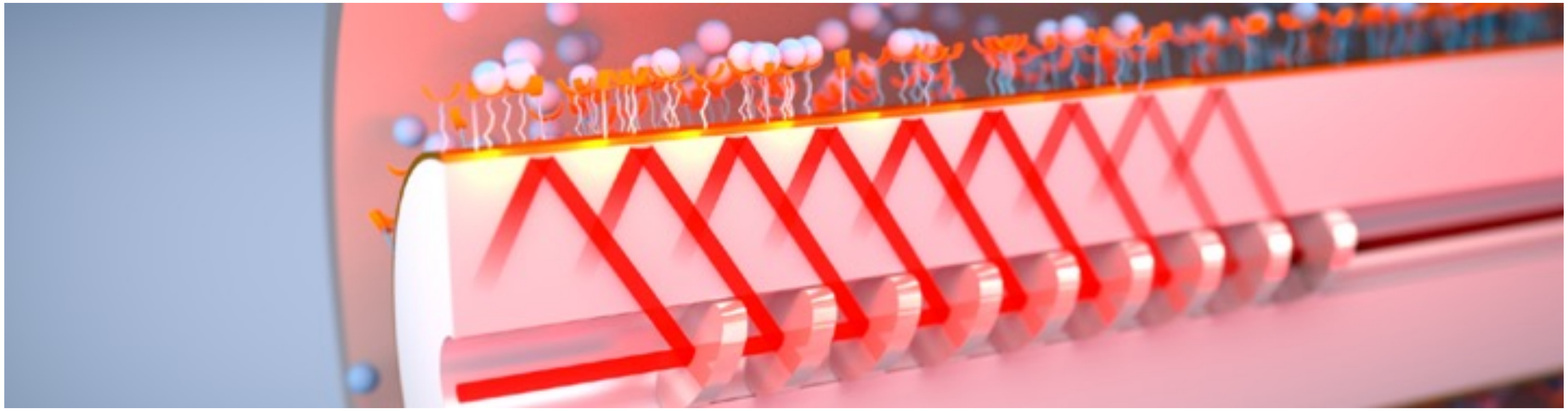


Tilted fiber Bragg gratings (TFBGs):
From multiparametric sensors to plasmonic biosensors

C. Caucheteur

University of Mons
Advanced Photonic Sensors ERC Unit, Mons, Belgium

christophe.caucheteur@umons.ac.be

Optica Webinar, 7th September 2023

TFBGs are the subject of several hundreds of publications!

Seminal papers

INSTITUTE OF PHYSICS PUBLISHING MEASUREMENT SCIENCE AND TECHNOLOGY
Meas. Sci. Technol. **12** (2001) 765–770 www.iop.org/Journals/mt PII: S0957-0233(01)20371-3

Tilted short-period fibre-Bragg-grating-induced coupling to cladding modes for accurate refractometry

G Laffont and P Ferdinand

CEA–LIST–DIMRI/SIAR, Centre d'Etudes de Saclay, F 91191 Gif-sur-Yvette, France

February 1, 2007 / Vol. 32, No. 3 / OPTICS LETTERS 211

Plasmon resonances in gold-coated tilted fiber Bragg gratings

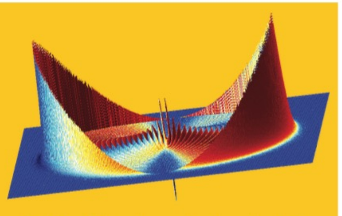
Yanina Y. Shevchenko and Jacques Albert

Department of Electronics, Carleton University, 1125 Colonel By Drive, Ottawa Ontario, K1S 5B6, Canada

Important reviews

LASER & PHOTONICS REVIEWS
Laser Photonics Rev., 1–26 (2012) / **DOI** 10.1002/lpor.201100039

Abstract Optical fiber gratings have developed into a mature technology with a wide range of applications in various areas, including physical sensing for temperature, strain, acoustic waves and pressure. All of these applications rely on the perturbation of the period or refractive index of a grating inscribed in the fiber core as a transducing mechanism between a quantity to be measured and the optical spectral response of the fiber grating. This paper presents a relatively recent variant of the fiber grating concept, whereby a small tilt of the grating fringes causes coupling of the optical power from the core mode into a multitude of cladding modes, each with its own wavevector and mode field shape. The main consequence of doing so is that the differential response of the modes can then be used to multiply the sensing modalities available for a single fiber grating and also to increase the sensor resolution by taking advantage of the large amount of data available. In particular, the temperature cross-sensitivity and power source fluctuation noise inherent in all fiber grating designs can be completely eliminated by referencing all the spectral measurements to the wavelength and power level of the core mode back-reflection. The mode resonances have a quality factor of 10^5, and they can be observed in reflection or transmission. A thorough review of experimental and theoretical results will show that tilted fiber Bragg gratings can be used for high resolution refractometry, surface plasmon resonance applications, and multiparameter physical sensing (strain, vibration, curvature, and temperature).



Tilted fiber Bragg grating sensors

Jacques Albert[1,*], Li-Yang Shao[2], and Christophe Caucheteur[3]

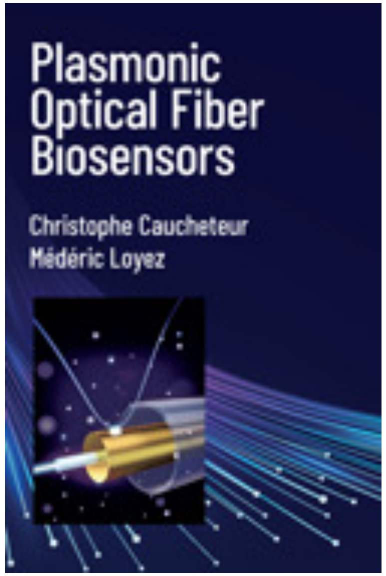
Review Vol. 14, No. 1 / March 2022 / *Advances in Optics and Photonics* 1

Advances in Optics and Photonics

Mode-division and spatial-division optical fiber sensors

CHRISTOPHE CAUCHETEUR,[1,*] JOEL VILLATORO,[2,3] FU LIU,[4,5] MÉDÉRIC LOYEZ,[1,6] TUAN GUO,[4] AND JACQUES ALBERT[5]

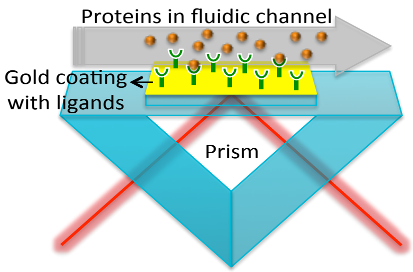
[1] *Electromagnetism and Telecommunication Department, University of Mons, 31 Boulevard Dolez, 7000 Mons, Belgium*
[2] *Department of Communications Engineering, University of the Basque Country UPV/EHU, Plaza Torres Quevedo 1, E-48013 Bilbao, Spain*
[3] *IKERBASQUE, Basque Foundation for Science, E-48011 Bilbao, Spain*
[4] *Institute of Photonics Technology, Jinan University, 855 Xingye East Av, Guangzhou 511443, Guangzhou, China*
[5] *Department of Electronics, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada*
[6] *Proteomics and Microbiology Department, University of Mons, 6 Avenue du Champ de Mars, 7000 Mons, Belgium*

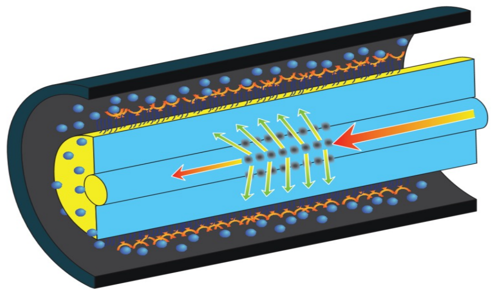


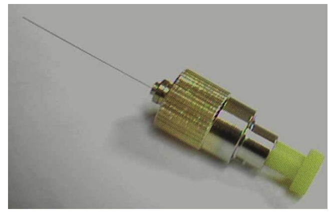
Artech House (2023)

Rationale of our work

- ❑ Transpose the Kretschmann prism into an optical fiber counterpart





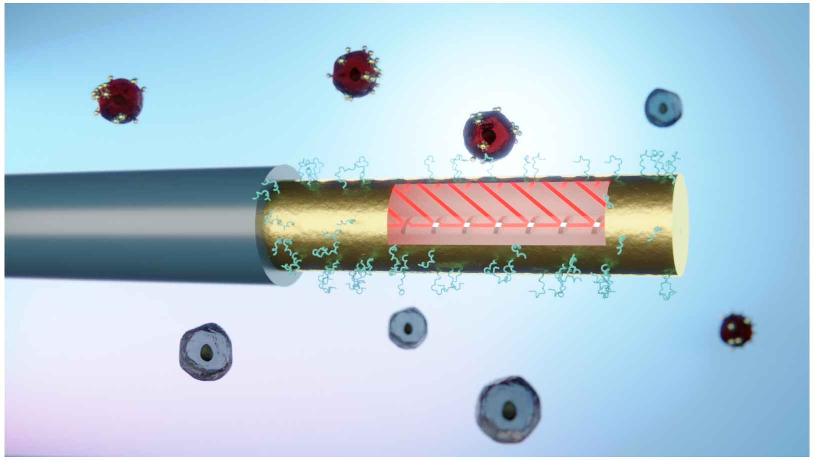


- ❑ Main advantages:
    - Weak intrusion → *In situ* measurement possible
    - Remote interrogation in very small volumes and real-time measurement
- ❑ We use near-infrared fiber Bragg gratings as spectral combs
- ❑ **Our probes are** able to excite **simultaneously but distinctively all** optical fiber **cladding modes**

Research context

- Towards *in vivo* cancer diagnosis in areas of critical access
- Focus on clinically-relevant biomarkers for lung and breast cancers:

  Cytokeratins (**CK**)
  mammaglobins (**MAM**) and human-epidermal growth factor receptors-2 (**HER2**)
- Collaborations with Prof. J. Albert (Carleton U.) and T. Guo (Jinan U.)

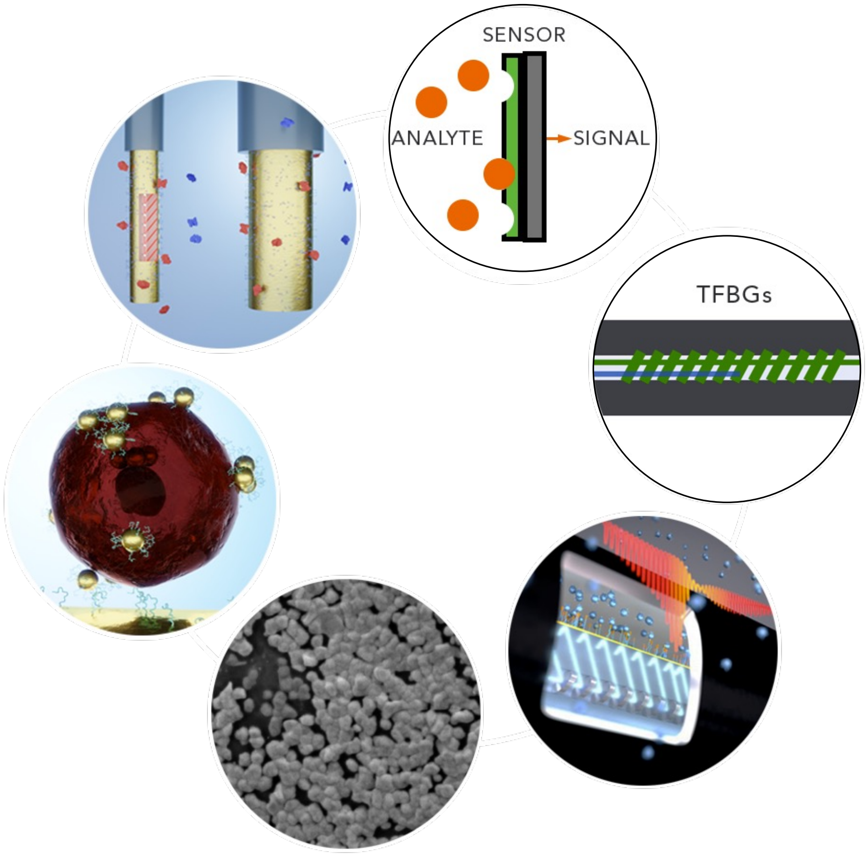


Our developments to achieve this:

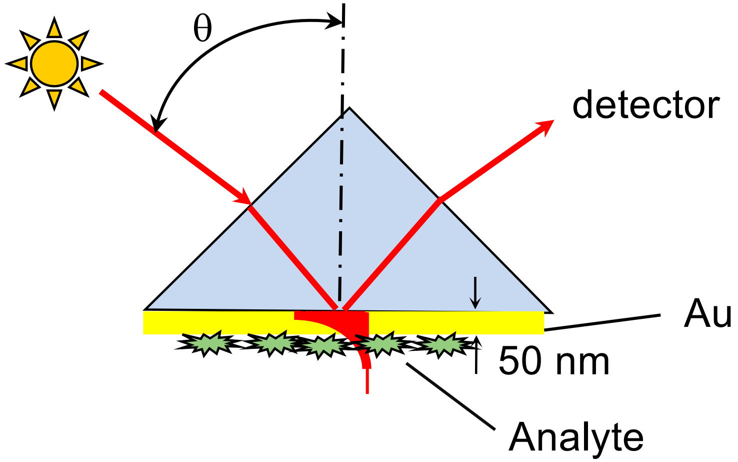
1. Optical fibre with tilted Bragg grating inside
2. Bare surface or thin gold overlay
3. Bioreceptors grafted on the surface
4. *In vitro* assays

