WE ARE ON

OSA Photonic Detection Technical Group

# Fiber Optic Sensing and Biosensing

Francesco Chiavaioli, National Research Council,
Institute of Applied Physics "Nello Carrara"


OSA
Technical
Groups

# Fiber optic sensing and biosensing

**Speaker: Dr. Francesco Chiavaioli**
**CNR, Italy**

OSA Webinar
Photonic Detection Group
24 February 2021
10:00 AM – 11:00 AM (EST)

OSA Photonic Detection Technical Group

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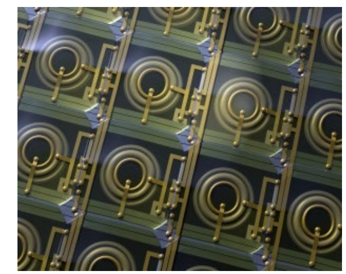
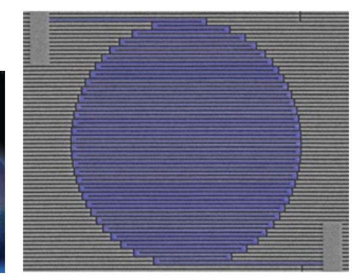
OSA Photonic Detection Technical Group

## About Us

The Photonic Detection technical group is part of the Photonics and Opto-Electronics Division of the Optical Society. This group focuses on the detection of photons as received from images, data links, and experimental spectroscopic studies to mention a few. Within its scope, the PD technical group is involved in the design, fabrication, and testing of single and arrayed detectors.





This group focuses on materials, architectures, and readout circuitry needed to transduce photons into electrical signals and further processing. This group's interests include: (1) the integration of lens, cold shields, and readout electronics into cameras, (2) research into higher efficiency, lower noise, and/or wavelength tunability, (3) techniques to mitigate noise and clutter sources that degrade detector performance, and (4) camera design, components, and circuitry.

# OSA Photonic Detection Technical Group

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OSA Homepage
www.osa.org/PD

LinkedIn Group
www.linkedin.com/groups/8297763/

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hotonic Detection (PD)

Get Involved

- Technical Divisions +
  - Bio-Medical Optics
  - Fabrication, Design & Instrumentation
  - Information Acquisition, Processing & Display
  - Optical Interaction Science
  - Photonics and Opto-Electronics +
    - Fiber Optics Technology (PF)
    - Integrated Optics (PI)
    - Laser Systems (PL)
    - Optical Communications (PC)

## Photonic Detection (PD)

This group involves the detection of photons as received from images, data links, and experimental spectroscopic studies to mention a few. Within its scope, it is involved in the design, fabrication, testing of single and arrayed detectors. Detector materials, structures, and readout circuitry needed to translate photons into electrical signals are considered by this group. Also included in this group is the integration of components such as lens, cold shields, and readout electronics into cameras. Research into higher efficiency, lower noise, and/or wavelength tunability is included here. Additionally, techniques to mitigate noise and clutter sources that degrade detector performance are within the purview of this group. In the imaging area, camera design, componentry, and circuitry are considered.

Announcer

Join the Photonic D
Group for their ina
Wednesday, 27 Api

In this webinar, Dr.
describe his recent
speed quantum ke
photonic integrate
scalable quantum i
processors based c
networks.

**Register for the W**

OSA Photonic Detection Technical Group

## Technical Group Activities

- ***Special Sessions*** at OSA conferences such as CLEO and OFC.
- ***Webinars***
- Interactions with local sections and student chapters.
- Interactive community for bringing together researchers across inter-disciplinary fields for tackling advances in photonic detection technologies.
- Example: Panel discussion on ***Silicon Photonics for LiDAR and Other Applications*** at OFC 2019


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# FIBER OPTIC SENSING & BIOSENSING


## FRANCESCO CHIAVAIOLI, PHD

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VIA MADONNA DEL PIANO 10, 50019 SESTO FIORENTINO, FIRENZE, ITALY


IFAC

**OSA MEETINGS**
**PHOTONIC DETECTION TECHNICAL GROUP**
**FEBRUARY 24, 2021**

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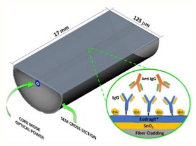
# Lecture outline



1. General information about CNR-IFAC & the research group
2. Fundamentals on fiber optics
   Classification in terms of type of sensing
   2.1. Physical sensing
   2.2. Chemical sensing
   2.3. Biomolecule sensing or Biosensing
3. Parameters for an objective assessment of sensor performance
   3.1. Parameters for bulk/volume sensing
   3.2. Parameters for surface sensing
4. Most interesting fiber optic devices for sensing and biosensing
5. “Food for Thoughts”



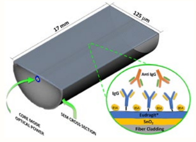
# What we do at CNR-IFAC




The Institute of Applied Physics “Nello Carrara” (IFAC) is part of the National Research Council (CNR), which is the main public organisation pursuing research and innovation in Italy. IFAC is the larger institute of the CNR Florence Research Area located at the "Polo Scientifico” of Sesto Fiorentino.

IFAC carries out research activities, experimental development and technological transfer in many areas of Applied Physics and ICT, as:

- SPACE, AEROSPACE and EARTH OBSERVATION
- HEALTH, NANOMEDICINE and SAFETY
- ENVIRONMENT and FOOD QUALITY MONITORING
- CULTURAL HERITAGE



# What we do in CBOS group

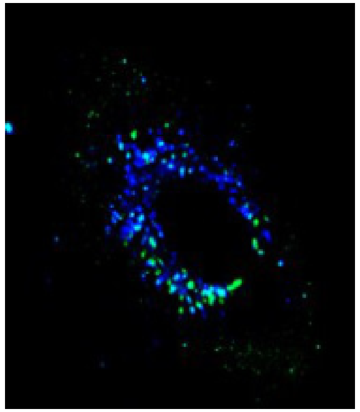


**Chemical & Biochemical Optical Sensor group** which I belong is one of the larger research group of CNR-IFAC. The group activity is mainly envisaging the design and development of optical sensors for the detection of chemical and biochemical parameters, with special focus on biophotonic diagnostics for both invasive/minimally invasive applications and *Point Of Care Testing* (POCT) devices.

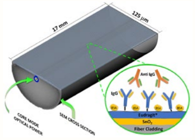
## Fluorescence-based sensing

ng

## Intracellular Optical Nanosensing



Key strength of the group is the high multidisciplinarity which includes scientists coming from different subjects (Physics, Engineer, Chemistry and Pharmaceutical Chemistry and Technology) which permits to face all the different issues encompassing the biophotonic diagnostics.



# What I do in CBOS group

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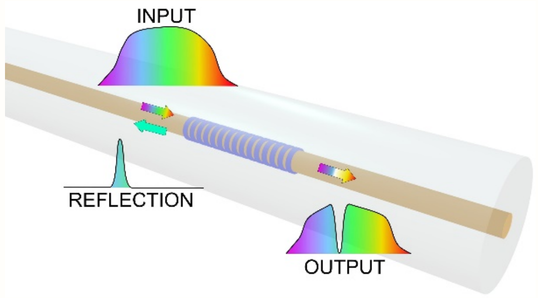
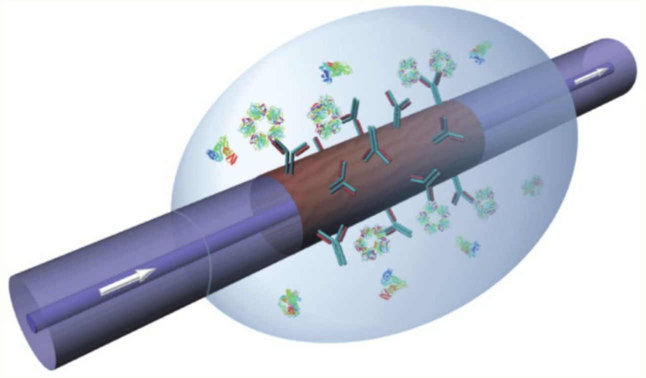
**General expertise to:**
Optical Fiber Sensors

Optical Biosensors

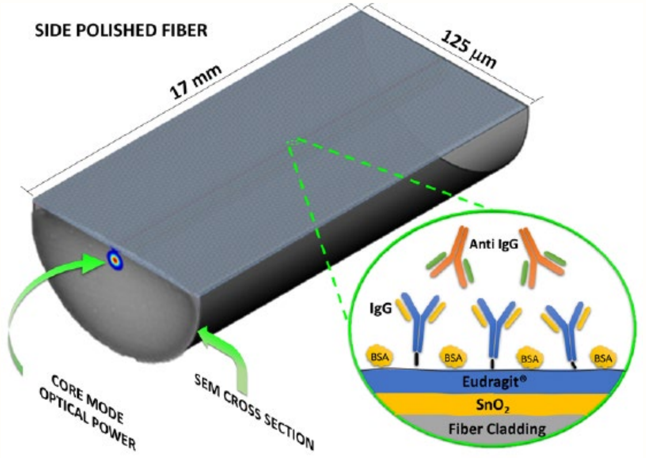
Label-free Sensing & Biomolecule Detection

Neurodegenerative Disease



**Specialties:**
1) Optical fiber sensors based on gratings (FBGs and LPGs);
2) Optical fiber sensors for the measurement of pH and bile;
3) LPGs as fiber coupler to whispering gallery mode (WGM) resonators;
4) SPR-based optical fiber devices;
5) Graphene-based sensors and modulators;
6) Lossy Mode Resonance (LMR) sensors;
7) In-fiber nanostructures;
8) Small biomolecule optical detection (cancer biomarkers, Alzheimer's disease biomarkers).

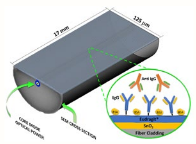


# Fundamentals on fiber optics



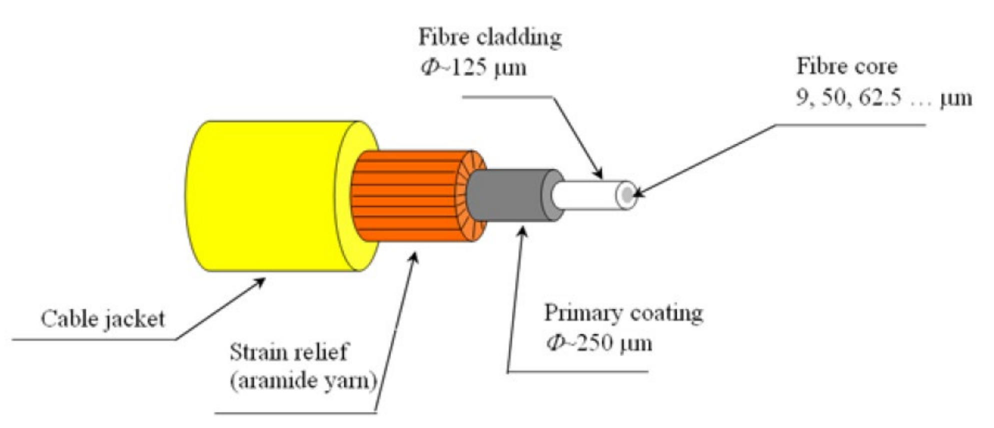
## LECTURE FOCUS (FIRST PART)

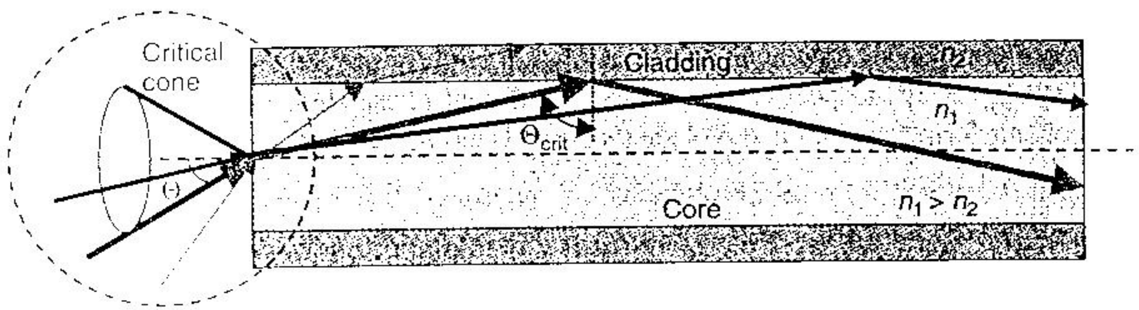
- Fundamentals on fiber optics
- Fiber optics-based systems & sensors
- Classification of fiber optic sensors

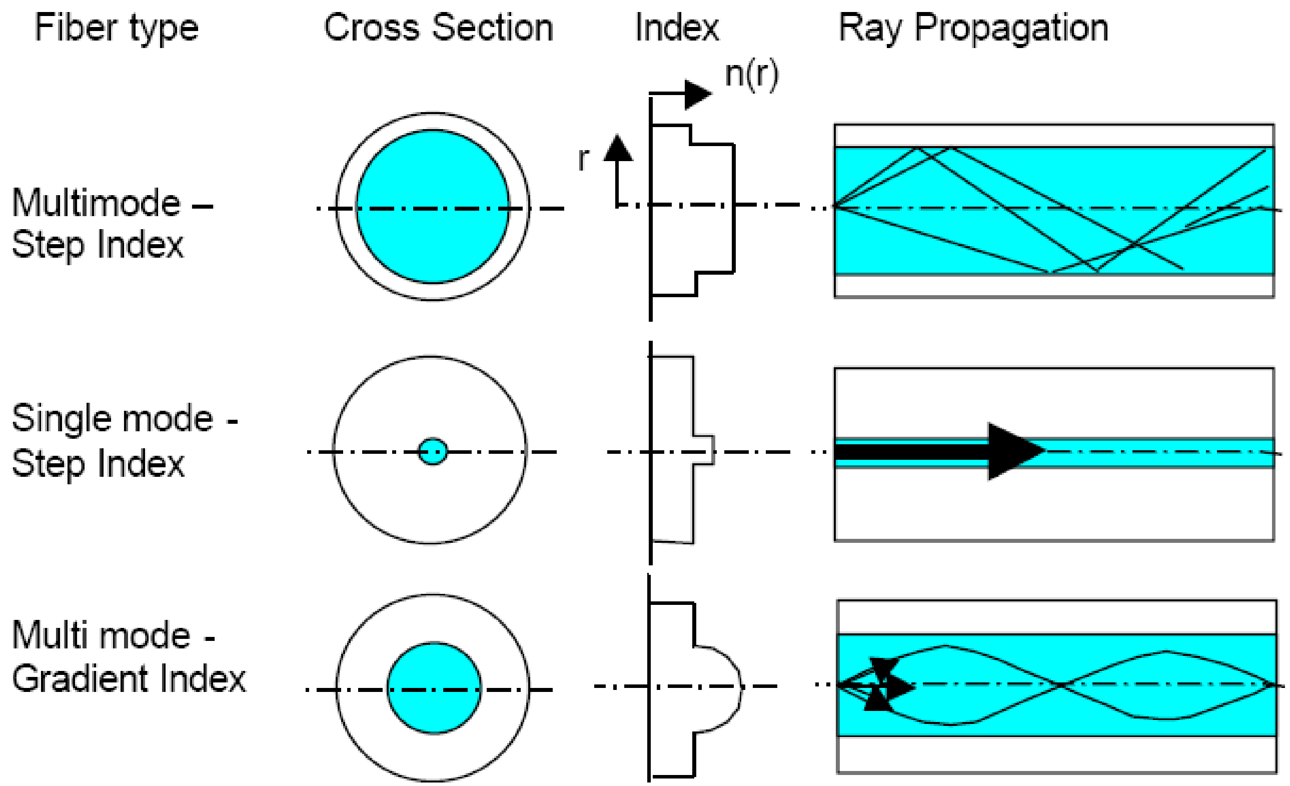


# Fundamentals on fiber optics

## Fiber optic structure and light propagation



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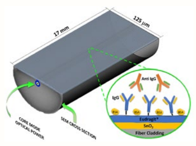
FIBER OPTIC SENSING & BIOSENSING

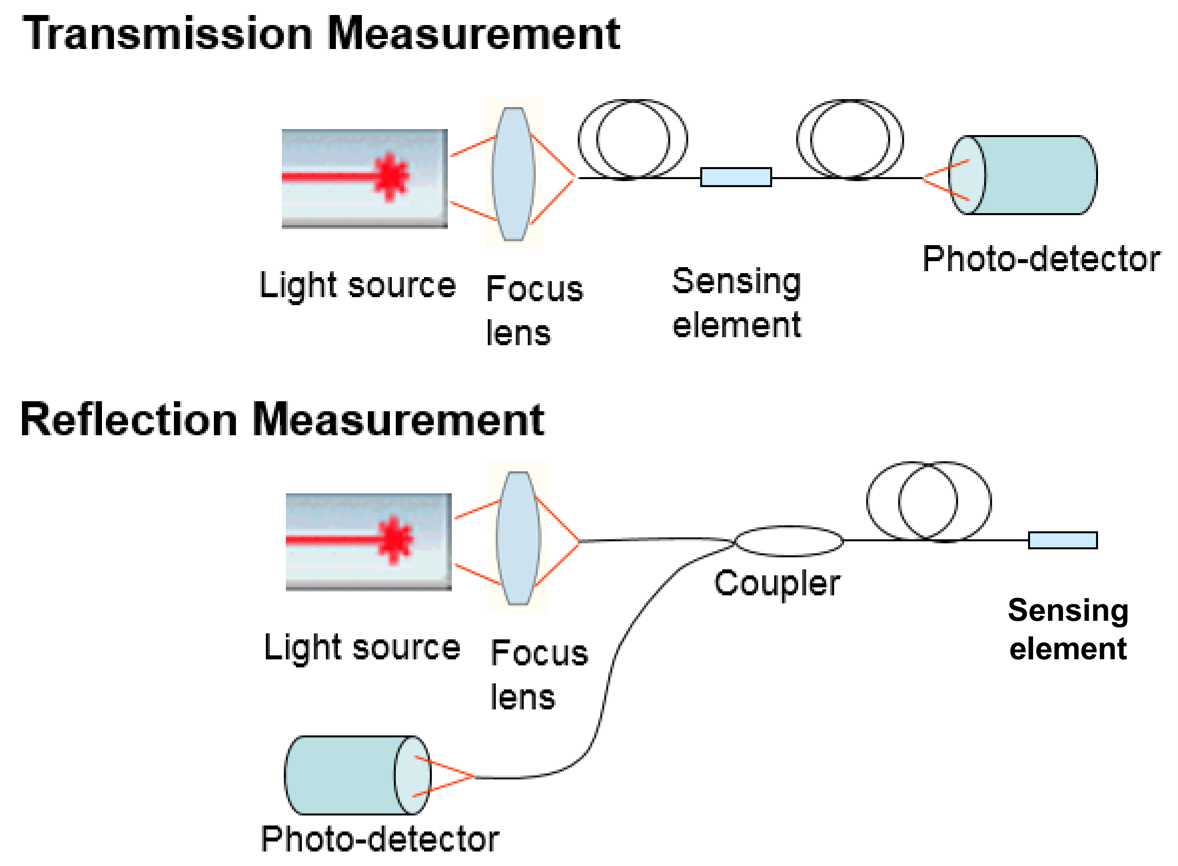
## Materials for fibers

- Silica glass fibers
- B/Ge-doped glass fibers
- Halide glass fibers
- Active glass fibers (rare-earth doped)
- Plastic fibers
- Bioresorbable fibers **NEW!!!**



# Fiber optics-based systems

## Typical fiber-optic operation modes




### Light Parameters

- Power/Intensity
  - Unit:
    - ➢ Watts
    - ➢ dbm: 10log(P*1000)
  - Attenuation/loss
    - ➢ db: $10\log(P_1/P_0)$
- Wavelength (spectral distribution)
- Polarization
- Phase (Optical path)

# Fiber optic sensors

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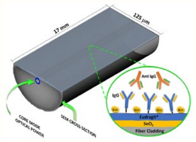
## Fundamentals

Fiber optic sensor: a sensor that measures a physical/chemical/biological parameter based on the signal modulation in terms of *intensity*, *wavelength*, *phase*, or *polarization* of light traveling through an optical fiber.

