Simulation of surface plasmon fiber-optic sensor including the effect of oxide overlayer thickness change

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Motivation

Some of the studied surface plasmon resonance (SPR) sensors use the semiconductor overlayer for the protection of the metallic layer generating the surface plasmon wave [1]. In the same time, the overlayer can help to improve the sensitivity of the sensor. The semiconductor overlayer protects the metal against the oxidation, but a native oxide layer can be formed on its top surface, when exposed to the atmosphere. This effect has been scarcely addressed, even if it can have an influence on the functionality of the sensor.

The SPR sensing structure

A theoretical model of SPR fiber-optic sensor based on the theory of attenuated total internal reflection is considered. The sensing part is a five-layer system (see Fig. 1), and it consists of a multimode fiber (MMF) core (fused silica), Au layer covered by Si polycrystalline overlayer with high refractive index. When the Si layer is exposed after the deposition to normal atmospheric conditions, the oxidation causes the forming of a thin $\mathrm{SiO_2}$ film. The outer boundary of that film is then in contact with the investigated analyte. The analysis of the sensor response is carried out in frame of optics of multilayered media and the spectral interrogation is considered.

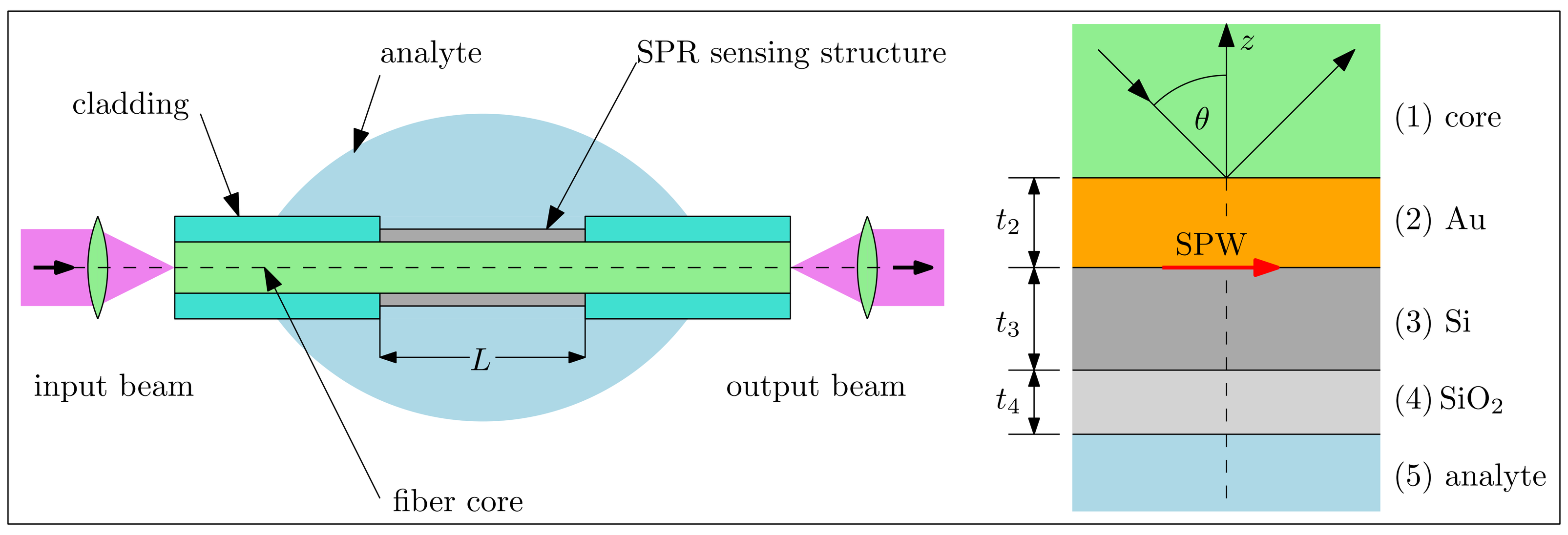

Figure 1: *The crossection of fiber optic sensor part and equivalent five-layer structure*