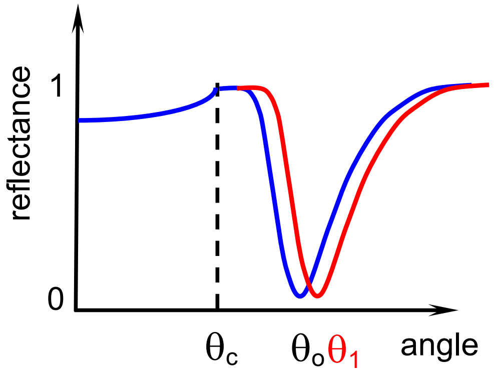
Outline

- ❑ Basics on plasmonic sensors
- ❑ Gratings production
- ❑ Gold-coating process
- ❑ Biofunctionalization process
- ❑ Bioassays



KRETSCHMANN prism configuration:
Light coupling by exploitation of total internal reflections





Surface plasmons = Collective oscillation of electrons at the inferface between a dielectric and a thin metal film

Evanescent wave characteristics:

- Near-field standing wave
- Extends about 1/2 λ
- Decays exponentially

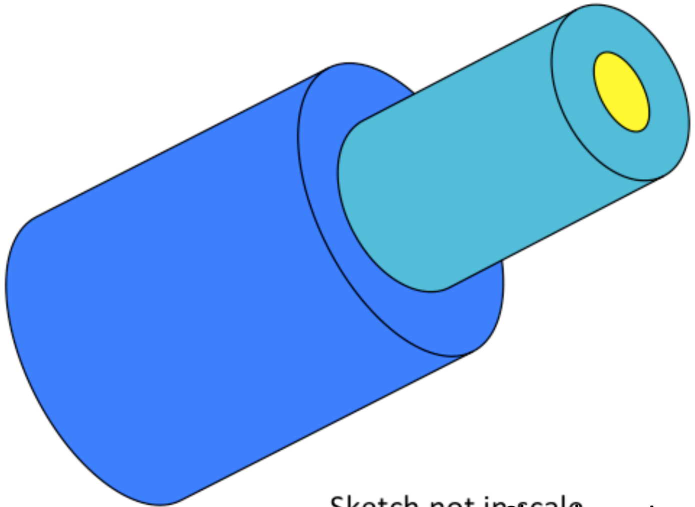
Configuration used to measure:

- Thickness changes
- Density fluctuation
- Molecular adsorption

We transpose this to single-mode optical fibers

Our sensors are manufactured into telecommunication-grade optical fibers

Optical fiber: three concentric cylinders



Core (5 – 8 µm)

Cladding (125 µm)

Polymer jacket (250 µm)

- Sketch not in scale -

- Sketch not in scale -

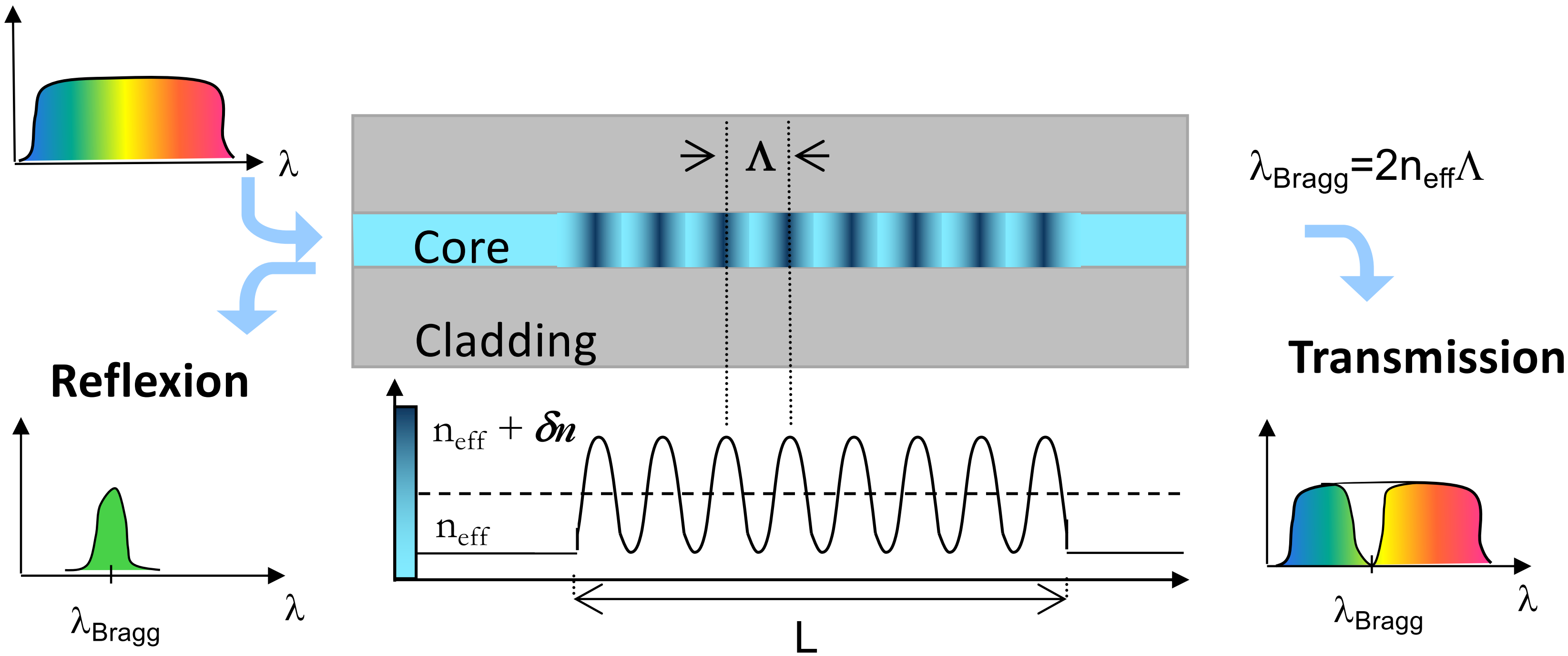
Core: $SiO_2 + GeO_2$ - Cladding: SiO_2

$n_{core} > n_{clad}$ → Light guidance by total internal reflections at the core-cladding interface (Cf. Snell law)

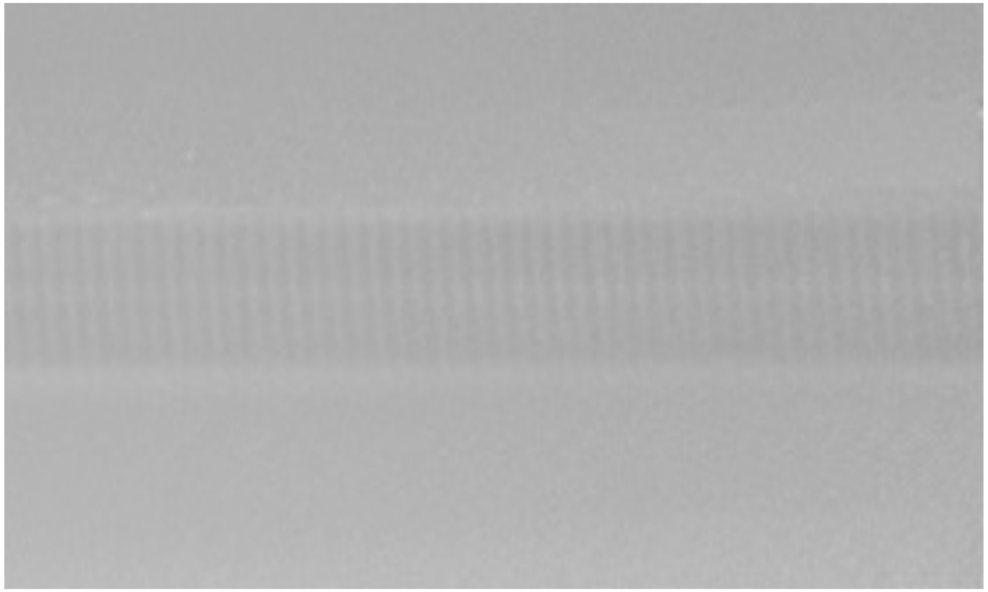
Single mode operation

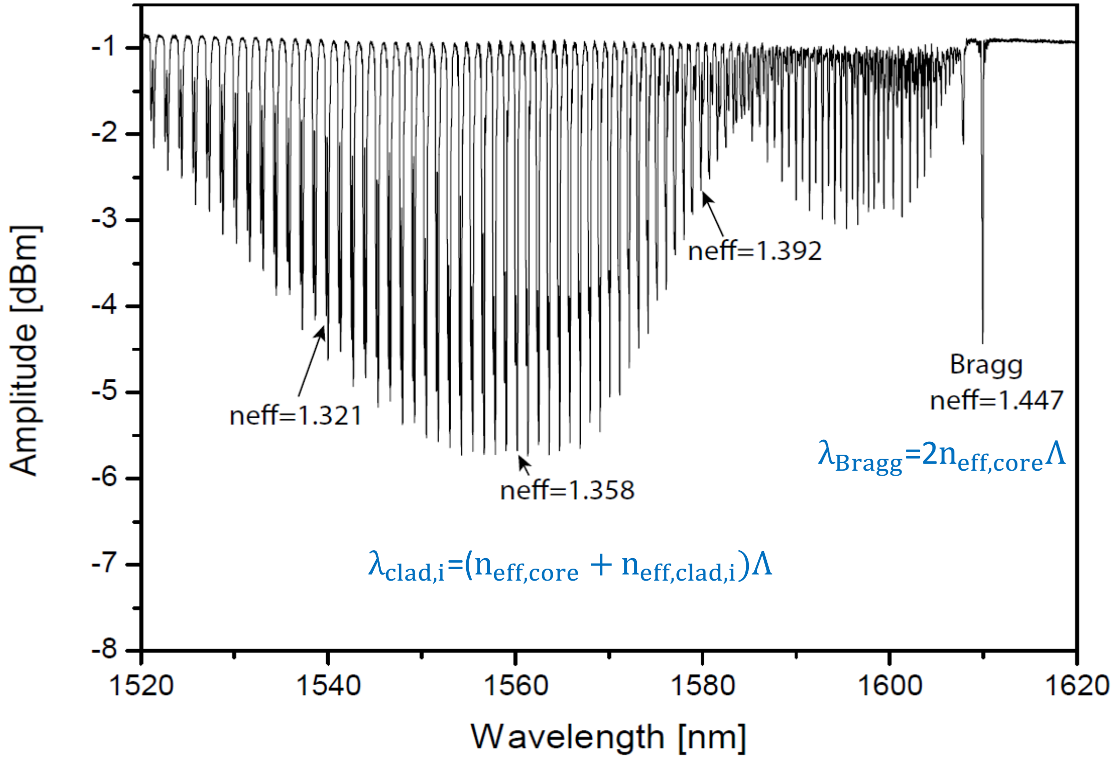
FIBRE BRAGG GRATINGS (FBGs)
The core is locally modified by photo-writing

- Periodic and permanent core refractive index modulation obtained by lateral illumination (interference of UV light)
- Index change possible thanks to the optical fiber photosensitivity



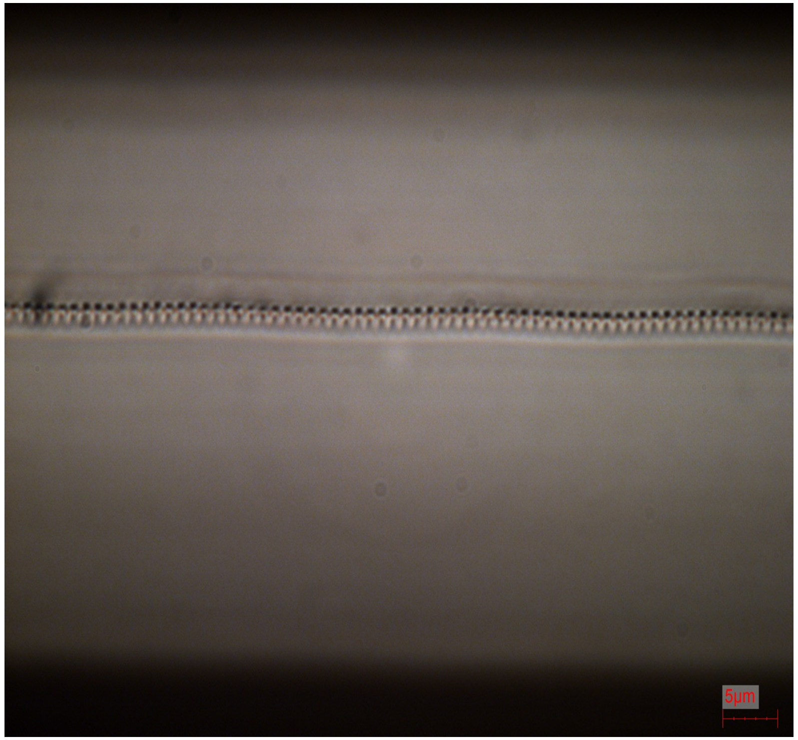
We mainly rely on tilted fiber Bragg gratings (TFBGs)

