NOVEL FIBER OPTIC SENSING ARCHITECTURES BASED ON SENSITIVE NANOFILMS

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Summary

- ❑ Introduction to the fiber optic sensor market
- ❑ Nanotechnology and fiber optic sensors?
- ❑ The Electrostatic Self-Assembled Monolayer Method
- ❑ Possible sensing architectures based on nano-films
    - ❑ Tapered ends
    - ❑ Tapered optical fibers
    - ❑ Hollow core fibers
    - ❑ Long period gratings
    - ❑ Optical fiber gratings
    - ❑ NanoFabry-Perot Cavities
- ❑ Conclusions

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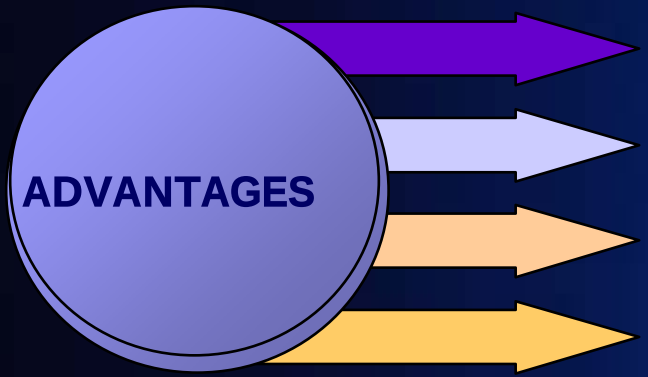
Technology Overview. Advantages



- Small and Lightweight
- Possibility of being embeded in composite materials
- Passive nature
- Large dynamic ranges
- Single- & Multi-Point Sensing Configurations
- Large wideband
- Low attenuation
- Multiplexing techniques
- EMI immunity

Technology Overview. Classification

Type of optical fiber sensors

Type of Modulation
- Intensity
- Interferometric
- Polarimetric
- Spectroscopic

Nature of transduction
- Intrinsic
- Extrinsic

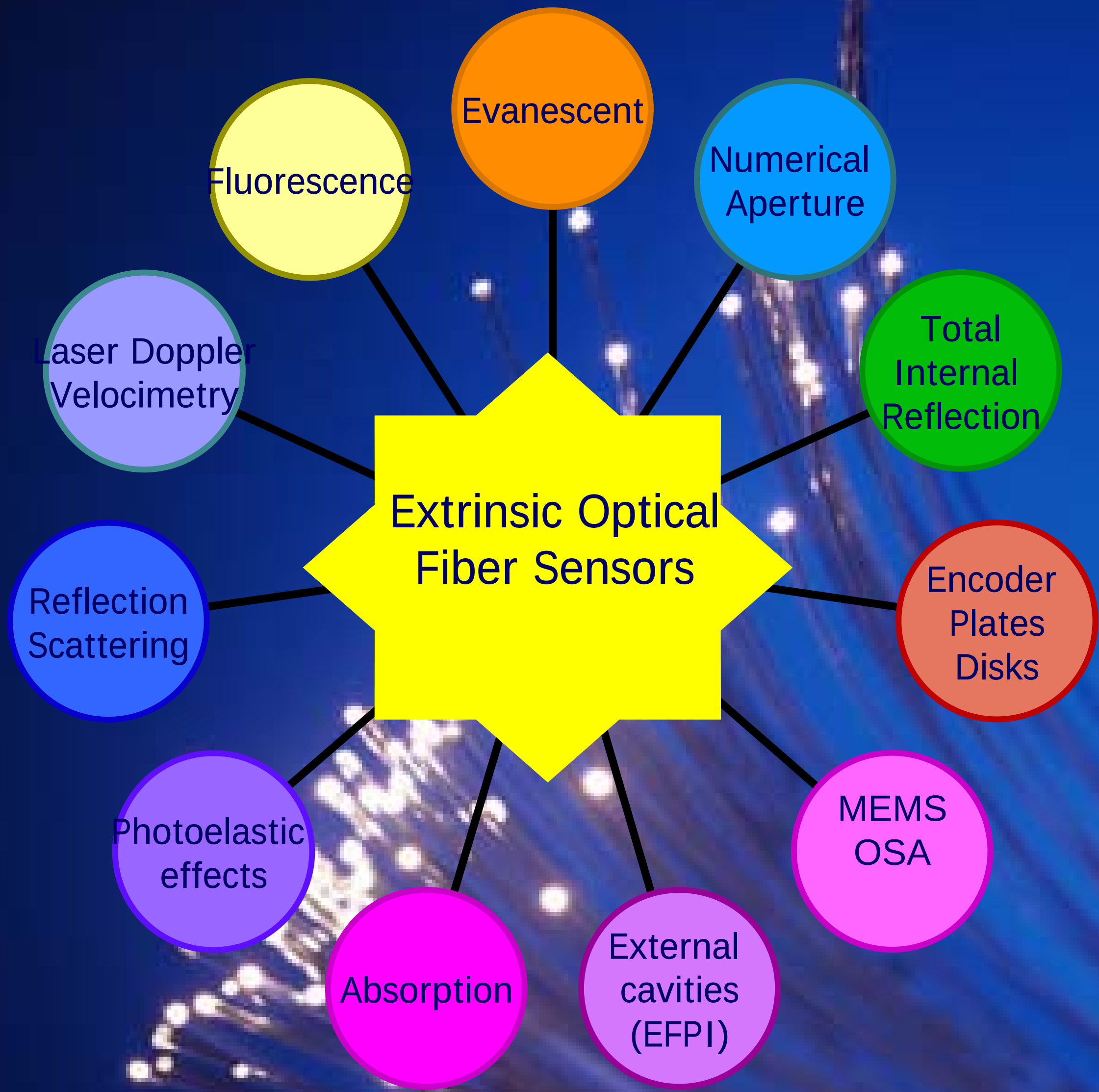
Spatial distribution
- Point
- Distributed
- Quasi-distributed

Physical Magnitude
- Voltage/current
- Temperature
- Radiation
- Biomedical
- Chemical/gas
- Electroagnetic fields
- Strain
- Rotation
- Mechanical

Bending/torsion, velocity, vibration/acceleration, displacemen/location, pressure/acoustics, force

Ignacio R. Matías et al. *Fiber optic sensors.* ***Encyclopedia of Sensors.*** Vol. 7, pp. 163-181.

