett, and J.S. Wilkinson, "Phase interrogation of an integrated optical SPR sensor," Sens. Actuators B **97**, 114 (2004).
15. R.C. Jorgenson and S.S. Yee, "A fiber-optic chemical sensor based on surface plasmon resonance," Sens. Actuators B **12**, 213 (1993).
16. A. Trouillet, C. Ronot-Trioli, C. Veillas, and H. Gagnaire, "Chemical sensing by surface plasmon resonance in a multimode optical fibre," Pure Appl. Opt. **5**, 227 (1995).
17. J. Ctyroky, J. Homola, P.V. Lambeck, S. Musa, H.J.W.M. Hoekstra, R.D. Harris, J.S. Wilkinson, B. Usievich, and N.M. Lyndin"Theory and modelling of optical waveguide sensors utilising surface plasmon resonance," Sens. Actuators B **54**, 66 (1999).
18. M. Weisser, B. Menges, and S. Mittler-Neher, "Refractive index and thickness determination of monolayers by multi mode waveguide coupled surface plasmons," Sens. Actuators B **56**, 189 (1999).
19. B.D. Gupta, and A.K. Sharma, "Sensitivity evaluation of a multi-layered surface plasmon resonance-based fiber optic sensor: a theoretical study," Sens. Actuators B **107**, 40 (2005).
20. M. Skorobogatiy, "Transverse lightguides in microstructured optical fibers," Opt. Lett. **30**, 2991 (2005).
21. H. Shin, M.F. Yanik, S.H. Fan, R. Zia, and M.L. Brongersma, "Omnidirectional resonance in a metal-dielectric-metal geometry," Appl. Phys. Lett. **84**, 4421 (2004).
22. H. Shin and S.H. Fan, "All-angle negative refraction for surface plasmon waves using a metal-dielectric-metal structure," Phys. Rev. Lett. **96**, 073907 (2006).
23. A. Karalis, E. Lidorikis, M. Ibanescu, J.D. Joannopoulos, and M. Soljacic, "Surface-plasmon-assisted guiding of broadband slow and subwavelength light in air," Phus. Rev. Lett. **95**, 063901 (2005).
24. S.G. Johnson, M. Ibanescu, M. Skorobogatiy, O. Weiseberg, T.D. Engeness, M. Soljacic, S.A. Jacobs, J.D. Joannopoulos, and Y. Fink, "Low-Loss Asymptotically Single-Mode Propagation in Large Core OmniGuide Fibers," Opt. Express **9**, 748 (2001).

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1. Introduction

Propagating at the metal/dielectric interface, surface plasmons [1] 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 [2]. 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 [3]. The course of a biological reaction can then be followed by monitoring angular [3, 4], spectral [5] or phase [6, 7] characteristics of the reflected light. However, the high cost and large size of commercially available systems [8] makes them useful only in a laboratory, while many important field and other applications remain out of the applicability of the method.

To miniaturize SPR biosensors, several waveguide-based implementations have been introduced [9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19]. 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. Such an approach based on planar waveguides has been indeed demonstrated in the visible to provide several compact designs of SPR biosensors [9, 10, 11, 12, 13, 14]. However,

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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 basic SPR theory [1], coupling at such grazing incidence angles leads to an inevitable decrease of sensitivity of an SPR method. Moreover, due to limitation to the lowest attainable value of the refractive index of waveguide materials, such sensors were demonstrated mostly in the visible where phase matching condition is easiest to enforce. 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 indices makes it hard to achieve phase matching between the two modes, with an exception of higher frequencies ($\lambda <$650nm) 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[15, 16, 17, 18, 19] (MMW). As seen from the plot of their dispersion relations (Fig. 1(b)), such modes can have significantly lower effective refractive indices 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 this paper, we demonstrate efficient SPR excitation with the lowest loss TM polarized Gaussian-like core mode of an antiguiding photonic crystal waveguide. The term antiguiding generally refers to the transmission mechanism where effective refractive index of a propagating mode is smaller than that of a waveguide cladding. Such unusual modes are called leaky modes as outside of a waveguide core they do not exhibit a traditional evanescent decay into the cladding, but rather they radiate slowly (leak) into the cladding. Examples of antiguiding systems are gas filled capillaries, hollow core Bragg fibers [24], and air core planar photonic crystal waveguides. We show that antiguiding design integrates advantages of both single mode and multimode schemes. Indeed, when the lowest loss mode of an antiguiding PC waveguide is used over sufficient device length, such waveguide can be considered as effectively single mode at any frequency within the bandgap due to efficient modal discrimination by radiation losses. Coupling from an external laser source into the lowest loss mode is very efficient as this mode can be made Gaussian-like even for TM polarization [20]. Moreover, dispersion relation and effective propagation angle of such an antiguided mode is easy to vary by changing the properties of a confining Photonic Band Gap reflector. This allows phase matching with plasmon at any desired wavelength for any analyte material. We also believe that variants of a proposed metal-dielectric periodic system can possess other hidden functionalities that can be further exploited for building efficient waveguide based sensors; for example, omnidirectionality, negative refractive indices, and gapless guidance in the low refractive index cores have been recently demonstrated in multilayered metal-dielectric systems [21, 22, 23].