Peculiarities of fiber optic sensors:

- Compact size and lightness;
- Remote access;
- Multiplexing and multi-functionality;
- Resistance to harsh environments;
- Immunity to electro-magnetic and radio-frequency interferences;
- Light management.



# Classification of fiber optic sensors

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## CLASSIFICATION IN TERMS OF TYPE OF SENSING

**Physical Sensing**

A physical sensor is a device that measures a physical quantity and converts it into a signal which can be read by an observer or by an instrument.

- Temperature
- Preassure
- Deformation or strain
- Humidity

**Chemical Sensing**

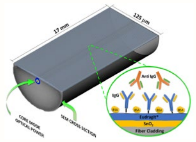
A chemical sensor is a device that transforms chemical information into an analytically useful signal which can be read by an observer or by an instrument.

- Chemical composition
- Presence of a particular element or ion
- Concentration of the investigated element or ion
- Chemical activity

**Biosensing**

A biosensor is an integrated receptor–transducer device that is able to provide selective quantitative or semi-quantitative analytical information about the investigated analyte using a biological recognition element deposited on a substrate.

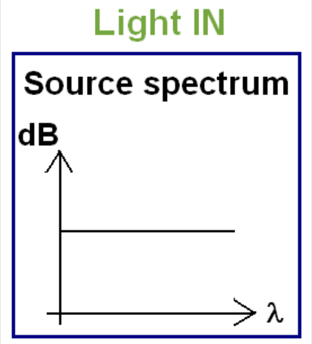
- Antibody/antigen interactions
- Enzymatic interactions
- Nucleid acid interactions
- Epigenetic modifications
- Cells and Tissue

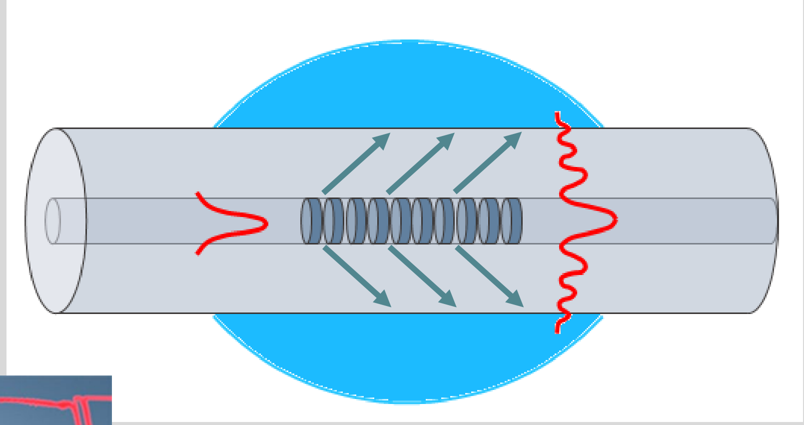


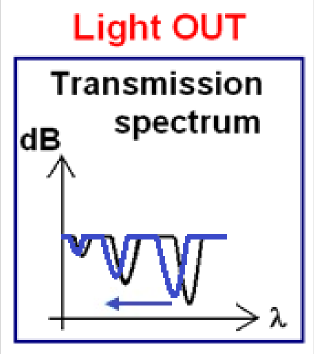
# Classification of fiber optic sensors

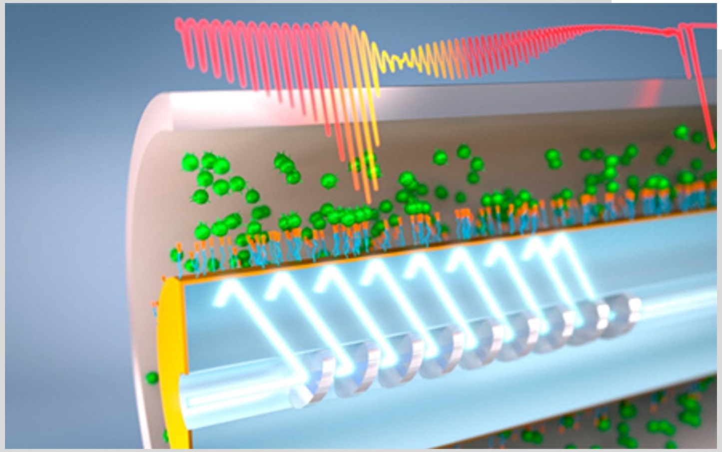


## RESONANCE-BASED DEVICES



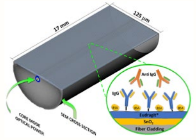


## APPROACHES

- Surface plasmon resonance (SPR) and localized SPR
- Interferometric configurations
- Fiber optic gratings (FBGs and LPGs)
- Surface wave resonances (Bloch wave, lossy and leaky modes)

Courtesy of: C. Caucheteur, T. Guo et al., *Nat. Comm.* **2016**, vol. 7, Article number: 13371

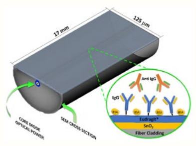


# Parameters for an objective assessment of sensor performance

FRANCESCO CHIAVAIOLI, PH.D.
FIBER OPTIC SENSING & BIOSENSING

## LECTURE FOCUS (SECOND PART)

- A metrological assessment of resonance-based fiber optic sensors with the aim of providing an objective evaluation of the sensing performance
- Concepts can also be applied to any resonance-based sensor, thus providing the basis for an easier and direct performance comparison of a great number of devices published in the literature up to now



# Parameters for an objective assessment of sensor performance



IEEE SENSORS JOURNAL, VOL. 1, NO. 3, OCTOBER 2001 183

## A Contribution on Some Basic Definitions of Sensors Properties

Arnaldo D'Amico, *Member, IEEE,* and Corrado Di Natale, *Member, IEEE*

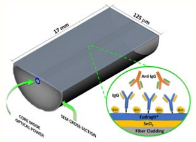
***Abstract*—This paper describes, through simple examples, the meaning of some key terms frequently used, sometimes incorrectly, in the field of sensors. They are *sensor response curve*, *sensitivity*, *noise*, *drift*, *resolution*, and *selectivity*. These words, if well-interpreted, represent a powerful vehicle of information and may symbolize part of a common knowledge useful for a sound dissemination of results relative to the sensors research. All of this is also aimed at stimulating any effort in order to facilitate the transition between sensor and sensor science development.**

***Index Terms*—Drift, noise, resolution, selectivity, sensitivity, sensor response curve.**

ence, is mandatory if we wish to see technology and fundamentals on sensor science develop together.

This paper will give an overview of a few definitions, sometimes disregarded, when the most frequently used quantities related to sensors are considered. These are: sensor response curve, sensitivity, noise, drift, resolution, and selectivity [1]. These quantities and definitions represent a significant part of a basic knowledge that should be known and utilized on behalf of the sensor community.

It is important to point out that, in this work, the word sensor



# Parameters for an objective assessment of sensor performance

biosensors
MDPI

*Review*

## Towards a Uniform Metrological Assessment of Grating-Based Optical Fiber Sensors: From Refractometers to Biosensors

**Francesco Chiavaioli [1,*,†], Carlos A. J. Gouveia [2,3,†], Pedro A. S. Jorge [2] and Francesco Baldini [1]**

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3. Institute INESC P&D Brasil, Rua José Caballero, 15, Gonzaga, 11055-300 Santos, Brazil

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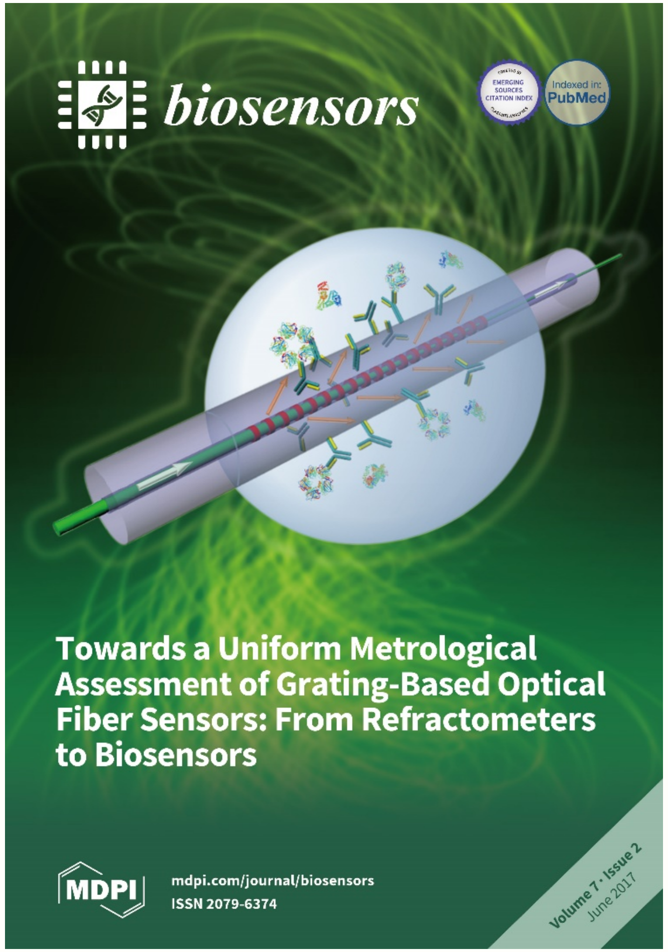
† These authors contributed equally to this work.

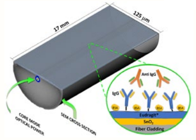
Received: 13 May 2017; Accepted: 20 June 2017; Published: 21 June 2017

**Abstract:** A metrological assessment of grating-based optical fiber sensors is proposed with the aim of providing an objective evaluation of the performance of this sensor category. Attention was focused on the most common parameters, used to describe the performance of both optical refractometers and biosensors, which encompassed sensitivity, with a distinction between volume or bulk sensitivity and surface sensitivity, resolution, response time, limit of detection, specificity (or selectivity), reusability (or regenerability) and some other parameters of generic interest, such as measurement uncertainty, accuracy, precision, stability, drift, repeatability and reproducibility. Clearly, the concepts discussed here can also be applied to any resonance-based sensor, thus providing the basis for an easier and direct performance comparison of a great number of sensors published in the literature up to now. In addition, common mistakes present in the literature made for the evaluation of sensor performance are highlighted, and lastly a uniform performance assessment is discussed and provided. Finally, some design strategies will be proposed to develop a grating-based optical fiber sensing scheme with improved performance.

**Keywords:** optical fiber grating; fiber Bragg grating; long period grating; resonance-based device; refractive index sensor; biosensor; sensitivity; resolution; limit of detection; specificity

*Biosensors* **2017**, *7*, 23; doi:10.3390/bios7020023 www.mdpi.com/journal/biosensors



# Parameters for an objective assessment of sensor performance

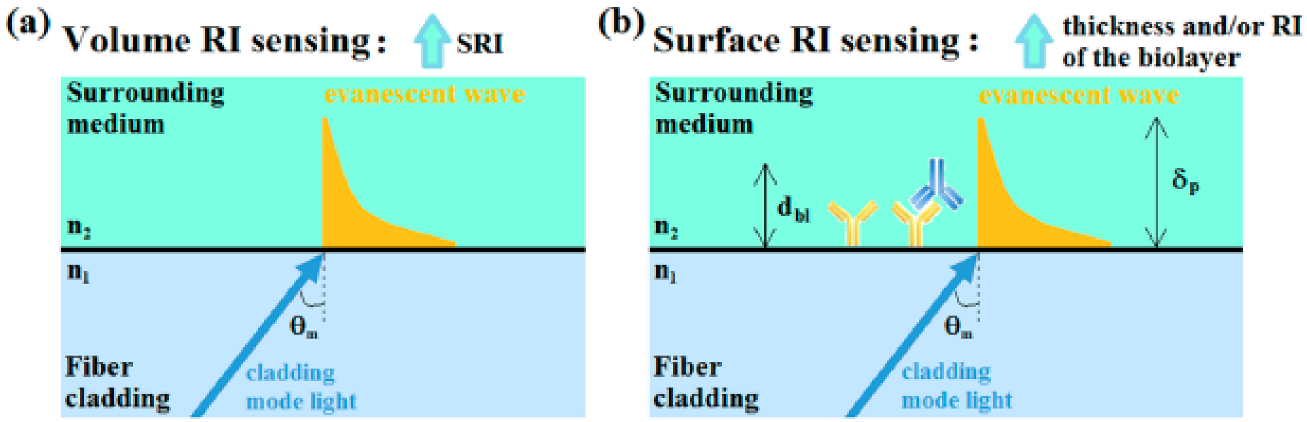



**Figure 5.** (a) Schematic representation of the RI sensing, based on a bulk or volume change; (b) schematic representation of the RI sensing, based on a surface change in which only a portion of the evanescent wave interacts with the bio-layer ($d_{bl} < \delta_p$). RI: refractive index; SRI: surrounding refractive index; $n_1$: fiber cladding RI (or generally the RI of the denser medium); $n_2$: surrounding medium RI (or generally the RI of the less dense medium); $d_{bl}$: bio-layer thickness; $\delta_p$: evanescent field penetration depth.

## Bulk or volume RI sensing

All the surrounding medium is involved in the sensing -> optical refractometer

## Surface RI sensing

Only the bio-layer is involved in the sensing -> optical biosensor

F. Baldini et al., *Anal. Bioanal. Chem.* **2012**, vol. 402 (1), p. 109-116.
F. Chiavaioli et al., *Biosensors* **2017**, vol. 7 (2), p. 23.

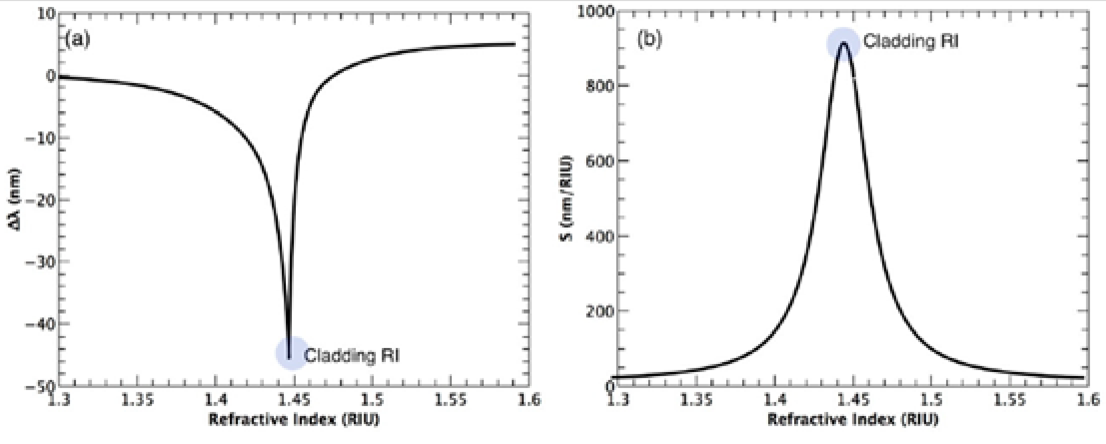
# Parameters for an objective assessment of sensor performance

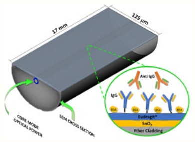
FRANCESCO CHIAVAIOLI, PH.D.
FIBER OPTIC SENSING & BIOSENSING

## PARAMETERS FOR BULK OR VOLUME SENSING

- Response curve and Sensitivity: $\frac{\partial\lambda}{\partial n_{sur}}$
- Resolution: the smallest variation of the investigated measurand that a sensing device is able to resolve; in other words, the lowest change in the investigated measurand that produces a measurable signal change.

$$R = \frac{3\sigma}{S}$$



# Parameters for an objective assessment of sensor performance

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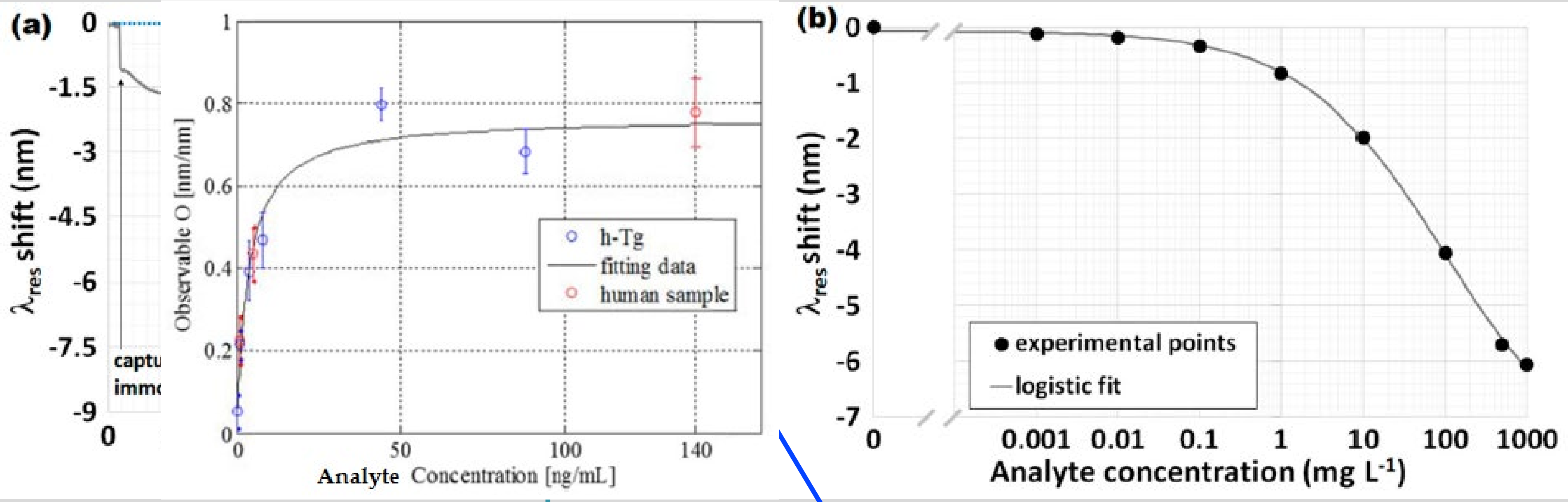
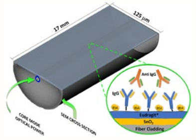
## PARAMETERS FOR SURFACE SENSING

