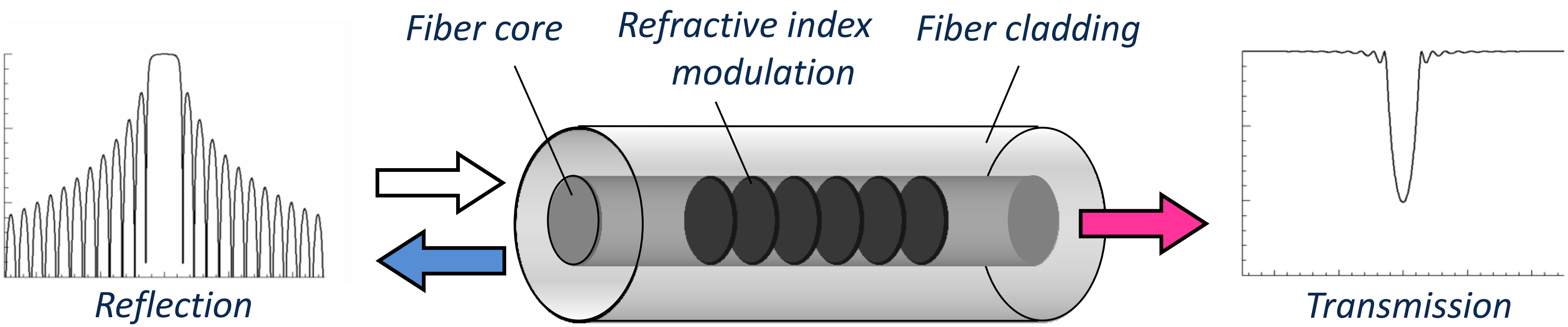
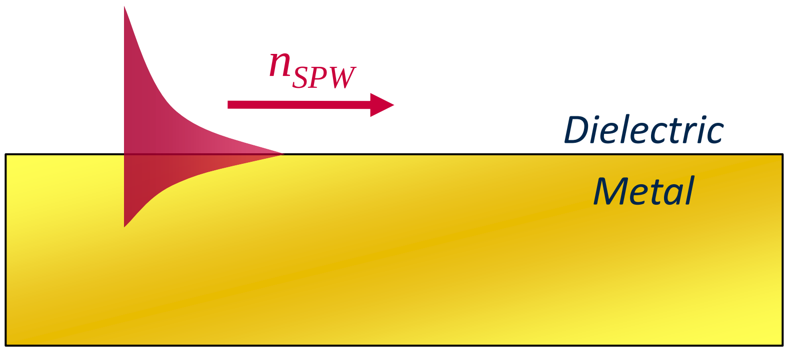
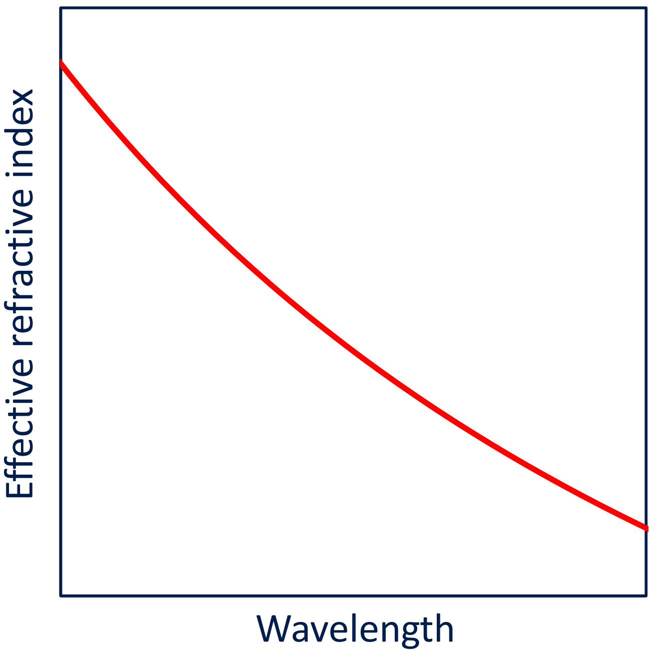
Fiber gratings