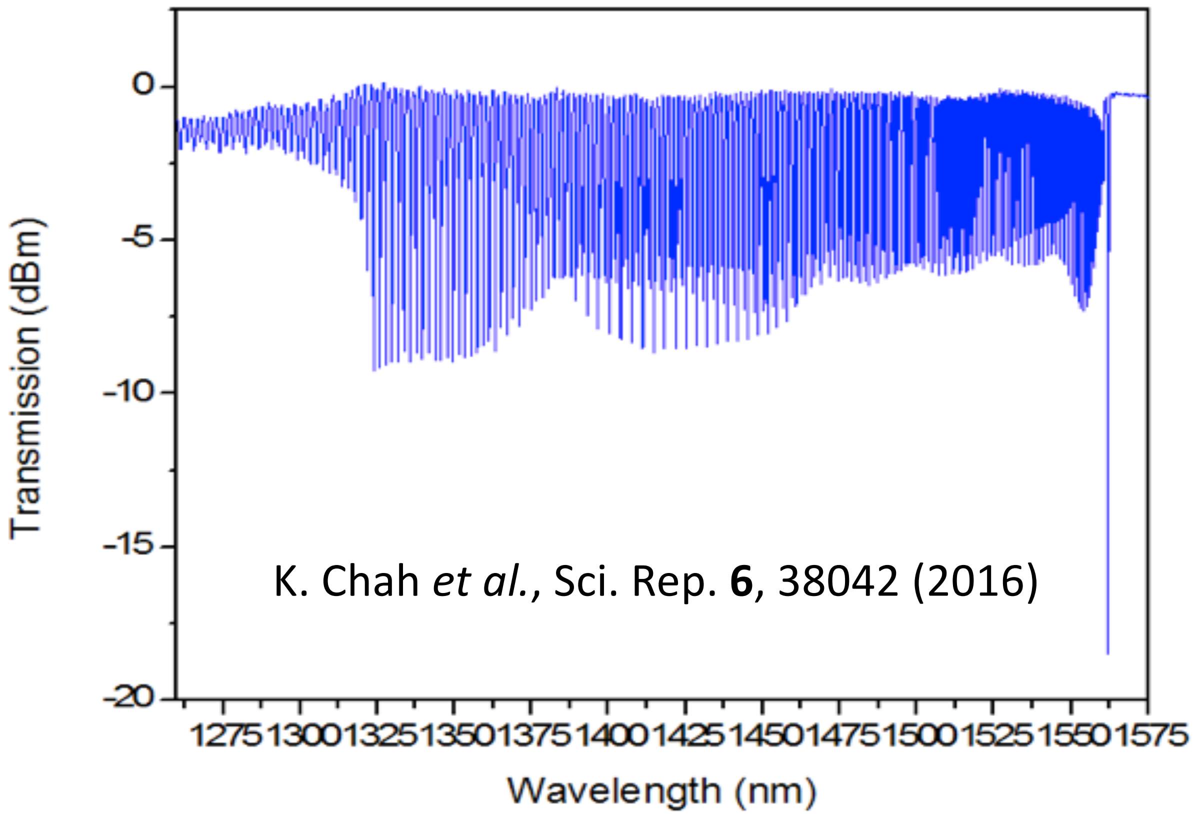




Cylindrical symmetry broken → SPR generation in gold-coated gratings

Eccentric gratings (EFBGs) can also be used





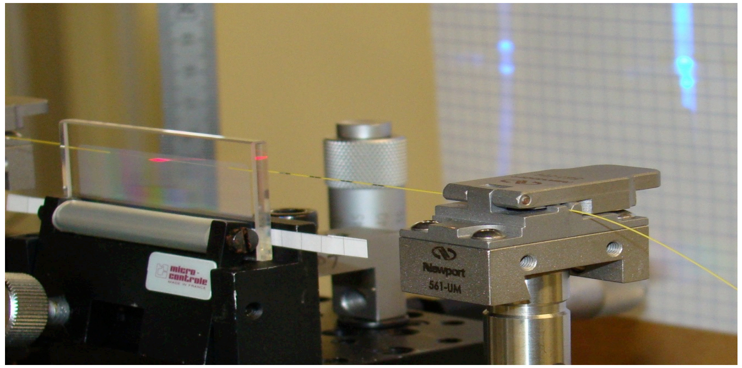
Cylindrical symmetry broken → SPR generation in gold-coated gratings

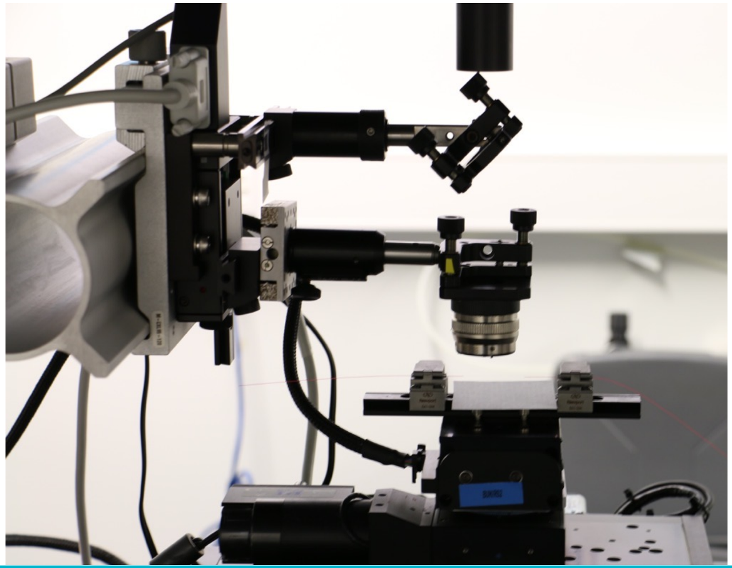
We have several options to produce such gratings

TFBGs

- ❑ Phase mask tilted in the plane perpendicular to the incident laser beam
  - 193 nm (excimer laser – NORIA system)
  - 244 nm (frequency-doubled Argon laser)
  - 266, 400 or 800 nm (fs pulses laser)