Power transfer through the sensing part

The surface plasmon resonance takes place for each of the modes separately, thus the angular distribution of the power among the guided modes has to be specified and integration over the angle of incidence θ representing 'mode continuum' has to be performed.The excitation by collimated beam focused on the input end of the fiber using some type of launching optics is assumed and only the meridional rays are considered. The expression for the normalized power P_{tn} at a specific wavelength λ at the end of the fiber sensing part can be written [2]:

$$P_{tn}(\lambda) = \frac{\displaystyle\int_{\theta_c(\lambda)}^{\pi/2} \frac{1}{2}([R_p(\lambda,\theta)]^{N_{\mathrm{ref}}} + [R_s(\lambda,\theta)]^{N_{\mathrm{ref}}}) \frac{n_1^2(\lambda)\sin\theta\cos\theta}{(1-n_1^2(\lambda)\cos^2\theta)^2}\,\mathrm{d}\theta}{\displaystyle\int_{\theta_c(\lambda)}^{\pi/2} \frac{n_1^2(\lambda)\sin\theta\cos\theta}{(1-n_1^2(\lambda)\cos^2\theta)^2}\,\mathrm{d}\theta}, \qquad N_{\mathrm{ref}} = \frac{L}{D\tan\theta}. \quad (1)$$

Here, N_{ref} represents the number of reflections in the finer sensing part (L is the length of the sensing part and D is the fiber diameter). The denominator represents the total incoming power at the beginning of the sensing part, the reflectances R_s and R_p are related to both polarization components, though only the p-polarized component is influenced by SPR phenomena. Optical dispersion of all materials is taken into account [3].

The sensitivity and detection accuracy

The parameters describing the performance of SPR fiber sensors using the wavelength interrogation method are the sensitivity S and detection accuracy DA. The quantity detected here is the mass concentration of ethanol in water (expressed using its mass fraction w_{eth}). Thus the sensitivity is the slope of the curve $\lambda_r(w_{eth})$.

$$\textbf{Sensitivity}: \ S = \left|\frac{\delta\lambda_r}{\delta w_{eth}}\right| \qquad \textbf{Detection accuracy}: \ DA_{10} = 1/\Delta\lambda_{10} \quad (2)$$

As a measure of the dip width, the spectral width $\Delta\lambda_{0.5}$ of the sensor response at 0.5 level of $P_{tn}(\lambda)$ is often used. The detection accuracy is then defined as $DA = 1/\Delta\lambda_{0.5}$. In our case, numerical simulation revealed broad and shallow dips, where the 0.5 level of $P_{tn}(\lambda)$ was not reached. Therefore we suggest slightly different criterion and instead of $\Delta\lambda_{0.5}$ we introduced the spectral width $\Delta\lambda_{10}$ taken at $1.1 \times P_{tn}(\lambda_r)$.

Thickness optimization of SPR layer

In order to estimate optimum value of the SPR gold layer thickness t_2, no oxide layer was assumed, i.e. $t_4 = 0$. The optimization was performed for three thicknesses $t_3 = 5, 7, 10\,\mathrm{nm}$ of Si overlayer and for two mass concentrations of ethanol given by mass fractions $w_{eth} = 0$ and $w_{eth} = 0.75$. The value of P_{tn} at resonance wavelength λ_r was minimized with respect to the Au layer thickness. BFL22-200 fiber from Thorlabs ($\mathrm{NA} = 0.22$, $D = 200\,\mathrm{nm}$, $L = 1\,\mathrm{cm}$) was considered. The material of fiber core was fused silica. The overlayer on the top of golden SPR layer consisted of polycrystalline Si. Based on computed results, the value of $t_2 = 40\,\mathrm{nm}$ was chosen to be the optimum thickness of the Au layer and was used in all subsequent simulations.

The influence of oxide layer thickness on sensor performance

The computation was performed for tree initial values of Si overlayer thickness $t_3 = 5, 7,$ and $10\,\mathrm{nm}$. The dependencies of sensitivity and detection accuracy (see Fig. 2) with respect to the increasing mass concentration of ethanol w_{eth} were obtained for increasing thickness t_4 of oxide layer. The thickness of the overlayer structure remains constant and it equals to the initial thickness of Si layer $t_{3,in} = t_3 + t_4$. As a reference data, the results obtained for Au layer only (without any overlayers) were used [3].