- **Periodic refractive index modulation of the fiber core**
  - Inscribed Ge-doped silica fiber with focused UV-Laser
  - Resonant exchange of power between different fiber modes
- **Resonance wavelength is determined by…**
  - … the grating period
  - … the propagation constant of the modes involved
- **Period < 1 µm: Fiber Bragg Gratings (FBG)**
  - Power exchange between counter propagating core modes
- **Period > 50 µm: Long-Period fiber Gratings (LPG)**
  - Power exchange between co-propagating core and cladding modes

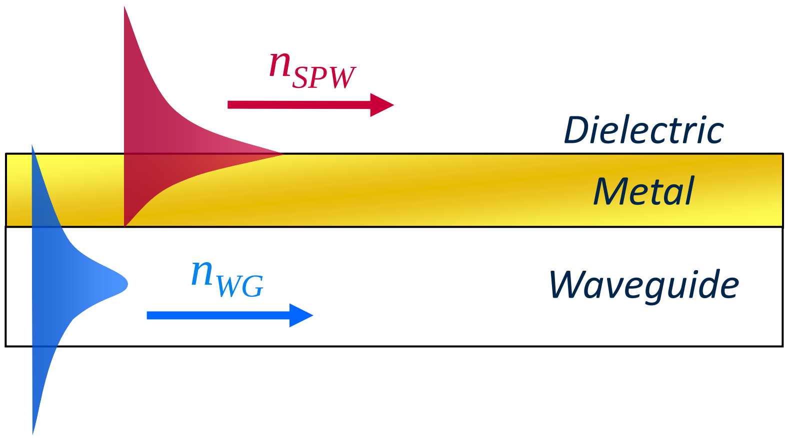
Surface Plasmon Resonance (SPR)

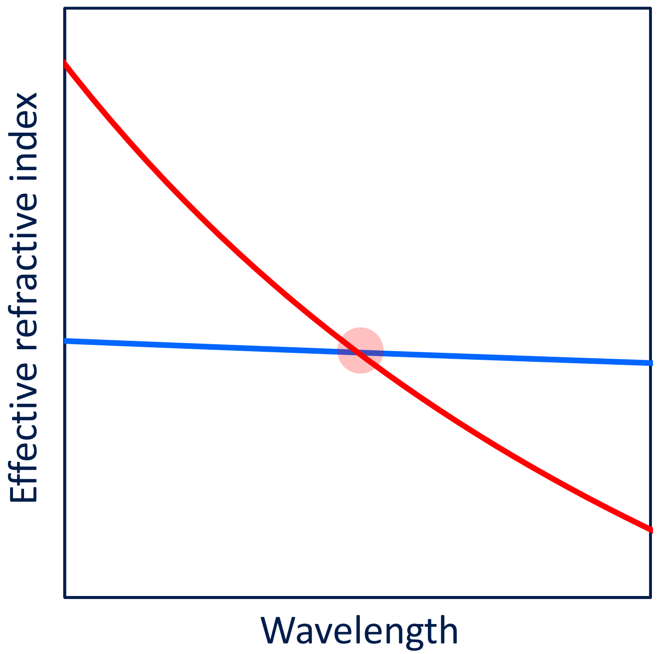




- **Surface plasmon waves**

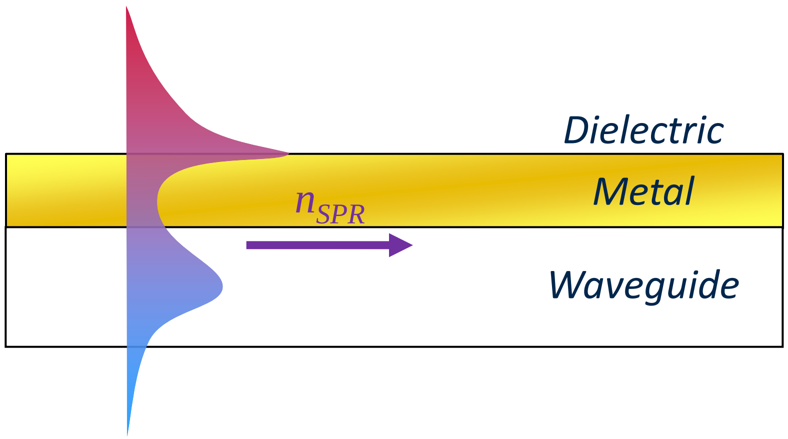
Surface Plasmon Resonance (SPR)