- Sensorgram and Calibration curve:




Association constant    Dissociation constant



# Parameters for an objective assessment of sensor performance

FRANCESCO CHIAVAIOLI, PH.D.
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## PARAMETERS FOR SURFACE SENSING

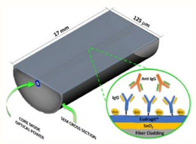
- Limit of detection (LOD):

1. First appraoch →
2. Second approach →
3. Third approach →

In the third (and final) approach, the determination of LOD is based on the sensor resolution and on the surface sensitivity ($S_{surface}$) [2,4,19], which is the RI change ($\Delta n$) divided by the surface density concentration ($\rho_{max}$) of the target analyte, as expressed in the following equation:

$$\mathrm{LOD} = \frac{R}{S_{surface}} = \frac{R}{\Delta n / \rho_{max}} \quad (7)$$

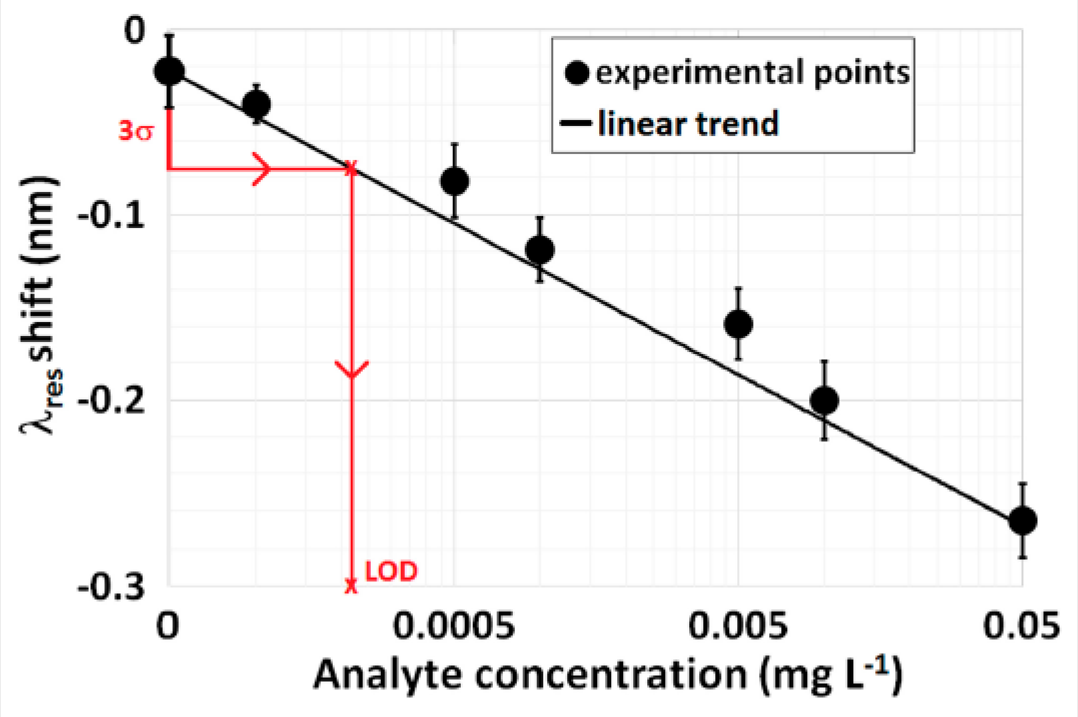
In ref. [2], instead of the RI change, the wavelength shift ($\Delta\lambda$) is reported, but it is not correct in view of the dimensional check. In addition, in using this last approach, some authors use the instrumental resolution and the slope of the calibration curve. This would mean that all the measurements fall mostly on the calibration curve, and the standard deviation of the experimental points is lower than the instrumental resolution. However, it seems that the best way to determine LOD would be the first or the second one, even if the third approach is quite common for SPR-based biosensors [42].



# Parameters for an objective assessment of sensor performance

## PARAMETERS FOR SURFACE SENSING

- Limit of detection (LOD):




F. Chiavaioli et al., *Biosensors* **2017**, vol. 7 (2), p. 23.

# Parameters for an objective assessment of sensor performance

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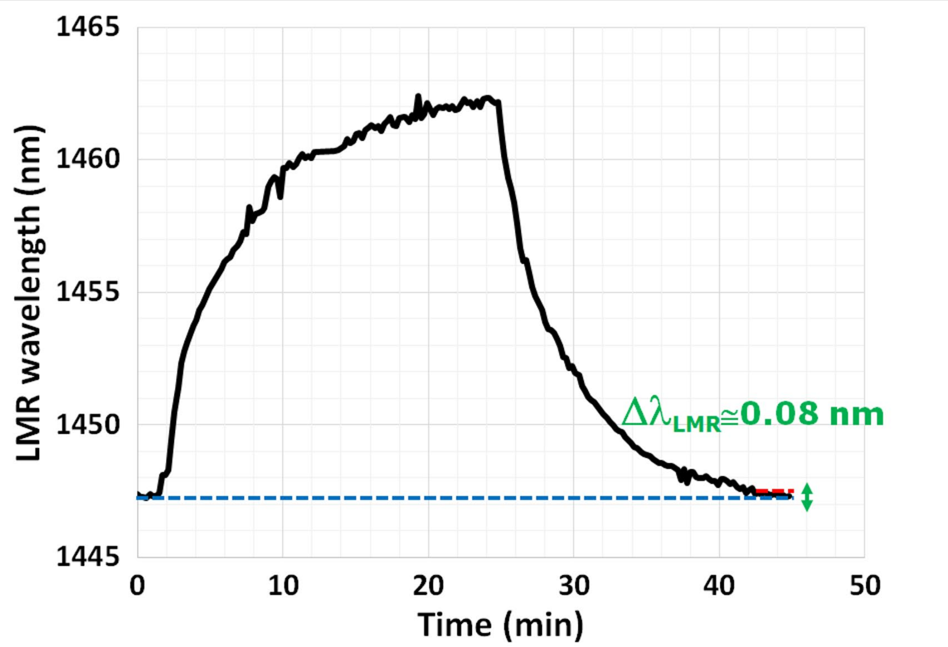
## PARAMETERS FOR SURFACE SENSING

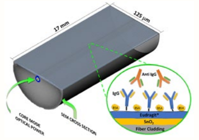
- Specificity or Selectivity:

  the sensor's ability to be sensitive to a specific or a selective measurand, instead of all the other interfering measurands, also called cross-sensitivity.

**Need for a negative control (different matrix complexity)**




F. Chiavaioli et al., *ACS Sensors* **2018**, vol. 3, p. 936-943.



# Parameters for an objective assessment of sensor performance

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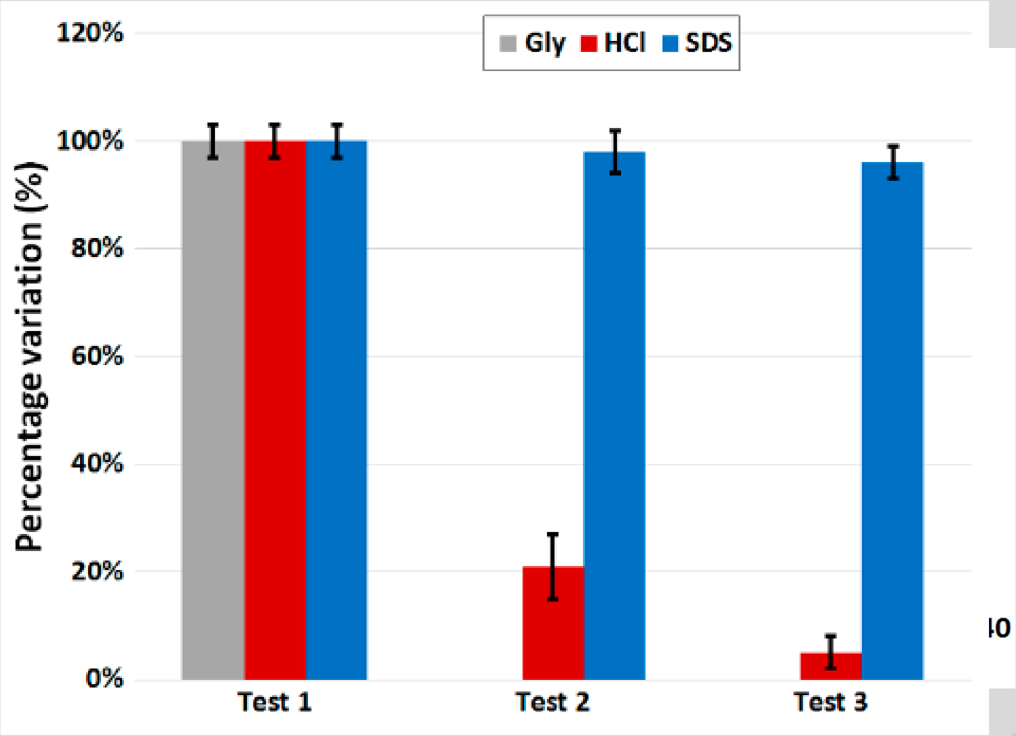
## PARAMETERS FOR SURFACE SENSING

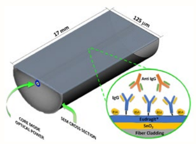
- Reusability or Regeneration:

  The regeneration step is needed for obtaining the specific biolayer available for a new interaction in consecutive assay cycles

**What is the best regeneration solution? NO ONE!**




MacCraith, B.; et al. *Sens. Actuators B Chem.* **1995**, 29, 51–57.
F. Chiavaioli et al., *ACS Sensors* **2018**, vol. 3, p. 936-943.

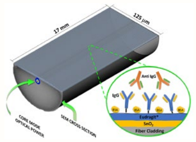


# State-of-the-art literature on fiber-optic sensors

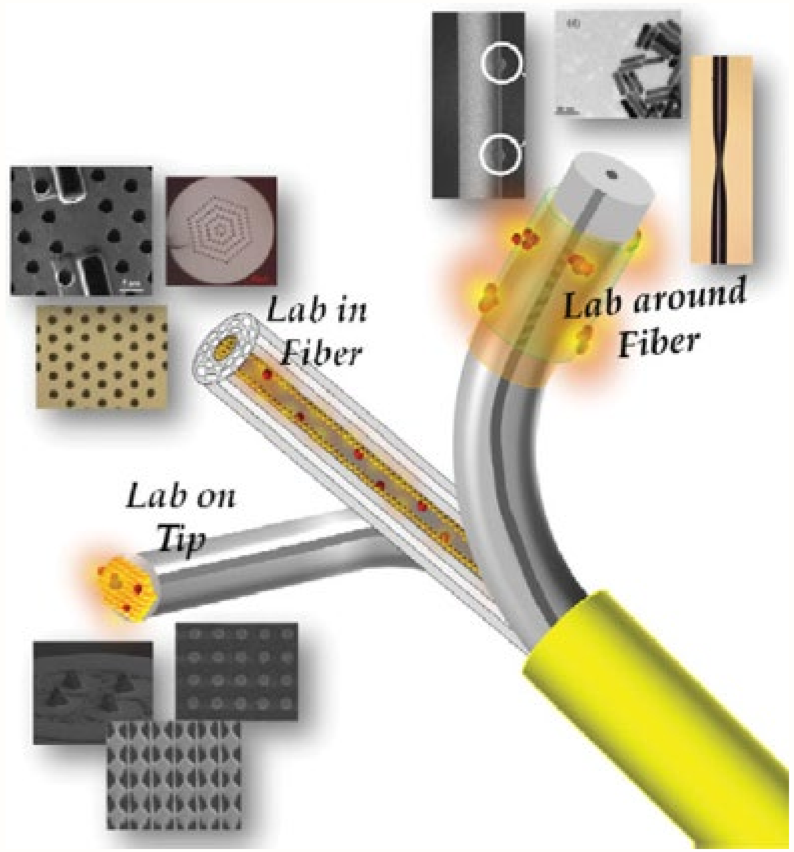


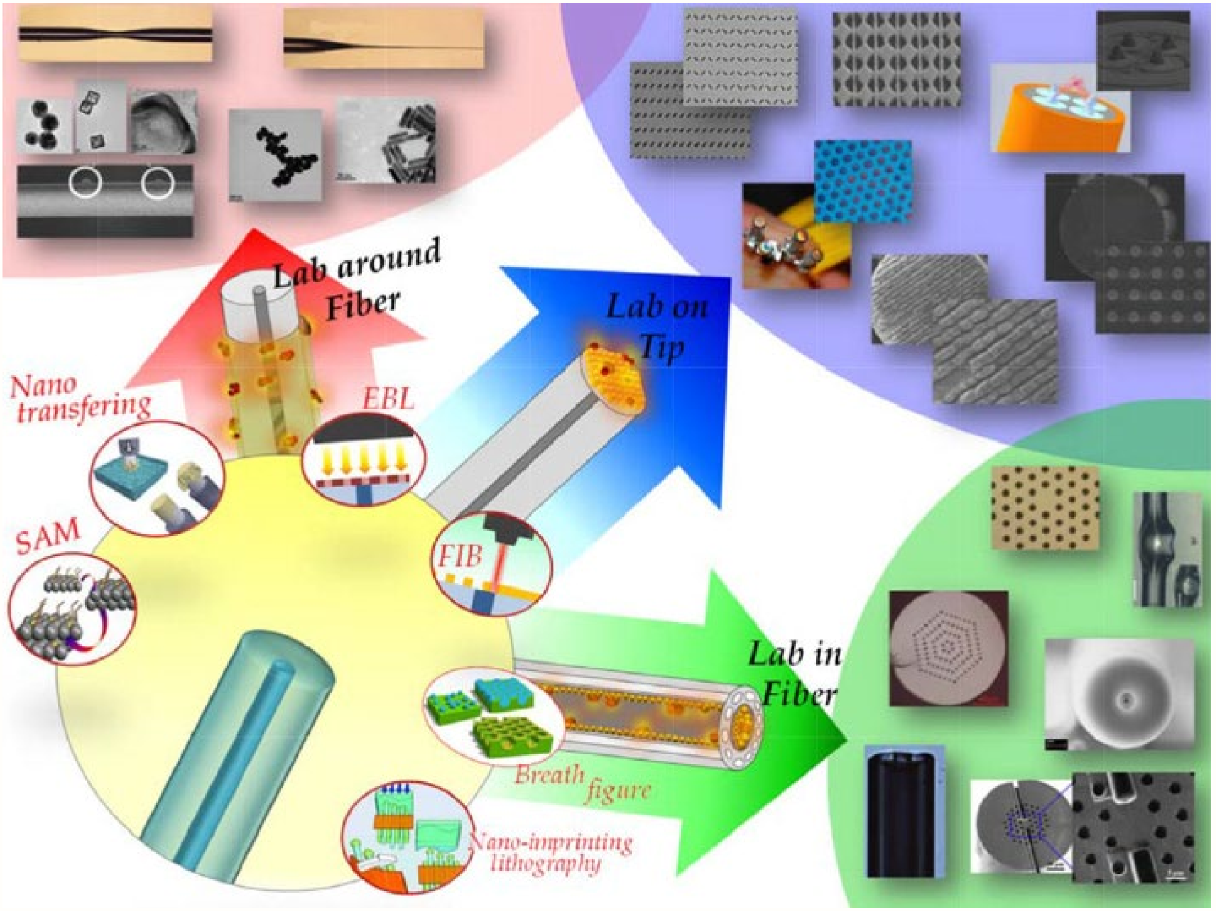
## LECTURE FOCUS (THIRD PART)

- Overview of the state-of-the-art literature on fiber optic sensors
- From **physical sensing** to **biosensing** passing by **chemical sensing**

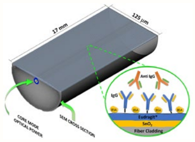


# Most interesting fiber optic sensing devices from the literature




Courtesy of: P. Vaiano et al., *Laser & Photonics Rev.* **2016**, vol. 10, p. 922-961.



# Most interesting fiber optic sensing devices from the literature: **physical sensing**

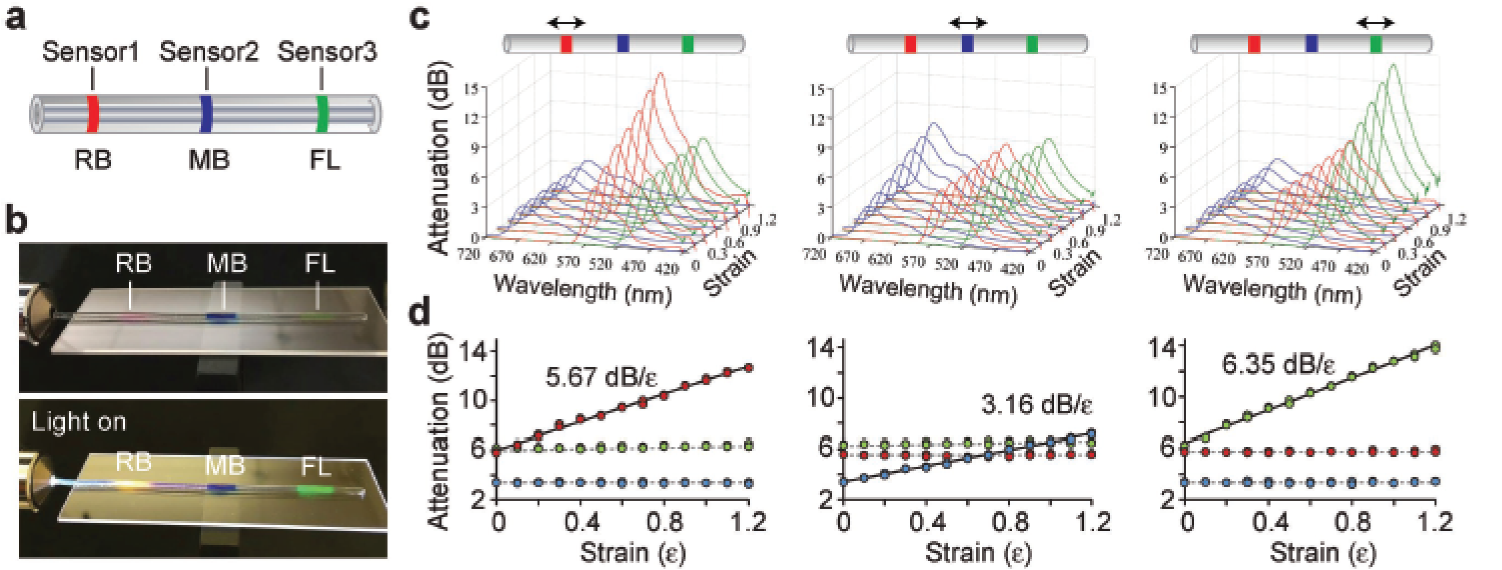



**Figure 4.** Multiplexed strain sensing. a) Schematic of a fiber with three sensor regions doped with different dyes, respectively: RB: rose Bengal, MB: methylene blue, FL: fluorescein. b) Photos showing a dye-doped fiber on a glass slide, without (top) and with (bottom) excitation broadband light. c) Extracted absorption spectra of the three sensors when local strain was applied to each sensor at a time. d) The dye absorption as a function of strain, showing linear readout in terms of dB/strain and negligible crosstalk between sensors.

