Model of a double-sided surface plasmon resonance fiber-optic sensor

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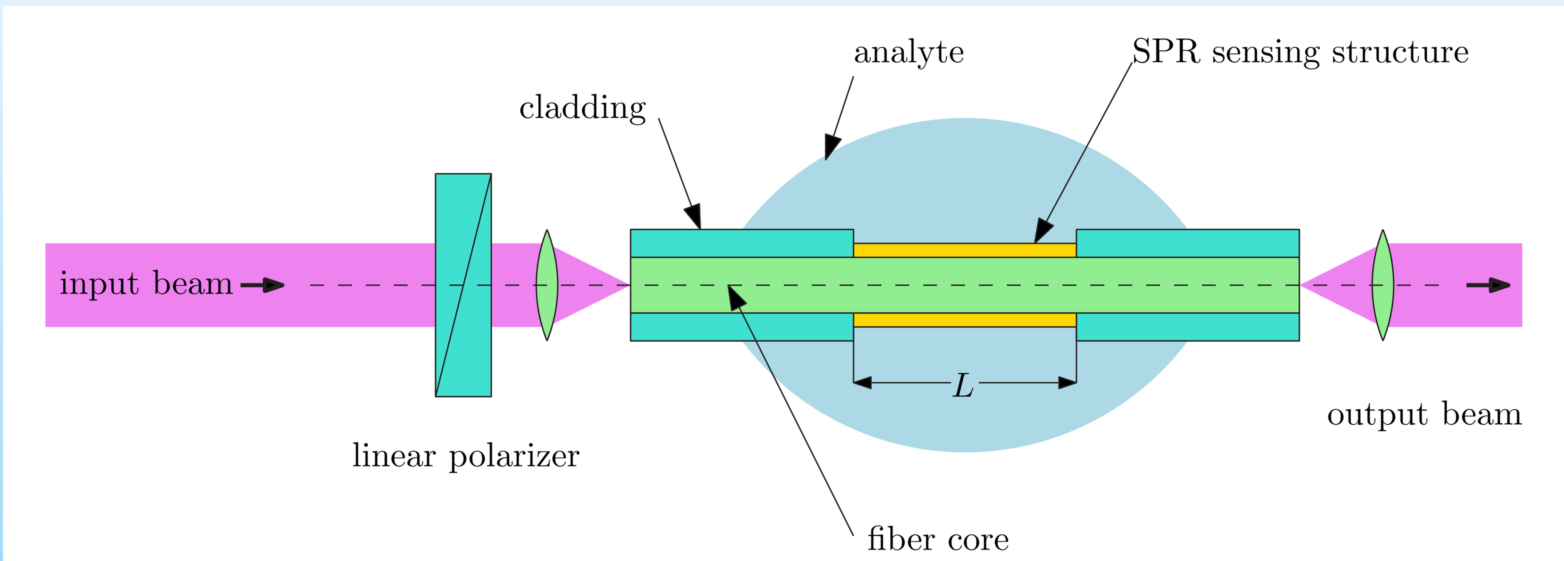
Motivation

- To understand the polarization properties of a double-side deposited surface plasmon resonance (SPR) fiber-optic sensor [1, 2].
- To evaluate the influence of SPR layer geometry on the sensor performance.

