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Theoretical Investigation of Light-Guiding Structures of Surface Plasmon Resonance Waveguide Sensors

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Abstract Two waveguide structures are numerically investigated for improved performance of the SPR waveguide sensors: one is the waveguide supporting higher-order modes and the other is the waveguide with an embedded core.

1 Introduction

Surface plasmon resonance (SPR) waveguide sensors have been studied for the integration into optical circuits. Note that theoretical studies of the SPR waveguide sensors were limited to two-dimensional (2-D) models [1]-[4]. Very recently, practical three-dimensional (3-D) models of the SPR waveguide sensors have been analyzed, in which the effect of the metal width on the sensing characteristics has been revealed [5].

The purpose of this article is to investigate two waveguide structures for the SPR sensor with strong absorption using the 3-D semi-vectorial beam-propagation method (BPM): one is the waveguide supporting higher-order modes in the horizontal direction and the other is the waveguide with an embedded core. It is shown that these two waveguide structures are effective in increasing the absorption at the resonance wavelength, leading to improved measurement precision.

2 Discussion

Fig. 1 illustrates the configuration of the SPR waveguide sensor to be studied. The adsorbed layer is inserted between the metal and analyte layers for the sensor operation around $\lambda = 0.6$ μm, where these layers are centered on the waveguide ($t_{\rm m} = 0.045$ μm and $t_{\rm ad} = 0.02$ μm). The sensing length with the metal is 200 μm. The refractive indices are chosen to be $n_{\rm co} = n_{\rm ad} = 1.47$ and $n_{\rm sub} = 1.46$. The metal is selected to be Au ($n_{\rm m} = 0.131 - j3.654$ at 0.6328 μm) and the dispersion property of its refractive index is taken into account using the Drude model dielectric function [5]. We excite the input waveguide with the field of the TM mode. Varying the operating wavelength, we evaluate the output power from the waveguide, which depends on the refractive index of an analyte $n_{\rm a}$. Water is used as the analyte, which is sufficiently thick (1 μm) to yield a converged solution.

First, we investigate the dependence of the core width $d_{\rm w}$ on the sensing characteristics, which cannot be treated in the 2-D model. The metal strip is wide enough to cover the core region. The core thickness is deliberately chosen to be $d = 2$ μm throughout this article so that the single-mode operation in the y direction may be maintained. This is based on the fact that the thick core supporting higher-order modes in the y direction gives rise to a broadening of the absorption dip in the wavelength response, when compared with the single-mode case [6].

Fig. 2 shows the output power of the multimode case ($d_{\rm w} = 12$ μm) as a function of wavelength for $t_{\rm b} = 0$ (semi-embedded core) and $n_{\rm a} = 1.332$. For reference, the results of the single-mode case ($d_{\rm w} = 2$ μm [5]) and the 2-D case ($d_{\rm w} = w = \infty$) are also included. The inset shows the enlarged view around the absorption peaks. It is seen that the output power for the multimode case is reduced when compared with the single-mode case. This is because the wide metal strip increases the absorption of light. It is interesting to note that the dips in the wavelength response are not broadened even for the higher-order modes. The slightly less absorption of the higher-order modes compared with the fundamental mode stems from the extension of the higher-order mode field. In Fig. 2, an appreciable difference can be found between the 3-D and 2-D results. Therefore, the 3-D analysis is indispensable for the accurate modeling of the practical model of the waveguide sensor.

Although the use of the multimode waveguide with the wide core has been shown effective for the strong absorption, the amount of the analyte increases in order for the analyte to cover the wide metal region. To achieve strong absorption maintaining a single-mode waveguide with a narrow metal region [5], we next investigate the characteristics of the waveguide sensor with an embedded core. Note that the effect of the embedded core is similar to that of a buffer layer placed between the core and the metal layer [2]-[4]. Theoretical investigations on this subject were, however, restricted to 2-D models. Although the embedded core was used for the ion-exchanged graded-index waveguide in [7], its effect was not explicitly presented. Here, we treat the 3-D structure with the step-index single-mode waveguide for $d_\mathrm{w} = 2\ \mu$m and $w = 3\ \mu$m. The effect of the embedded core is illustrated in Fig. 3, in which the inset shows the enlarged results around the absorption peaks. It can be seen that the output power for $t_\mathrm{b} = 0.3\ \mu$m is reduced by more than 4 dB, compared with the semi-embedded case ($t_\mathrm{b} = 0$). This reduction of the power results from the strong coupling between the waveguide and surface plasmon polariton modes.

3 Conclusions

We have analyzed the practical 3-D structures of the SPR waveguide sensors using the BPM. It is shown that the waveguide supporting higher-order modes in the transverse direction and the waveguide with the embedded core are effective in reducing the output power at the resonance wavelength. For each structure, more than a 4 dB reduction can be achieved. The reduction leads to a sharp dip in the wavelength response, which is expected to contribute to the improved measurement precision.

Acknowledgment

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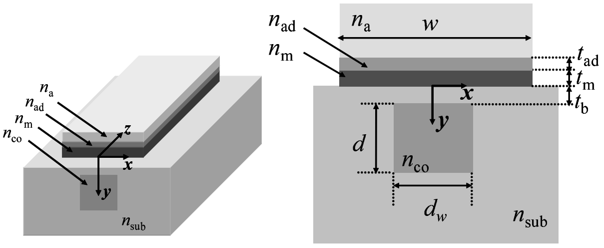

Fig. 1 Configuration of a waveguide sensor.

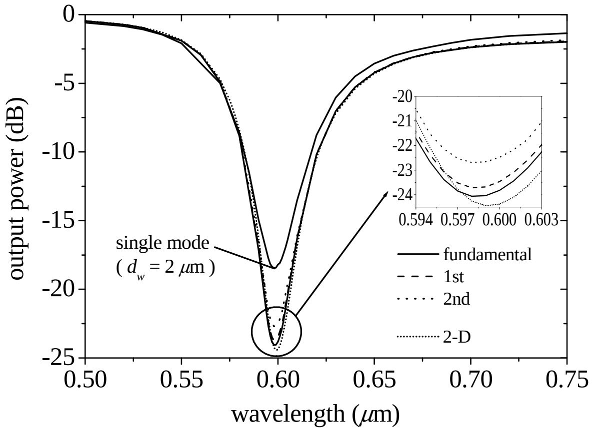

Fig. 2 Output power as a function of wavelength ($t_\mathrm{b} = 0$ and $n_\mathrm{a} = 1.332$).

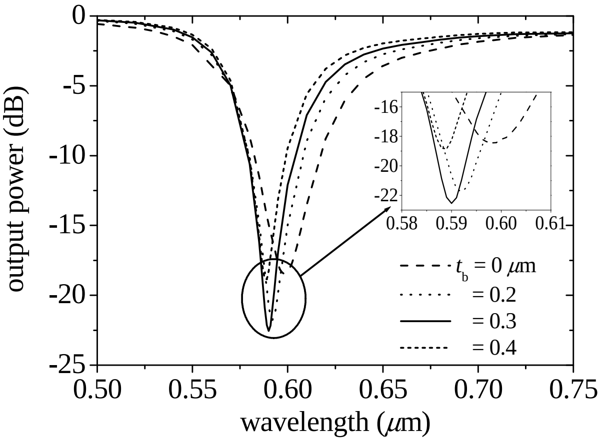

Fig. 3 Output power as a function of wavelength ($d_\mathrm{w} = 2\ \mu$m and $n_\mathrm{a} = 1.332$).