## HYDROGEL FIBERS for STRAIN SENSING

- Highly stretchable
- Main features: fiber diameter of 750/1100 µm, Young's modulus of ≈80 kPa, large elongation up to 730% and a high failure stress of 230 kPa

Courtesy of: J. Guo et al., *Adv. Mater.* **2016**, vol. 28, p. 10244-10249.

# Most interesting fiber optic sensing devices from the literature: **physical sensing**

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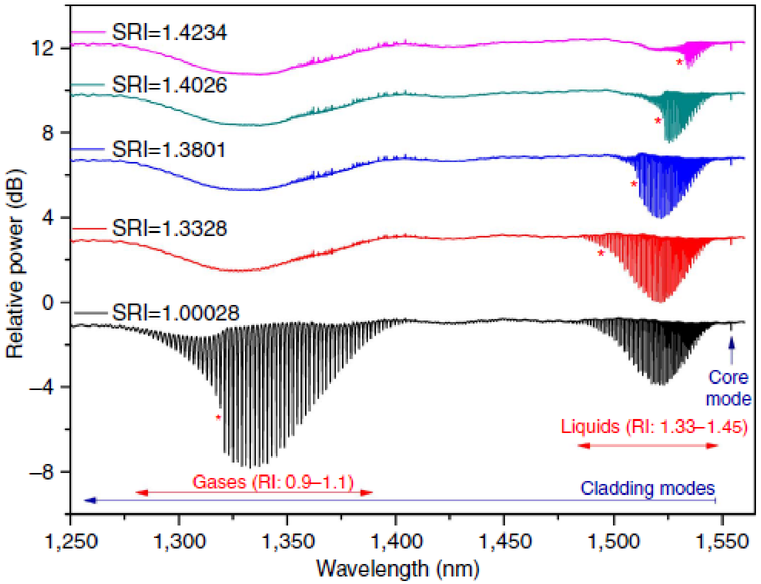



**Figure 1 | Transmitted power spectra of an uncoated 16-mm-long 37° TFBG in air and liquids.** Spectra measured for different surrounding refractive indices (SRIs) are plotted with an offset in the vertical scale. Red stars identify the cutoff wavelength in each medium.

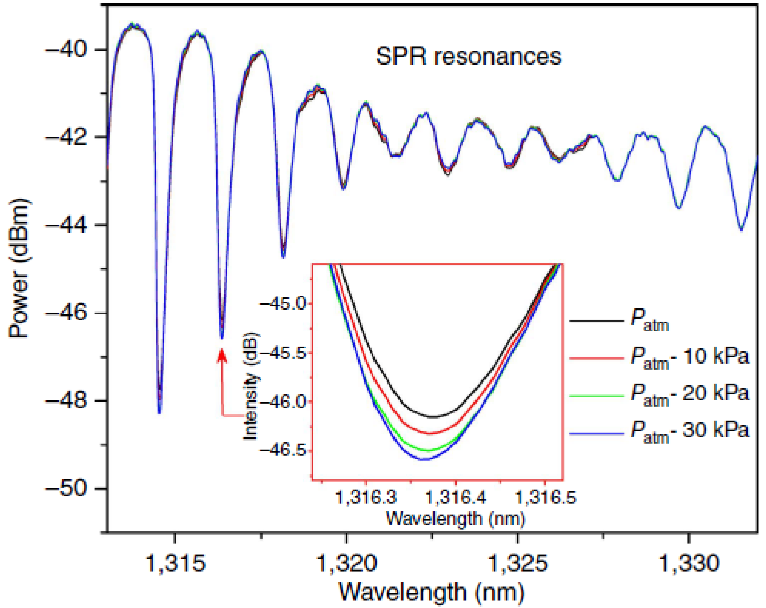
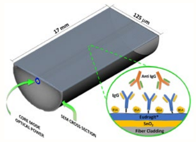



**Figure 5 | P-polarized transmitted power spectrum evolution due to atmospheric pressure changes.** The inset shows the evolution of the most sensitive cladding mode resonance (centred at 1,316.37 nm) among those within the SPP attenuation band (∼1,312–1,332 nm).

## SPR-based TILTED FBGs for SENSING in AIR

- Acustic wave detection by pressure changes
- Main features: highly tilting angle of 37°, sensing around 1.0 RIU, $10^{-8}$ RIU resolution
- Gas sensing application

Courtesy of: C. Caucheteur, T. Guo et al., *Nat. Commun.* **2016**, vol. 7, 13371.



# Most interesting fiber optic sensing devices from the literature: **physical sensing**

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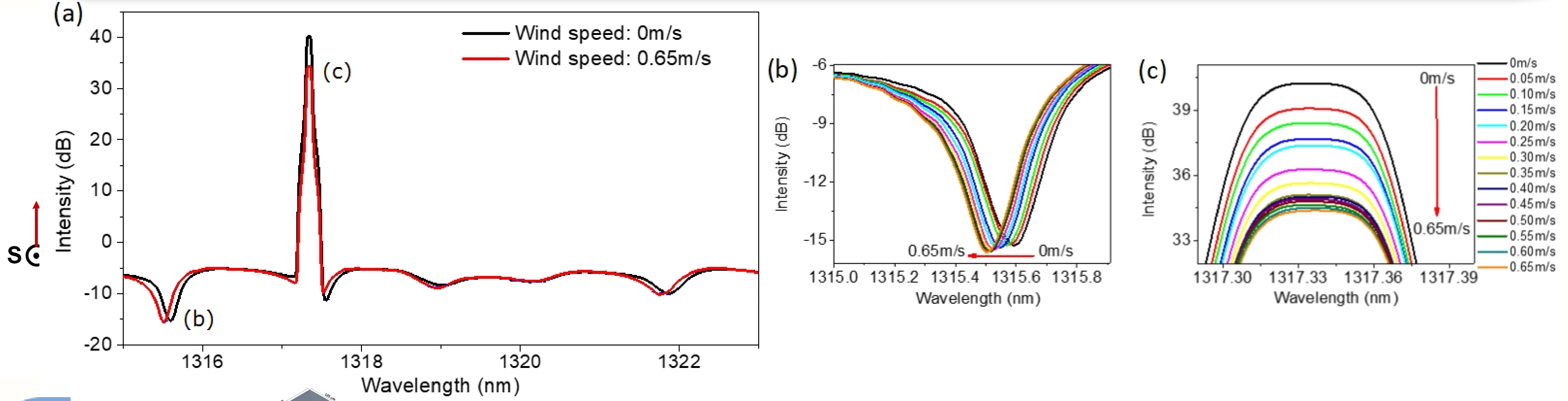
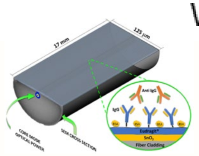
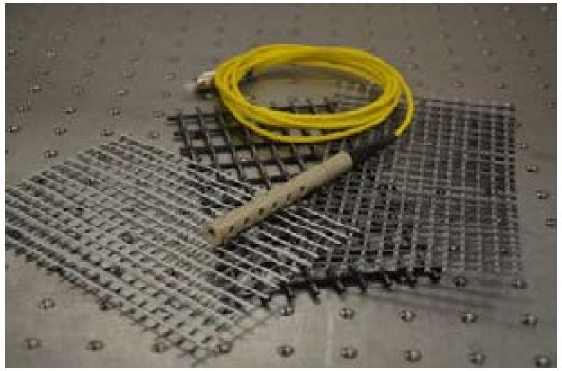
## PHOTOTHERMAL ANEMOMETER BASED ON CARBON NT-COATED TFBG-ASSISTED SPR SENSOR

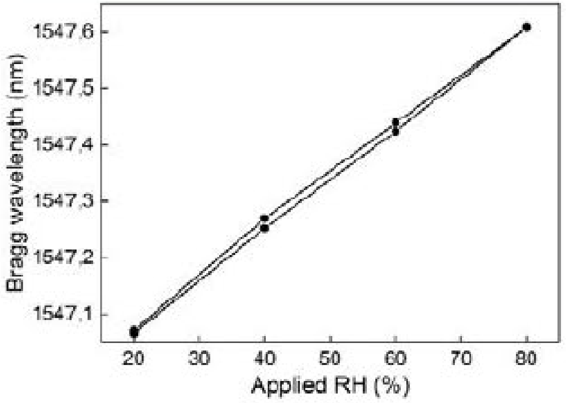
- Real-time wind speed measurement by carbon nanotubes as high-efficiency photothermal conversion element
- Sensing principle: *all-in-fiber* hot wire anemometer (HWA) where TFBG acts as high-resolution temperature sensor and SPR serves to improve light-matter interaction

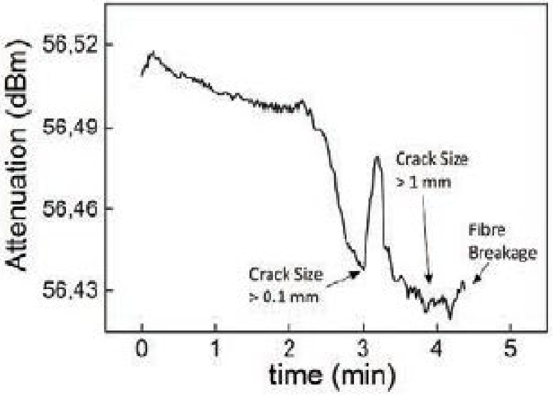


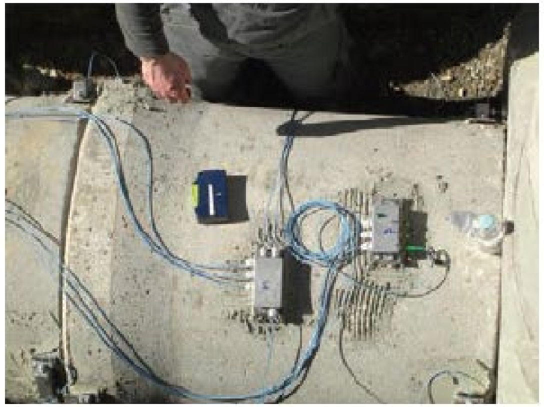



# Most interesting fiber optic sensing devices from the literature: **physical sensing**





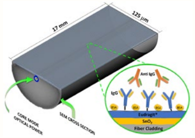



## FIBER OPTIC SENSING IN STRUCTURAL HEALTH MONITORING

- Mostly based on fiber Bragg grating
- Main applications: humidity sensing, detection of crack or leakage

Courtesy of: K. Bremer et al., *Proc. Technol.* **2016**, vol. 26, p. 524-529.



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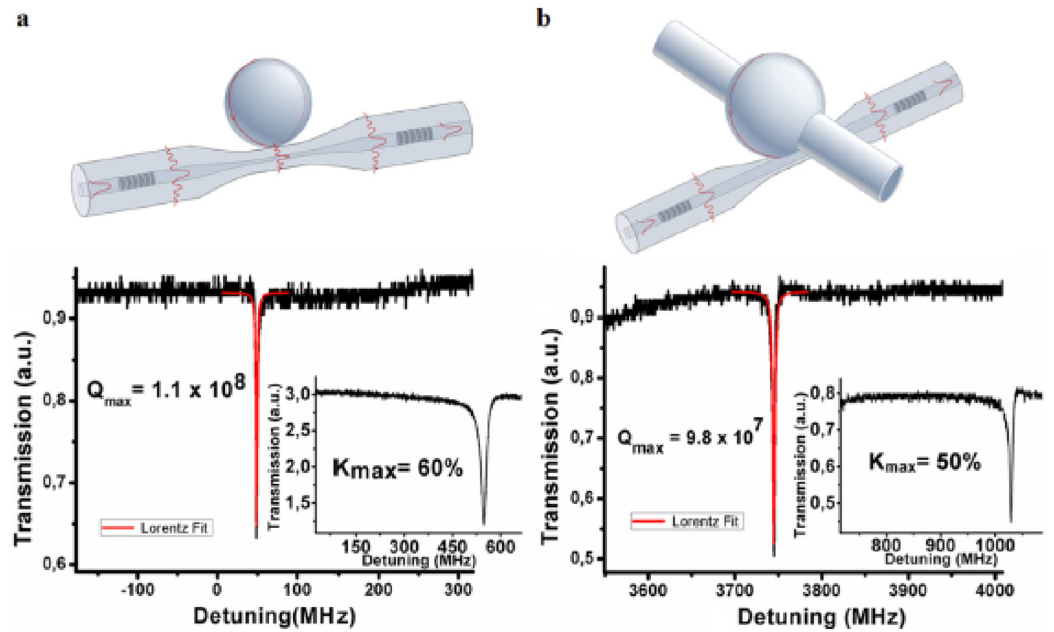
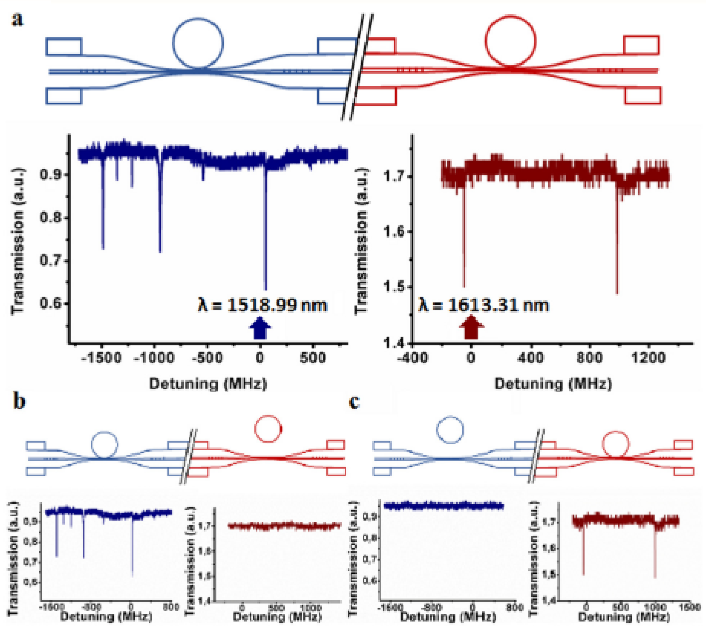
# Most interesting fiber optic sensing devices from the literature: **physical sensing**

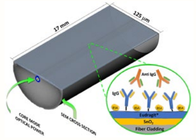
## WGM RESONATORS COUPLED BY LONG PERIOD FIBER GRATINGS

- Novel method to couple light into whispering gallery mode (WGM) resonators
- Main features: differently-shaped WGM resonators, high coupling efficiency (60%), wavelength selective addressing, quasi-distributed sensing approach




D. Farnesi, F. Chiavaioli et al., *Opt. Express* **2015**, vol. 23 (16), p. 21175-21186.



http://cbs.ifac.cnr.it/

# Most interesting fiber optic sensing devices from the literature: **physical sensing**

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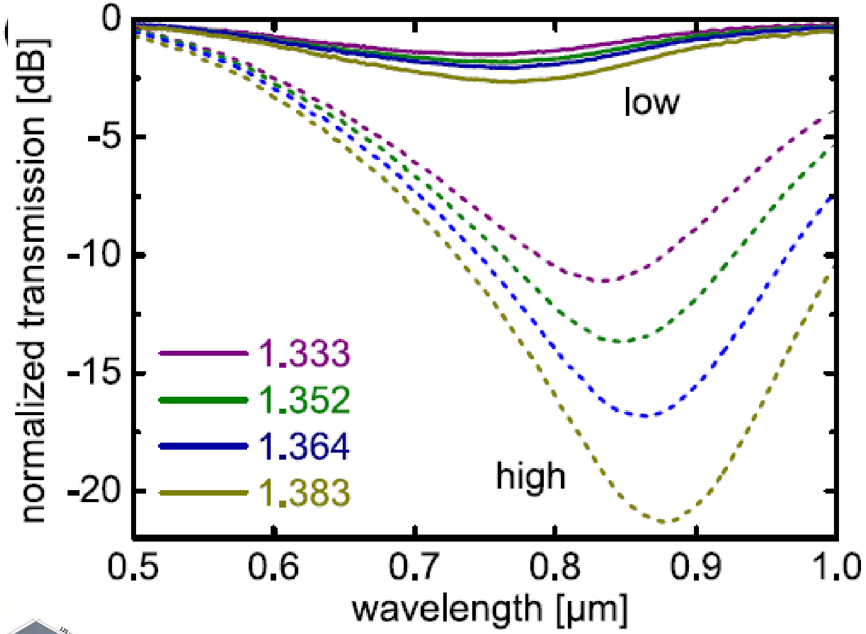
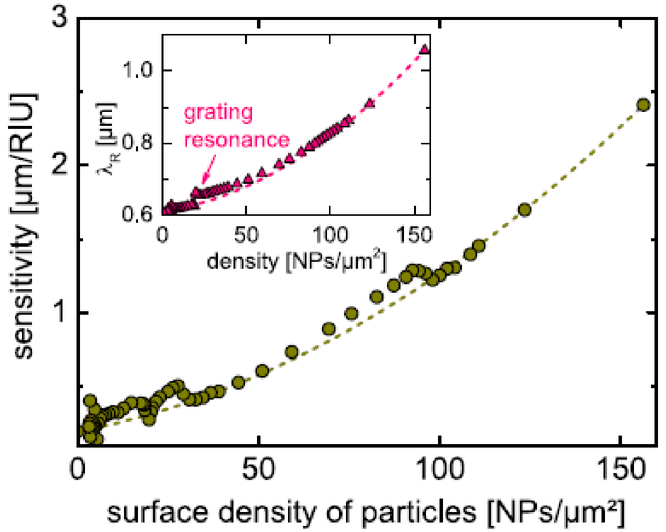
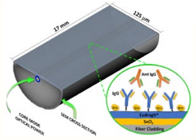
## FIBER TAPERS WITH GOLD-REINFORCED SILVER NANOPRISMS

- Hybrid plasmonic-photonic system based on gold-reinforced silver nanoprisms
- Main features: localised SPR, 40 nm diameter and 9 nm thickness, high particle density of 210 particle/μm$^2$, bulk sensitivity of 900 nm/RIU, designed for biosensing



