Plasmonic photonic-crystal slab as efficient optical sensor

A. V. Baryshev,[1,2] A. M. Merzlikin,[3,4] M. Inoue[4]

[1]Electronics-Inspired Interdisciplinary Research Institute
Toyohashi University of Technology
Toyohashi 441-8580, Aichi, Japan
[2]Ioffe Physico-Technical Institute
St. Petersburg 194021, Russia
email: baryshev@erc.tut.ac.jp
[3]Institute for Theoretical and Applied Electromagnetics
Moscow 125412, Russia
email: a.m.merzlikin@gmail.com
[4]Toyohashi University of Technology
Toyohashi 441-8580, Aichi, Japan
email: inoue@ee.tut.ac.jp

Abstract

A one-dimensional photonic crystal terminated by a noble metal film–plasmonic photonic-crystal slab–has been analysed for the optical response at variation of the dielectric permittivity of an analyte. Sensor based on such a slab exhibited an enhanced sensitivity and a larger qualitative robustness than that of conventional surface-plasmon and Bloch surface wave sensors. In particular, the responses of considered sensor are a more tolerant to a variation of the angle of incidence and the sensor's structural parameters.

1. Introduction

Optical sensors where refractive index sensing is achieved by dispersion of surface plasmon resonance (SPR) are widely applied for detecting tiny variations in biological and chemical analytes [1]. Another effective approach to high-resolution sensing is usage of the Bloch surface wave resonance (SWR) [2] excited on a surface of dielectric multilayer (1D photonic crystals, PhC) [3], we refer to this principle as conventional SWR sensing [4]. The binding event is well detectable only in close vicinity of the sensor surface since the SPR-generated near field is pinned to it and is not extended into an analyte. However, for diseases detection on early stages and for probing negligible changes within an analyte, sensors with (i) higher sensitivity and (ii) allowing to screen an extended volume can be of great value. Both (i) and (ii) might be satisfied by conventional SWR-based sensors. However, the experimental accuracy for SWR excitation must be extremely high, and maximum light-material interaction is observed close to total internal reflection (TIR). Can the mentioned above limitations of the optical sensors be solved while keeping their advantages? Apparently, a sensor with a new functioning principle is necessary to satisfy the mentioned issues which will have (iii) a larger qualitative robustness–a sensor with high performance margins at lower requirements to structural parameters and measurement tolerance.

In this work we demonstrate sensing performances of a structure comprising a 1D PhC and a plasmonic layer of a thin gold film (the PPhC sensor, hereafter). The analysis was done for the p polarization. Results showed that the PPhC sensor is surpassing the sensitivity of the SPR-based sensors and performance margins of the conventional SWR-based ones.

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2. Analysis of sensing performance

Figure 1(a) shows a PPhC sensor together with its main elements and a schematic distribution of resonant wave amplitude. We will discuss below that light absorption in Au due to SPR can indicate existence of a surface wave in reflection spectra.

The distinctive feature of the PPhC sensor is that a spectral line (its amplitude and width) associated with a p-polarized SWR from the periodical structure is not restricted by the dispersion of Au and can be significantly narrower (a resonance have a higher quality factor, in other words) than that of SPR, see Fig. 1(b). Indeed, the quality factor of the p-polarized SWR depends on number of unit cells in a PPhC, the quality of interfaces between layers composing it, and the absorption in Au. We have chosen a PhC with eleven binary unit cells because it is feasible from manufacturing point of view; also it is practicable for spectroscopy. Further increase for the number of and a complexity of the unit cell do not have principal importance for the present analysis.