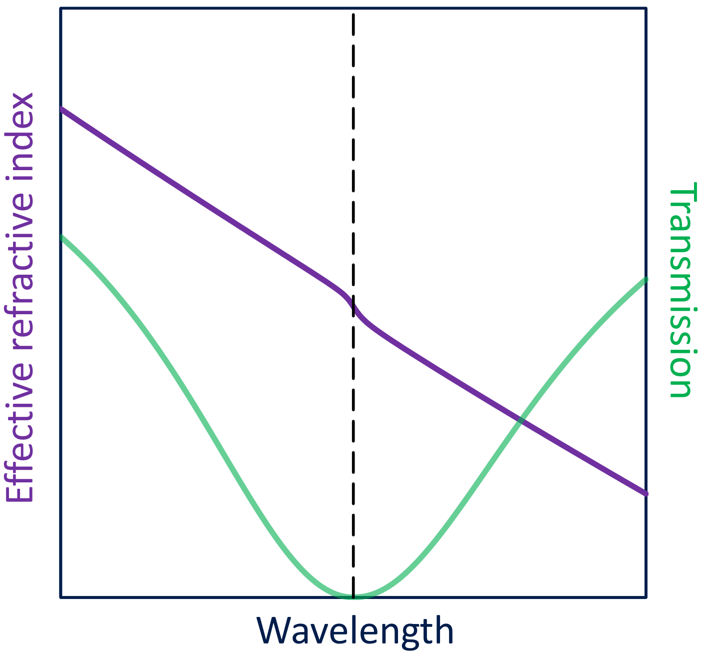




- **Surface plasmon waves & optical waveguide**
- **Resonance conditions:**
  - Phase matching ($n_{WG} = n_{SPW}$)
  - Transversal magnetic (TM) polarisation
  - Metal layer with suitable thickness (50 nm)

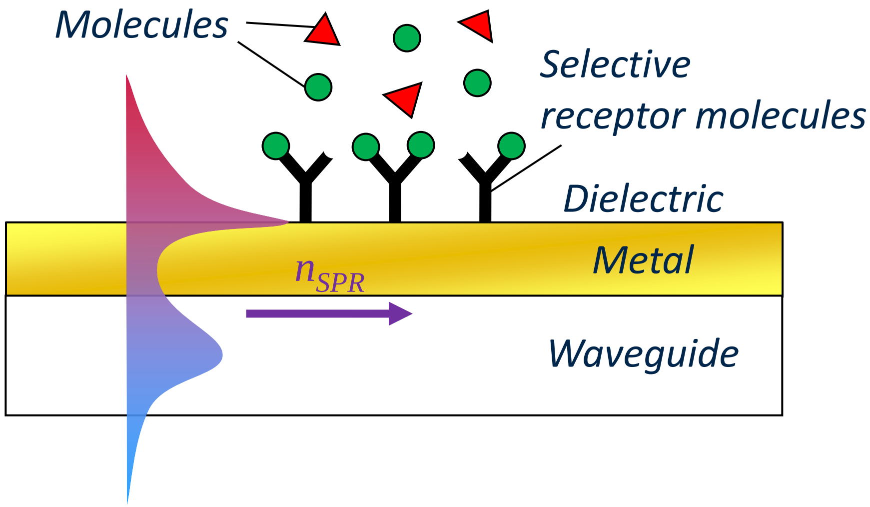
Surface Plasmon Resonance (SPR)