  L ~ 1 cm, θ ~ [6° – 10°] to cover RI of liquids

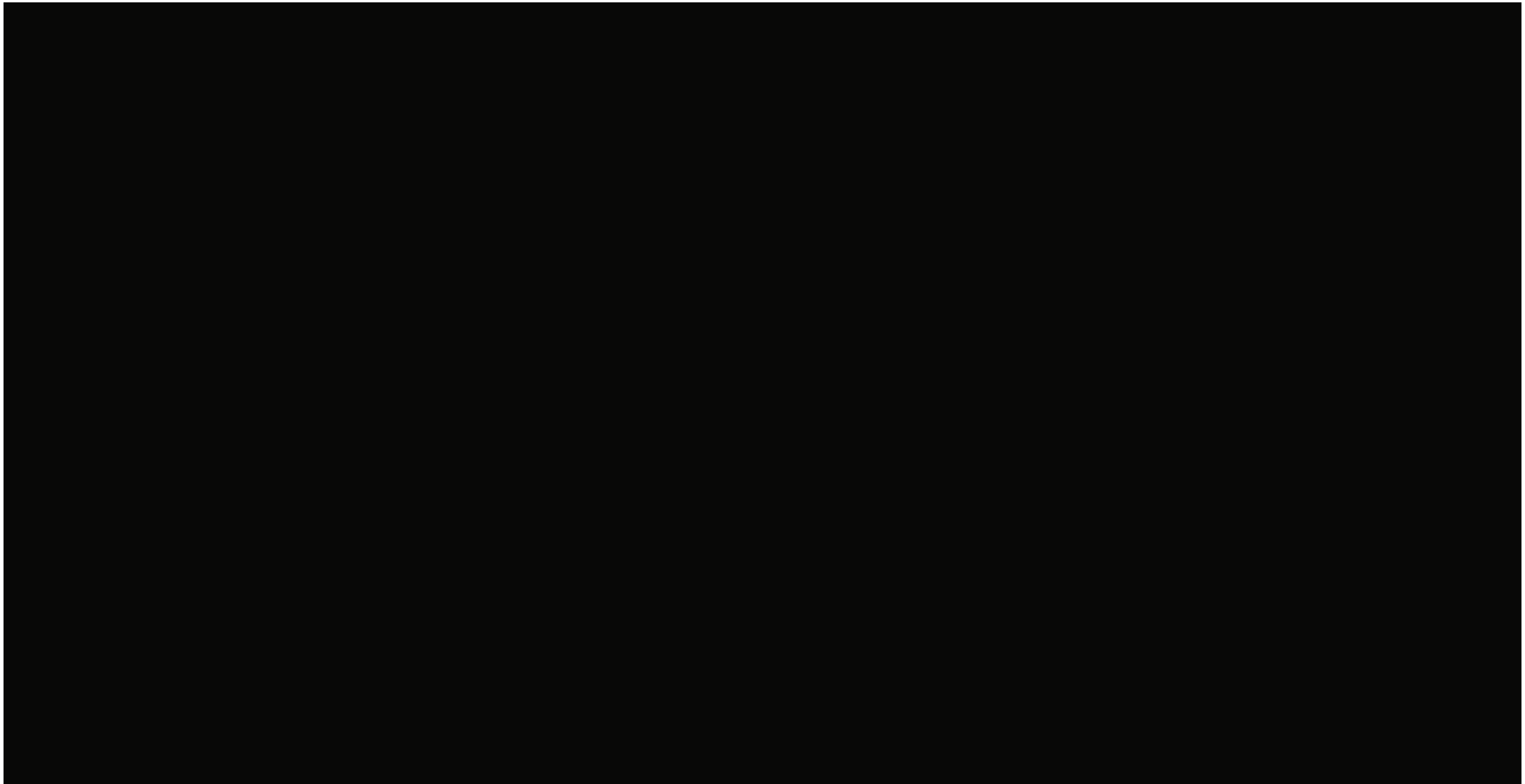




EFBGs

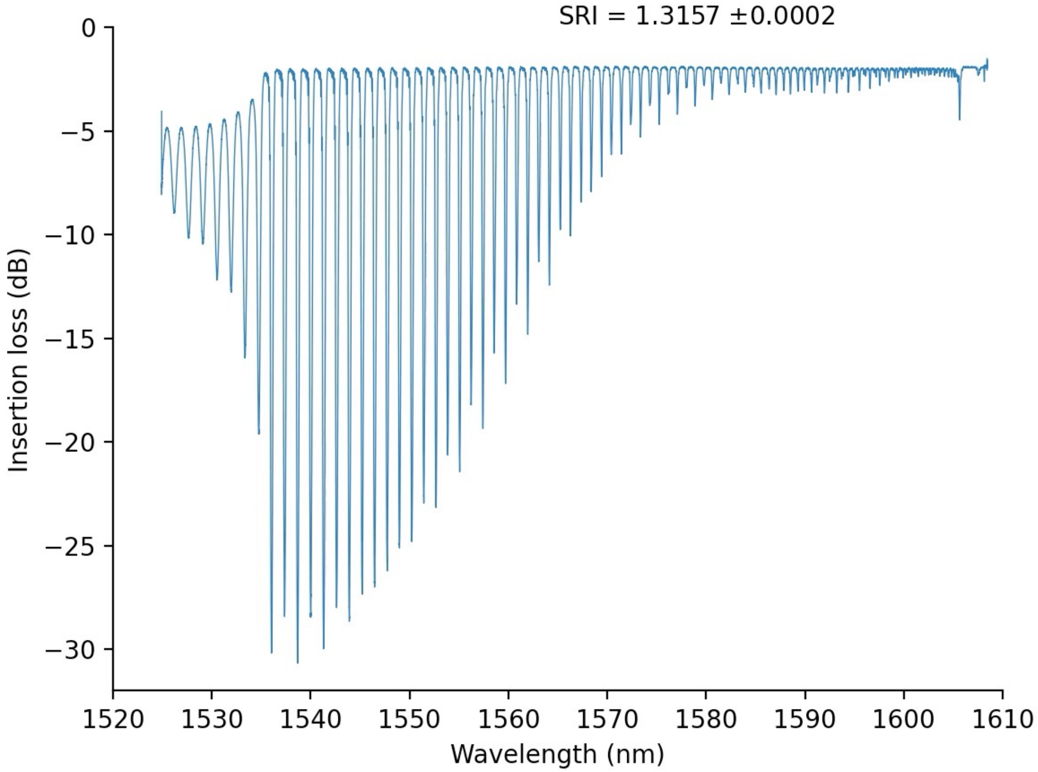
- ❑ Point-by-point with fs pulses laser

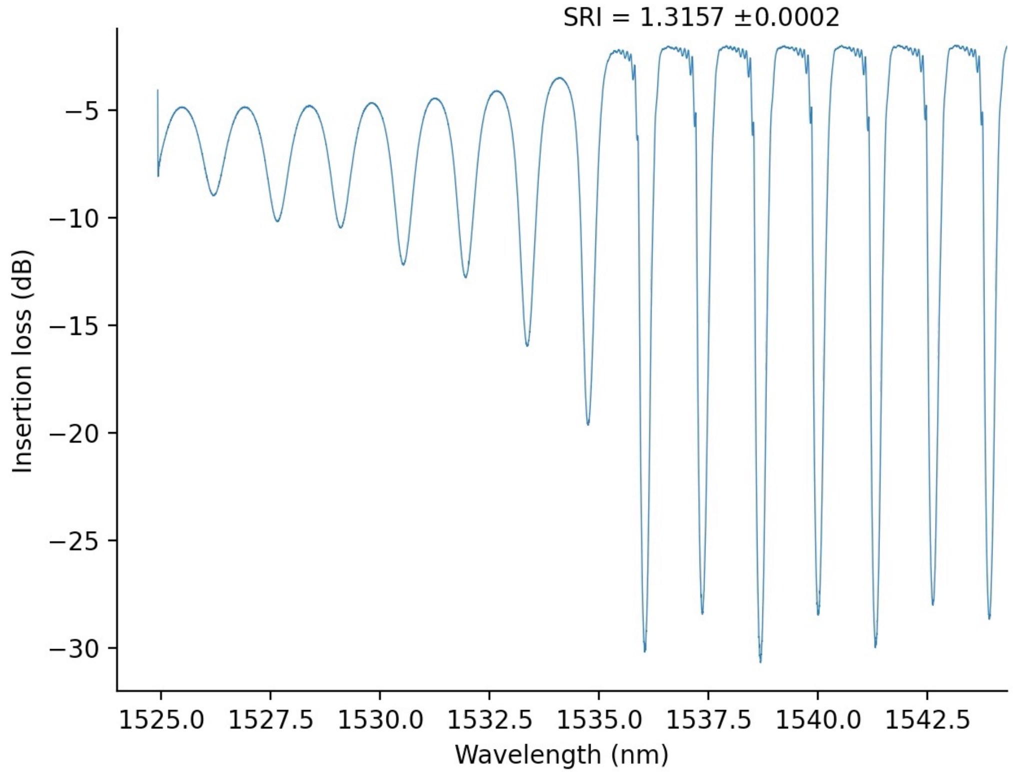
Focus on the NORIA Facility



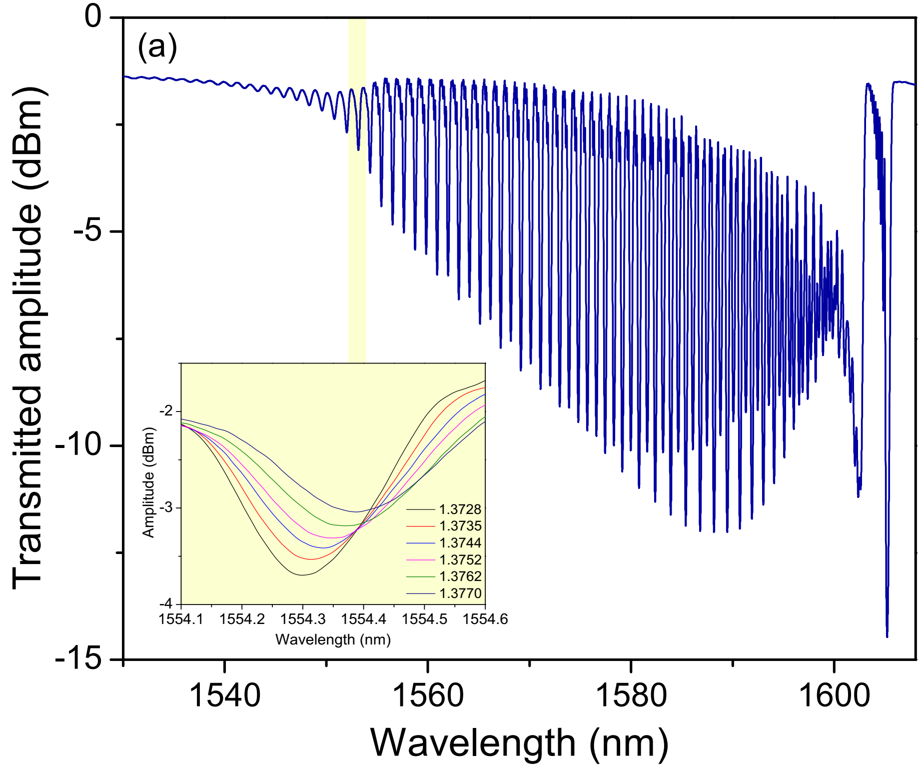
For bare gratings, the cut-off mode is used to track slight surrounding refractive index changes (1/2)

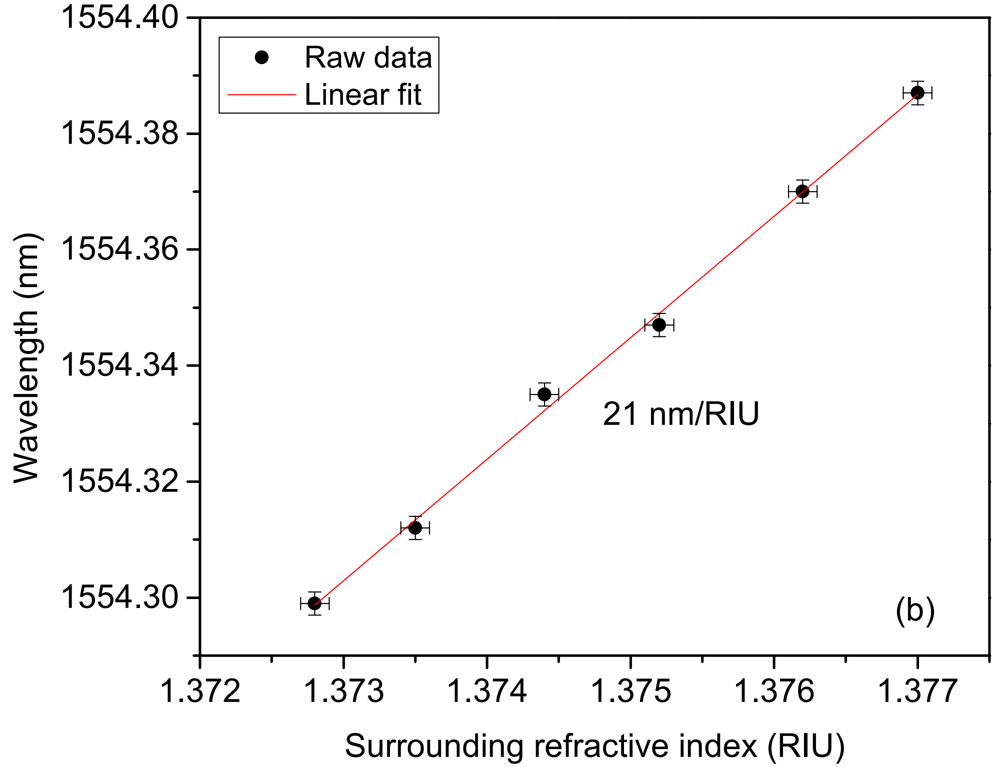
Change of the surrounding refractive index





For bare gratings, the cut-off mode is used to track slight surrounding refractive index changes (2/2)

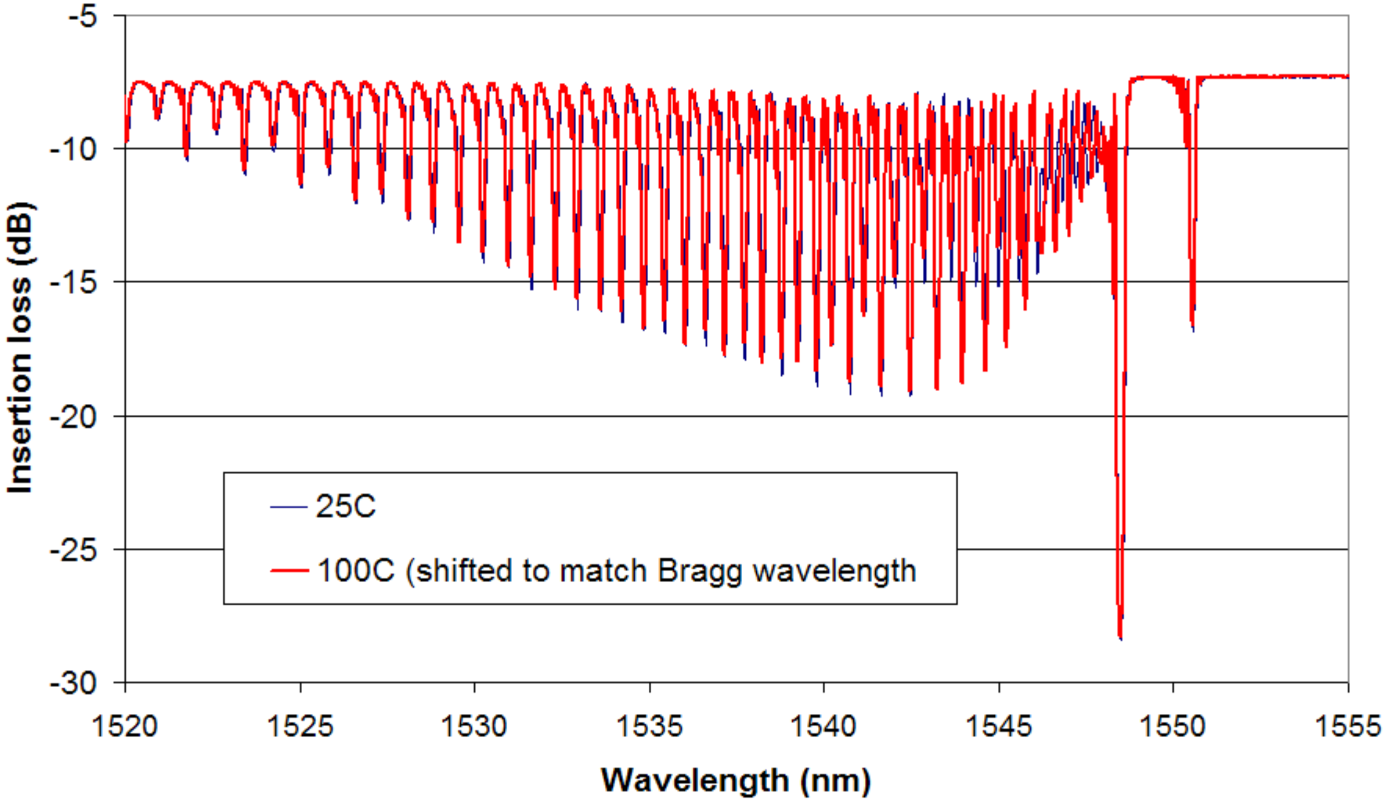




- ❑ Linear sensitivity: ~20 nm/RIU
- ❑ Temperature self-compensation thanks to the core mode resonance

Temperature sensitivity

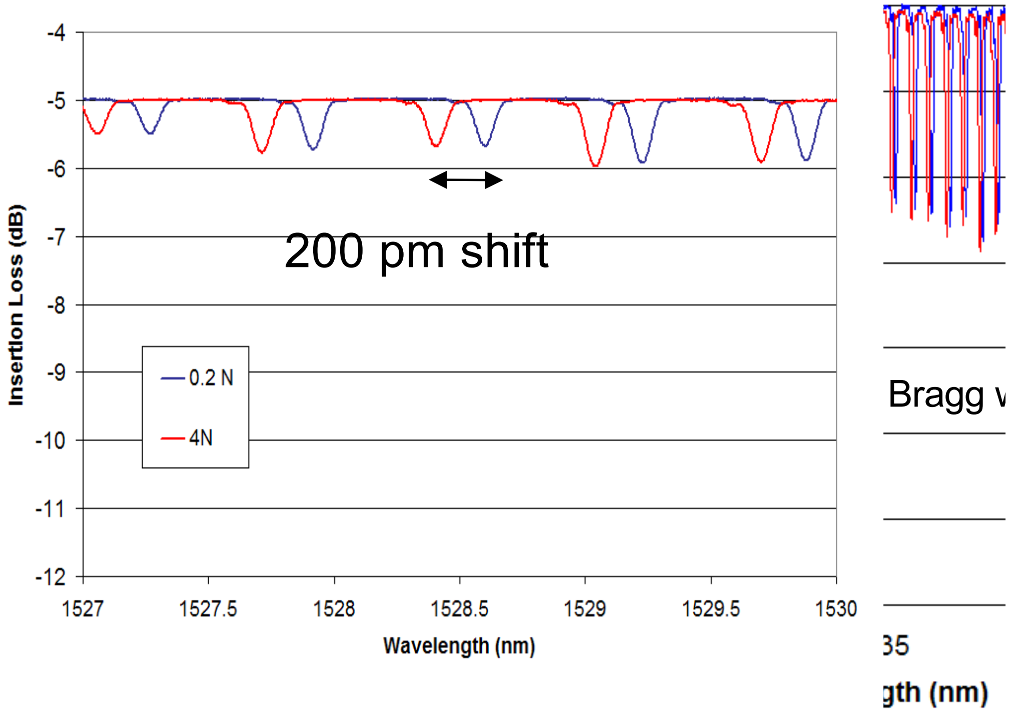
The cladding modes resonances translate almost exactly with the Bragg peak as the temperature changes



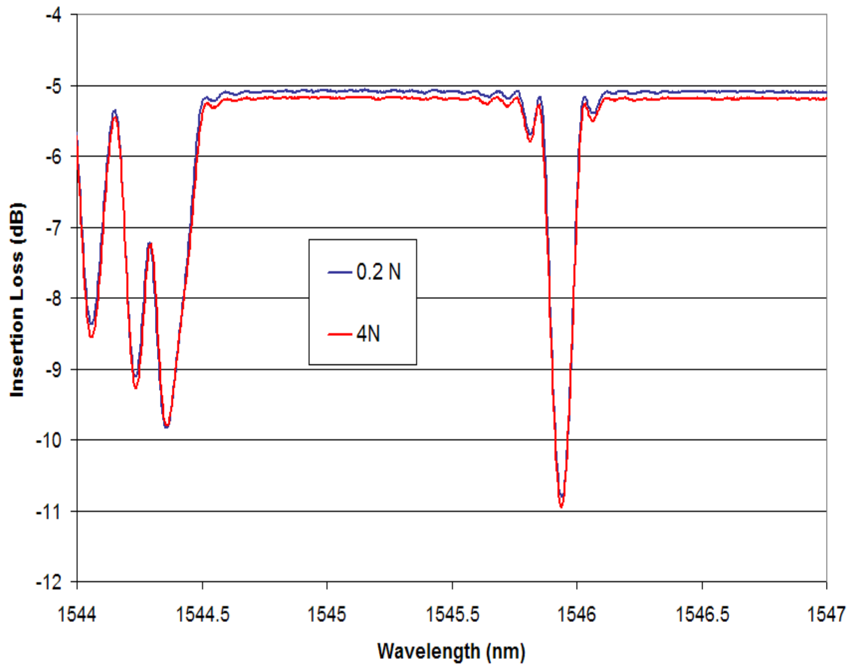
Axial strain sensitivity (1/2)

The cladding modes resonances do not translate exactly with the Bragg peak as the axial strain is applied

