Metal oxide layer influence on the sensitivity of SPR fiber optic sensor

Dalibor Ciprian and Petr Hlubina

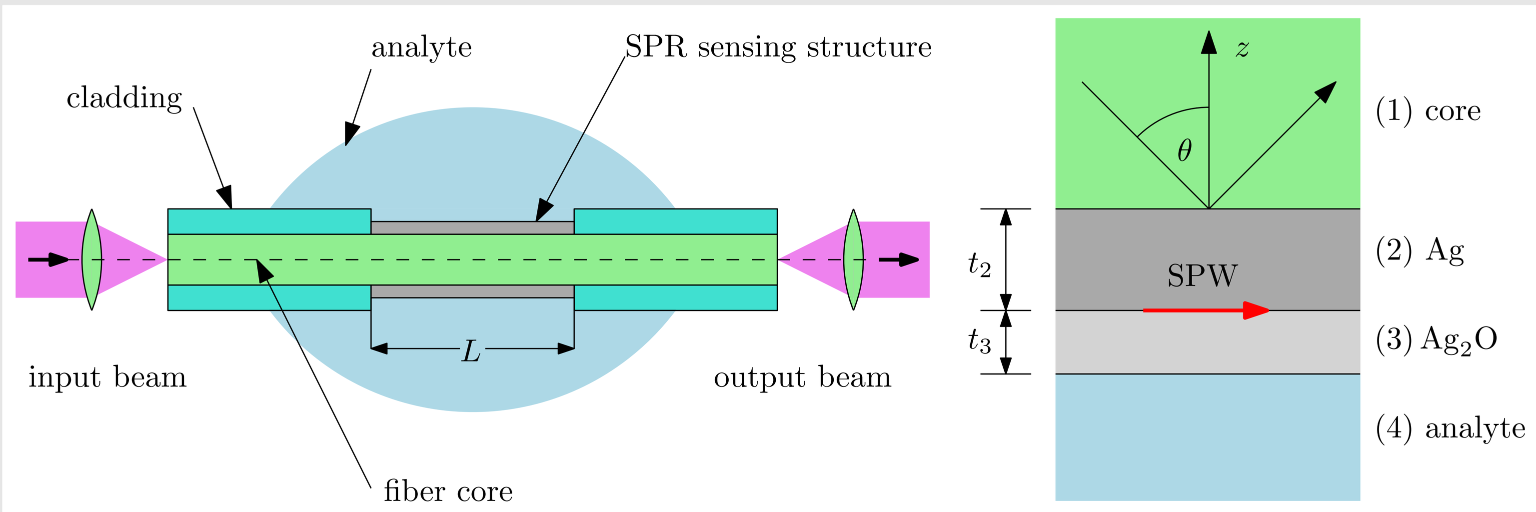
Department of Physics, Technical University Ostrava,
17. listopadu 15, Ostrava 70833, Czech Republic
`dalibor.ciprian@vsb.cz, petr.hlubina@vsb.cz`

Motivation

- To enhance the sensitivity of SPR fiber-optic sensor based on silver film
- To solve potential problems related to chemical stability of Ag film using protective overlayer (formed by Ag layer oxidation)
- To simulate the response of the sensor with respect to potential application case (ethanol content investigation in ethanol-water mixture)

Theoretical model of the sensor

- Sensing structure is based on step-index, multimode optical fiber (easy coupling and decoupling of the light beam)
- The interrogation in the wavelength domain is considered
- The real cylindrical geometry is approximated in frame of planar optics by four-layer thin film structure



- Performance parameters are computed using the normalized power transfer spectrum for the case of excitation by collimated centrosymmetric beam focused at the fiber core center (no skew rays):

$$P_{tn}(\lambda) = \frac{\displaystyle\int_{\theta_c(\lambda)}^{\pi/2} \frac{1}{2}\left([R_p(\lambda,\theta)]^{N_{ref}} + [R_s(\lambda,\theta)]^{N_{ref}}\right) \frac{n_1^2(\lambda)\sin\theta\cos\theta}{(1-n_1^2(\lambda)\cos^2\theta)^2}\,d\theta}{\displaystyle\int_{\theta_c(\lambda)}^{\pi/2} \frac{n_1^2(\lambda)\sin\theta\cos\theta}{(1-n_1^2(\lambda)\cos^2\theta)^2}\,d\theta}$$