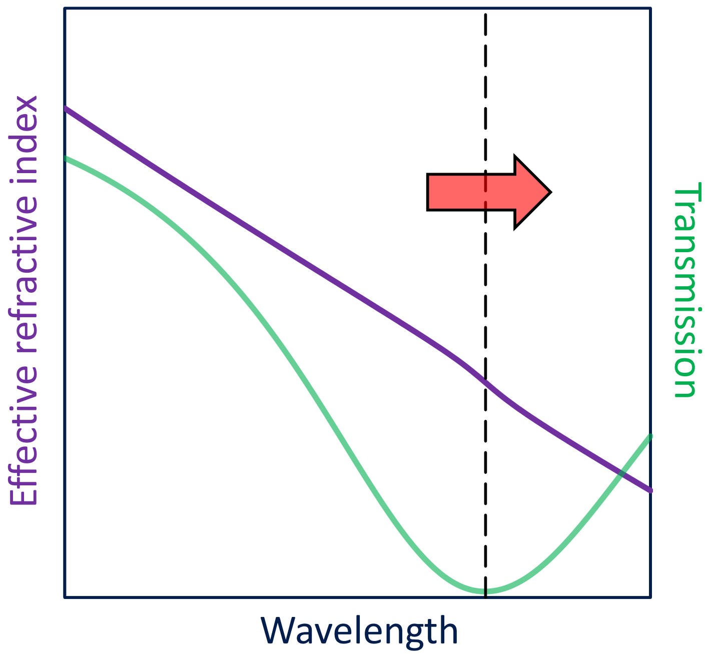




- **Surface plasmon resonance**
- **Impact on the guided light:**
  - High loss due to strong field concentration on the metal surface
  - Characteristic shift of the effective refractive index
- **High sensitivity to refractive index changes on the metal surface**

Surface Plasmon Resonance (SPR)