High order mode resonances

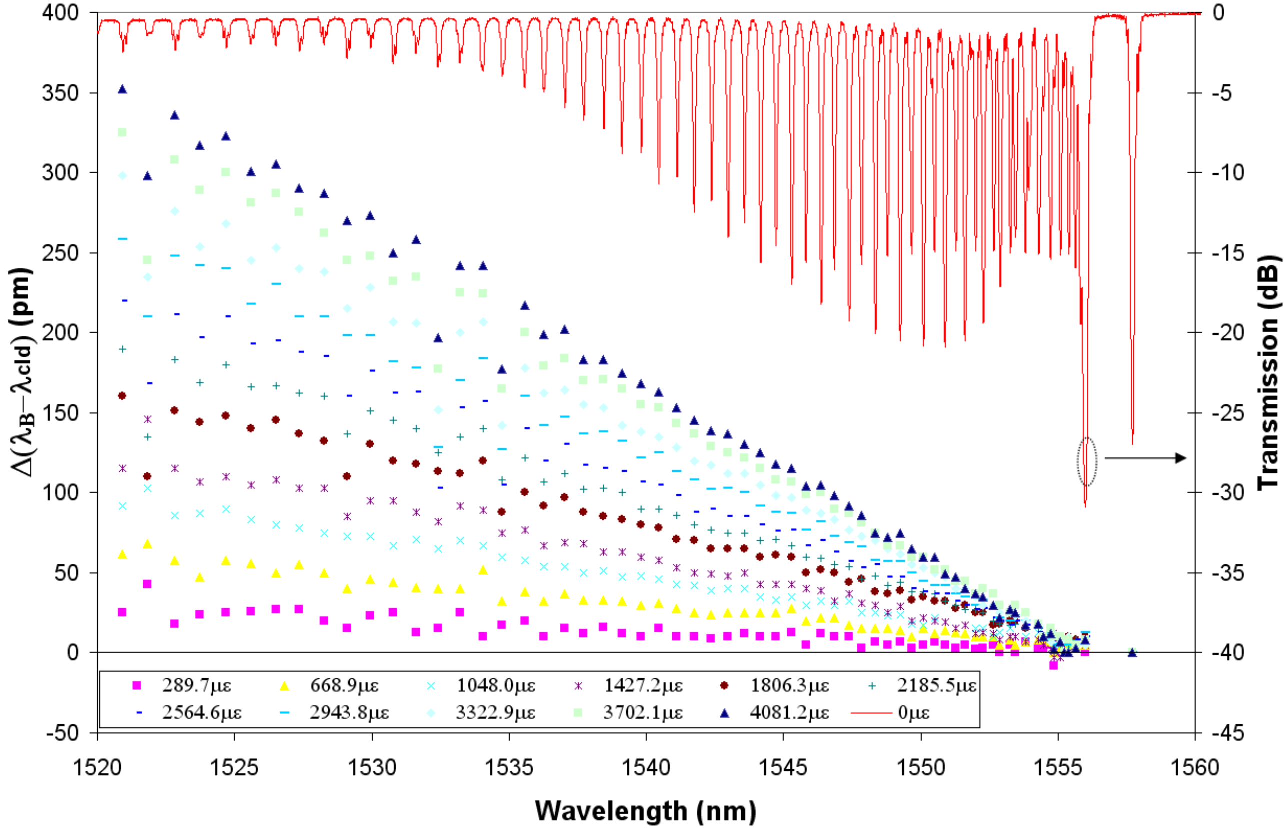


Bragg resonance



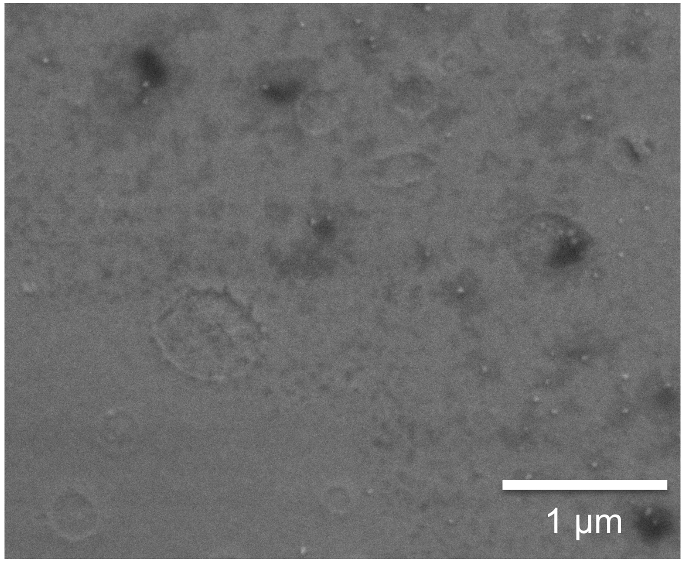
Axial strain sensitivity (2/2)

The shift between the Bragg wavelength and a cladding mode resonance increases with the axial strain and the mode order



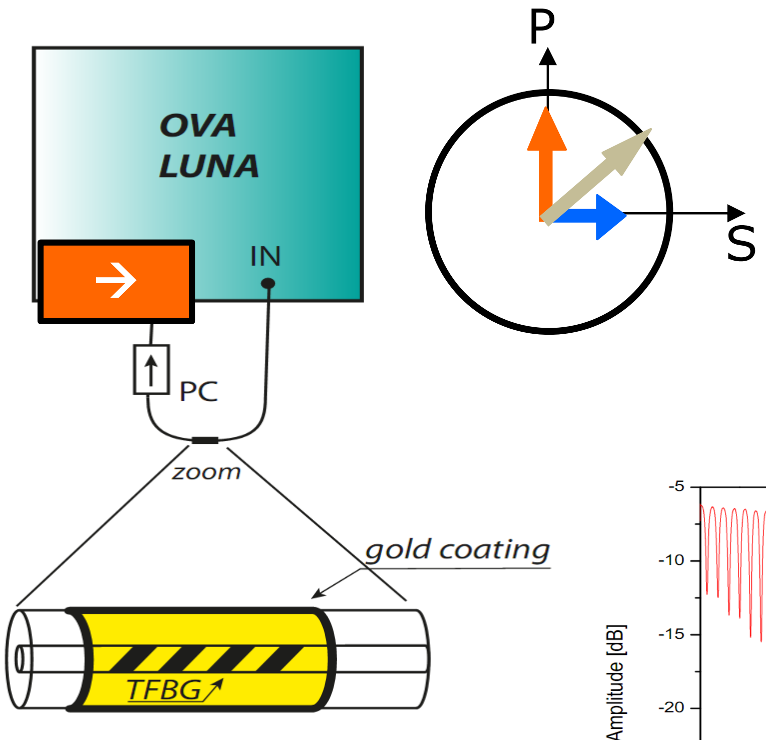
Gold is deposited by sputtering

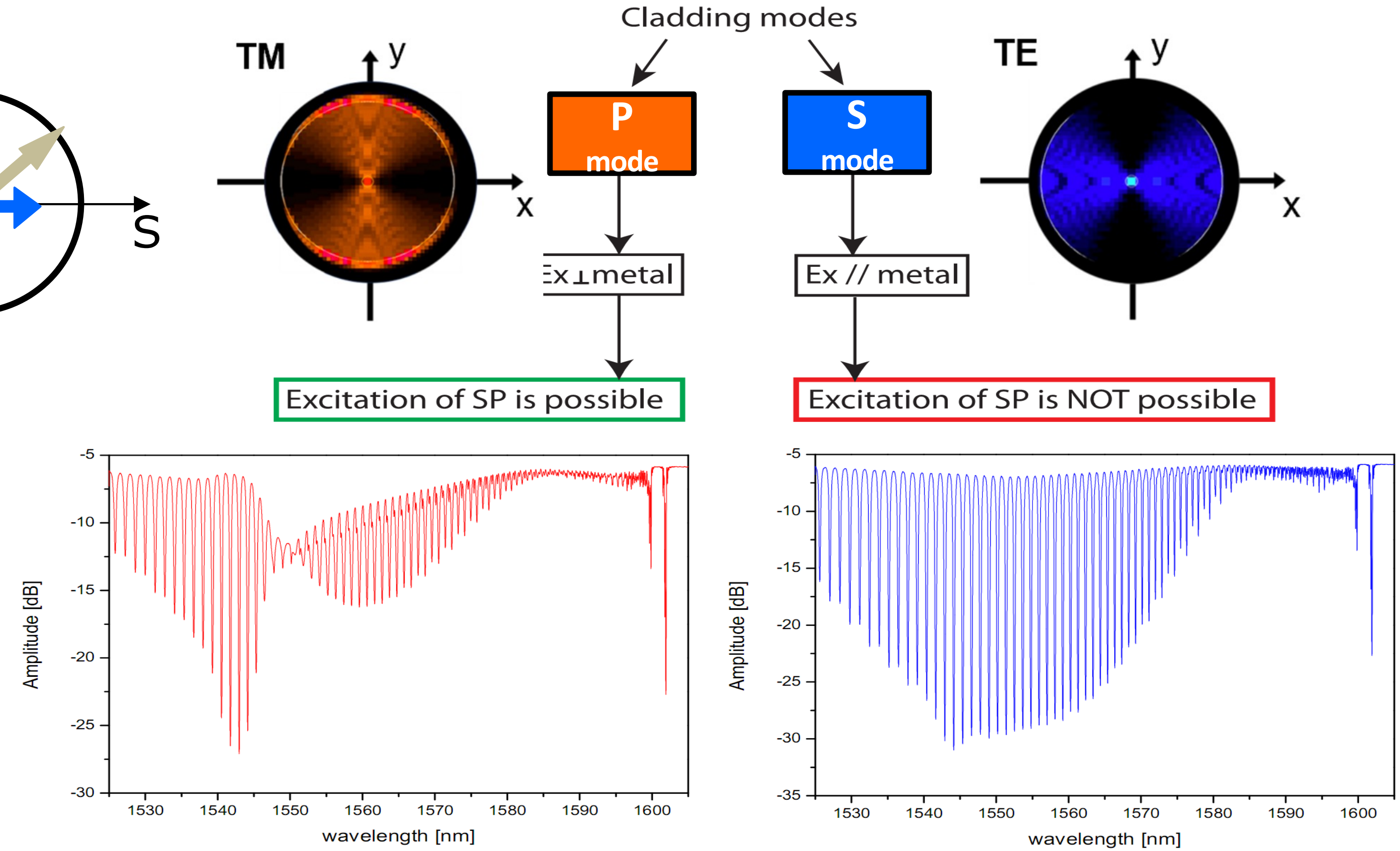
- **Sputtering**
  - Use of a sputter coater (Leica EM SCD500) with 99.99 % purity gold target
  - Gold thickness measured by a built-in Quartz microbalance
- **Thermal annealing** to improve adhesion



→ Good uniformity of the gold sheath

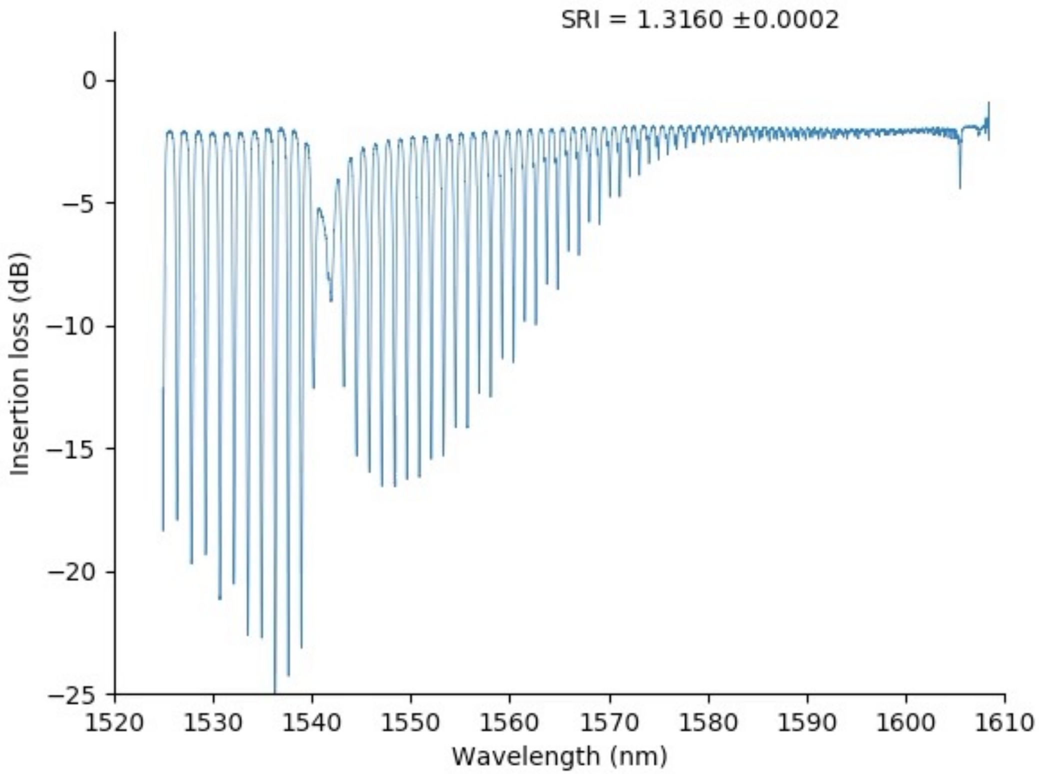
For clean SPR generation in liquids, the optimal gold thickness lies between 30 and 50 nm