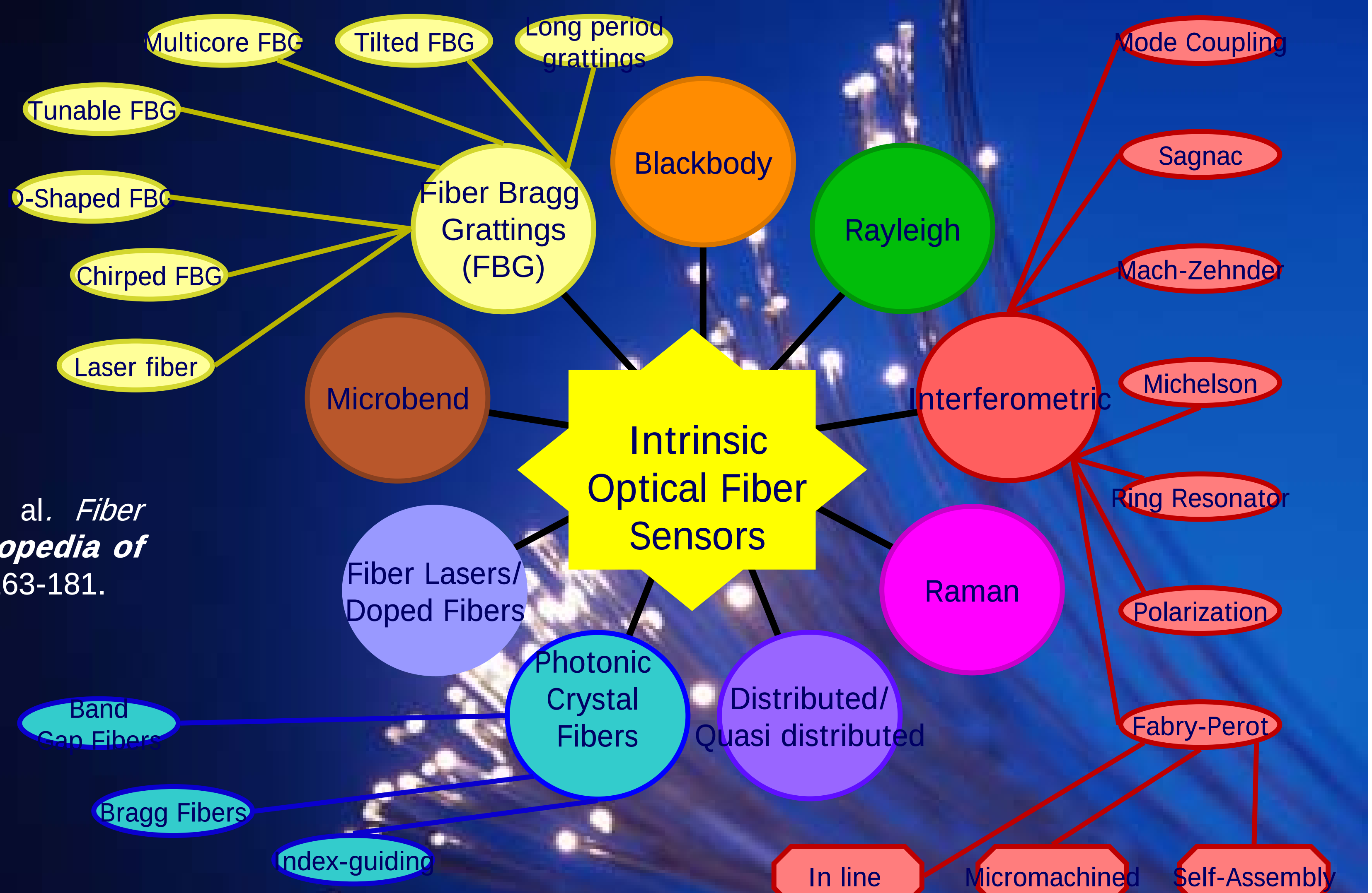
Technology Overview. Extrinsic sensors



Ignacio R. Matías et al. *Fiber optic sensors.* ***Encyclopedia of Sensors.*** Vol. 7, pp. 163-181.

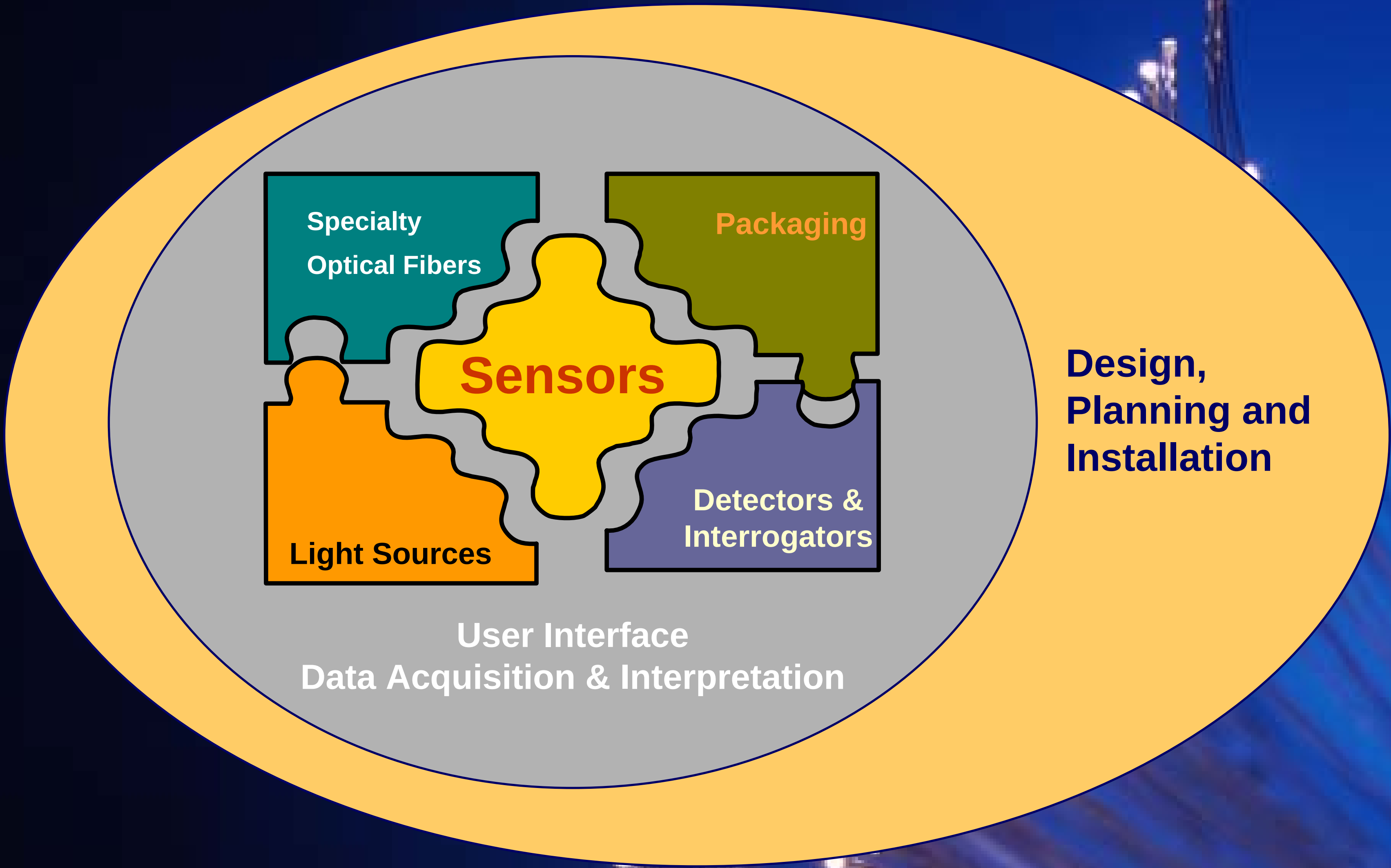
Novel fiber optic sensing architectures based on sensitive nanofilms

Technology Overview. Intrinsic sensors



Ignacio R. Matías et al. *Fiber optic sensors.* ***Encyclopedia of Sensors.*** Vol. 7, pp. 163-181.