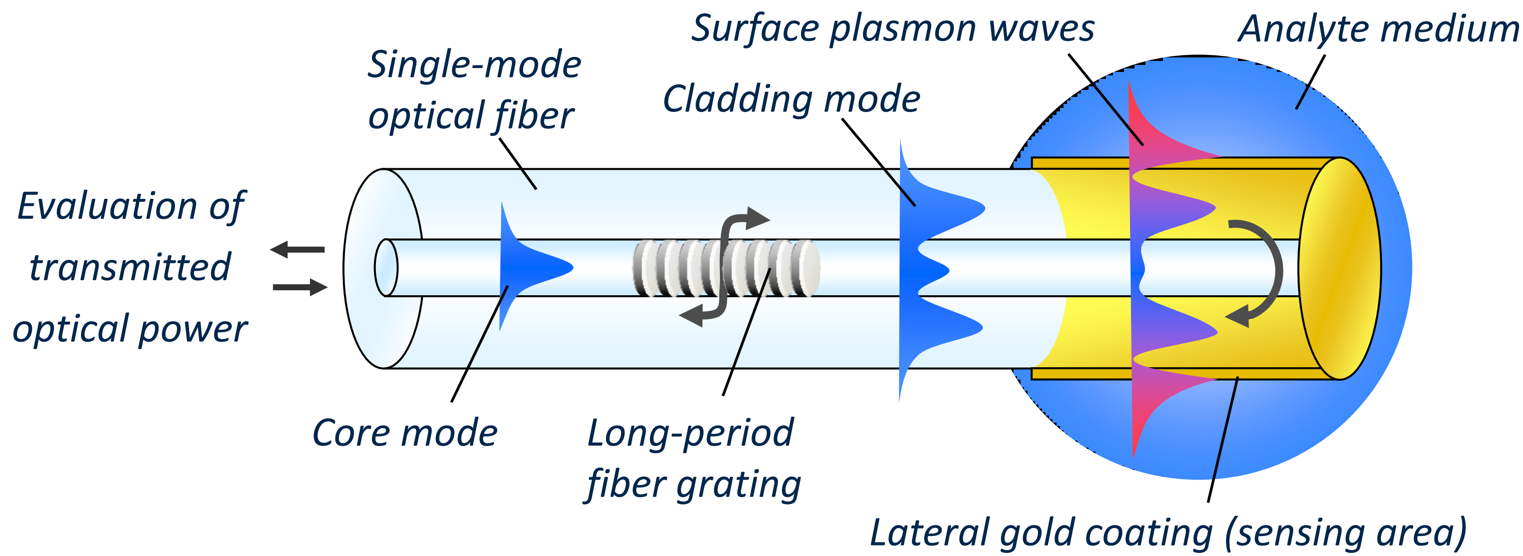




- **Surface plasmon resonance**
- **Impact on the guided light:**
  - High loss due to strong field concentration on the metal surface
  - Characteristic shift in the effective refractive index
- **High sensitivity to refractive index changes on the metal surface**
  - Detection of molecular binding events

PhD thesis

- **Novel fiber-optic sensor concept**



- **Advantages**
  - Small sensing area enables in-situ investigation of small analyte volumes
  - Fiber (Ø 125 µm) is mechanically robust & independent of polarization
  - LPG facilitates highly sensitive SPR of a single cladding mode
  - Simple evaluation of transmitted power at a suitable wavelength