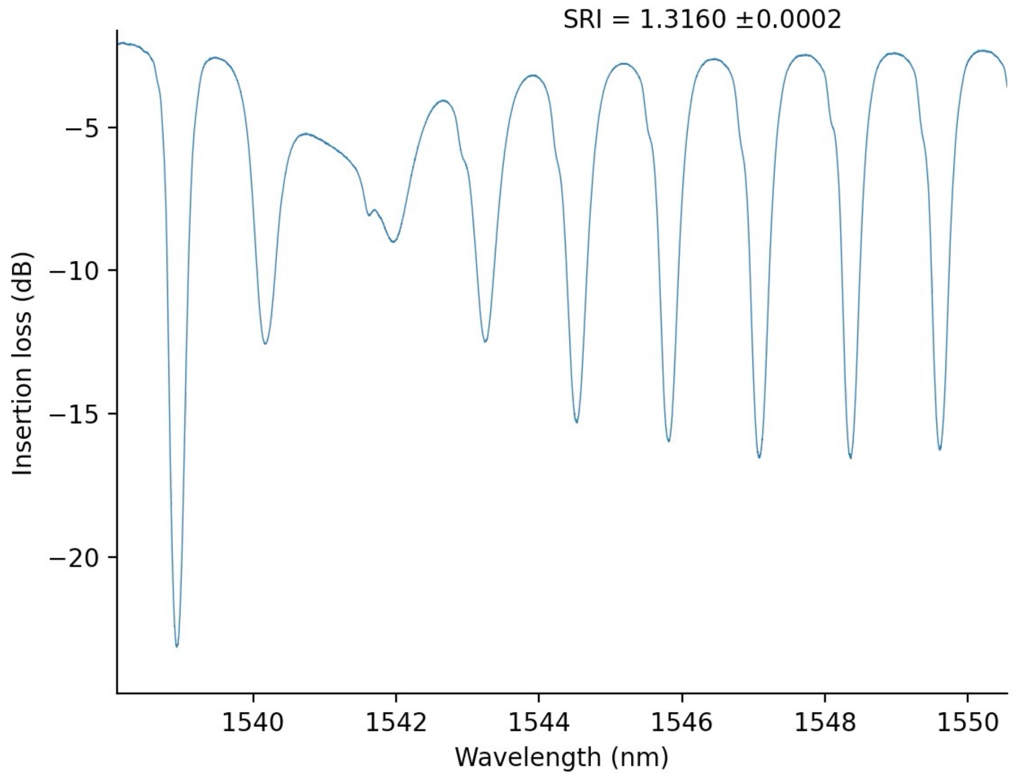




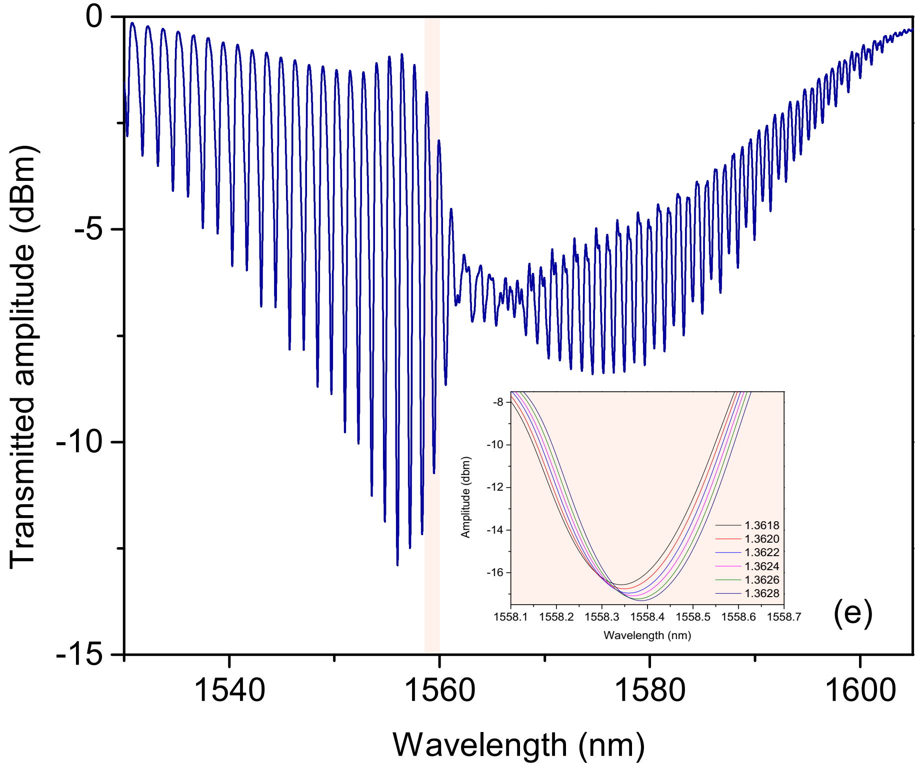
The SPR mode shifts in wavelength and in amplitude in response to refractive index changes (1/2)

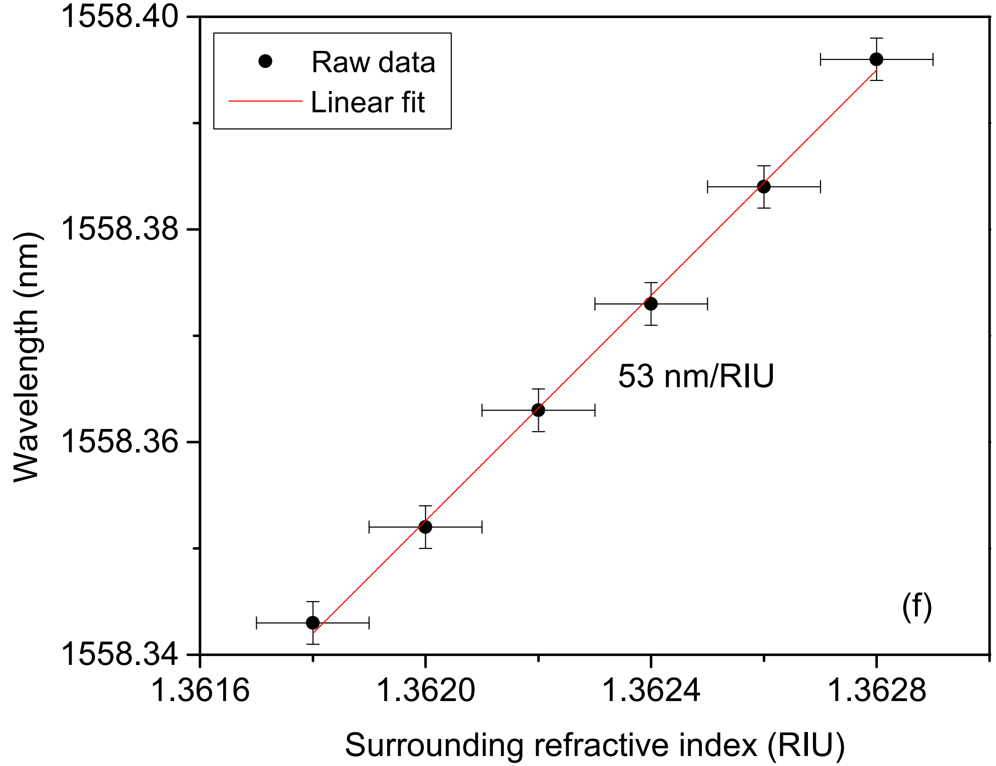
Change of the surrounding refractive index





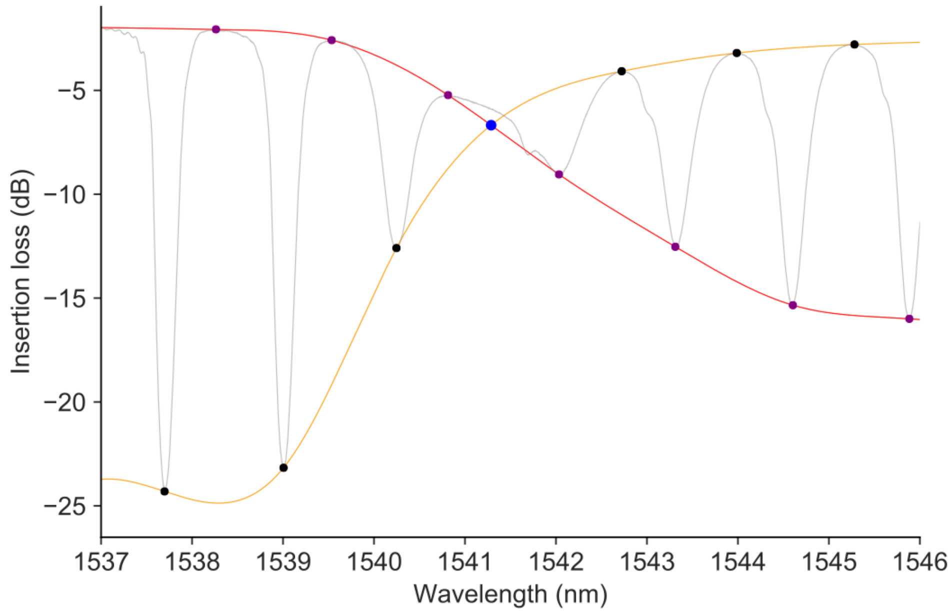
The SPR mode shifts in wavelength and in amplitude in response to refractive index changes (2/2)

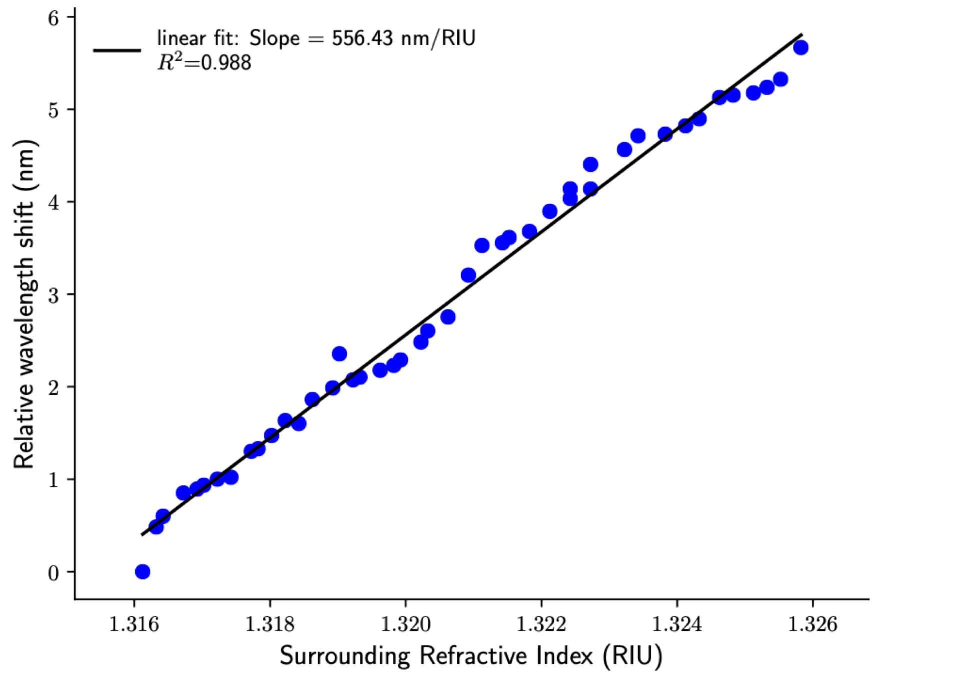




- ❑ Linear evolution: ~50 nm/RIU for single-peak tracking
- ❑ Possibility to tune the SPR wavelength by playing on the grating period

The demodulation from the envelopes of the spectrum yields the ultimate sensitivity



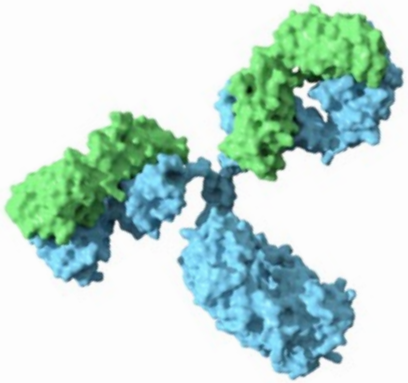


M. Lobry *et al.*, J. Lightwave Technol. **39**, 7288 (2021)

- ❑ Linear evolution: ~550 nm/RIU
- ❑ Can be readily implemented in a real-time signal analysis

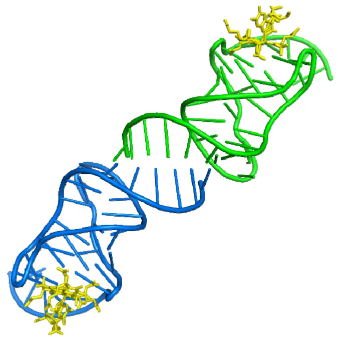
The functionalization on gold is a 2-step process

BIORECEPTORS



Antibodies	Aptamers
	« Nucleic Acid Antibodies »
~15 nm 125 kDa	~2 nm 5-25 kDa
Limited to physiologic conditions (pH, T) Immunogenic targets	More stable (pH, T), longer shelf life Immunogenic and non-immunogenic targets
Produced *in vivo* / cell cultures Low amount, expensive Batch-to-batch variations	Produced *in vitro* and easy to modify (5', 3') Large amount, expensive Improved batch-to-batch consistency
High Affinity, High Specificity Large panel commercially available	High Affinity, High Specificity Not yet widely available

aptus (Latin): to fit
meros (Greek): part

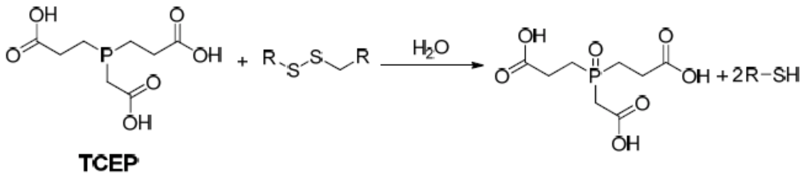


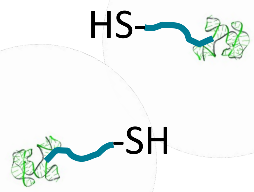
The functionalization on gold is a 2-step process