Fiber Optic Sensing System Key Building Blocks



Courtesy of Alexis Méndez. *MCH Engineering, LLC*

Fiber Optic Market Status

Fragmented

Niche markets

Foothold in niche applications

Slow adopting industries

Positive investment environment

Major franchises emerging

Positive and continued steady growth

Important growth in chemical/ bio-detection

Market Drawbacks

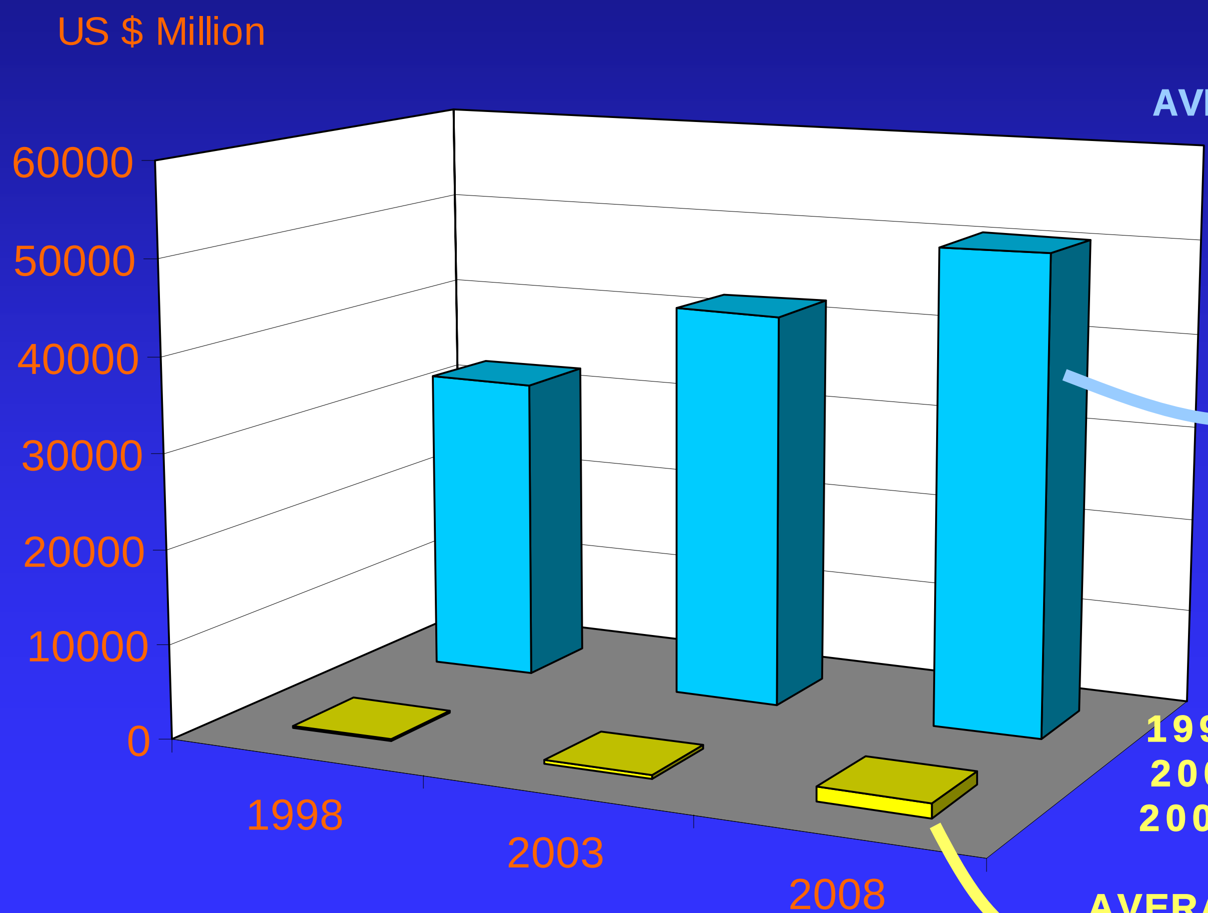
- Unfamiliarity with the technology
- Conservative/no-risk attitude of some industries
- Need for a proven field record
- Compatibility with existing equipment
- Cost
- Availability of trained personnel
- Turn-key type systems (total sensing solution)
- Lack of standards
- Quality, performance, packaging & reliability deficiencies across vendors
- Major sensing initiatives likely dominated by wireless

Courtesy of David Huff (Oida) Source: Quorex

Novel fiber optic sensing architectures based on sensitive nanofilms

Sensors Market Size

Development of the World Market Share of Fiber Optical Sensors until 2008



SENSORS WORLD MARKET

1998 – U$32,534.0M
2003 – U$42,158.4M
2008 – U$50,594.3M

AVERAGE OF ANNUAL GROUTH RATE – 4,5%

FOS WORLD MARKET

1998 – U$ 175 M – MKT SHARE (0,54%)
2003 – U$ 283 M - MKT SHARE (0,67%)
2008 – U$ 1450 M –MKT SHARE (2,87%)

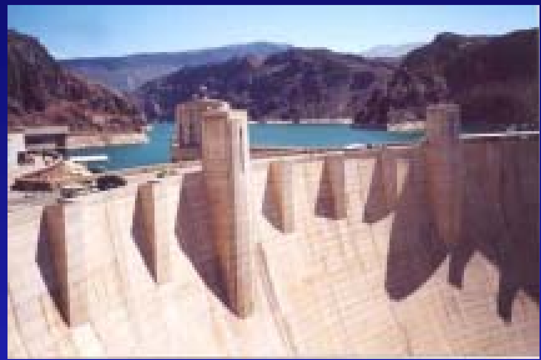
AVERAGE OF ANNUAL GROUTH RATE – 23,5%

Source: INTECHNO CONSULTING

Novel fiber optic sensing architectures based on sensitive nanofilms

Civil (bridges, roads, dams, tunnels)

Oil & Gas (Reservoir monitoring, downhole P/T sensing, seismic arrays)



Transportation (Rail monitoring, Weight in motion, Carriage safety)

Applications

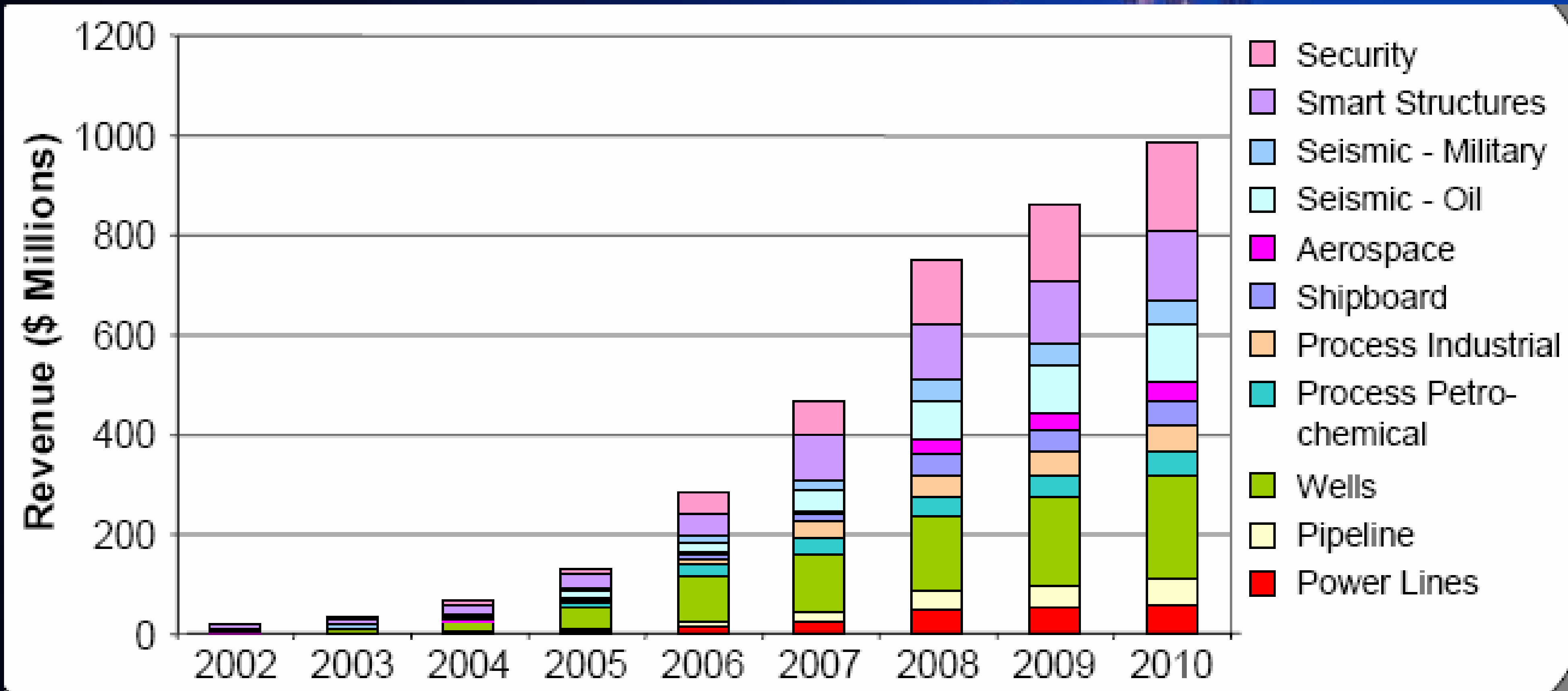
Energy Industry (Power plants, Boilers & Steam turbines, Power cables, Turbines, Refineries)