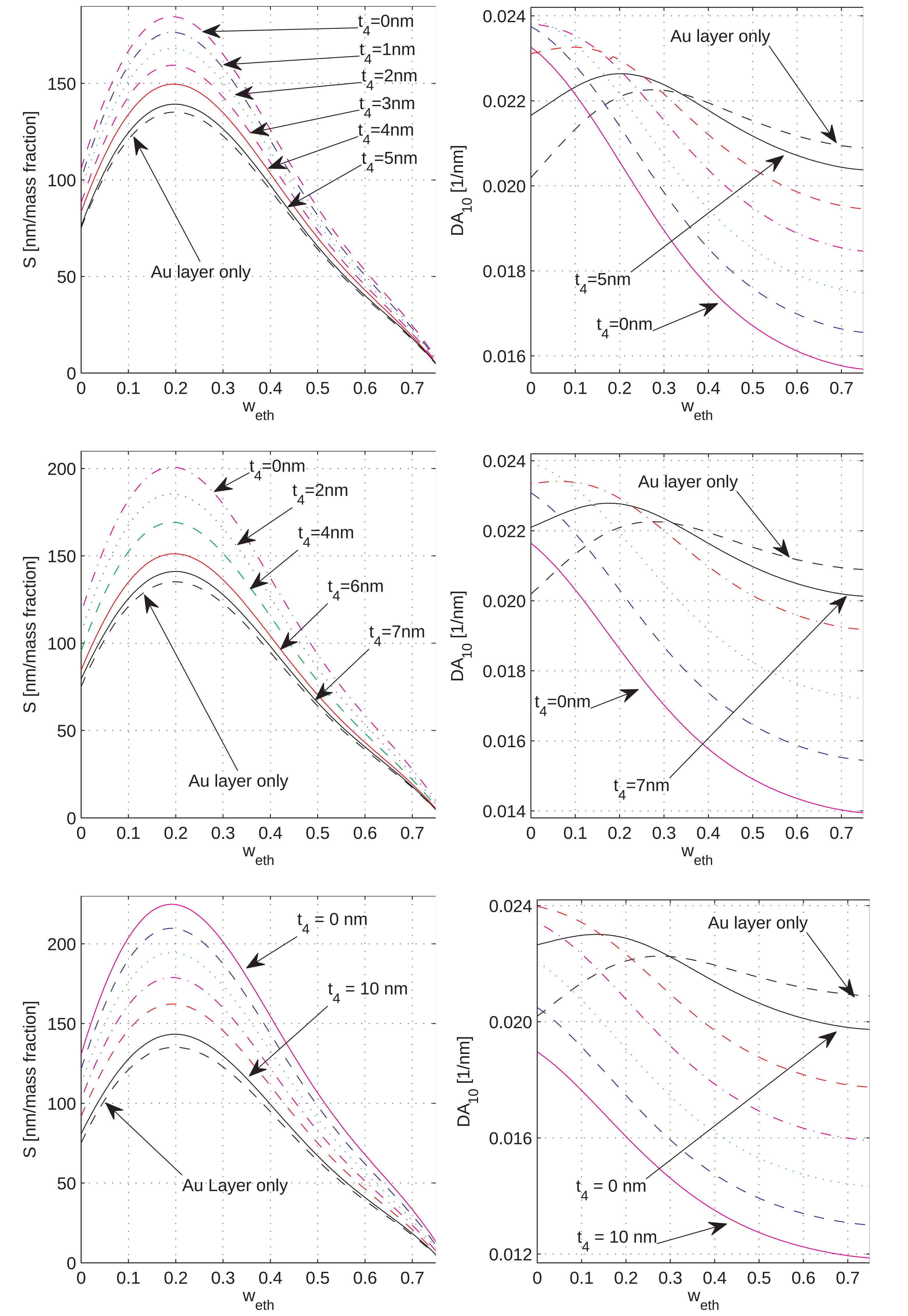

Figure 2: *Left column - Sensor sensitivity as a function of ethanol concentration, right column - detection accuracy as a function of ethanol concentration. The rows are related to the total thickness of* $\mathrm{Si}\,|\,\mathrm{SiO_2}$ *overlayer structure* $t_3 + t_4 = 5, 7$ *and* $10\,\mathrm{nm}$. *Increasing thickness of oxide layer* t_4 *is the parameter in each picture.*

Conclusion

The simulation carried out in the frame of thin-film optics revealed that the presence of the low-refractive index oxide layer formed on the top the high-refractive index Si overlayer introduces the decrease of red shift (with respect to the case without the oxide layer) as well as the decrease of the sensor sensitivity. In the same time it increases detection accuracy. Therefore the proper tunning of the oxide layer thickness can shift the operational range of the sensor to the required spectral range, and to achieve reasonable values of the sensitivity and detection accuracy.

Acknowledgment

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