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# Most interesting fiber optic sensing devices from the literature: **physical sensing**

## INTERNALLY-TILTED LONG PERIOD FIBER GRATINGS

- Optical refractometer with improved sensitivity
- Main features: point-by-point inscription technique with rotation stage, red-shift of the resonance bands, exponential behaviour curvature VS RI sensitivity

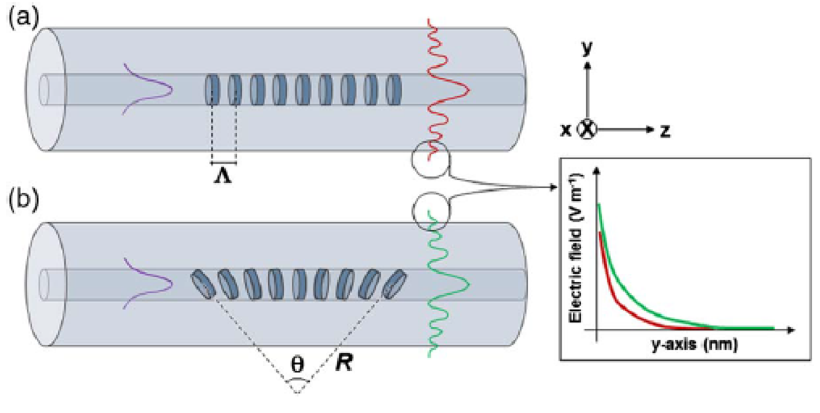
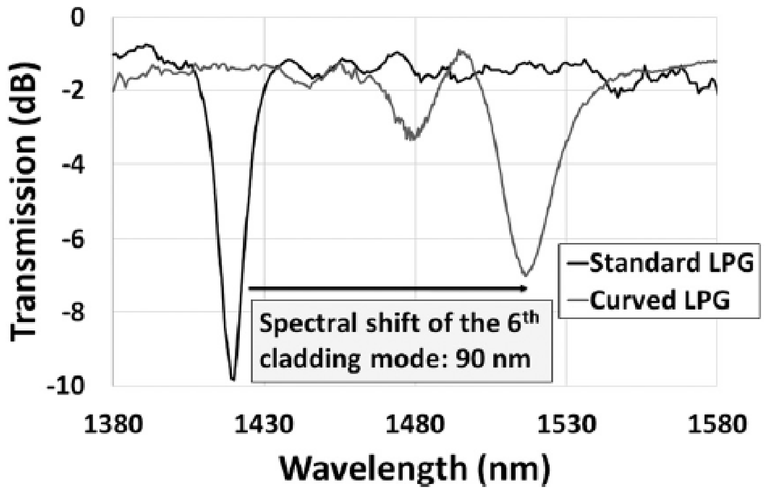
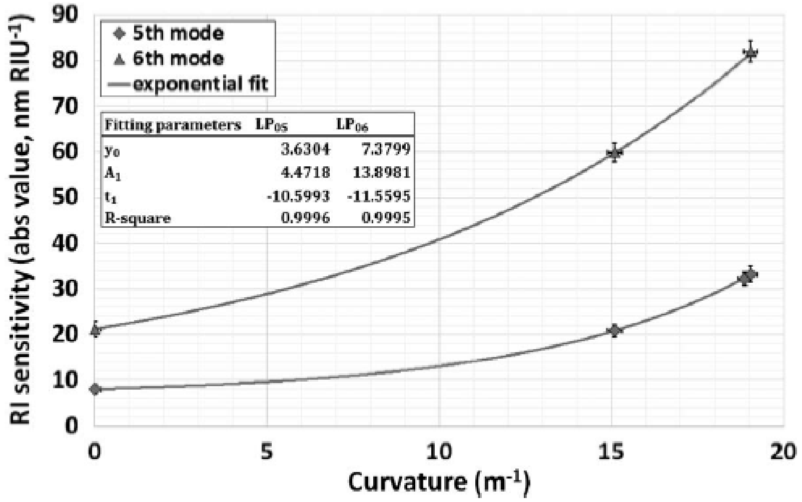
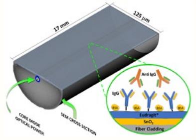



**Fig. 1.** 3D sketch of (a) a standard LPG and (b) an internally tilted LPG. Inset: difference evanescent wave extent (*y*-axis) related to the coupled cladding mode for a standard LPG (red) and an ITLPG (green).




F. Chiavaioli et al., *Appl. Phys. Lett.* **2013**, vol. 102, 23110929.
F. Chiavaioli et al., *Opt. Lett.* **2016**, vol. 41 (7), p. 1443-1446.



# Most interesting fiber optic sensing devices from the literature: **chemical sensing**

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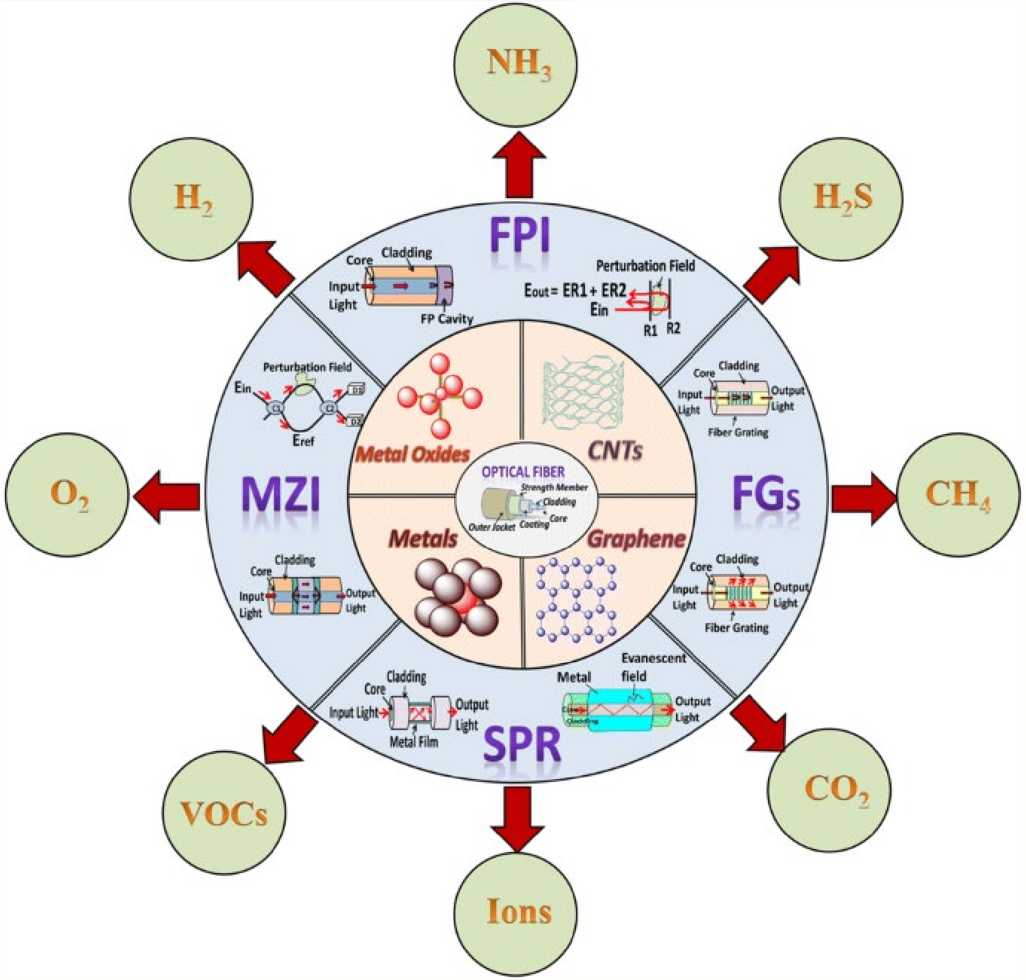
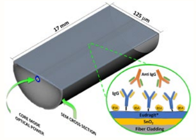
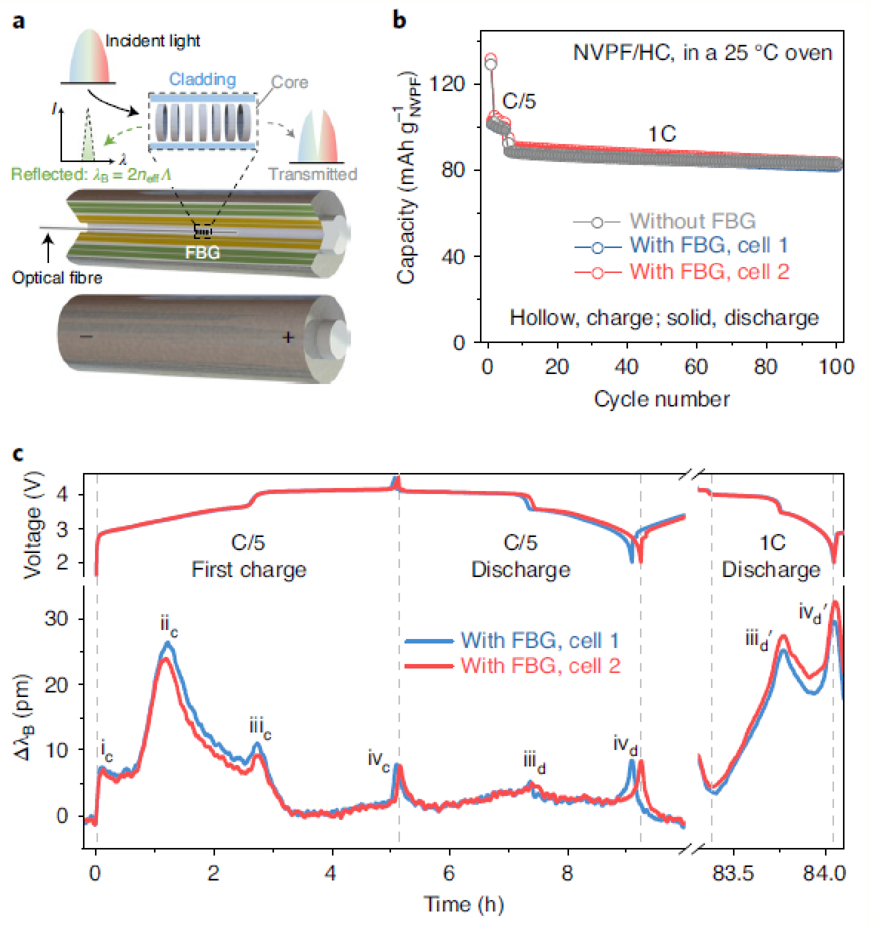
**NANOMATERIAL-MODIFIED FIBER SENSORS FOR GASES, VAPORS AND IONS**




Courtesy of: D. Pawar and S. N. Kale, *Microchimica Acta* **2019**, vol. 186, p. 253.



# Most interesting fiber optic sensing devices from the literature: **chemical sensing**




## FIBER OPTICS FOR BATTERY/CELL MONITORING

- Monitoring the dynamic chemical and thermal state of a cell during operation
- Tracking of chemical events such as solid electrolyte interphase formation and structural evolution by assessing temperature and pressure changes
- Main features: Li-ion cells

Courtesy of: J. Huang et al., *Nature Energy* **2020**, vol. 5, p. 674-683

# Most interesting fiber optic sensing devices from the literature: **chemical sensing**

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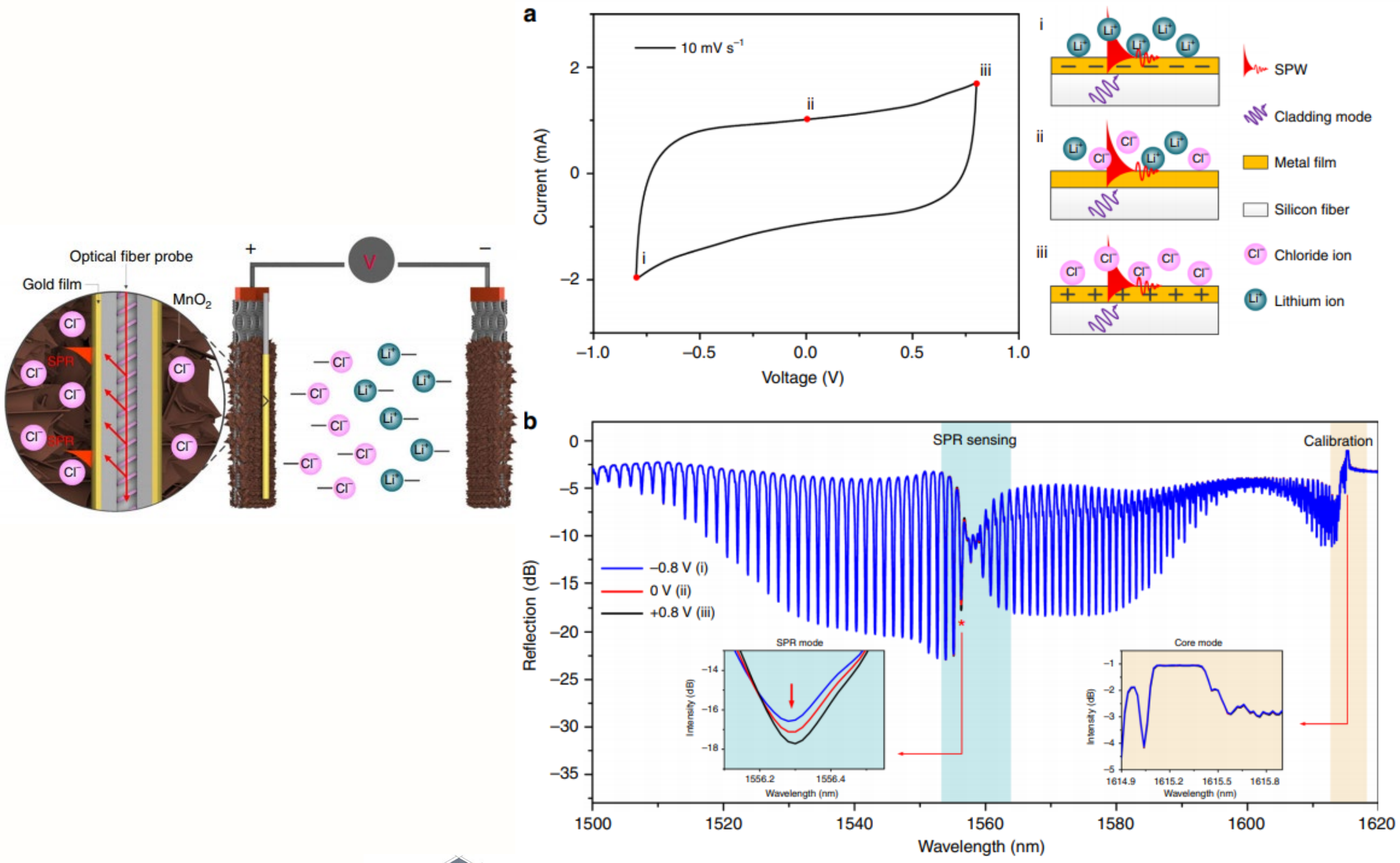
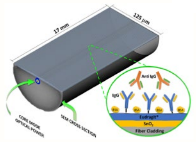



## FIBER OPTICS FOR BATTERY/CELL MONITORING

- Continuous monitoring of electrochemical activity of supercapacitors, such as the electrode potential and the state of charge of the energy storage devices
- SPR-assisted tilted fiber Bragg grating

Courtesy of: J. Lao et al., *Light Sci. Appl.* **2018**, vol. 7, 34



# Most interesting fiber optic sensing devices from the literature: **chemical sensing**

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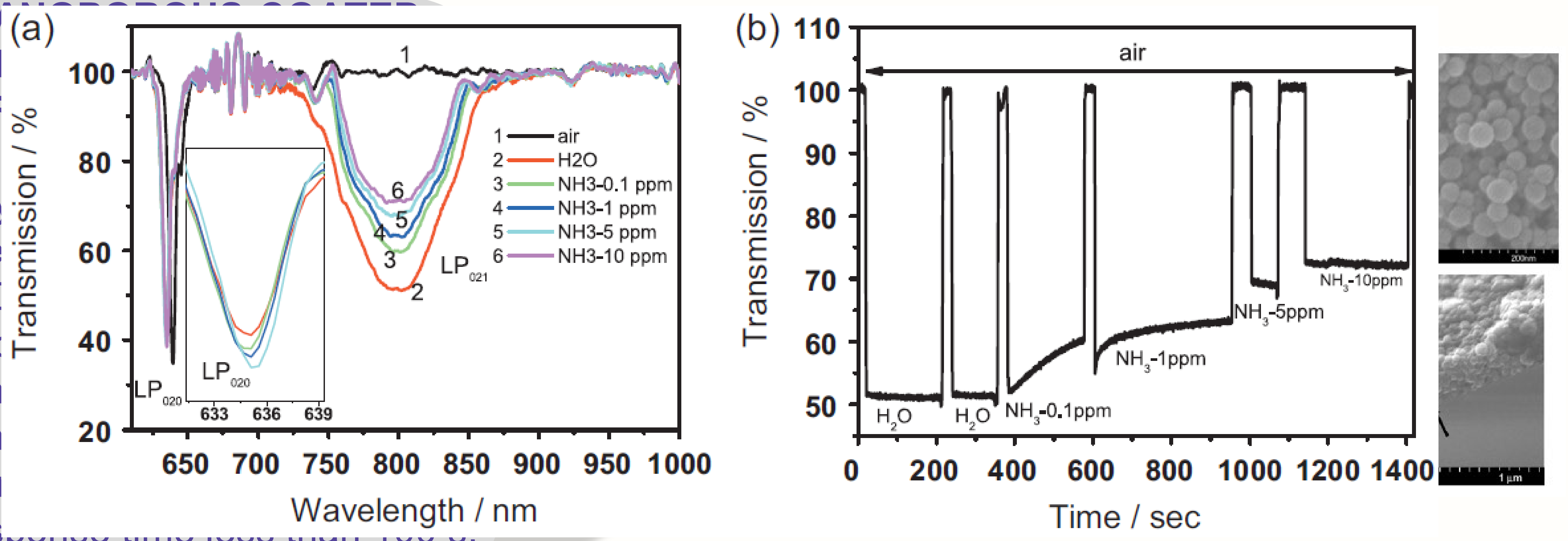
NA…
I…
GF…

- Lay… me… (PD… and…
- Ma… fun… fro… respo… limit of detection of 140 ppb

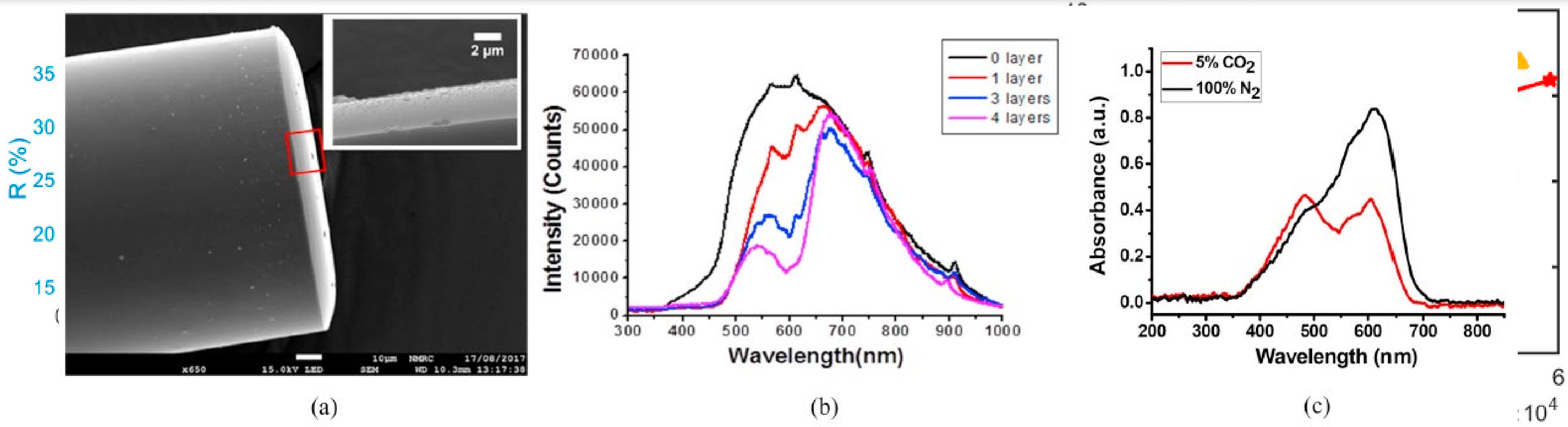



Courtesy of: S. Korposh et al., *Mater. Chem. Phys.* **2012**, vol. 133, p. 784-792.