Border security and power line monitoring

Aerospace (Jet engines , Rocket & propulsion systems, Fuselages)

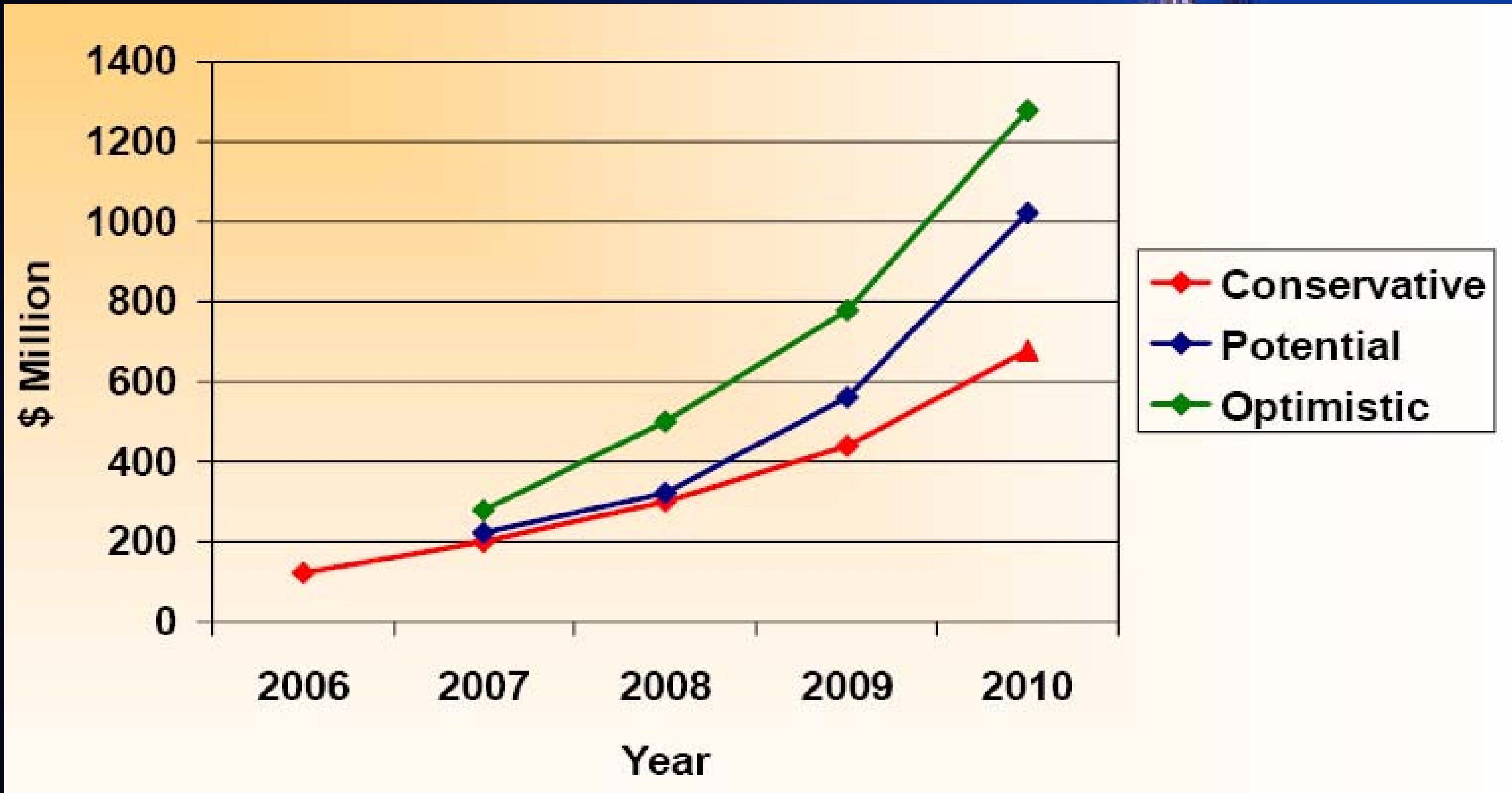
Courtesy of David Huff and Alexis Mendez

Optical Fiber Sensor Market Revenues Breakdown



Courtesy of David Huff (Oida). Source: Light Wave Venture

Optical Fiber Sensor Market Forecast



Courtesy of David Huff (Oida). Source: Light Wave Venture

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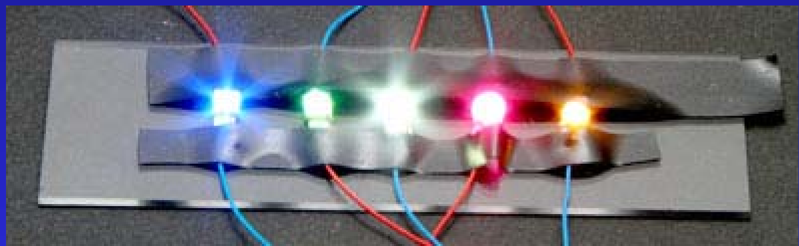
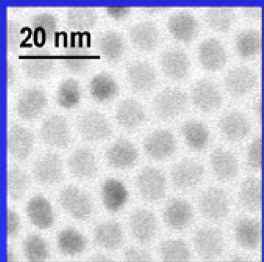
Nanotechnology and fiber optic sensors?

Nanostructure with a size between molecular and microscopic

layers of subwavelength thickness (*botton-up*)





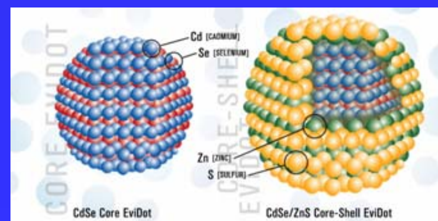
Nanotubes

2D

1D Nanofilm 3D

Nanotextured surfaces

Nanoparticles



Nanotechnology and fiber optic sensors?

Deposition techniques for sensing coatings in OFS

- Chemical vapor deposition
- Spin, dip coatings
- Sputtering in a radio frequency
- Electron beam, physical and thermal evaporating
- planar magnetron systems
- Langmuir-Blodgett
- Layer-by-layer
- Gel solutions

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Introduction

- 1960s: Layer-by-layer adsorption of oppositely charged colloidal particles was first proposed by R. K. Iler R.K. Iler, J. Colloid Interface Sci., 21, 569-594 (1966) “Multilayers of colloidal particles”

- 1990s: reappearance of works on this topic with Decher and co-workers as the pioneers G. Decher, J.-D. Hong, Makromol. Chem., Macromol. Symp., 46, 321-327 (1991).

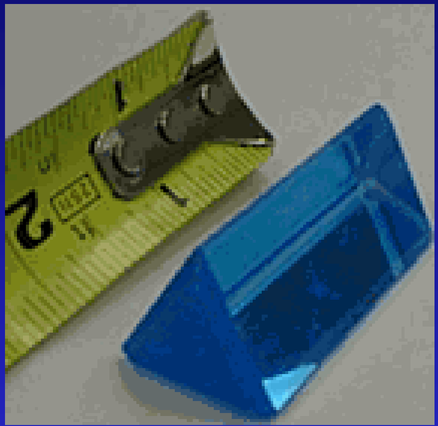
- Today: Layer-by-Layer Electrostatic Self-Assembly (ESA) is one of the most promising techniques for the deposition of nanostructured tailored materials on complex surfaces

- Possible ESA substrates: metals, plastics, ceramics, oxydes, semiconductors with different sizes and shapes such as prisms, concave or convex surfaces.