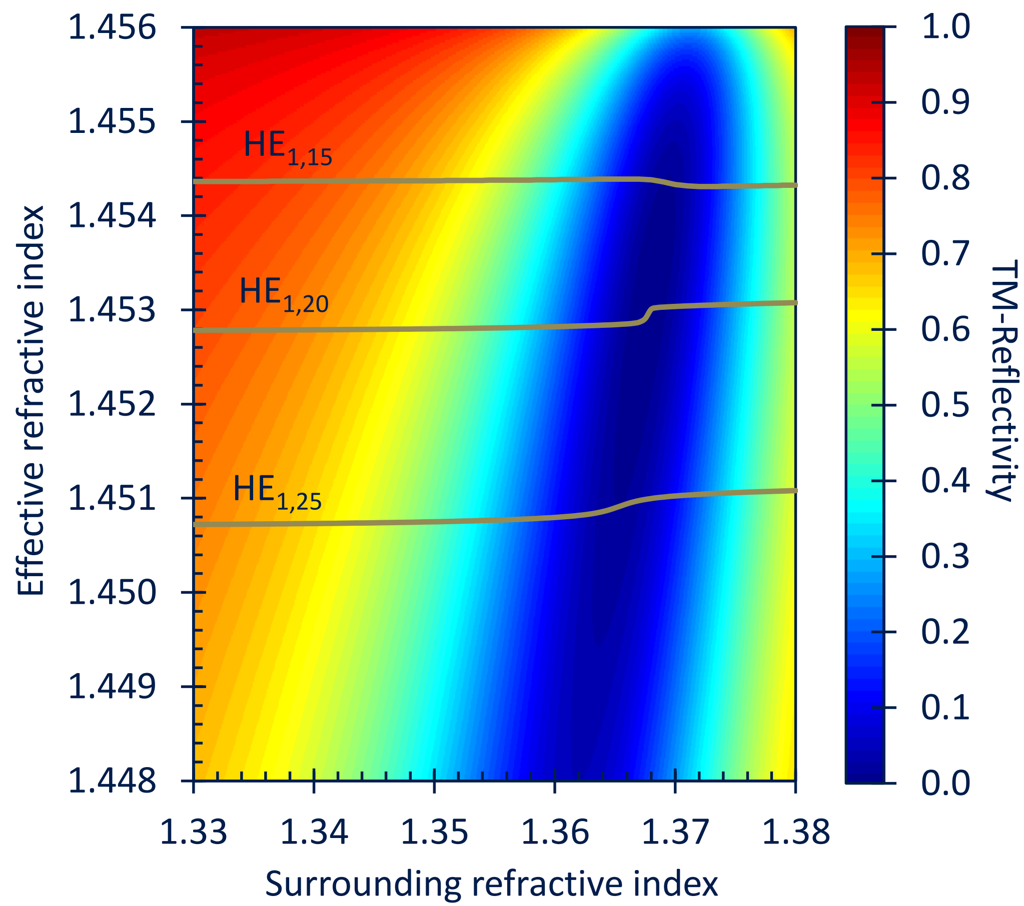
PhD thesis – main challenges

- **Efficient, precise modelling of cladding modes in SPR**
  - FEM, FDTD software or classical numerical solver are not suitable
  - Relatively large geometry in relation to operating wavelength (660 nm)
  - High polarization-dependent losses of cladding modes
- **Omnidirectional deposition of a thin gold film**
  - Ensures high sensitivity & low polarization dependency
  - Evaporation or sputtering facilities are designed for planar substrates
- **Experimental investigation of the sensor transfer function**
  - Interference of the core and cladding mode
  - Losses attributable to a variety of factors

PhD thesis – Modelling

- **$HE_{1,X}$ cladding modes**
  - Hybrid polarization
  - Axially symmetric field
- **Planar approximation**
  - Geometrical optics
- **Gold coating with complex reflection coefficient**
  - Phase $\boldsymbol{\varphi} = \angle \underline{\boldsymbol{r}}$
  - Reflectivity $\boldsymbol{R} = |\underline{\boldsymbol{r}}|^2$
- **Effective refractive index**
  - Standing wave condition
- **Attenuation**