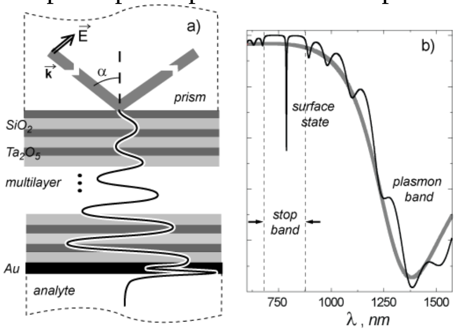

Fig. 1: (a) Geometry of analysis with a schematic distribution of the E-field for a resonant wave. (b) P-polarized reflection spectra of a 40-nm-thick Au layer (gray) and a PPhC sensor (black) terminated by the same Au layer. Spectra plotted in Fig. 1(b) were calculated for a PPhC of $(Ta_2O_5/SiO_2)^{11}/Au$ at $\alpha = 63.3°$, $D = 30$ nm.

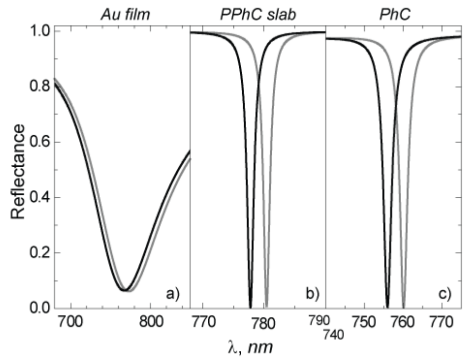

Fig. 2: (a)–(c) Reflectance from a SPR-based, PPhC and SWR-based sensor respectively. Spectra illustrate the change in reflectance at a variation of the refractive index $\Delta n = 10^{-3}$. (a) Response of an SPR-based sensor; the angle of incidence was selected such that SPR was observed in a range of SWR excitation. Plots (b) and (c) are for optimized sensors. Calculation parameters: (a) single Au with $D = 44$ nm, $\alpha = 67°$; (b) PPhC with $D = 13$ nm, $\alpha = 62.2°$; (c) the $(Ta_2O_5/SiO_2)^{11}$ multilayer with an uniformly introduced loss of $\varepsilon'' = 9.5{\cdot}10^{-4}$, $\alpha = 61.824°$ corresponds to TIR.

In fact, the principle of SPR (SWR) sensing is that the absorption (resonant attenuation) peak shifts as the dielectric constant of an analyte changes. This is measured, for example, as a change of the reflected light intensity. Provided that a sensor has a high-Q resonance with a same or even slightly less spectral shift, one can expect a higher sensitivity, see Fig. 2. Here, as an example of analyte for testing the sensors' performances, we have considered water with a variation of the nondispersive refractive index from 1.33 to 1.331 ($\Delta n = 10^{-3}$). One-dimensional photonic crystal comprised eleven unit cells–$(Ta_2O_5/SiO_2)^{11}$ multilayer. Such multilayer was terminated by a single Au layer or Au/ SiO_2 layer. Thicknesses (refractive indices) of dielectric layers were fixed: 148 nm (2.1) and 260 nm (1.46) for Ta_2O_5 and SiO_2 respectively. Dispersion of Au was taken from *Handbook of Optical Constants of Solids* by E. D. Palik (Academic Press, 1991). Thickness of Au layer was a varying parameter when studying the SPR-based and PPhC sensors. For analysis of the SWR-based sensor, absorption (in terms of imaginary part of dielectric permittivity ε'') was uniformly introduced into the $(Ta_2O_5/SiO_2)^{11}$ multilayer; ε'' was a varying parameter in a range of $2{\cdot}10^{-6}$– $4{\cdot}10^{-3}$. Coupling prism had a nondispersive refractive index of 1.51 close to that of the BK7 glass in the studied spectral of 700–1500 nm.

In Fig. 2(a) parameters of the SPR sensor were adjusted for observation of the plasmon band in the same range as that for SWR; these parameters were not optimal in terms of sensitivity. For optimized parameters [absorption (thickness of Au (D) for PPhC or imaginary part of dielectric permittivity ε'' for PhC), angle of incidence (α) and wavelength (λ)], a maximum change in reflectance, $\Delta R_{max} = R_{n=1.33} - R_{n=1.331}$, was about 0.4, 0.97 and 0.97 for the SPR-based, PPhC and SWR-based sensors, respectively. Large ΔR_{max} shows the principal advantage of the SWR-based sensing.