- Possible ESA coating materials: metals, semiconductors, polymers, dyes, indicators, quantum dots, enzymes and many others (Au, Pt, Al_2O_3, Fe_3O_4, SiO_2, TiO_2, ZrO_2, poly(sodium-4-styrenesulfonate) (PSS), poly(diallydimethyl ammonium chloride) (PDDA), poly acrylic acid (PAA), poly(allylamine hydrochloride) (PAH), poly R-478, poly S-119, Neutral Red, Fluorescein, HPTS, PPV, Prussian Blue, Glucose Oxidase, Silica, Quantum Dots...)

Novel fiber optic sensing architectures based on sensitive nanofilms

The ESA Method: diverse applications

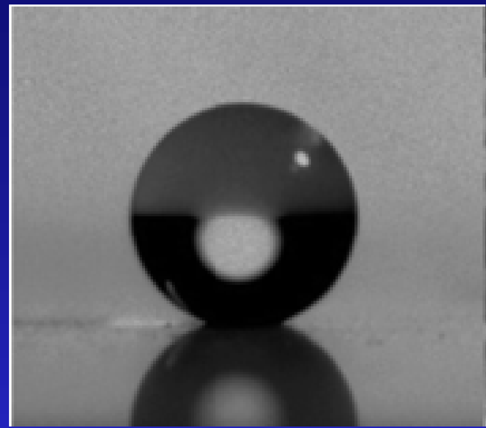


PRISMS

LENS

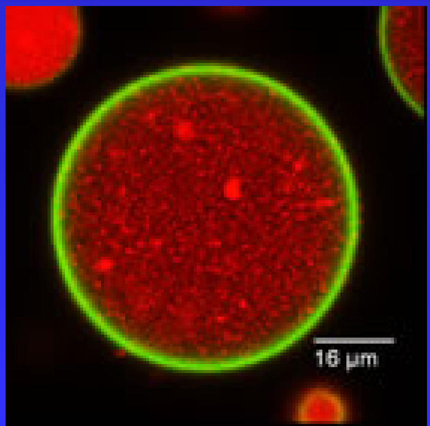
FLEXIBLE SUBSTRATES

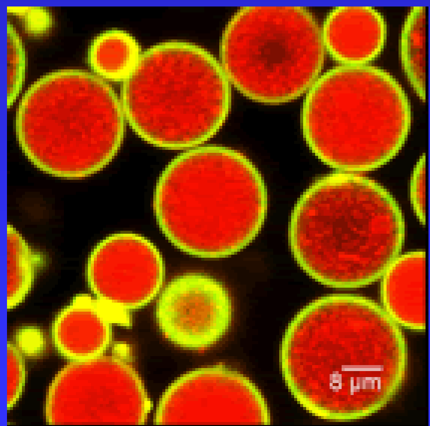
NANOSONIC, INC., R. O. Claus et al.



SUPERHYROPHOBIC SURFACES

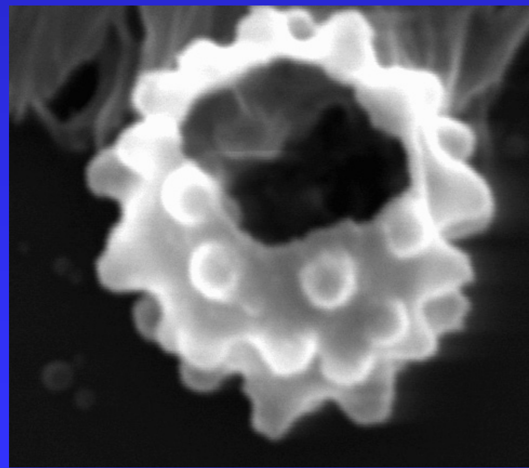
M.I.T., M. F. Rubner et al.





MICROSPHERES

TEXAS A&M, M. McShane et al.



COATINGS ON BIOLOGICAL CELLS

University of Melbourne, F. Caruso et al.

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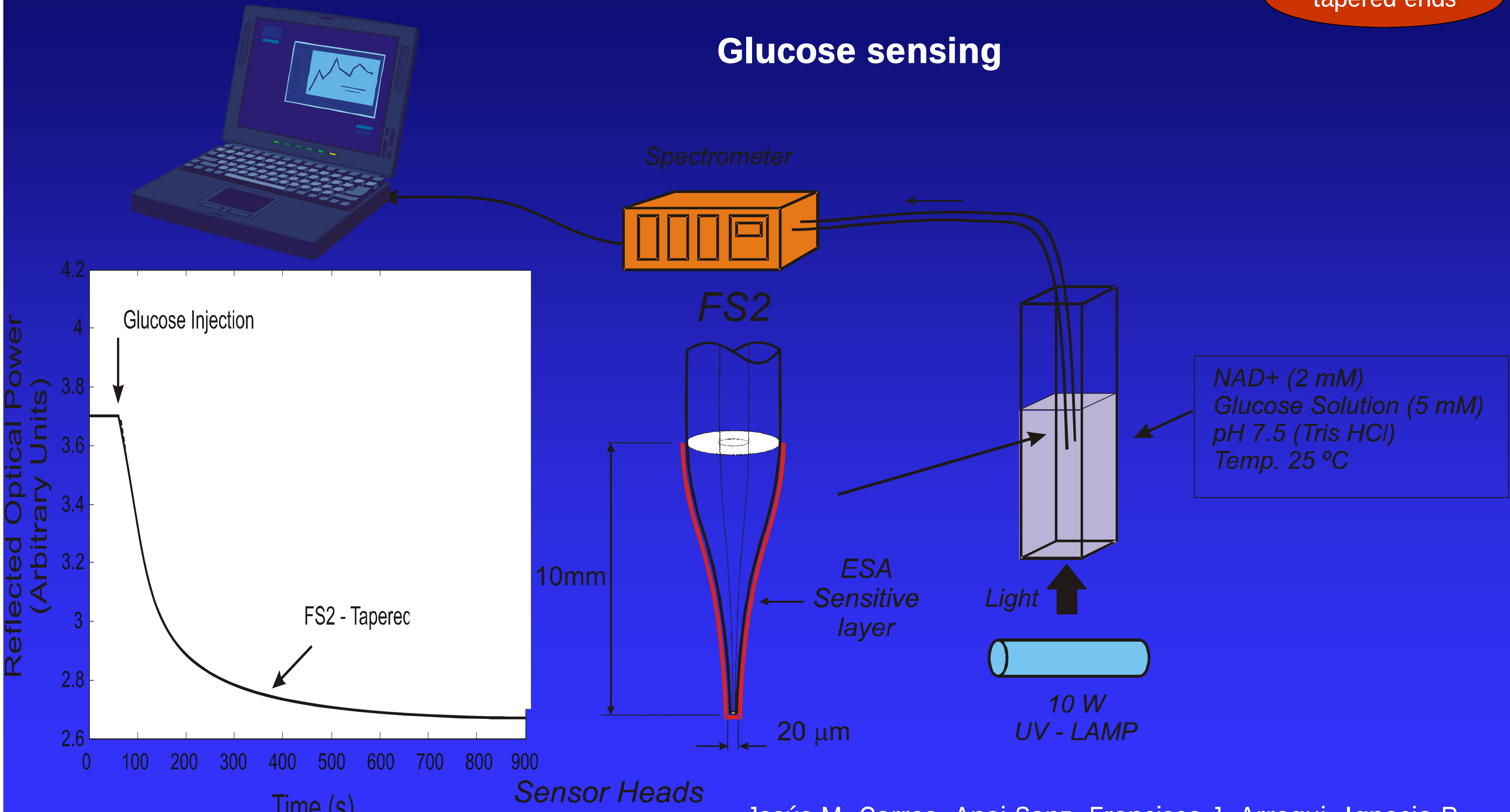
Nanostructured coatings onto tapered ends of optical fibers

tapered ends

Glucose sensing



Jesús M. Corres, Anai Sanz, Francisco J. Arregui, Ignacio R. Matías and Joaquín Roca. "Fiber optic glucose sensor based on bionanofilms". *Sensors and Actuators B. Not publiseh yet*