Thiolated-Aptamers

1. Reduction process (TCEP)

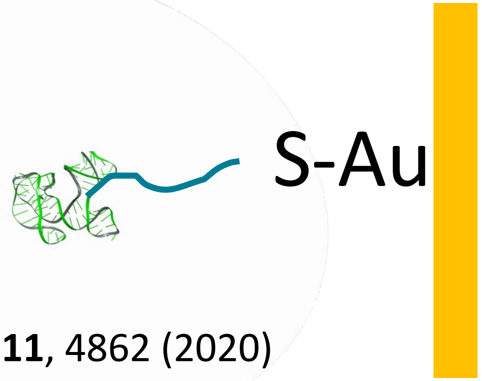
Aptamers are linked together
Through disulfide bonds





2. Immobilization on gold-coated TFBGs

Immobilized aptamer

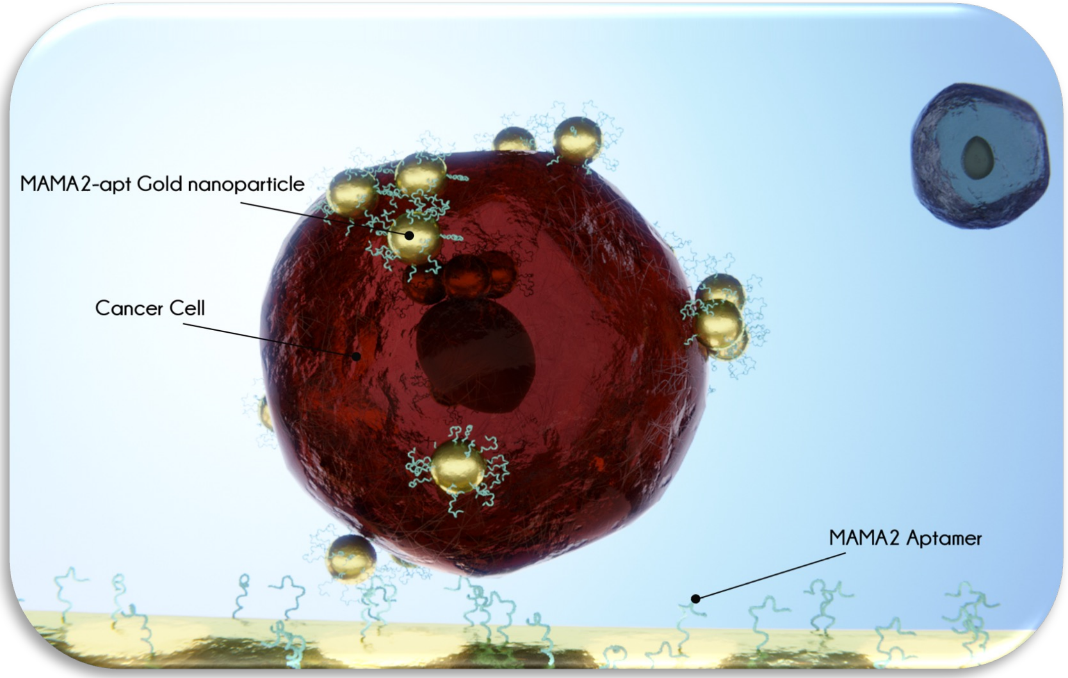


1 hour at room temperature in solution

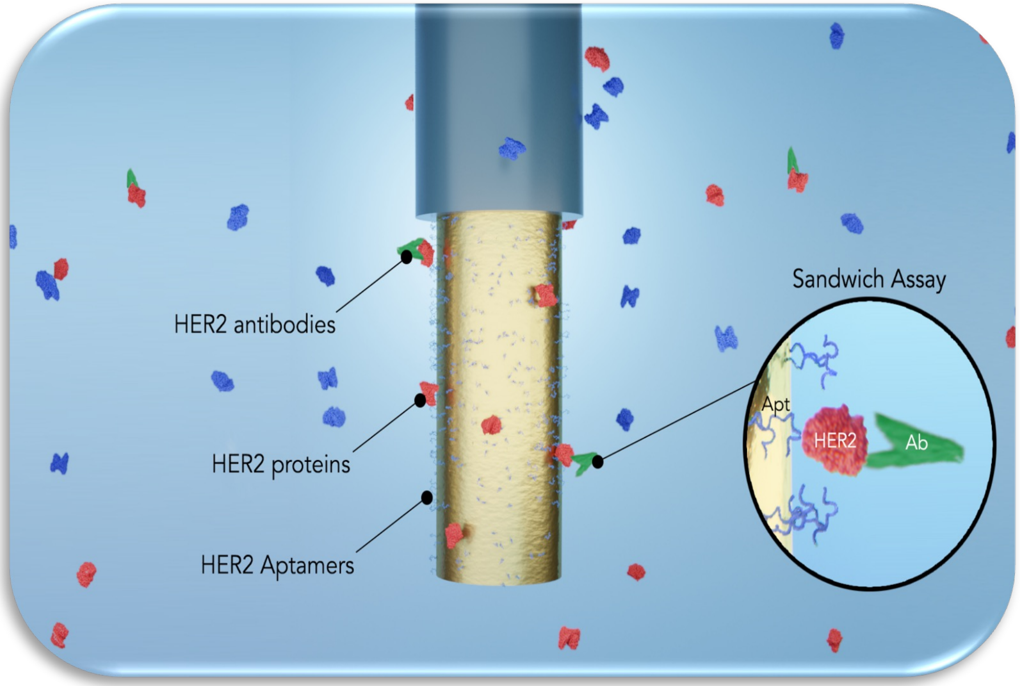
M. Lobry *et al.*, Biomed. Opt. Express **11**, 4862 (2020)
M. Loyez *et al.*, ACS Sensors **5**, 454 (2020)

Examples of *in vitro* bioassays

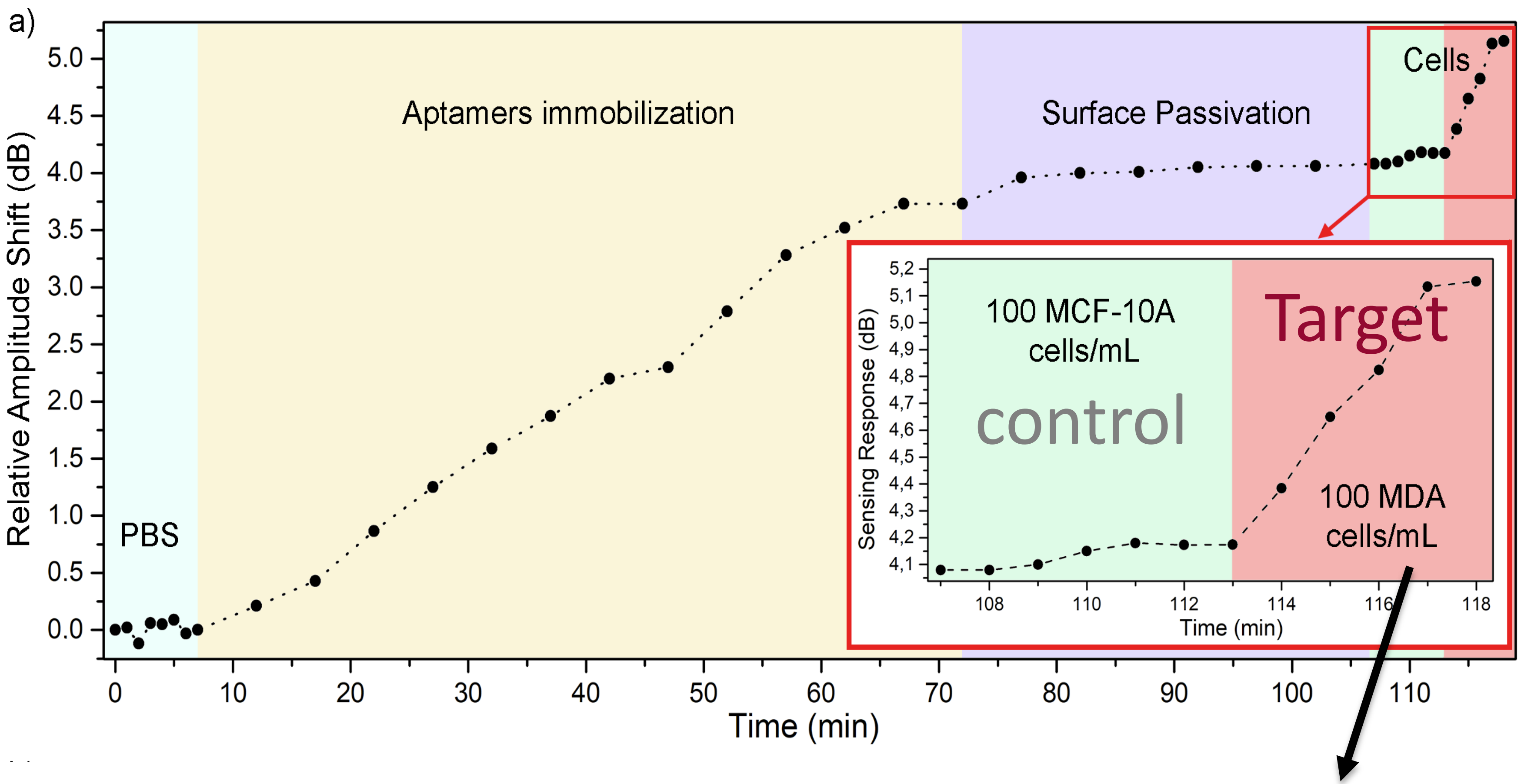
Mammaglobin-protein detection on cancer cells



Human Epidermal Receptor 2 (Breast Cancer Biomarker)