$N_{ref} = L/(D\tan\theta)$ is the number of reflections in the sensing part, L is the sensing part length, D is the fiber diameter, R_s, R_p are power reflectances, θ_c is the critical angle (wavelength dependent)

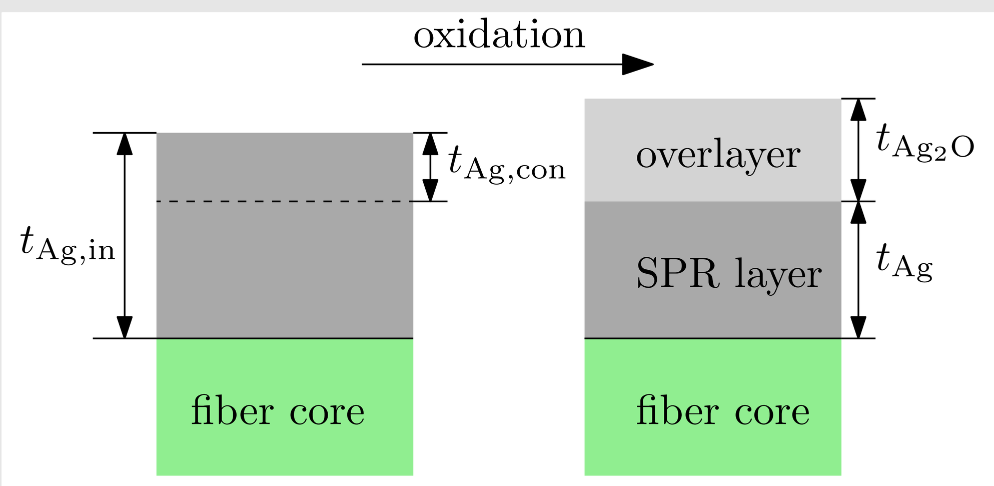
- When the fiber is approximated by planar structure, the contribution of both polarization component has to be taken into account
- Optical dispersion of all media has to be included into the computation

Optical dispersion of used materials

- Fiber core: fused silica, dispersion described by three-term Sellmeier formula [1]
- SPR layer: Ag, dispersion described by Drude-Lorentz model [2]
- Protective overlayer: Ag_2O, dispersion described by single-oscillator model [3]
- Analyte: ethanol-water mixture, refractive index obtained by Lorentz-Lorenz formula [4], its value controlled by content of ethanol (concentration c_{Eth} expressed in mass%)

Protective oxide layer

- SPR silver layer has to be protected to keep its chemical stability
- Silver layer itself can be oxidized to form a protective overlayer (for example by oxygen-containing plasma)
- The oxidation process is connected with the expansion of the formed silver oxide layer thickness, described by expansion ratio $K = 1.55$ (see the schematic picture)



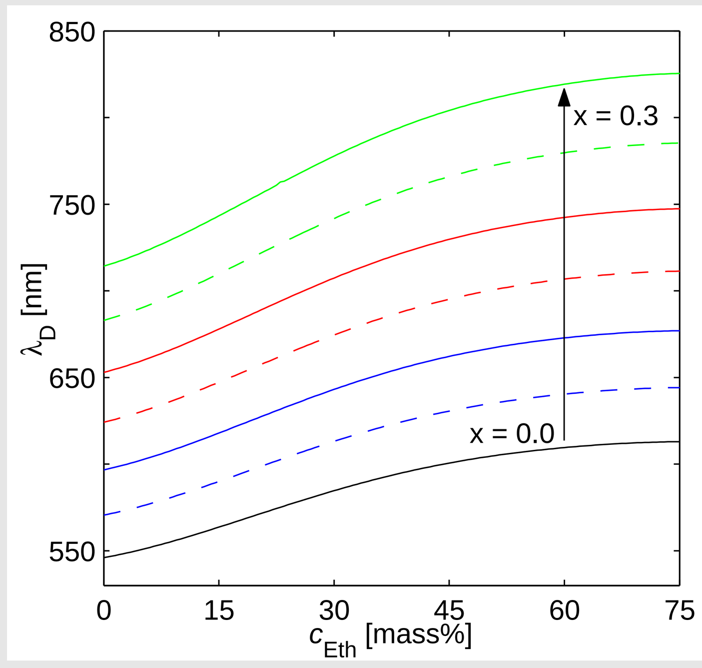
x	t_{Ag}	t_{Ag_2O}	label
–	[nm]	[nm]	–
0.00	40.00	0.00	—
0.05	38.69	2.04	- -
0.10	37.32	4.15	—
0.15	35.91	6.34	- -
0.20	34.44	8.61	—
0.25	32.92	10.97	- -
0.30	31.34	13.43	—