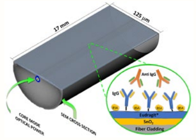
# Most interesting fiber optic sensing devices from the literature: **chemical sensing**

## REFLECTION-MODE FIBER OPTIC SENSOR FOR $CO_2$ DETECTION

- Organically-modified silica film based on thymol blue and tetramethylammonium hydroxide
- Main features: colorimetric change of pH indicator, reflectivity, $CO_2$ range from 0 to 6%, response time of 19 s, $CO_2$ measurements from breath sample




Courtesy of: L. Liu et al., *Sens. Biosens. Res.* **2019**, vol. 22, 100254.



# Most interesting fiber optic sensing devices from the literature: **biosensing**

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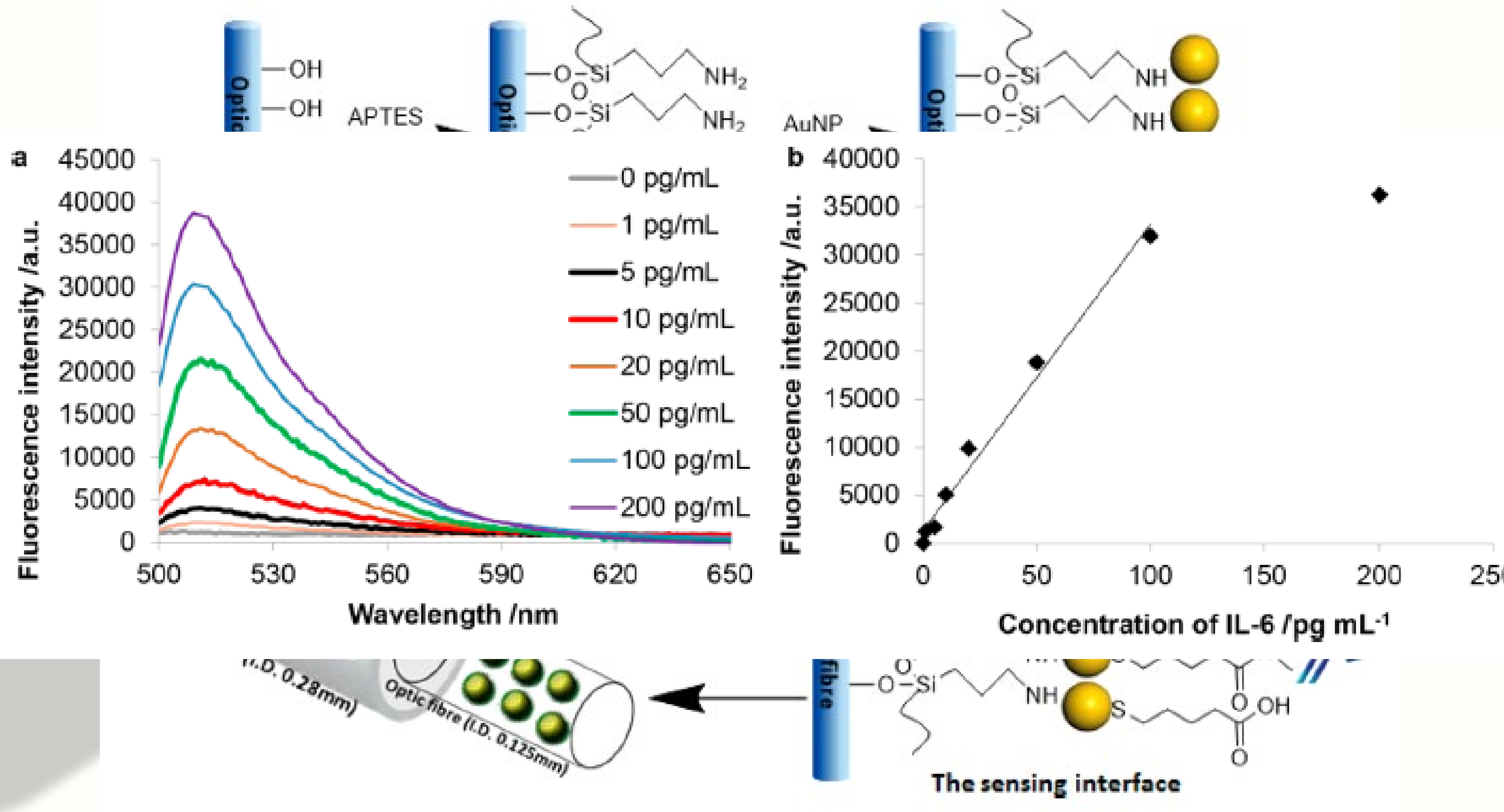
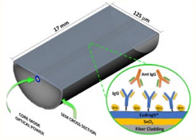
**SPECIAL FIBER-BASED CATHETER FOR CYTOKINE DETECTION**

- Gold NP-coated fiber embedded into an hole drilled intrathecal catheter
- Main features: cytokine interleukin-6 (IL-6) detection, fluorescence measurement, LOD of 1 pg mL$^{-1}$, specificity in live BV2 cells




Courtesy of: G. Liu et al., *ACS Sensors* **2017**, vol. 2, p. 218-226.

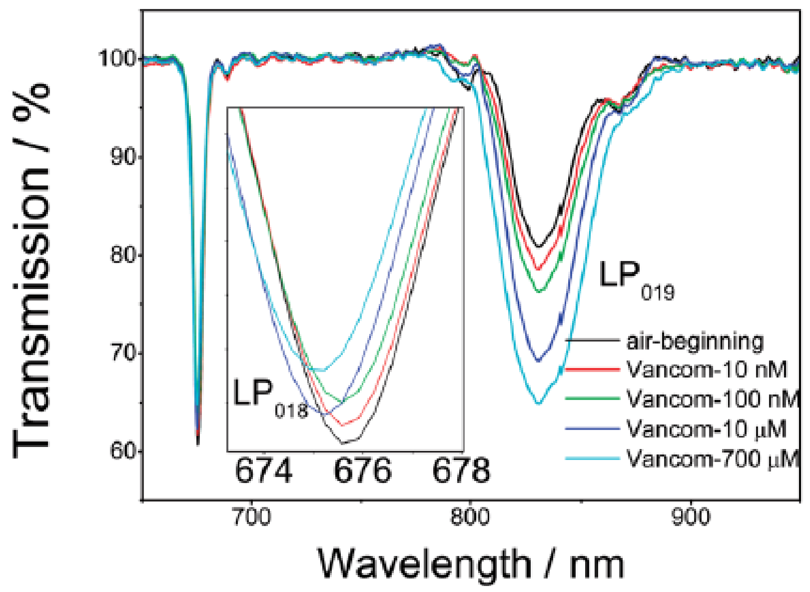


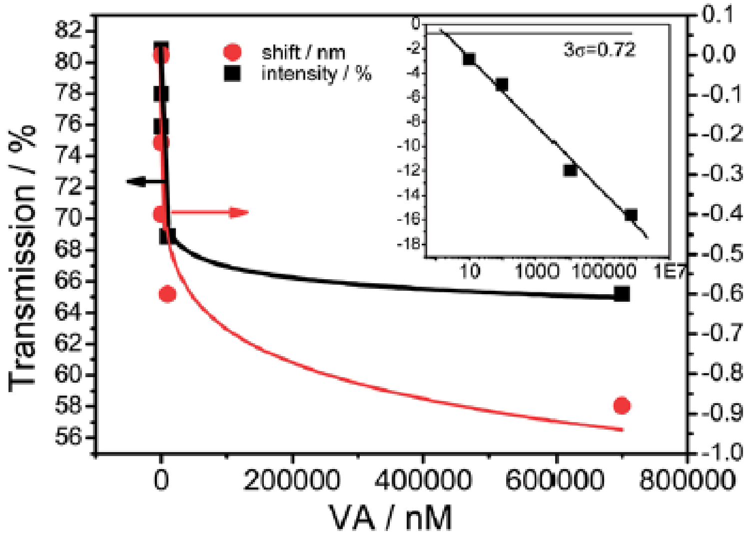
# Most interesting fiber optic sensing devices from the literature: **biosensing**

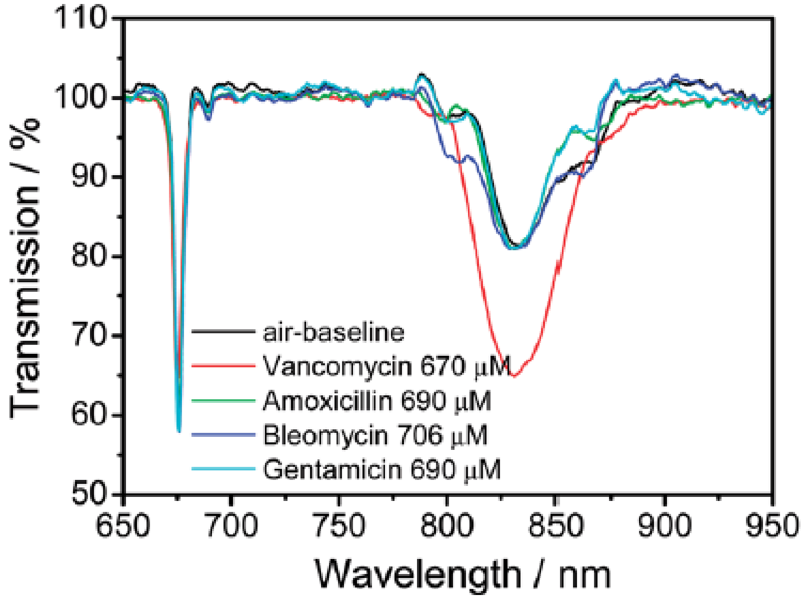


## LPFG WITH MIP-NANOPARTICLES FOR ANTIBIOTICS DETECTION

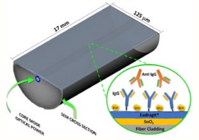
- Molecularly imprinted polymer nanoparticles to reduce the non-specific binding
- Main features: transition mode, vancomycin detection, label-free, 10 nM lowest concentration, specificity




Courtesy of: S. Korposh et al., *Analyst* **2014**, vol. 139, p. 2229-2236.



# Most interesting fiber optic sensing devices from the literature: **biosensing**

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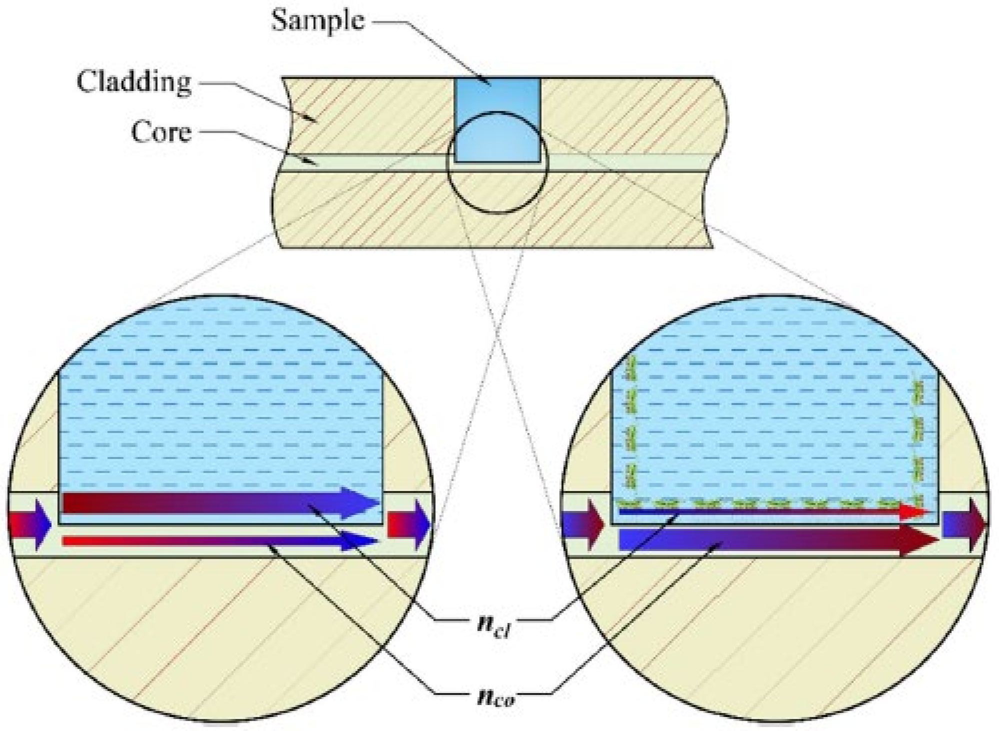
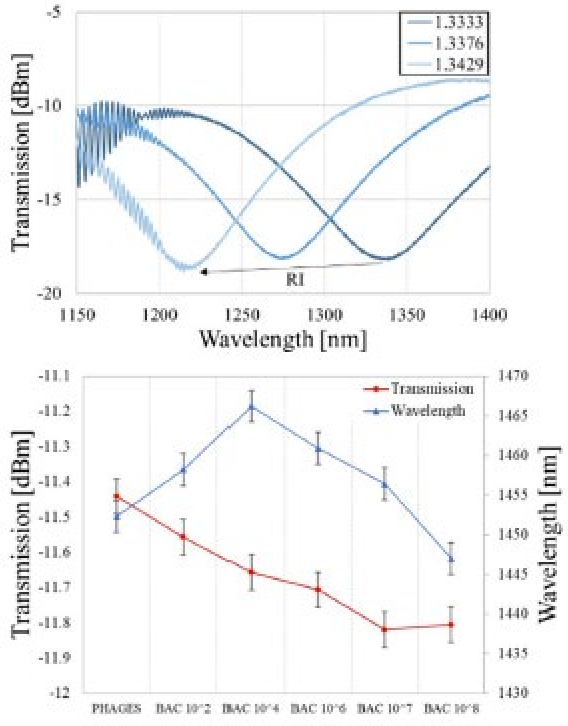
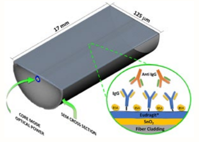
## μ–CAVITY IN-FIBER MACH-ZEHNDER INTERFEROMETER FOR *E. COLI* BACTERIA DETECTION

- Surface functionalization by silanization (APTES) and deposition of amine groups (glutaraldehyde)
- Main features: 50 μm diameter, 15 μm/RIU bulk sensitivity, 100 colony forming units (CFU)/mL as lowest *E. Coli* bacteria concentration




M. Janik et al., *Sci. Rep.* **2018**, vol. 8, p. 17176.

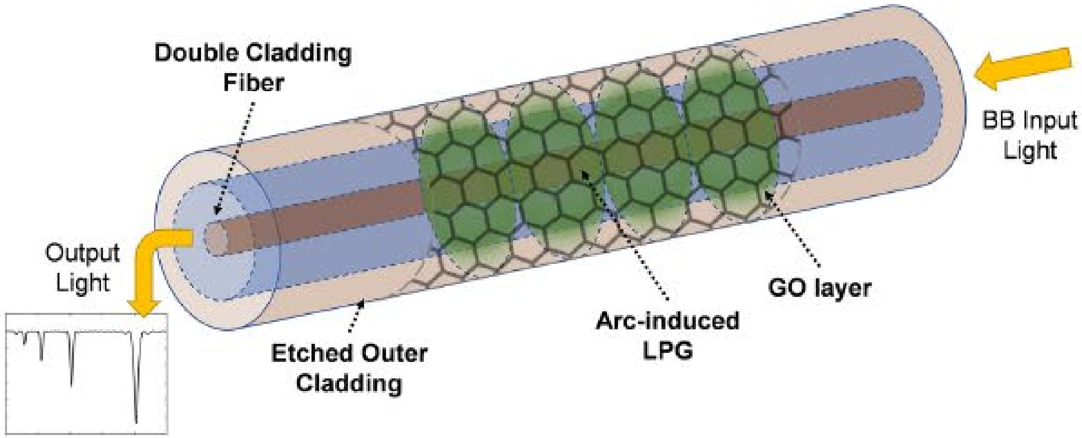


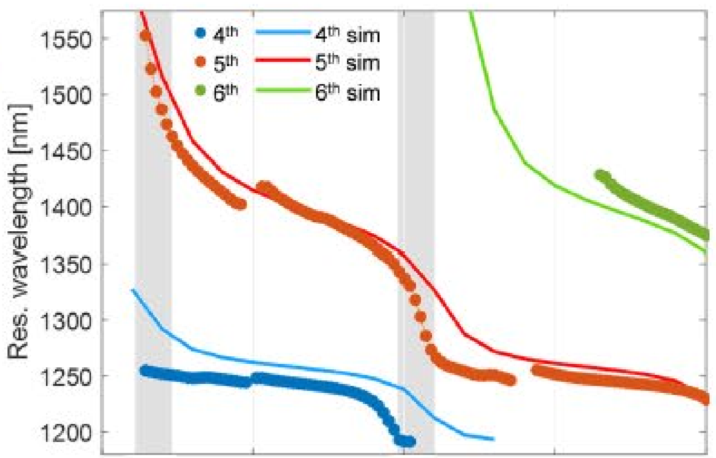
# Most interesting fiber optic sensing devices from the literature: **biosensing**