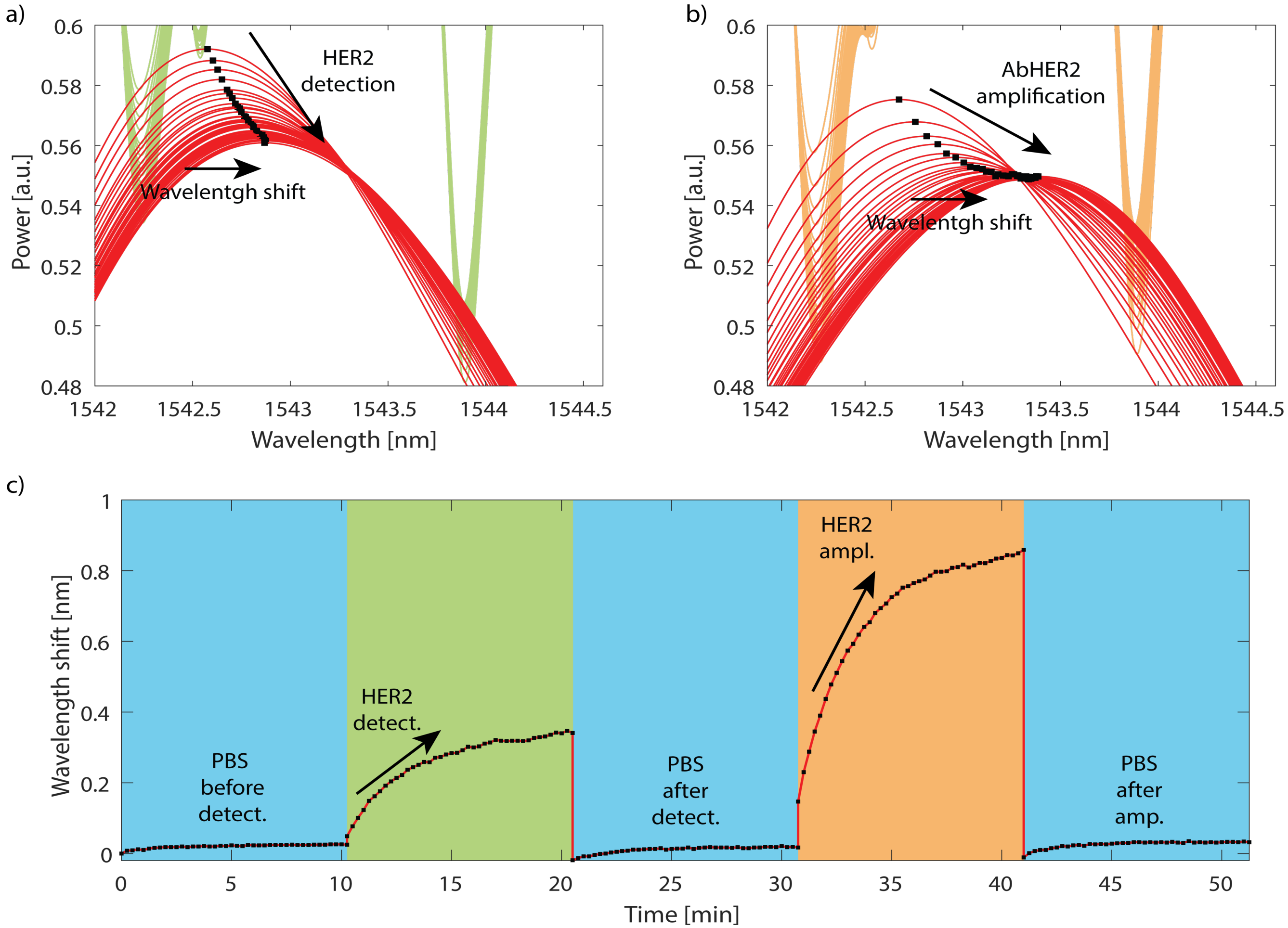


Mammaglobin-protein detection on cancer cells

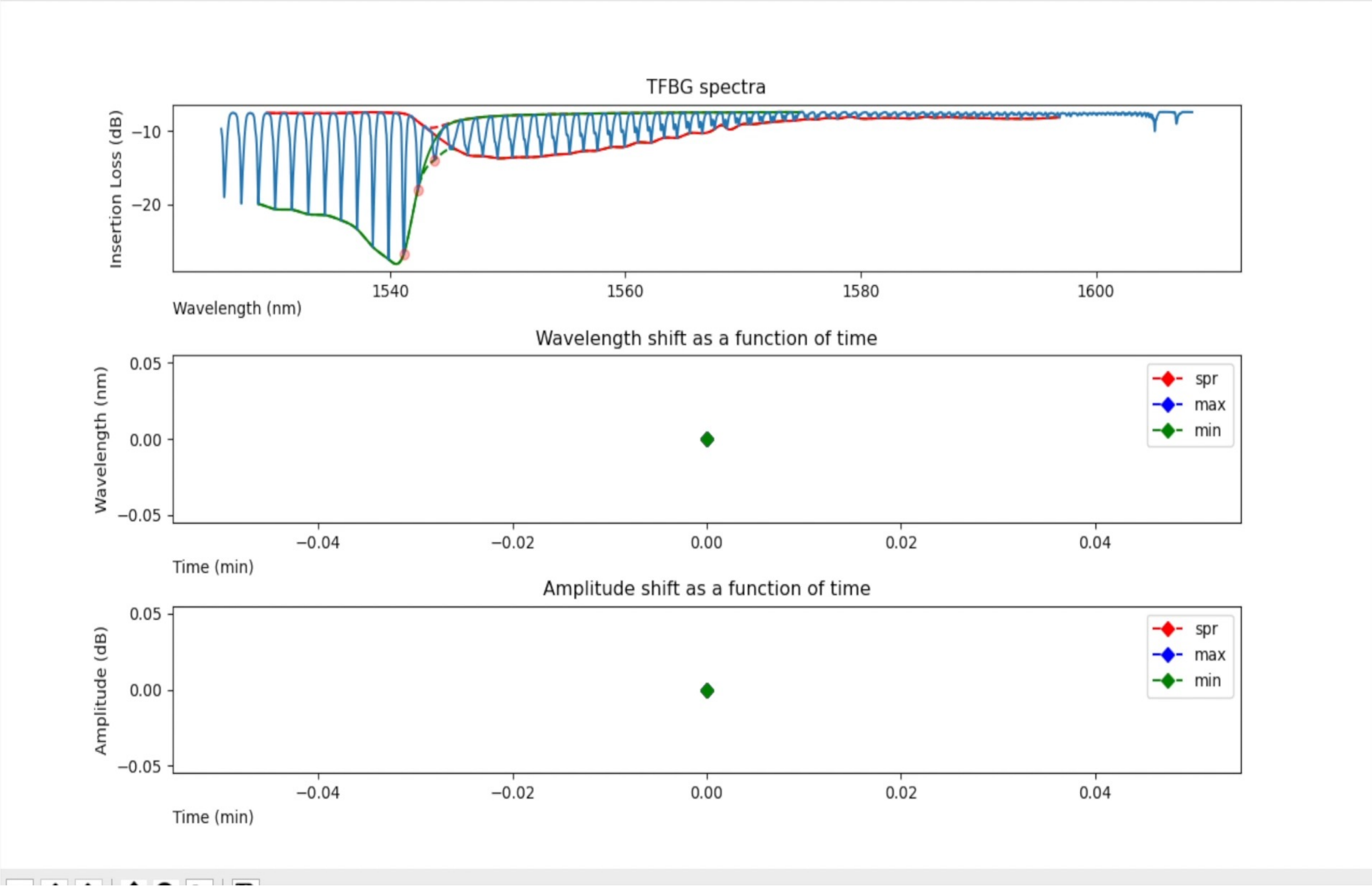


Specific detection of targeted cancer cells

HER2 detection & Signal amplification using antibodies



Example of automatic read-out



The spectrum of a TFBG is very rich and its read-out has been the subject of numerous recent works!

- Enhance the performances
- Provide real-time and cost-effective solutions

3046 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 40, NO. 9, MAY 1, 2022

Machine Learning Approach to Data Processing of TFBG-Assisted SPR Sensors

Eugeny D. Chubchev, Kirill A. Tomyshev, Igor A. Nechepurenko, Alexander V. Dorofeenko, and Oleg V. Butov

976 Vol. 48, No. 4 / 15 February 2023 / *Optics Letters* Letter

Optics Letters

Plasmonic biosensing with tilted fiber Bragg gratings interrogated using a 512-pixel spectrometer

MAXIME LOBRY,[1,*] CORENTIN GUYOT,[2] DAMIEN KINET,[1,2] KARIMA CHAH,[1] AND CHRISTOPHE CAUCHETEUR[1]

[1]*Electromagnetism and Telecommunication Department, University of Mons, 31 Bld Dolez, 7000 Mons, Belgium*
[2]*B-SENS SPRL, 31 Bld Dolez, 7000 Mons, Belgium*

sensors MDPI

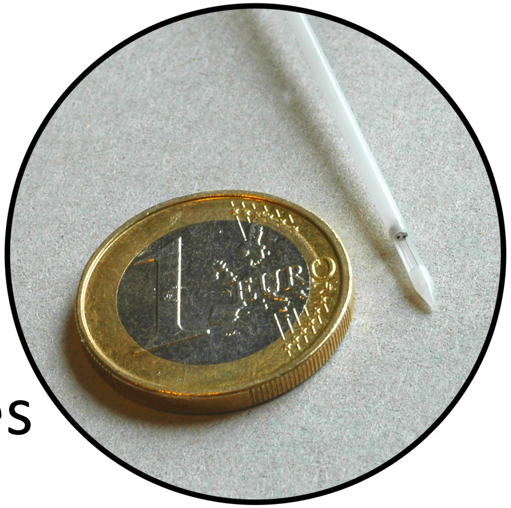
Article

Relevance of the Spectral Analysis Method of Tilted Fiber Bragg Grating-Based Biosensors: A Case-Study for Heart Failure Monitoring

Miguel Vidal [1], Maria Simone Soares [1], Médéric Loyez [2], Florinda M. Costa [1], Christophe Caucheteur [2], Carlos Marques [1], Sónia O. Pereira [1] and Cátia Leitão [1,*]

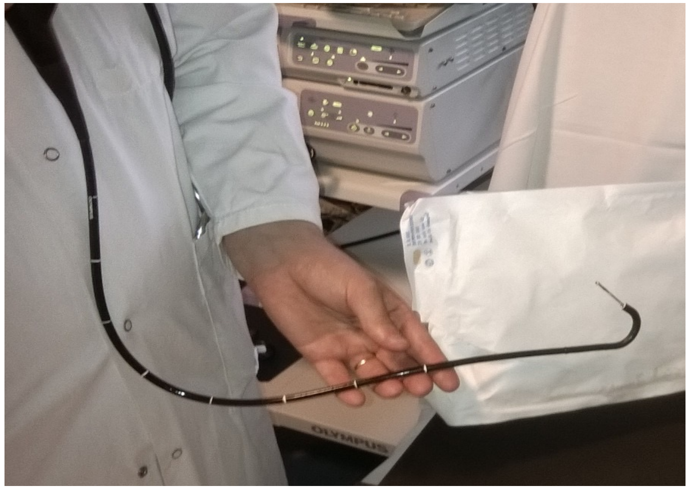
1 Physics Department & I3N, University of Aveiro, 3810-193 Aveiro, Portugal; miguelvidal@ua.pt (M.V.); msimone.fsoares@ua.pt (M.S.S.); flor@ua.pt (F.M.C.); carlos.marques@ua.pt (C.M.); sonia.pereira@ua.pt (S.O.P.)
2 Electromagnetism and Telecommunication Department, University of Mons, 31 Bld Dolez, 7000 Mons, Belgium; mederic.loyez@umons.ac.be (M.L.); christophe.caucheteur@umons.ac.be (C.C.)

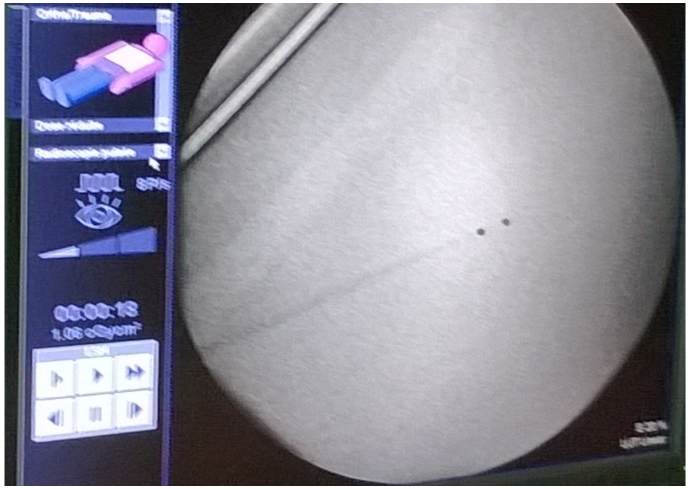
Our sensors are also developed for *in vivo* diagnosis

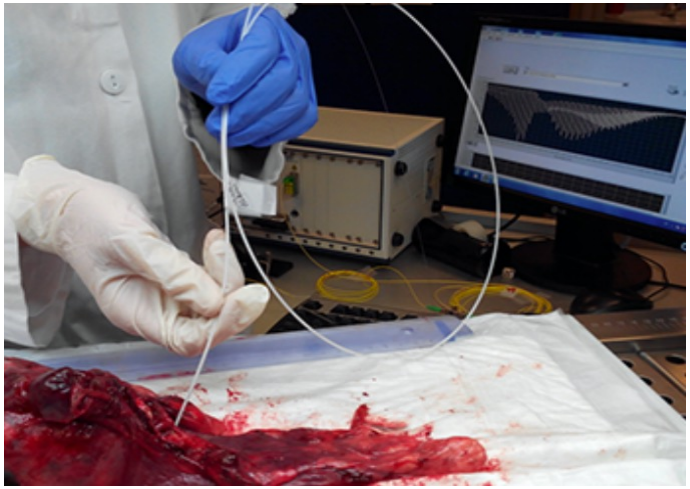


- ❑ Dedicated packaging
  - ✓ Biodegradable polymer valve operational in a catheter
  - ✓ Stainless steel blocks to hold the fiber sensors
- ❑ Discrimination between healthy and tumorous tissues

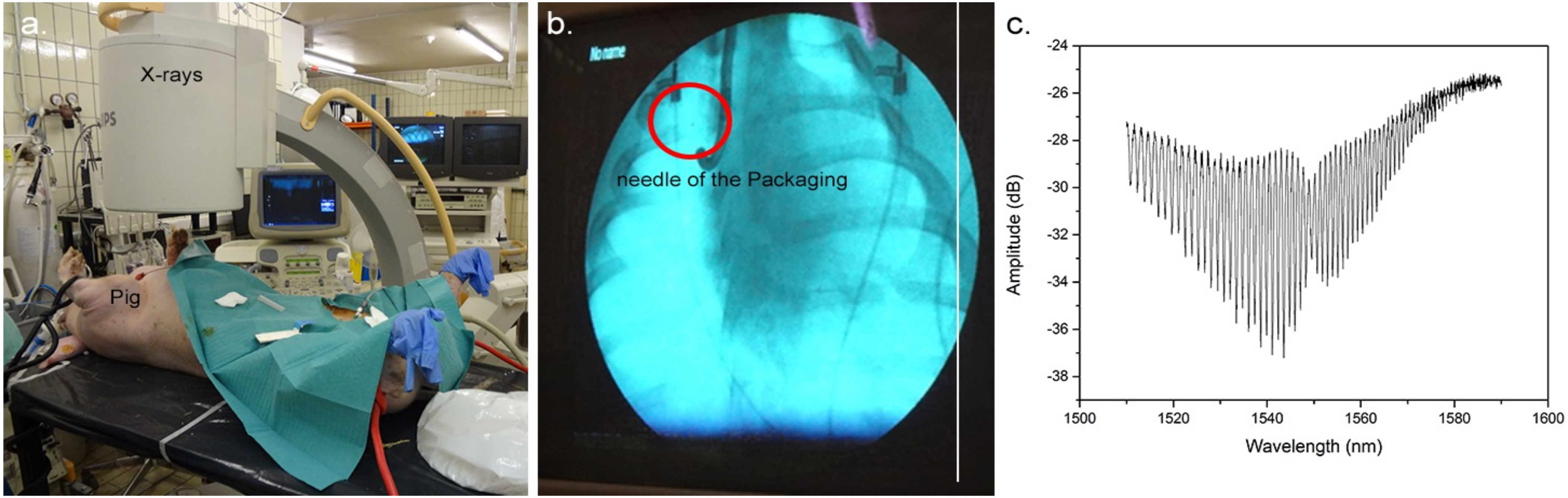
M. Loyez *et al.*, Biosens. Bioelectron. **131**, 104 (2019)







Towards *in vivo* experiments…



- Biosensor inserted into the operating channel
- Live operation in a pig
- Record of an SPR signature within a living body

In conclusion

- Tilted fiber Bragg gratings are multiparametric sensors
  - Suited to measure **temperature** and **strain** or **compensate** them
  - **Low cost** (pigtailed standard single mode fiber, any wavelength)
  - **Robust** system with ample evidence of repeatability and high sensitivity
- In biosensing
  - **Low loss** system to probe molecular interactions or other reactions
  - **Limit of detection** suited for target applications in cancer diagnosis

European Research Council

FREEDOM TO RESEARCH