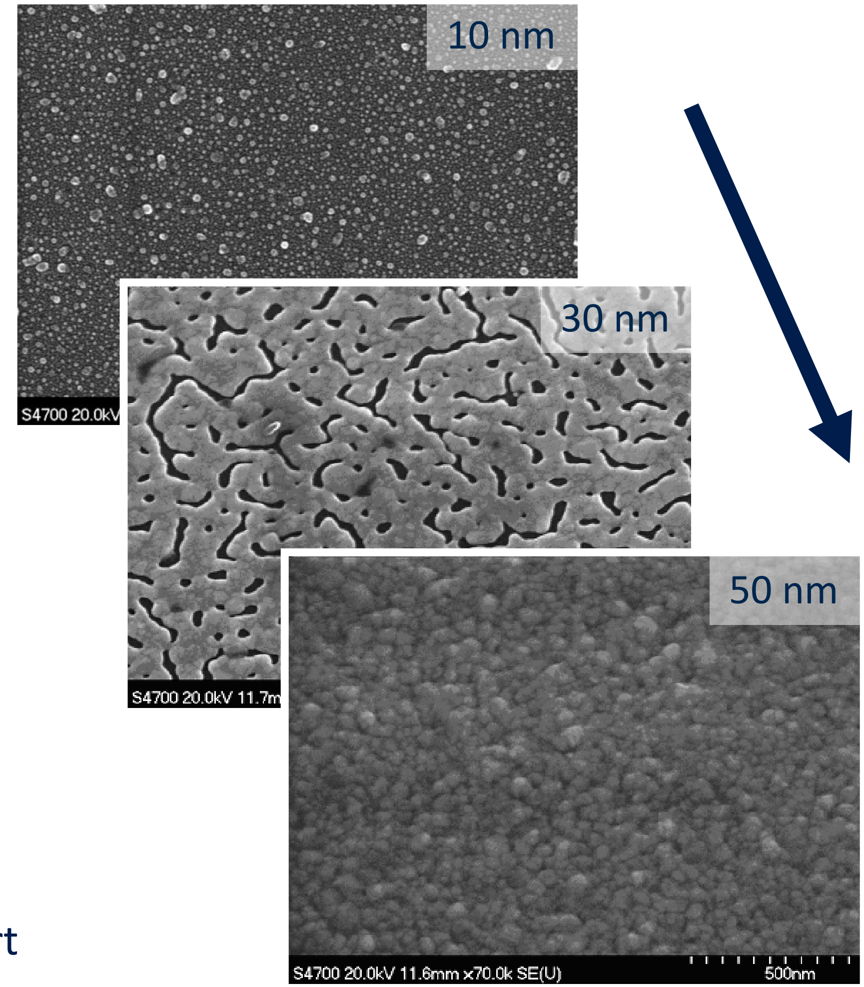
$$A_{SPR(1,X)} = R_{TM}^{a/D_{TR}}$$



30 nm thick gold layer , ideal permittivity, λ = 660 nm

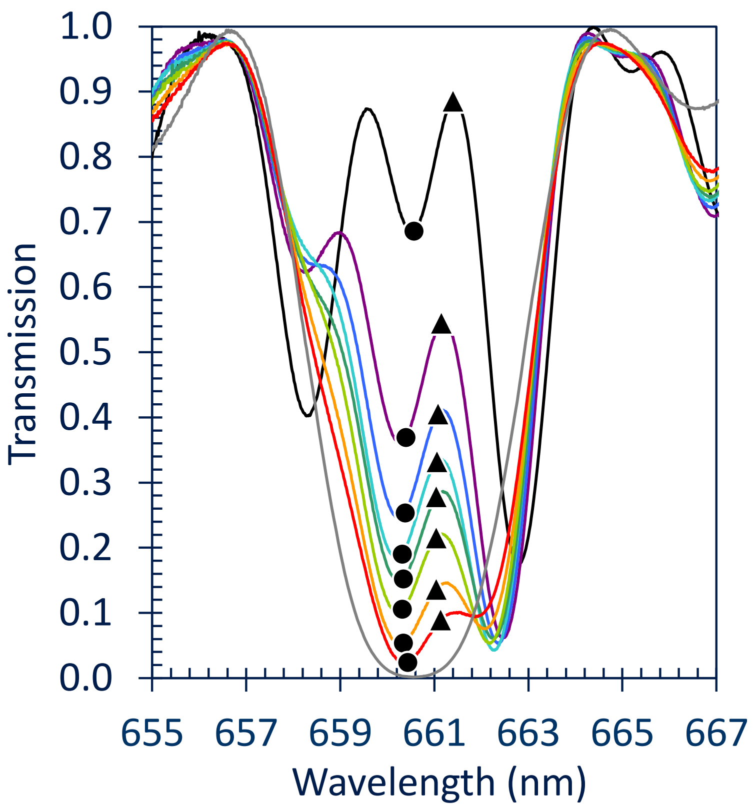
PhD thesis – Electroless gold plating

- **Metal deposition out of an aqueous solution**
  - Uniform thickness on every shape of substrate
  - Efficient material consumption
- **Redox reaction requires catalytic substrate**
  - Activation of silica substrate with gold nano particles
  - Island-like growth of gold layer
- **SPR measurements**
  - LPG underneath gold coating
  - Optical properties depend on thickness of the deposition
  - Effective permittivity with increased real- and imaginary part