- The structure containing oxide overlayer is characterized by dimensionless parameter: relative oxide layer thickness $x = t_{Ag_2O}/(t_{Ag_2O} + t_{Ag})$
- For the computation, the initial thickness of Ag layer was chosen as $t_{in} = 40\,\mathrm{nm}$
- For the chosen set of parameter x (see the thicknesses in the table), the sensing structure works in wavelength range from $380\,\mathrm{nm}$ to $1000\,\mathrm{nm}$ in pure SPR regime (no lossy-mode-resonance is excited)

Computed results and discussion

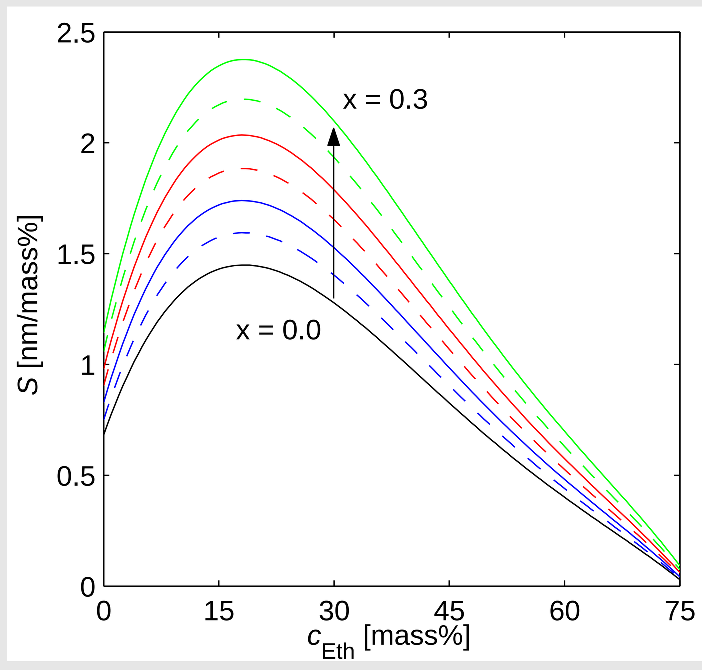
Numerical simulations were performed for step-index, silica core, multimode optical fiber characterized by $NA = 0.22$, $D = 200\,\mu\mathrm{m}$, and the sensing part length $L = 1\,\mathrm{cm}$.

The shift of dip position λ_D



- Dip position was computed as a function of ethanol mass concentration c_{Eth}
- Dip shift exhibits monotonous increase with increasing c_{Eth} - it is given by increasing of analyte refractive index
- Growth of silver oxide dielectric layer introduces notable red shift even for overlayer thickness in nanometer range (x increase is denoted by arrow direction)
- Operational range in wavelength domain is extended with growing overlayer thickness