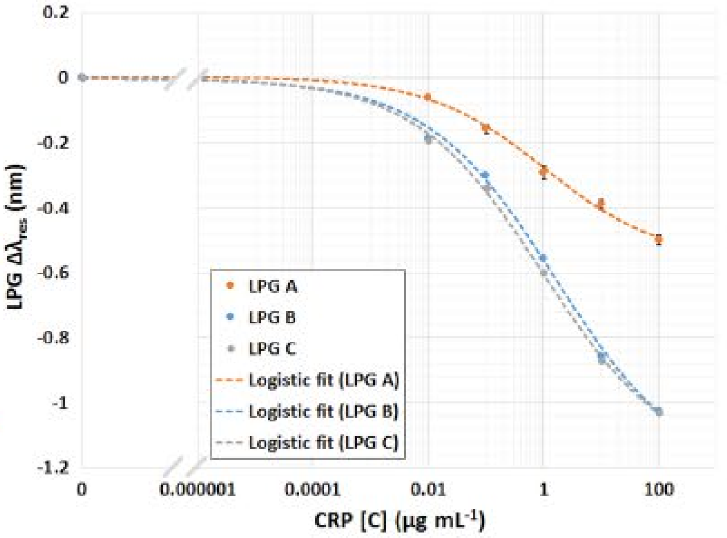


## GRAPHENE-OXIDE COATED LPG IN DOUBLE-CLAD FIBER FOR CRP DETECTION

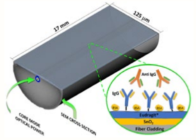
- GO deposited by dip-coating technique and able to directly provide carboxyl (-COOH) functional groups
- Mode transition in an all-silica structure by chemical etching of the outer fiber cladding
- Main features: CRP detection in serum, large working range of clinical relevance (1 ng $mL^{-1}$ – 100 $\mu$g $mL^{-1}$), LOD of 0.15 ng $mL^{-1}$




F. Esposito et al., *Biosens. Bioelectron.* **2021**, vol. 172, p. 112747.



# Most interesting fiber optic sensing devices from the literature: **biosensing**

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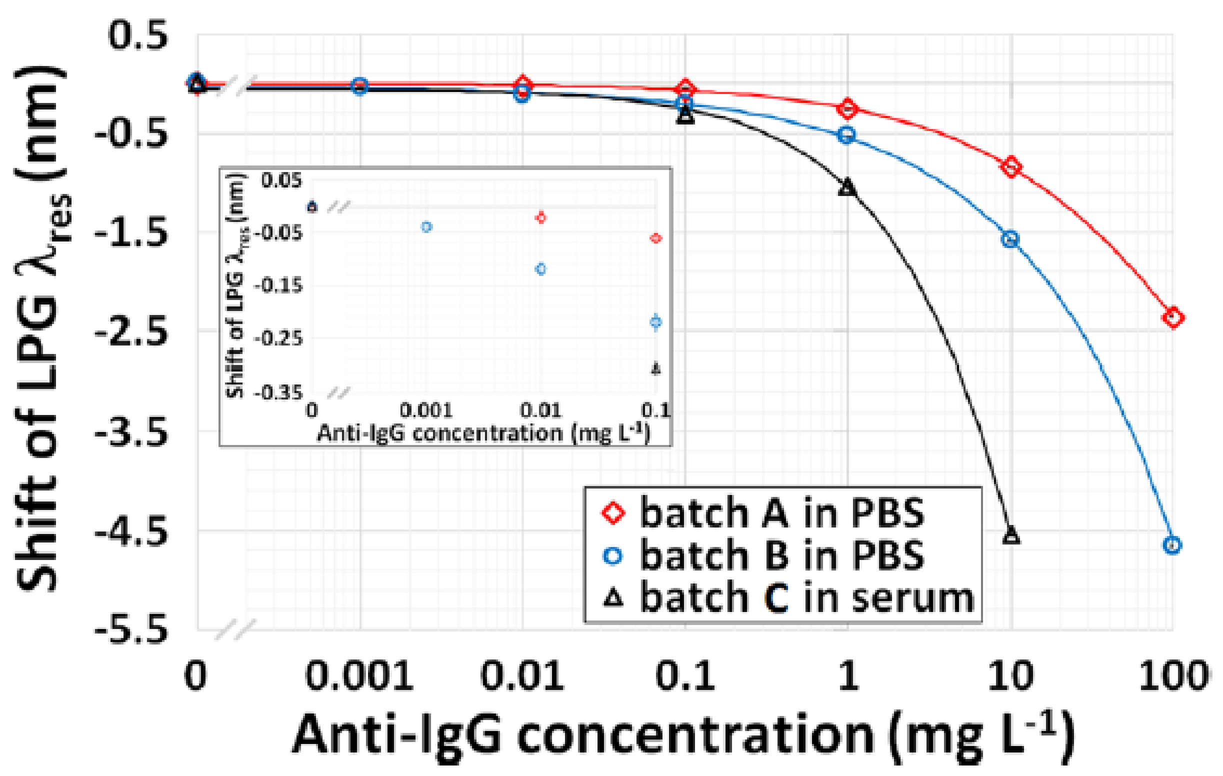
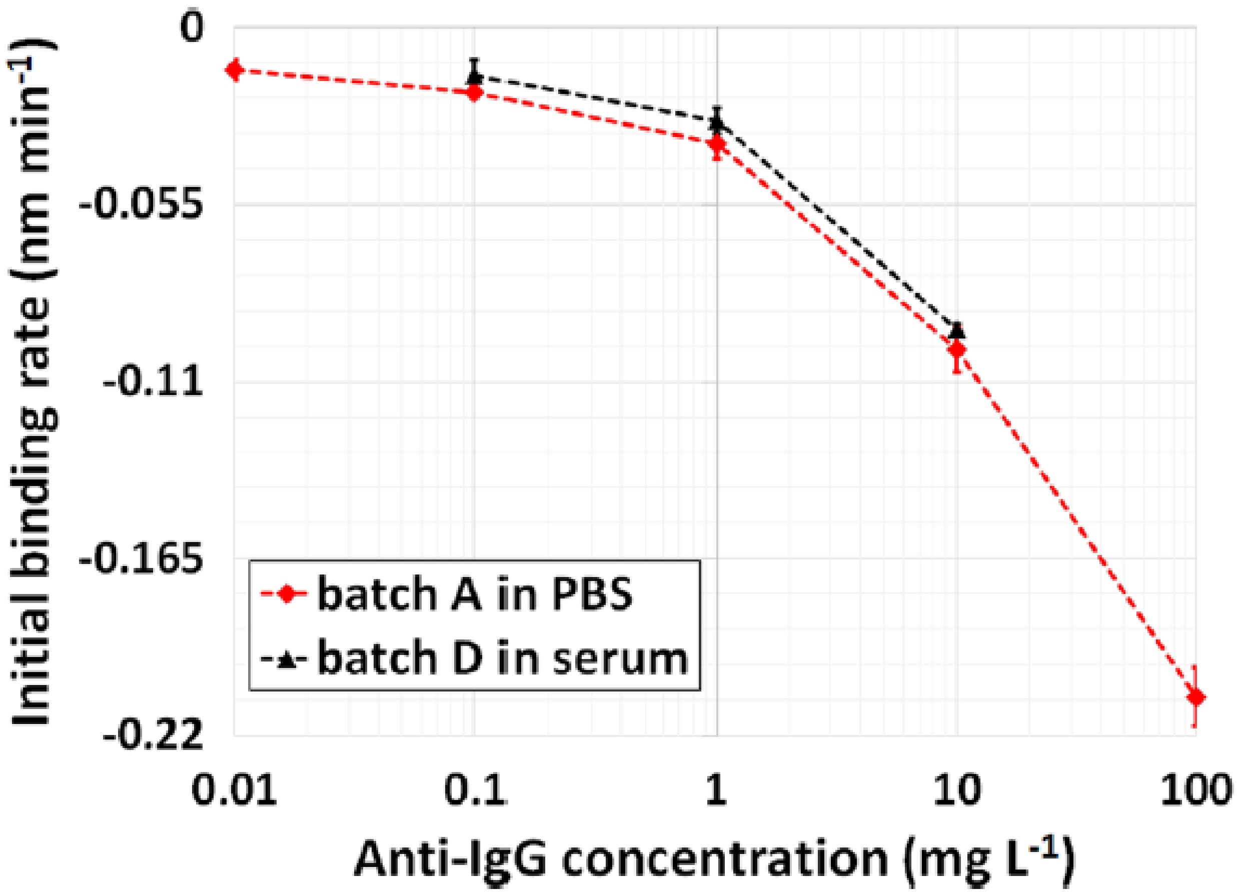
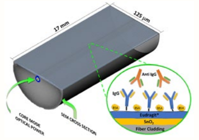


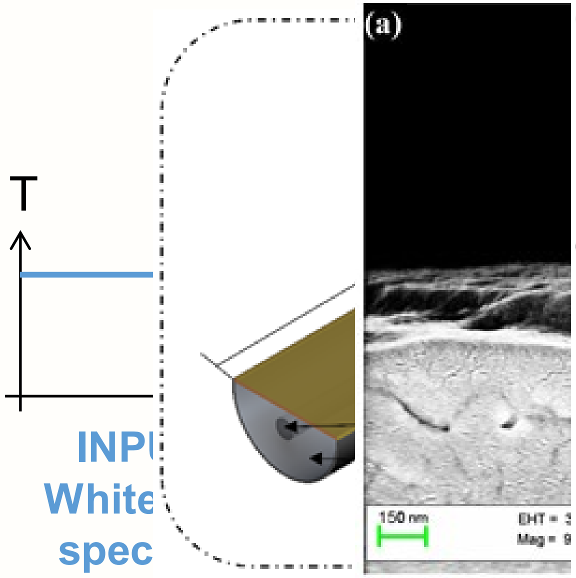

F. Chiavaioli et al., *ACS Anal. Chem.* **2015**, vol. 87, p. 12024−12031.

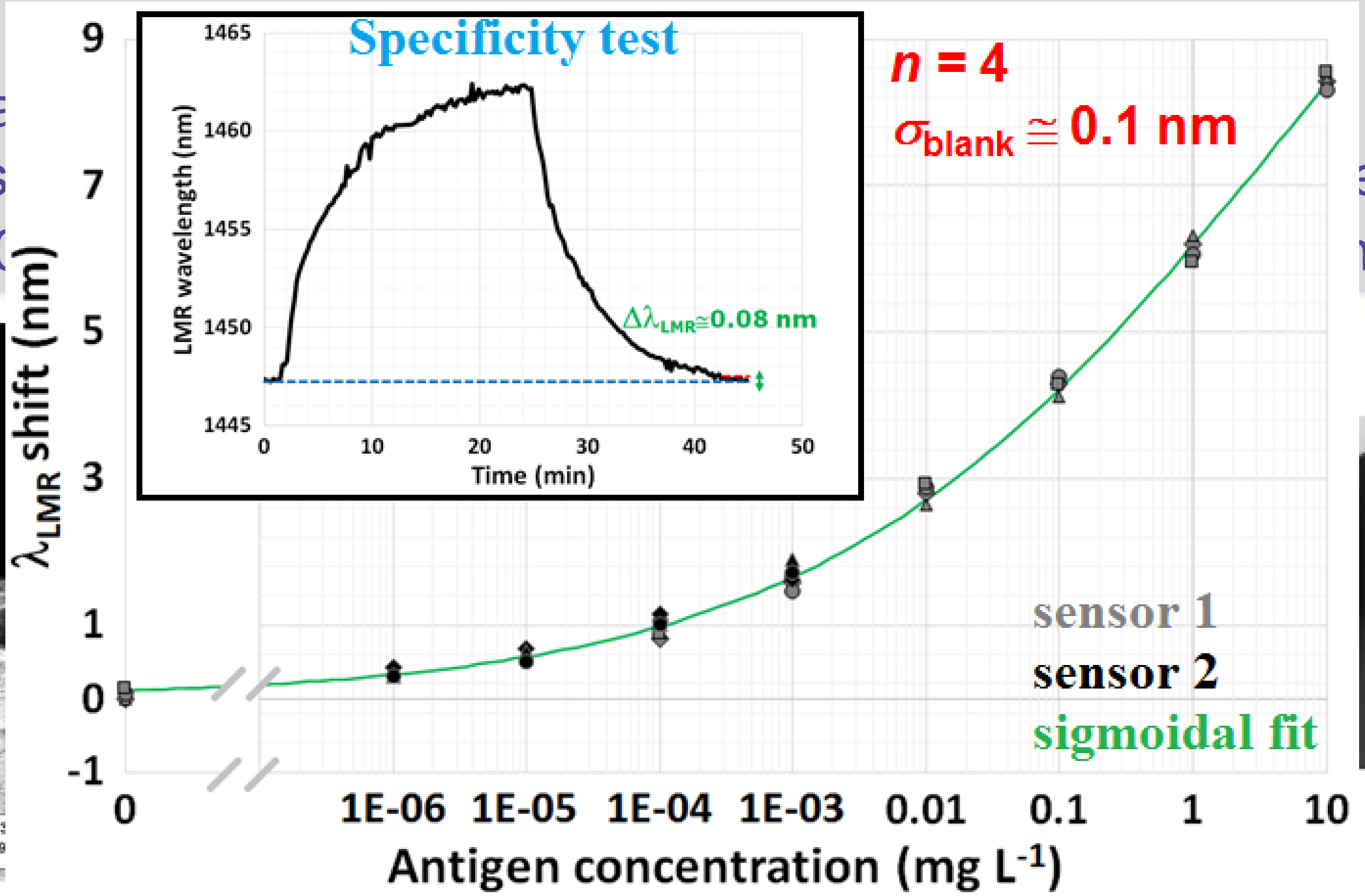


# Most interesting fiber optic sensing devices from the literature: **biosensing**

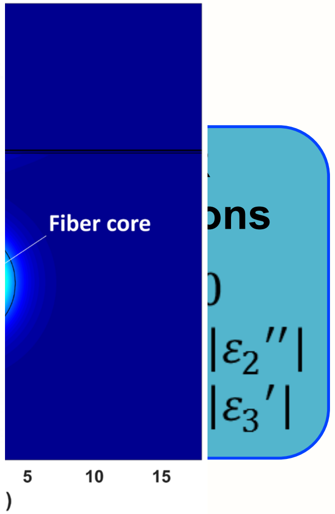
## LOSSY MODE ... DETECTION

- Novel physica...
- Main features ... ee IGG detection, >1... n serum

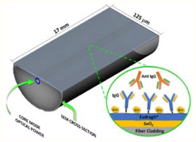







F. Chiavaioli et al., *ACS Sensors* **2018**, vol. 3 (5), p. 936–943.



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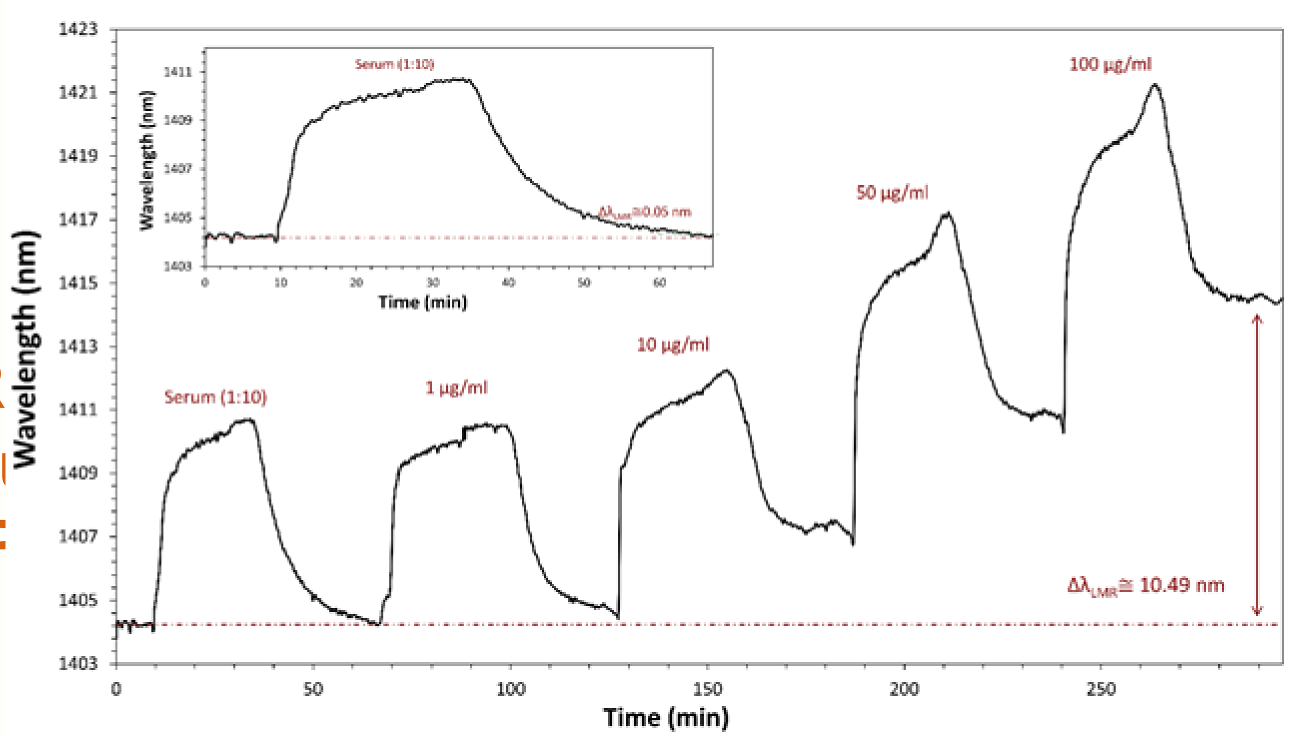
# Most interesting fiber optic sensing devices from the literature: **biosensing**