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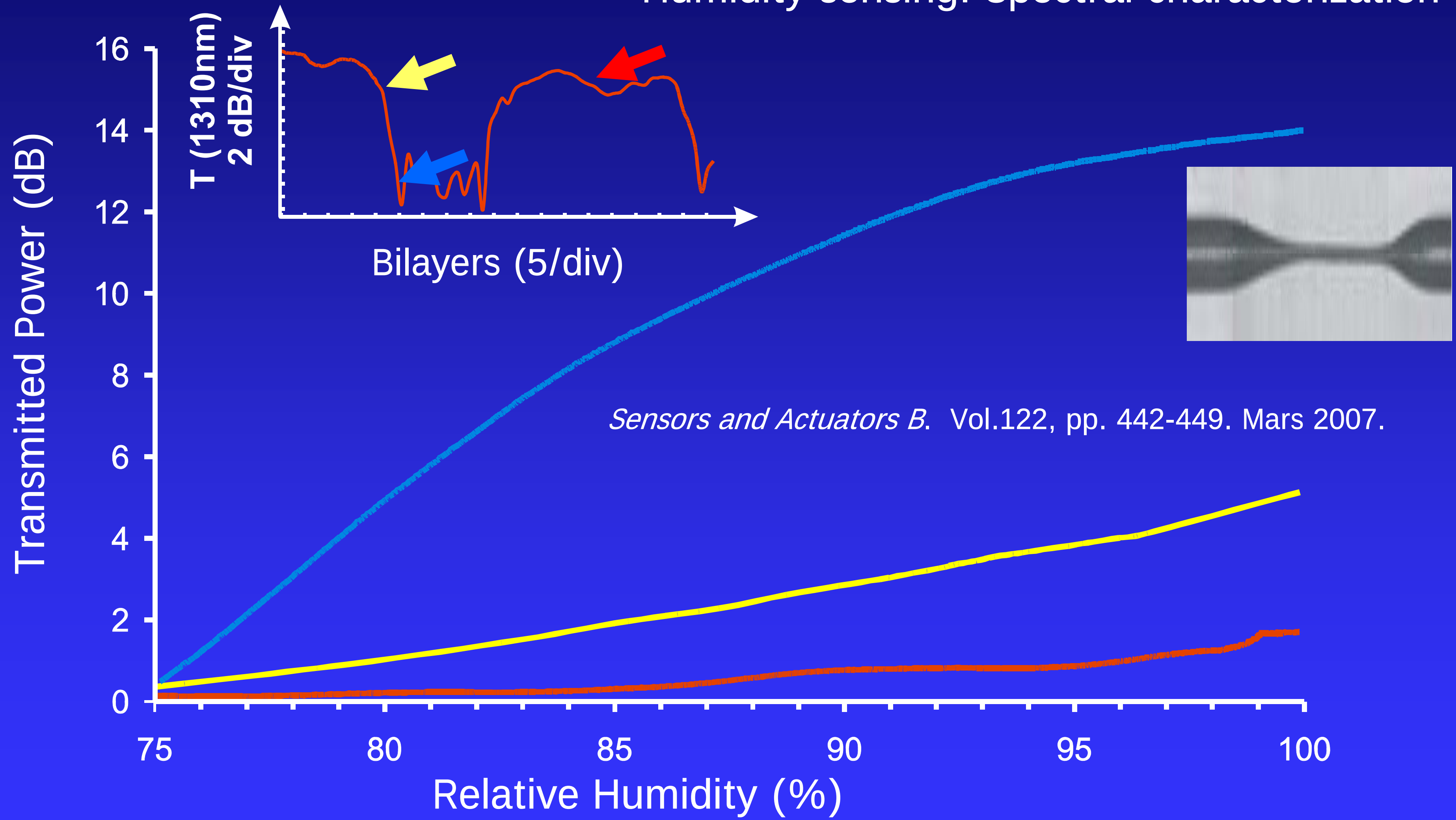
Sensors based on Tapered Optical Fibers

TOF

Humidity sensing. Spectral characterization

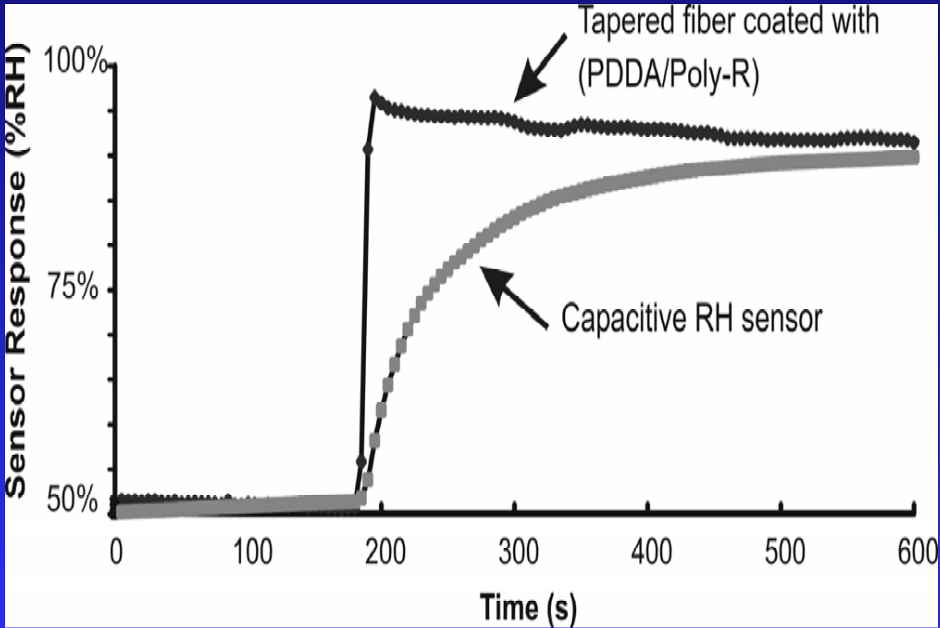


Sensors and Actuators B. Vol.122, pp. 442-449. Mars 2007.