Sensitivity of the system

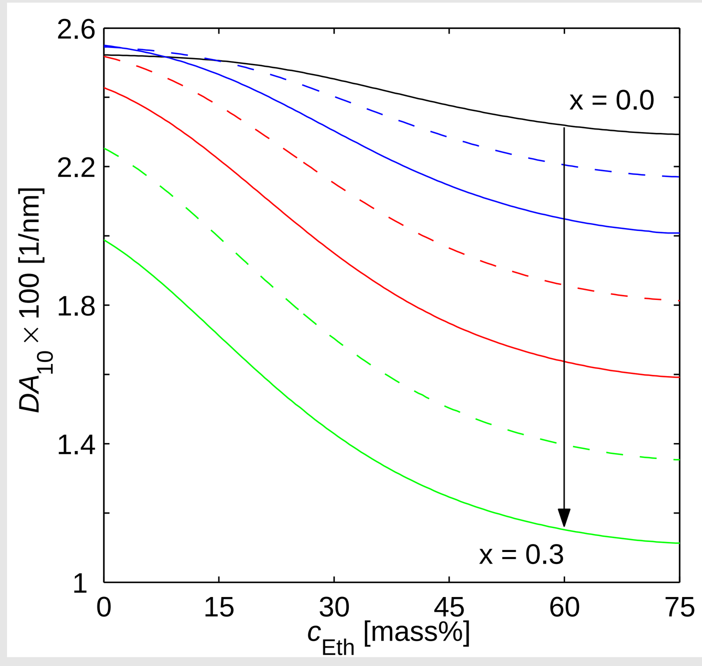


- Sensitivity of the sensor with respect to ethanol mass concentration is defined as:

$$S = \left|\frac{\delta\lambda_D}{\delta c_{Eth}}\right|$$

- Sensitivity of is substantially enhanced with the growing of overlayer thickness
- Despite of the overlayer thickness increase, the top sensitivity keeps its position
- The top sensitivity enhancement ratio $1 : 1.647$ was achieved for the overlayer thickness corresponding to $x = 0.3$

Detection accuracy

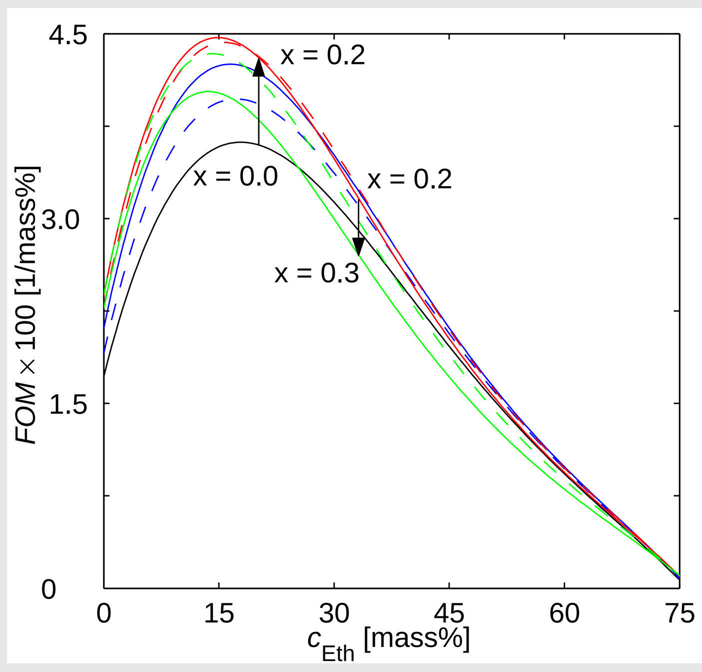


- Because of broad shallow dips, detection accuracy is defined as (dip width $\delta\lambda_{10}$ taken at $1.1 \times P_{tn}(\lambda_D)$):

$$DA_{10} = 1/\delta\lambda_{10}$$

- Sensitivity enhancement is accompanied by the broadening of the spectral dip ⇒ DA_{10} decreases with the relative oxide thickness
- Only in the case of low content of ethanol in water ($c_{Eth} < 10\,\mathrm{mass\%}$) and very thin overlayers ($x \leq 0.1$), presence of the overlayer enhances the detection accuracy

Figure if merit of the sensor



- Figure of merit is defined as the ratio between the sensitivity and dip width:

$$FOM = S \times DA_{10}$$

- At first FOM increases with the overlayer thickness up to $x \approx 0.2$ (see left arrow), then it goes down (right arrow)
- FOM behavior goes on the account of detection accuracy DA_{10}
- For any specific ethanol concentration $c_{Eth} \in (0, 75)\,\mathrm{mass\%}$ an optimal value of relative oxide thickness exists

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