PhD thesis – Transfer function

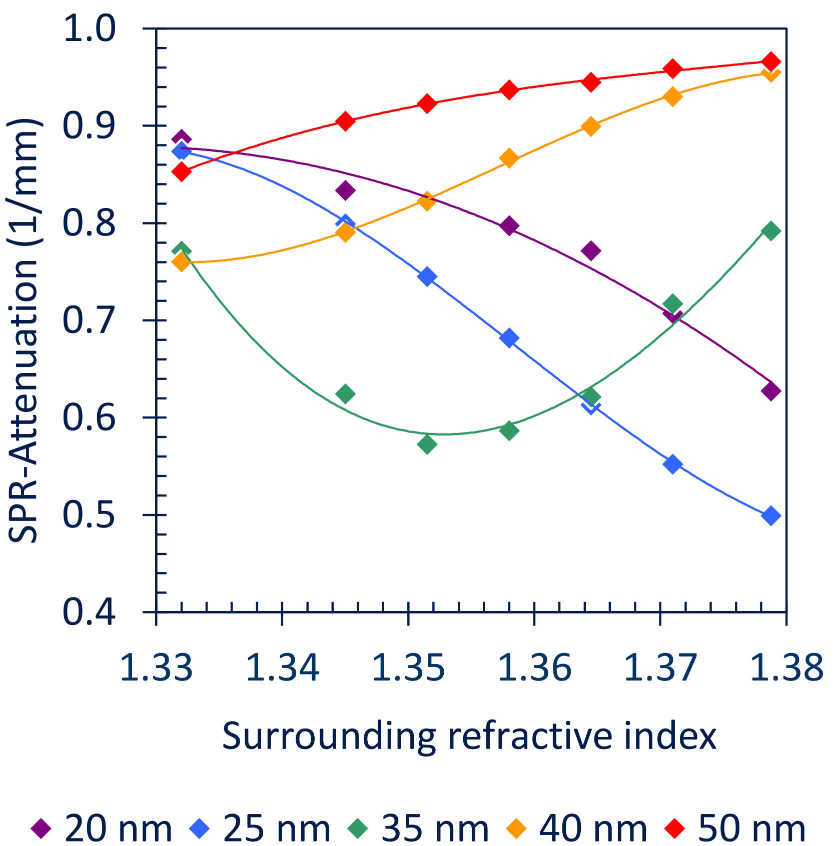
- **Interference of phase-shifted core and cladding mode**
  - Michelson-Interferometer
- **Characteristic sensor spectrum determined by:**
  - Location, amplitude- and phase response of LPG
  - Effective refractive indices & losses of involved modes
- **Maximum sensitivity**
  - Constructive interference
  - Near LPG resonance
  - Up to 14.5 RIU^{-1} @ n_A = 1.34, 1.37
  - Electroless plated gold layer (t_{opt} = 35 nm, L_{opt} = 1.2 mm)



Cladding mode: $HE_{1,20}$,
LPG: Λ=114 µm, L=30 mm,
Gold layer: t_M=25 nm, L_M=3.5 mm
Surrounding refractive index: n_A= 1, 1.33 – 1.38

PhD thesis – SPR Attenuation

- **Separation of additional losses**
  - Reflection at fiber end face
  - Transition to sensing area
  - Scattering at rough surface
- **Measurments with variable**
  - Length of gold coating
  - Surrounding refractive index
- **Experimental results correspond well with simulations**
  - Scaling factor $a \approx 0.35$
  - Independent from:
    - Thickness of gold coating
    - Order of the cladding mode
    - Wavelength



$HE_{1,20}$ cladding mode, λ = 660 nm

PhD thesis – Summary

- **Novel fiber-optic sensor for the detection of refractive index changes**
  - High sensitivity due to SPR of a single cladding mode enabled by an LPG
- **Quick, accurate modelling**
  - Transfer function derived from a Michelson interferometer
  - SPR modelled using a planar approximation for $HE_{1,X}$ cladding modes
- **Omnidirectional electroless plating on the sensor fiber**
  - High sensitivity & low polarization dependency
  - Island-like growth
- **Experimental investigations to support and validate sensor modelling**
  - Electroless plated gold depositions exhibit effective permittivity
  - Various optical losses affect sensor transfer function
- **Sensor performance comparable with commercial volume optical systems**
  - Refractive index resolution $< 10^{-8}$ RIU in aqueous media
  - Simple transmission measurements at a specific wavelength
  - Compact sensing area (< 2 mm) permits investigation of small analyte volumes

PhD thesis – Outlook

- **Compact device for detection of specific biochemical substances**
  - No need for a microfluidic system
  - Point-of-care devices , lab-on-chip systems
  - Medical or environmental diagnostics, bioprocess engineering
- **Packaging and bio-functionalization**
- **Compensation of secondary refractive index changes**
  - Temperature fluctuations or non-specific binding events
  - Differential interrogation of two identical fiber-optic sensors
  - Residual cross sensitivity determined by sensor’s polarization dependency (< 10%)
- **Optimized electroless plating process**
  - Improved structure and permittivity
  - Higher reproducibility
- **Dielectric intermediate layer**
  - SPR shifts towards higher wavelengths
  - Higher sensitivity