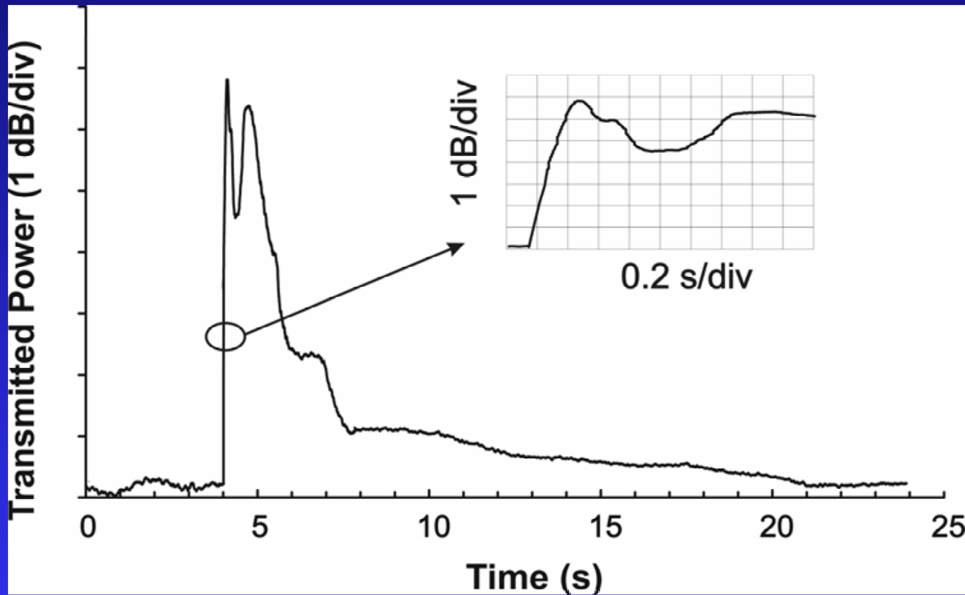
Experimental response of a 20m waist diameter TOF-based humidity sensors to RH corresponding to three working points of coating thicknesses: 23, 26 and 62 bilayers

Sensors based on Tapered Optical Fibers

Humidity sensing. Response time



Humidity response time compared to a commercial one
(*Blue box humidity sensor T12000/6, from Philip Harris*)



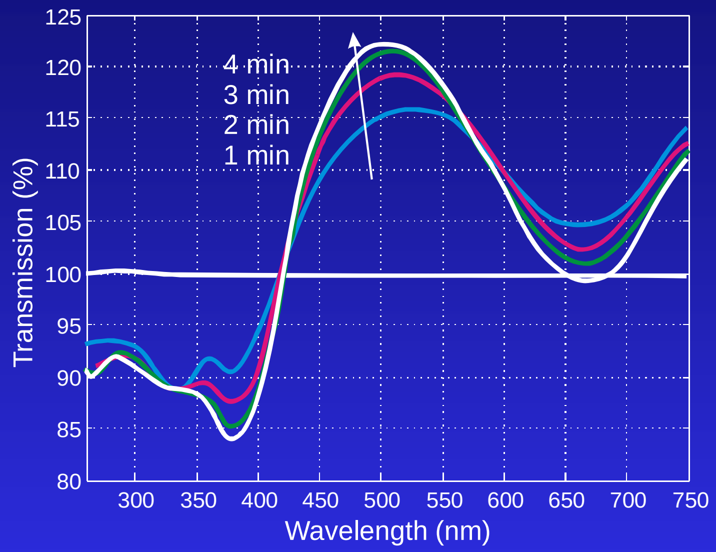
Experimental response to the human breath

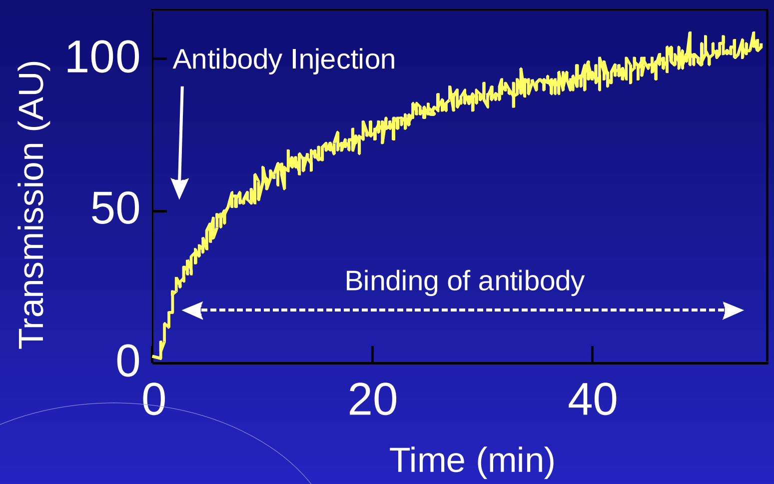
J. M. Corres, F. J. Arregui and Ignacio R. Matias. “Design of Humidity Sensors based on Tapered Optical Fibers”. *IEEE Journal of Lightwave and Technology* vol. 24 (11); pp.4329-4336 . Nov. 2006

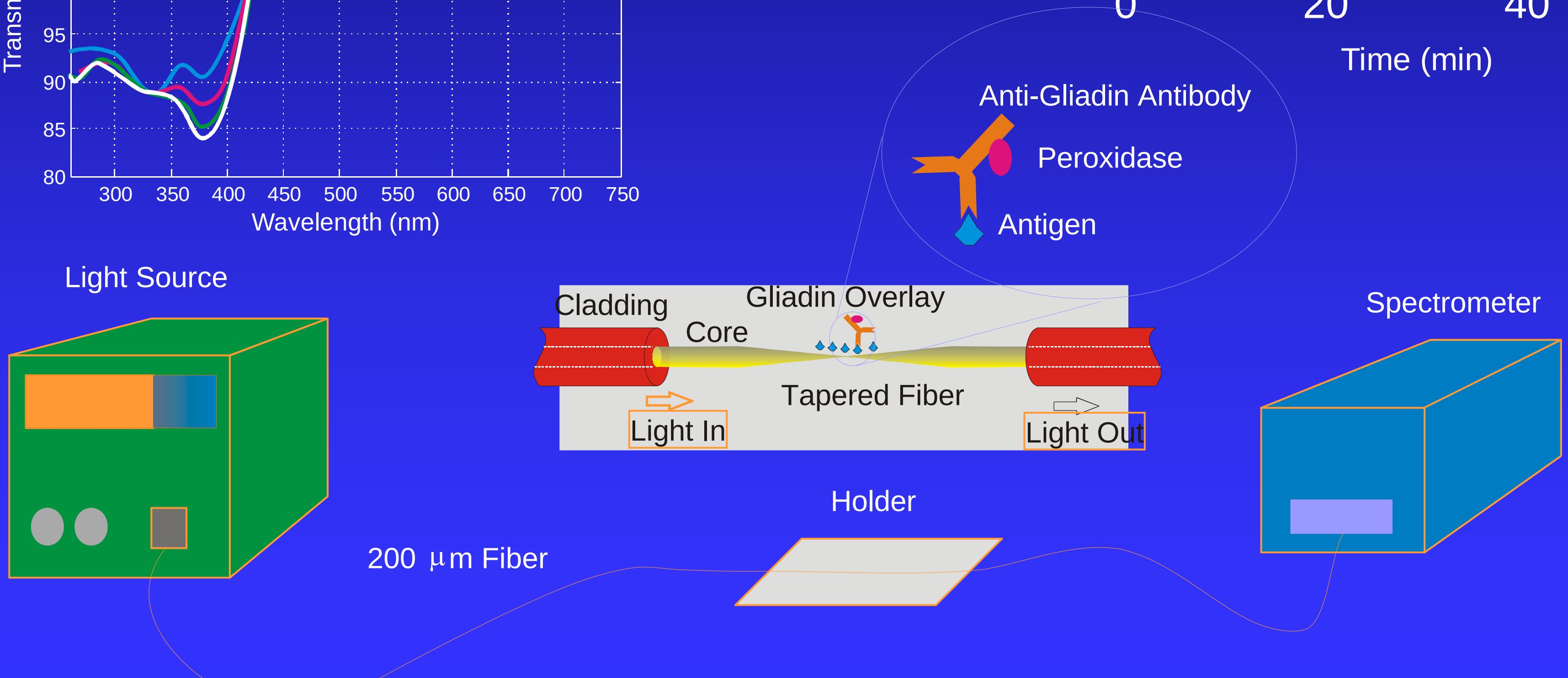
Novel fiber optic sensing architectures based on sensitive nanofilms

Sensors based on Tapered Optical Fibers

Gliadin sensing (gluten detection)







Tapered Optical Fiber Biosensor for the Detection of Anti-Gliadin Antibodies” . IEEE Sensors Conference 2007.