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It is well known that theoretically predicted increase of sensitivity can result from unreasonable idealizations of the system. That is why a question appears: How stable (robust) is the response from a sensor at fluctuations of their structural parameters of *D*, ε'', and measurement tolerance defined by the range of incident angles Δα?

In order to compare the PPhC sensor with the SPR and conventional SWR counterparts the maximum of reflectance ΔR_{max} was evaluated when searching in a spectral range of 700–1500 nm (700–3000 nm for SPR) through *D*, α and ε''. Figure 3 summarizes data on the qualitative robustness of the sensors. The SPR-based sensor (plot **a**) showed $\Delta R_{max} = 0.4$, and a contour line corresponding to a level of ΔR = 0.3 was significantly limited by α and *D*. The conventional SWR-based sensor (plot **b**) exhibited a TIR-limited contour line for maximal operating margins of ΔR = 0.9 at Δα = 0.1°. This contour line was also considerably constrained by ε''; note that practical realization of a sensor with through-structure, fine-tuned ε'' is difficult. As for the PPhC sensors (plot **c** and **d**), high performance margins were significantly extended; see a contour line of ΔR = 0.9. One can see that the PPhC sensors without and with a 50-nm-thick SiO_2 layer had a value of Δα = 0.83° and Δα = 1.69° at ΔR = 0.87; let us compare these margins with that of the conventional SWR–Δα = 0.13° at ΔR = 0.87 and SPR–Δα = 0.71° at ΔR = 0.3.

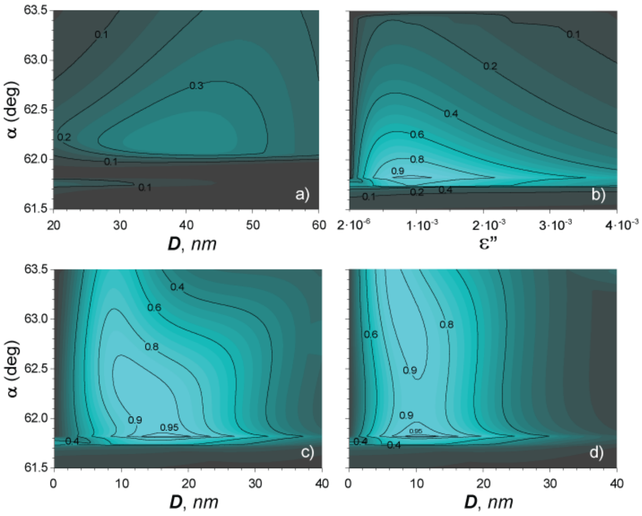

Fig. 3: (a)–(d) Diagrams illustrating the robustness of an SPR-, an SWR-based and two PPhC sensors, respectively. Solid contour lines show sensitivity levels (maximum ΔR in corresponding wavelength ranges) at $\Delta n = 10^{-3}$, when varying parameters of the sensors. (c) and (d)–PPhC sensors without and with a 50-nm-thick SiO_2 layer covering the Au layer respectively. (a) Scanned spectral range of 0.7–3 μm; (b)–(d) Scanned spectral range of 0.7–1.5 μm. For given absorption (thickness of Au (*D*) for PPhC or imaginary part of dielectric permittivity ε'' for PhC) and angle of incidence α, we calculated differential spectra of $\Delta R = R_{n=1.33} - R_{n=1.331}$ corresponded to the refractive index of analyte 1.33 and 1.331, and after that maxima ΔR_{max} with respect to wavelength was found.

3. Conclusion

Demonstrated PPhC sensor exhibited the better sensitivity than that of the SPR-based sensor. This surpassing performance results from the spectral shift of the reflection peak associated with excitation of the high-Q resonant surface wave. Moreover, high-performance characteristics of the PPhC sensor are tolerant to wider variation of the angle of incidence if one compares with the conventional SWR-based sensor, i.e. the PPhC sensor is more robust.

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