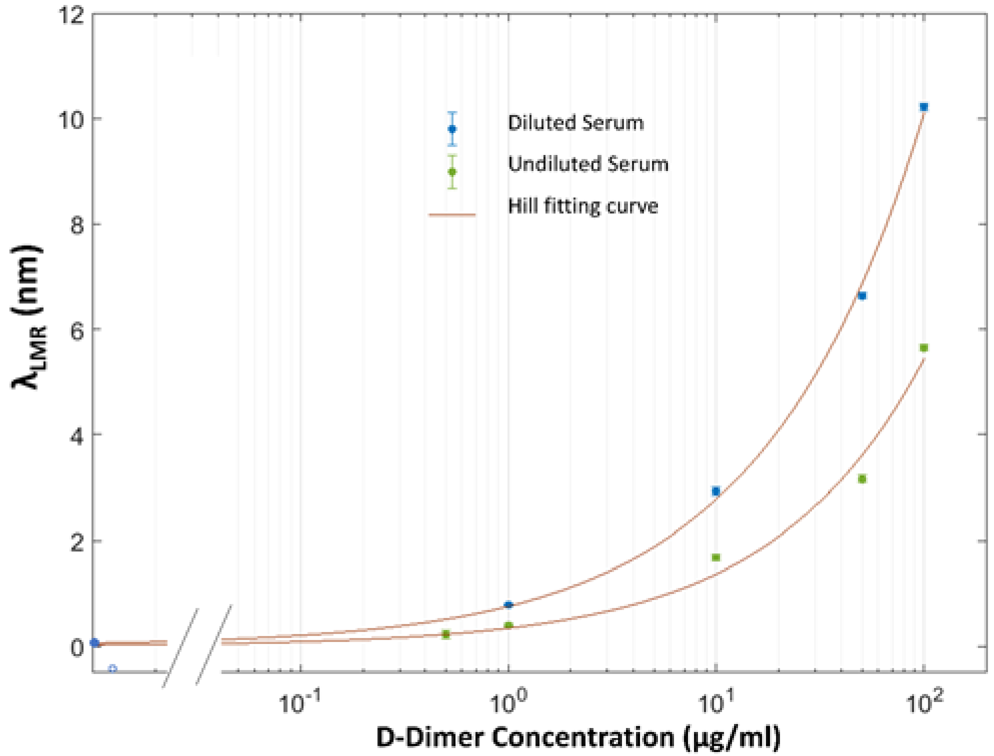
## LMR-BASED D-SHAPED FIBER FOR D-DIMER DETECTION

## Real matrix (Serum)

- D-dimer is a useful diagnostic biomarker for deep vein thrombosis or pulmonary embolism,

R
bi
(F

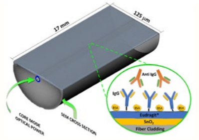



0 20 40 60 80 100 120 140 160
Time (min)

$10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$
D-Dimer Concentration (µg/ml)

P. Zubiate et al., *Biosens. Bioelectron. X* **2019**, vol. 2, 100026



# “Food for Thoughts”



## LECTURE FOCUS (LAST PART)

- «Food for Thoughts» in fiber optic sensing

# “Food for Thoughts”

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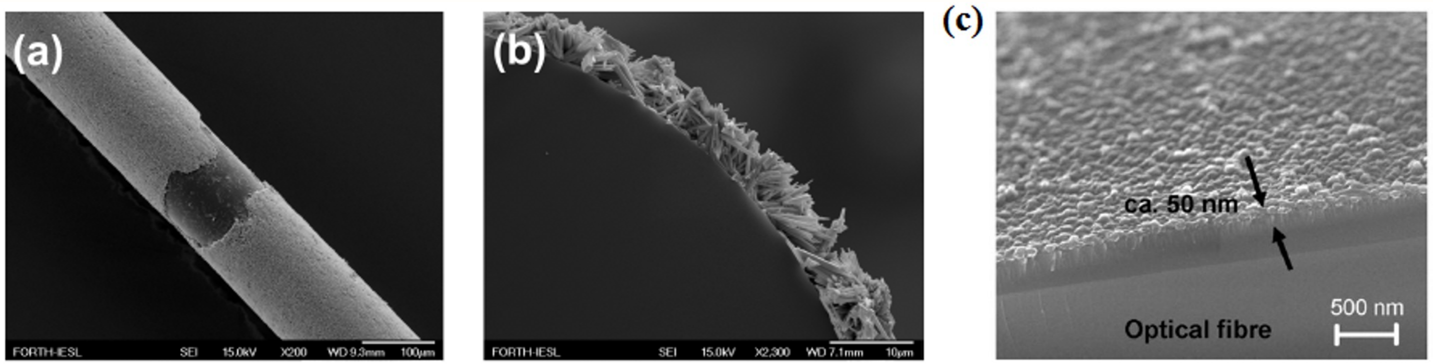
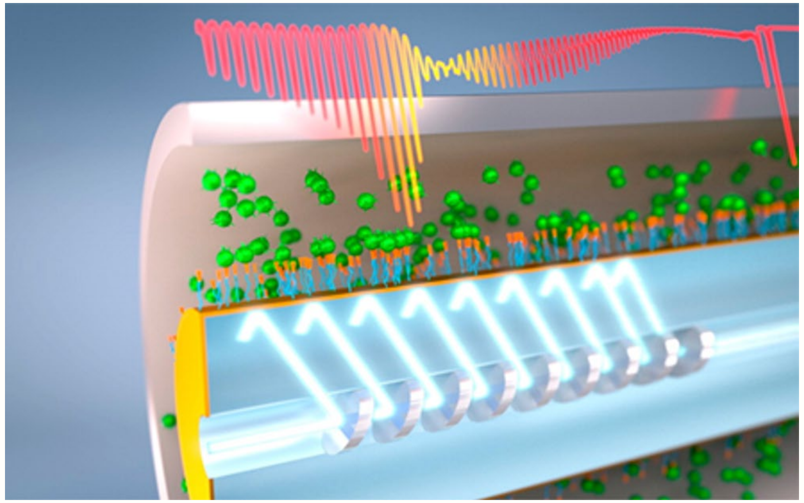
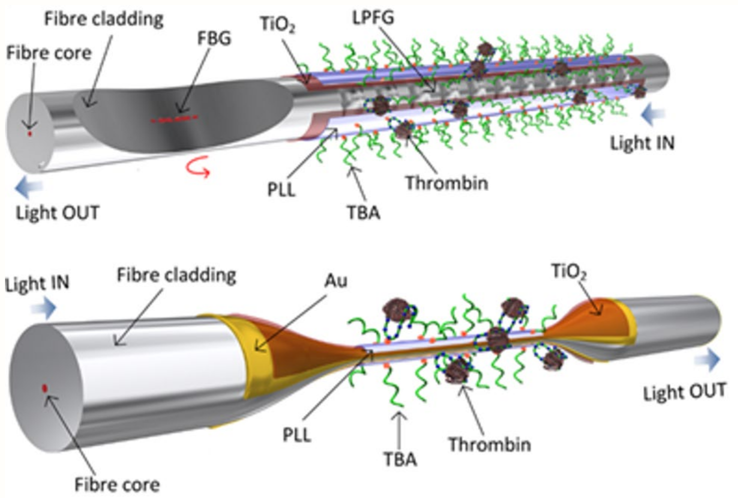
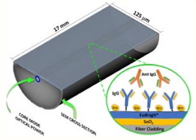



**Novel nanostructures**
**Novel materials**
**Novel shapes**
**Novel sensing devices**






F. Chiavaioli et al., *Nanophotonics* **2017**, vol. 6 (4), p. 663-679.



# "Food for Thoughts"



## Novel shapes
## Novel sensing devices

SCIENCE ADVANCES | RESEARCH ARTICLE

APPLIED SCIENCES AND ENGINEERING

### Twist-induced guidance in coreless photonic crystal fiber: A helical channel for light

Ramin Beravat, Gordon K. L. Wong,* Michael H. Frosz, Xiao Ming Xi, Philip St.J. Russell

A century ago, Einstein proposed that gravitational forces were the result of the curvature of space-time and predicted that light rays would deflect when passing a massive celestial object. We report that twisting the periodically structured "space" within a coreless photonic crystal fiber creates a helical channel where guided modes can form despite the absence of any discernible core structure. Using a Hamiltonian optics analysis, we show that the light rays follow closed spiral or oscillatory paths within the helical channel, in close analogy with the geodesics of motion in a two-dimensional gravitational field. The mode diameter shrinks, and its refractive index rises, as the twist rate increases. The birefringence, orbital angular momentum, and dispersion of these unusual modes are explored.

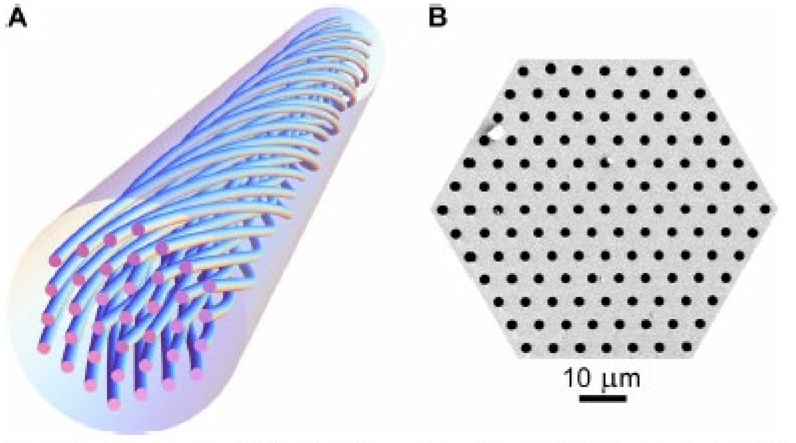



**Fig. 1. The geometry of the twisted coreless PCF.** (**A**) Schematic of a twisted coreless PCF. The axis of rotation coincides with the hollow channel in the center. (**B**) Scanning electron micrograph of the microstructure.

Courtesy of: R. Beravat et al., Sci.Adv. **2016**, vol. 2, e1601421.

# “Food for Thoughts”

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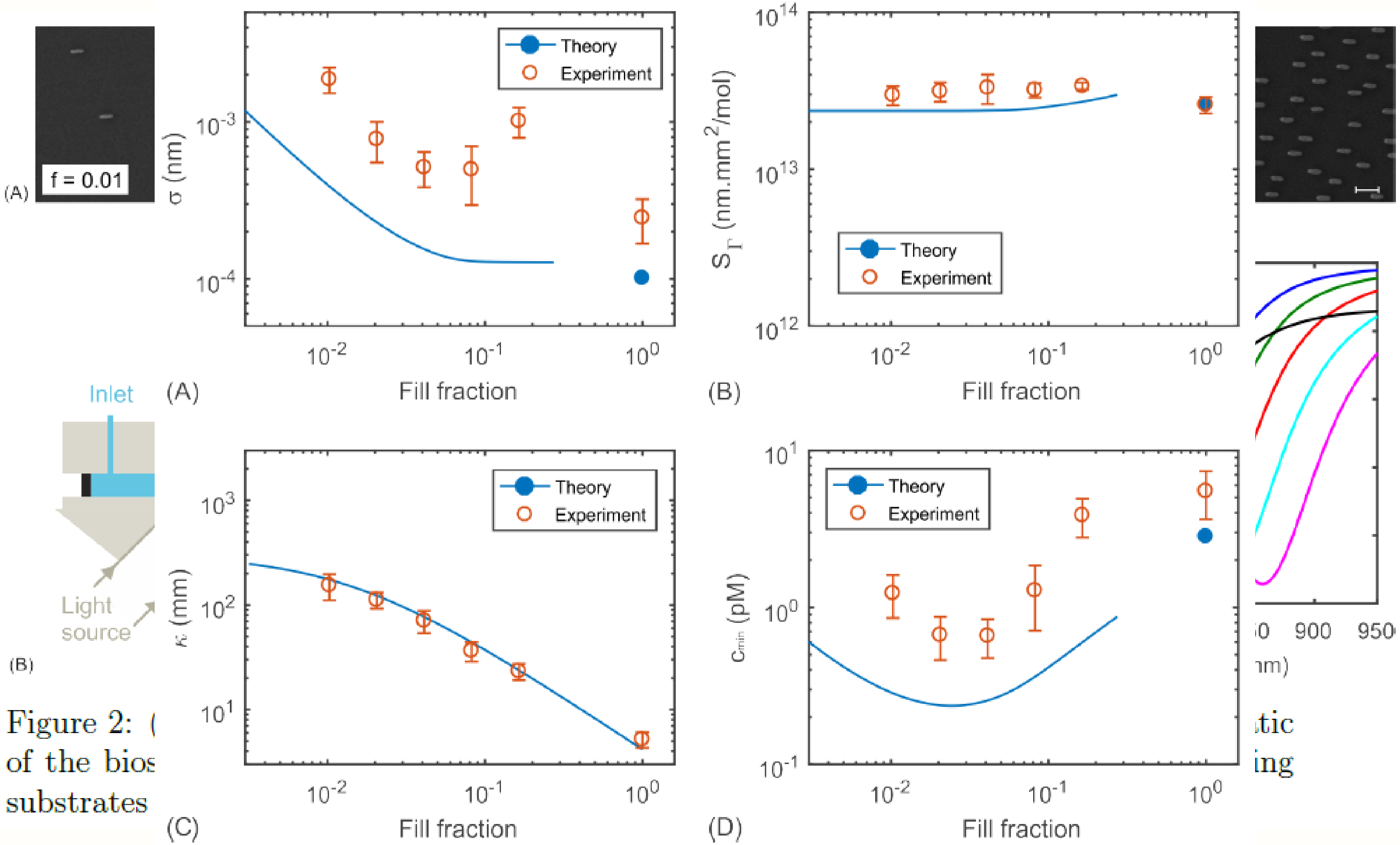
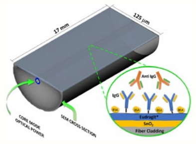
## New insight into nanostructures for biosensing: both optical and mass transport aspects

$$c_{min} = \frac{3\sigma}{S_\Gamma \cdot \kappa}$$



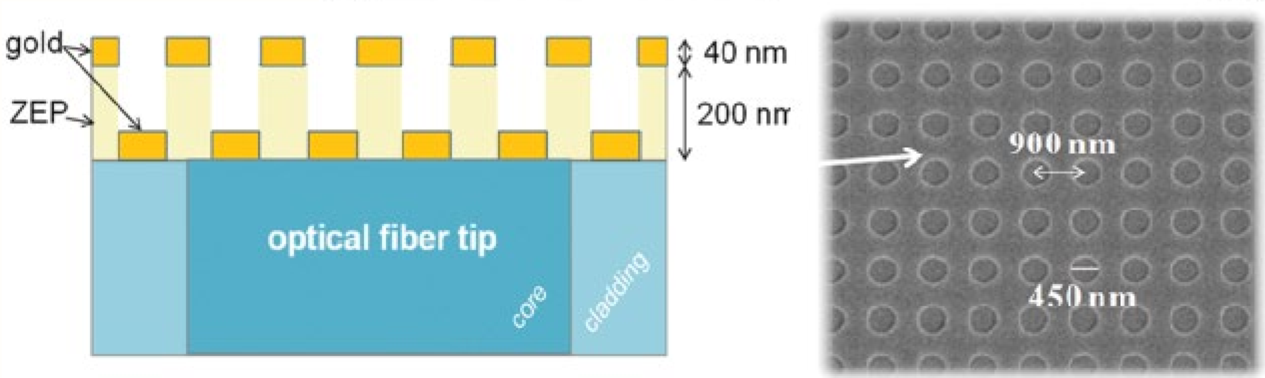

Courtesy of: B. Spačková et al., *ACS Photonics* **2018**, vol. 5, p. 1019-1025.

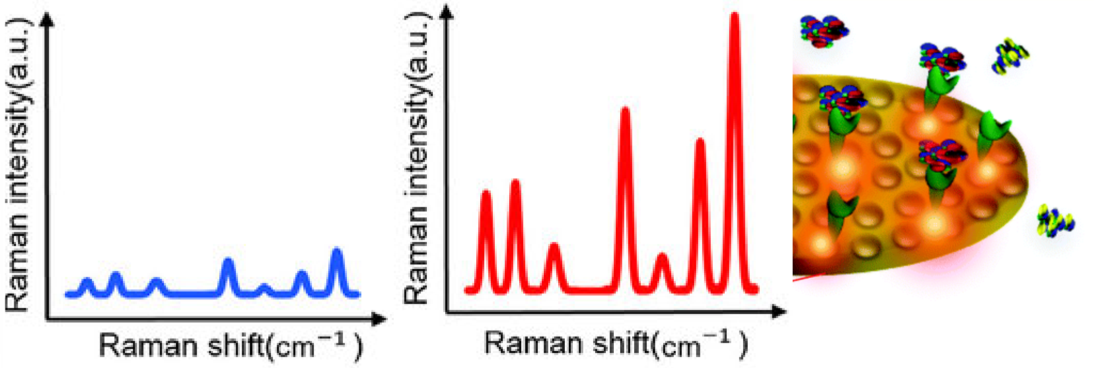


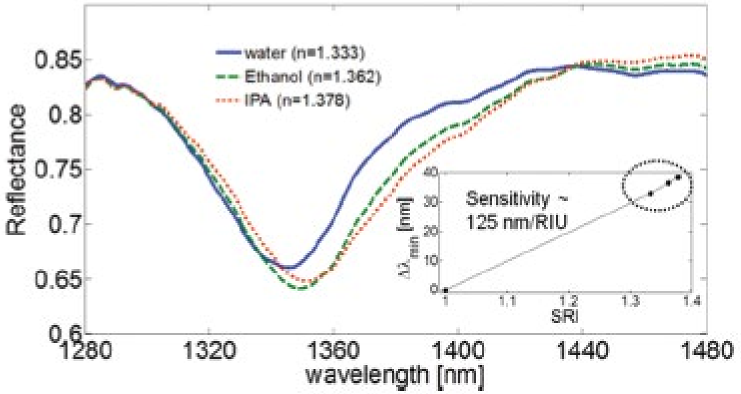
# "Food for Thoughts"

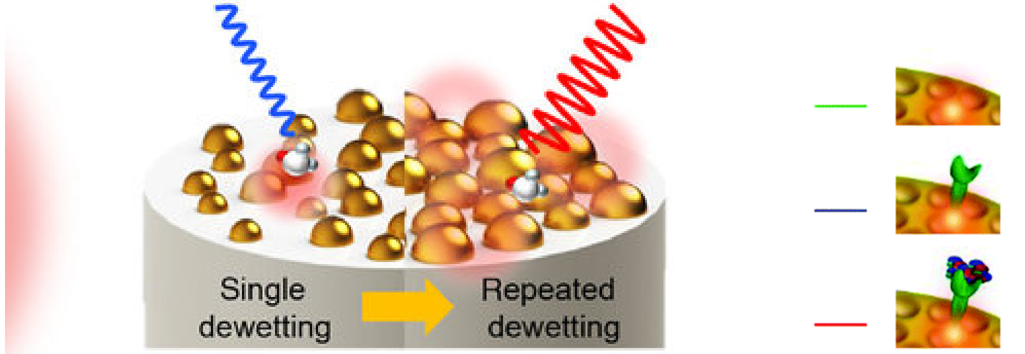


## Novel sensing configuration: Lab-on-Fiber (tip)



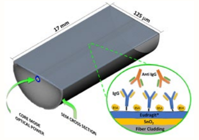




Intense plasmonic hotspots by nanogap-rich gold nanoislands on a fiber-top surface

Courtesy of: M... p. 8068–8079.

Courtesy of: J. Kwak et al., J. Biomed. Opt. 2019, vol. 24, no. 3, p. 037001.

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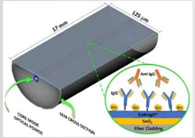
# Thanks for your kind attention!



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**OSA MEETINGS**
**PHOTONIC DETECTION TECHNICAL GROUP**
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