2. Plasmon excitation by a Gaussian-like core mode

In what follows we consider plasmon excitation by a Gaussian-like TM polarized mode of an antiguiding 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

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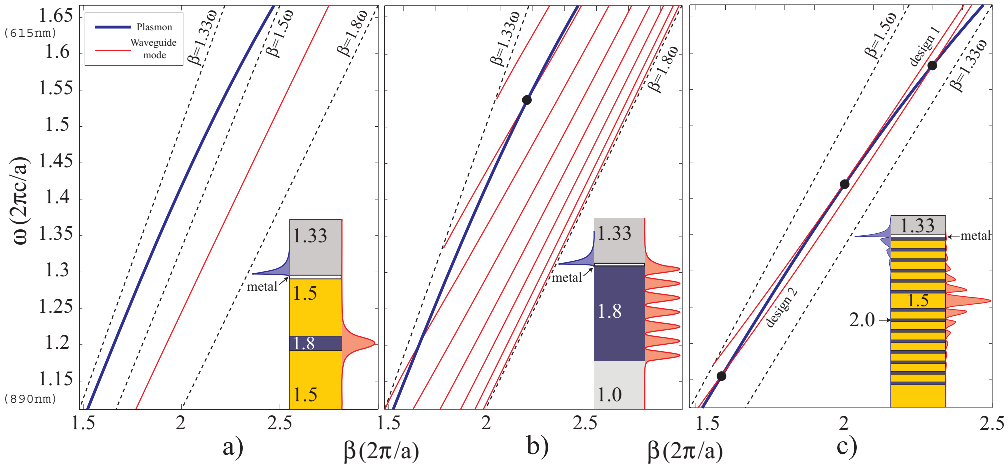

Fig. 1. Band diagrams of a) a SMW mode (red) and a plasmon (blue). Inset - coupler schematic; $|H_y|^2$ of a plasmon (left) and a SMW mode (right). b) The MMW modes (red) and a plasmon (blue). Inset - coupler schematic; $|H_y|^2$ of a plasmon (left) and a high order MMW mode (right) at the phase matching point (black circle). c) The core mode of a PC waveguide (red) and plasmon (blue). Two waveguide designs are presented demonstrating that phase matching point (black circles) can be chosen at will. Inset - coupler schematic; $|H_y|$ of a plasmon (left) and a Gaussian-like core mode of a PC waveguide (right).

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 fibers with filled lower index cores can be used to implement radial index distribution of Fig. 1(c). Also, microstructured holey fibers operating in a band gap regime with metallized holes on the periphery could be employed, further investigation of these sensor geometries is currently underway.

Photonic crystal waveguide under consideration consists of 27 alternating layers with indices $n_h = 2.0$, $n_l = 1.5$. Core layer is number 12 with index $n_c = n_l$. Analyte (first cladding) is water $n_s = 1.332$ bordering a 50nm layer of gold. Substrate index is 1.5. Theory of the planar PC waveguides with infinite reflectors where $n_c = n_l$ (see [20, 24] and references of thereof), predicts that for a design wavelength λ_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 [20]. 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

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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. 2). As plasmon exhibits very high propagation loss, the loss of a core mode (lines with circles in Fig. 2) will also exhibit sharp increase near the phase matching point. For comparison, dashed line at the bottom of Fig. 2 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. 2), for comparison, dashed line at the top of Fig. 2 corresponds to the plasmon losses in the absence of a multilayer.