Sensor setup

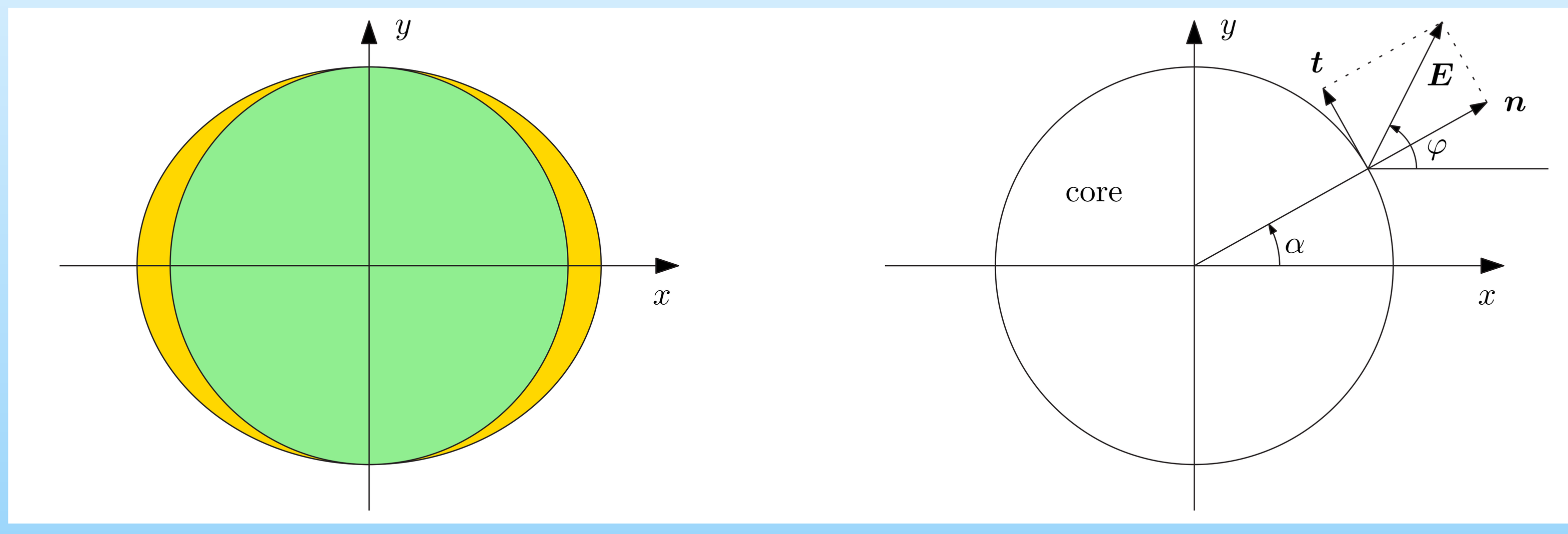
- Sensing structure is based on a step-index, multimode optical fiber.
- Interrogation in the wavelength domain is considered.
- Analysis carried out in frame of thin film optics.



- Fiber excited by a collimated/focused centered (CFC) beam.
- Input beam is linearly polarized.
- Double-side deposition of metal sensing SPR layer.

Double-side geometry

- Double-side deposition leads to *inhomogeneous layer* $\Rightarrow$ layer thickness depends on polar angle: $t = t(\alpha)$, $t \in \langle t_{\min}, t_{\max} \rangle$.
- The outer layer boundary approximated by an ellipse: semi-major axis: $a = t_{\max} + \frac{D}{2}$, semi-minor: axis $a = t_{\min} + \frac{D}{2}$.
- Because the layer thickness is much smaller than fiber core diameter D (low-eccentricity ellipse), skew rays in the layer are *omitted*.



- Input polarization azimuth given by φ (with respect to $x-$axis).
- Local decomposition of linear polarization to $p-$component (normal $\boldsymbol{n}$) and $s-$component (tangent $\boldsymbol{t}$) is needed.

Power transfer calculation

- Polar angle dependence is considered $\Rightarrow$ double integration.
- Normalized power transfer spectrum on output of sensing part:

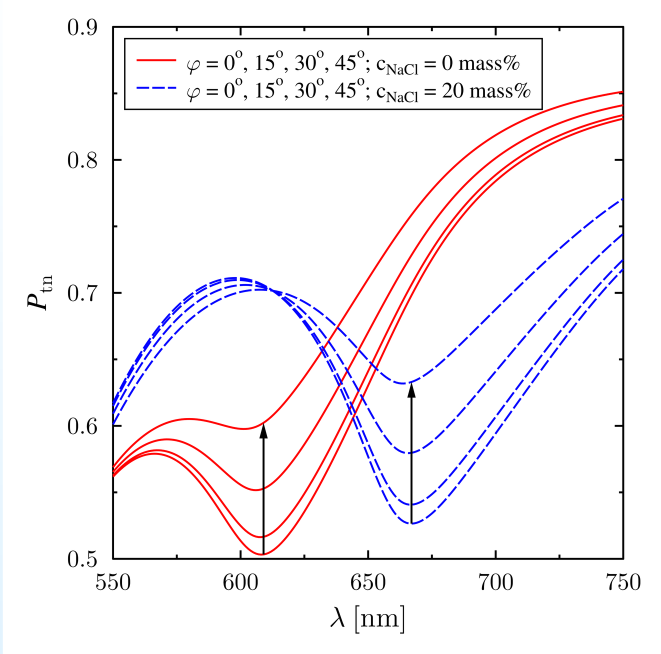
$$P_{\text{tn}}(\lambda) = \frac{\int\limits_{\alpha}^{2\pi} \int\limits_{\theta_c(\lambda)}^{\pi/2} \left[p^2(\varphi,\alpha) R_p^N(\lambda,\theta) + s^2(\varphi,\alpha) R_s(\lambda,\theta)^N\right] A(\theta)\, \mathrm{d}\theta \mathrm{d}\alpha}{\int\limits_{\alpha}^{2\pi} \int\limits_{\theta_c(\lambda)}^{\pi/2} A(\theta)\, \mathrm{d}\theta \mathrm{d}\alpha}.$$

- Integration with respect to polar angle α and angle of incidence θ.
- $R_{p,s}$ - reflectances, $N_{\text{ref}} = L/(D \tan\theta)$ - number of reflections.
- Polarization projectors: $p = \frac{1}{\sqrt{2\pi}} \cos(\varphi - \alpha)$, $s = \frac{1}{\sqrt{2\pi}} \sin(\varphi - \alpha)$.
- Angular power distribution: $A(\theta) = \frac{n_1^2(\lambda) \sin\theta \cos\theta}{(1 - n_1^2(\lambda) \cos^2\theta)^2}$ (CFC beam).

Parameters of computation

- Opt. fiber: $NA = 0.22$, $D = 200\,\mu$m, $L = 1$ cm, fused silica core.
- Sensing layer: Au on a bare fiber core, $t_{\min} = 0$, $t_{\max} = 50$ nm.
- The shape of layer outer boundary is approximated by an ellipse.
- Model analyte: aqueous solution of NaCl.