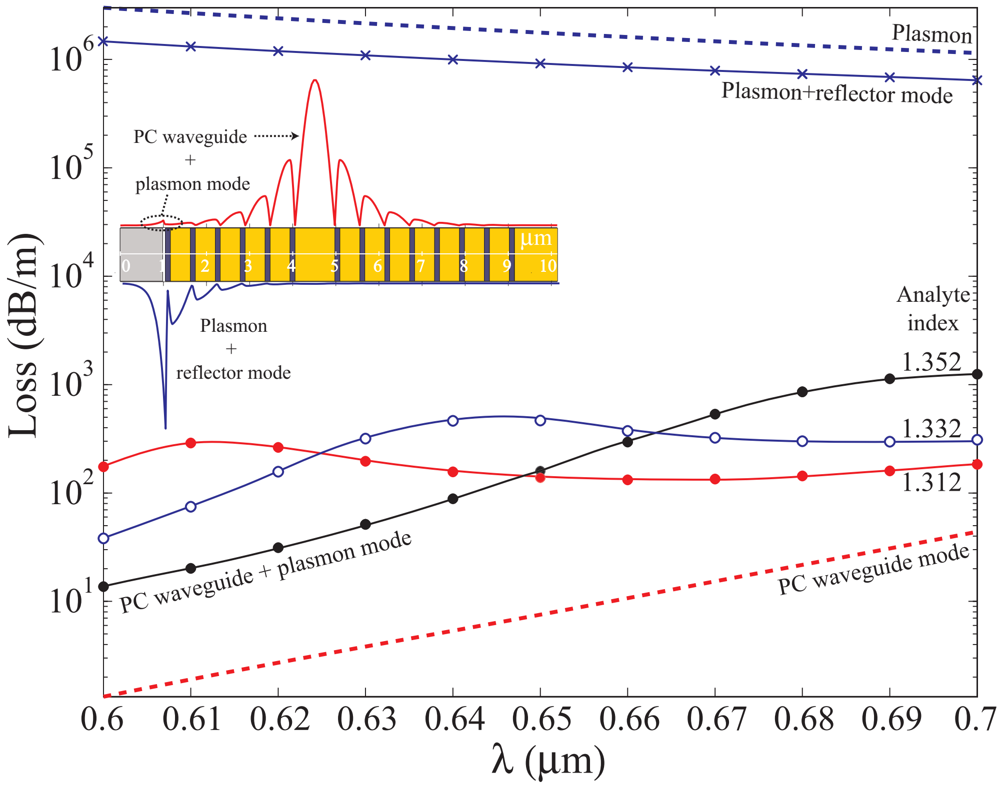

Fig. 2. Solid lines with circles - loss of a waveguide mode near the phase matching point with a plasmon for different values of an ambient refractive index. Inset: $|H_y|$ field distribution in the waveguide and plasmonic modes.

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(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

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from the air-multilayer interface was less than 3%.

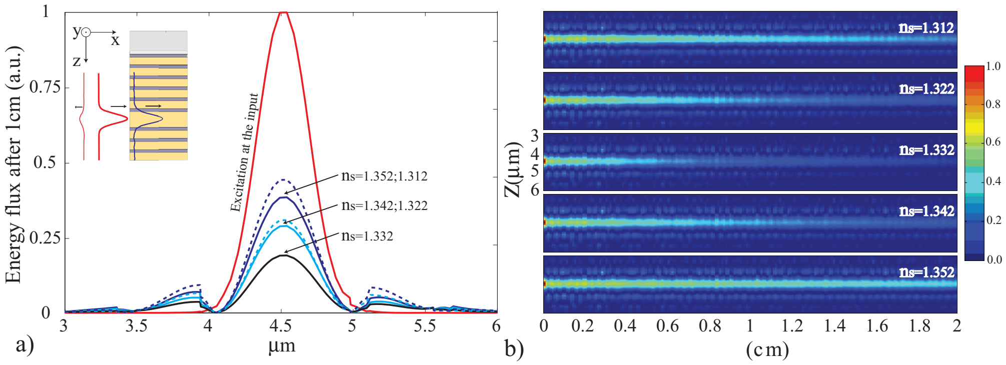

Fig. 3. S_x energy flux in a multilayer waveguide for various values of the ambient refractive index. a) distribution across waveguide crossection after 1cm of propagation b) distribution over 2cm of propagation.

In Fig. 3(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. 3(a) we present S_x distribution across a waveguide crossection 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 $\Delta P/P_{1.332} \simeq 60 \cdot |n_a - 1.332|$; 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_{bio} of a biological material with refractive index 1.42. In this case sensitivity of the same design will be $\Delta P/P_{1.332} \simeq 0.05 \cdot d_{bio}/1nm$; 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.