Results

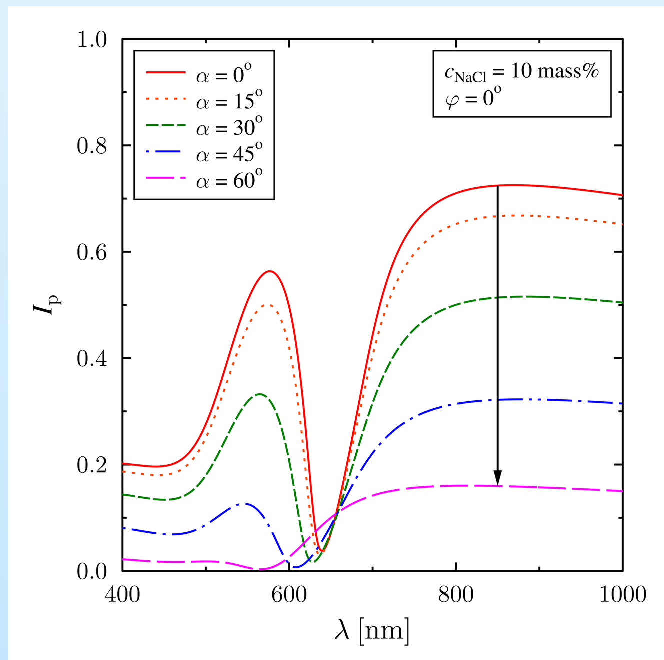


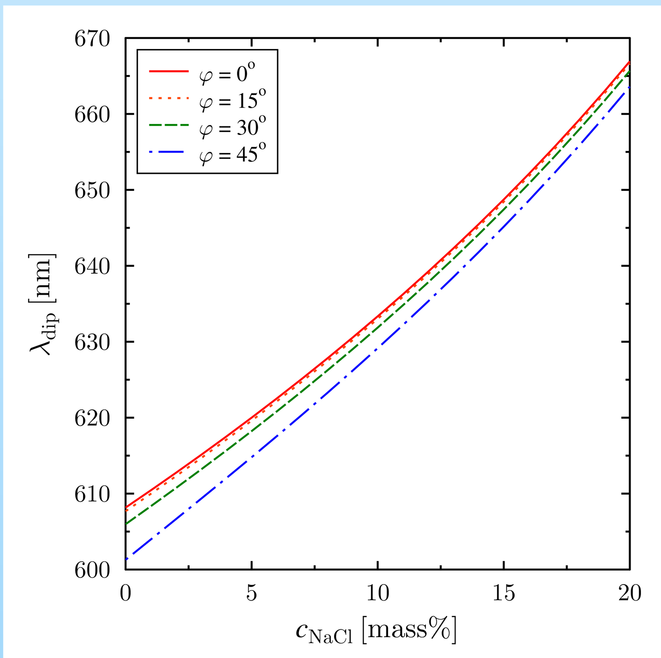
Influence of φ on SPR spectra

- ▷ The dip position is affected by φ.
- ▷ The effect is higher for low c_{NaCl} - low refractive index of analyte.
- ▷ Increasing φ leads to broad shallow dips $\Rightarrow$ detection ability decreases.
- ▷ For $\varphi > 47°$ the detection is not possible for low c_{NaCl}.

Effect of layer geometry

- ▷ Double-side deposition leads to thickness change along the circumference of the core.
- ▷ The position of SPR resonance dip depends on film local thickness.
- ▷ The p-polarized component spectra I_p with different dip position are summed $\Rightarrow$ integration over polar angle α leads to 'average' dip.



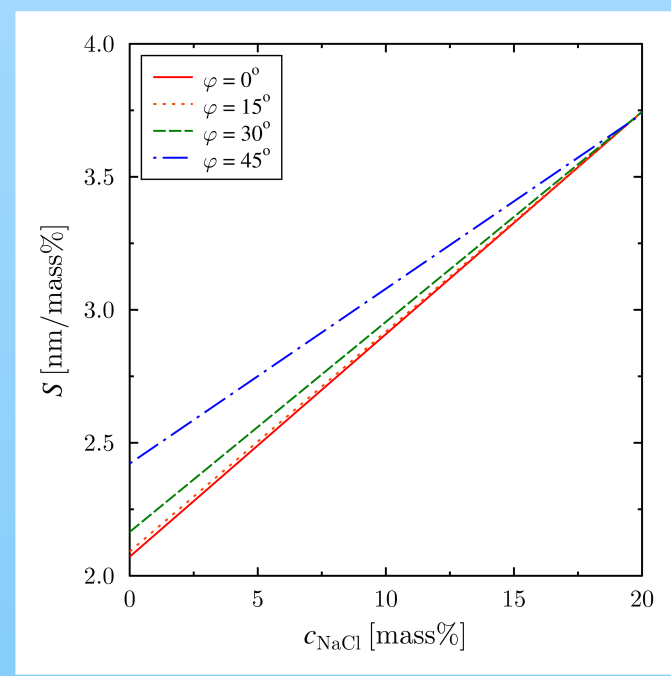


Dip shift with concentration

- ▷ For increasing c_{NaCl} the dip position is shifted to longer wavelength as the analyte refractive index increases.
- ▷ The increasing azimuth causes an opposite effect.
- ▷ The effect of azimuth orientation is more pronounced for low c_{NaCl}.

Sensitivity of the setup

- ▷ The sensitivity $S = \frac{\Delta\lambda_{\text{dip}}}{\Delta c_{\text{mass}}}$ increases with the analyte refractive index (increasing c_{NaCl}).
- ▷ The increase can be approximated by a linear function.
- ▷ The sensitivity increases with the input linear polarization azimuth.



References

[1] Gonzalez-Cano, A. et all. *Sensors* **14**, 4791-4805, (2014)
[2] Nguyen Tan Tai et all. *Opt. Express* **22**, 5590-5598, (2014)

Acknowledgments

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