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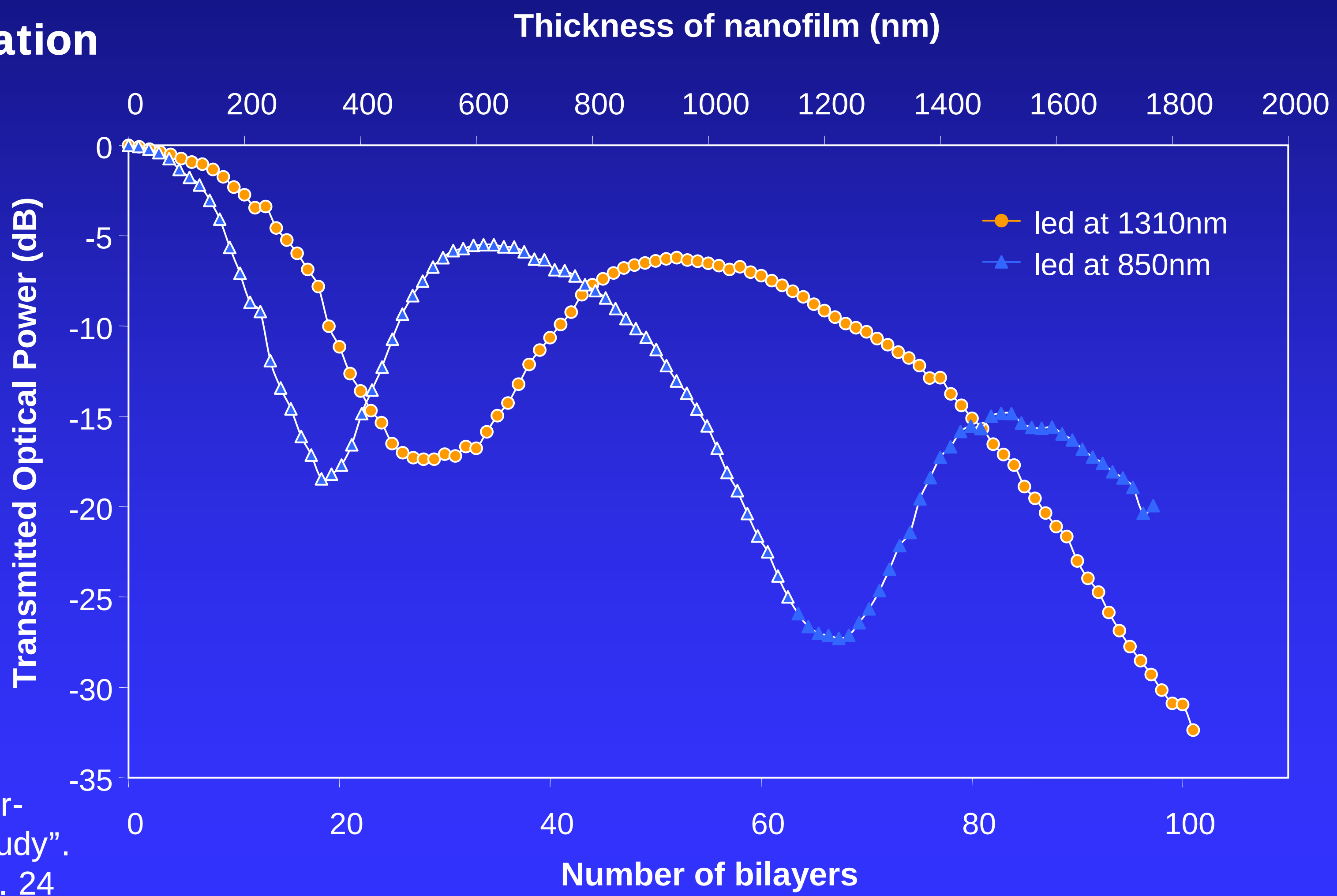
HCF

Sensors based on Hollow core fibers

Humidity sensing based on evanescent wave

Spectral characterization

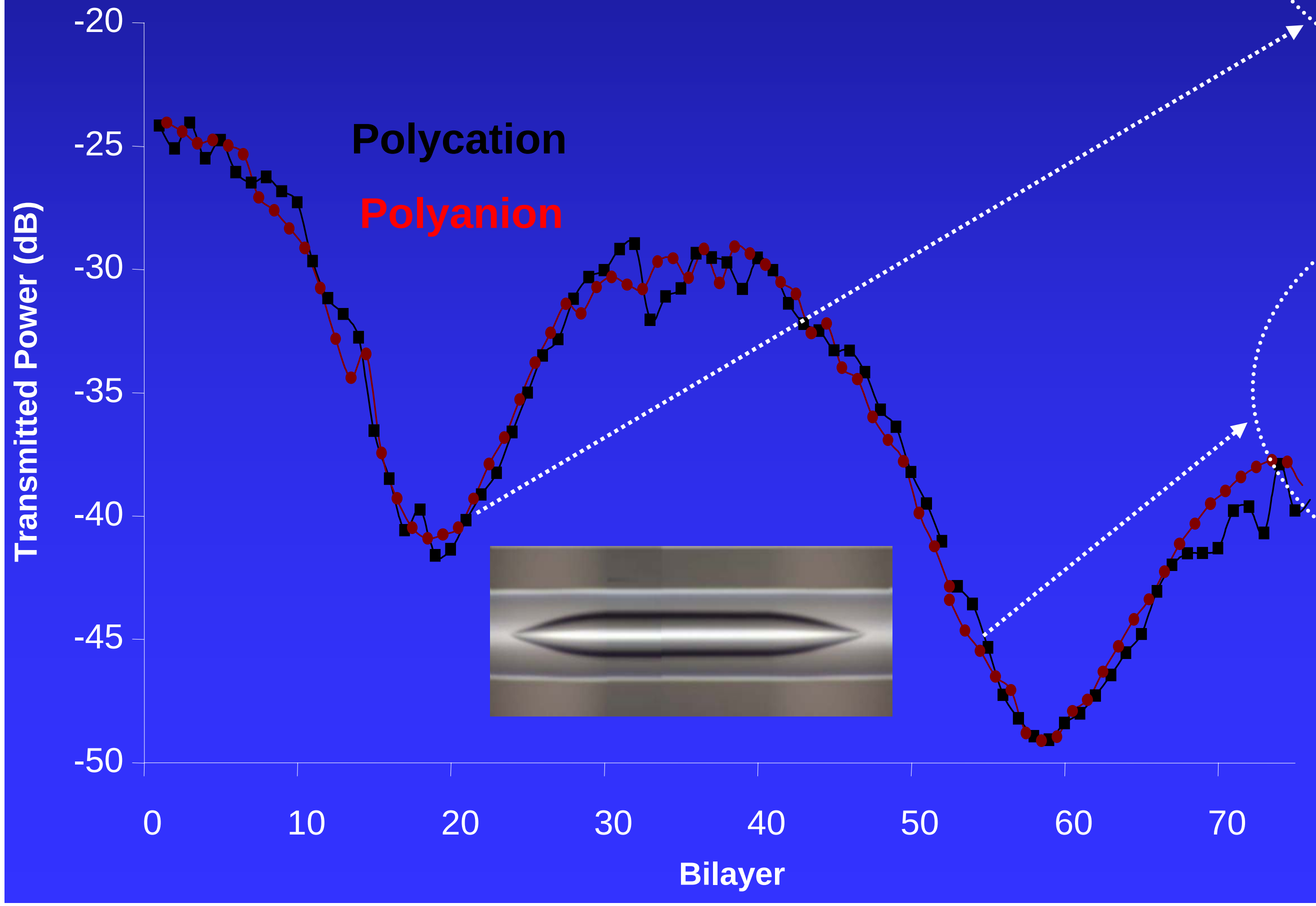


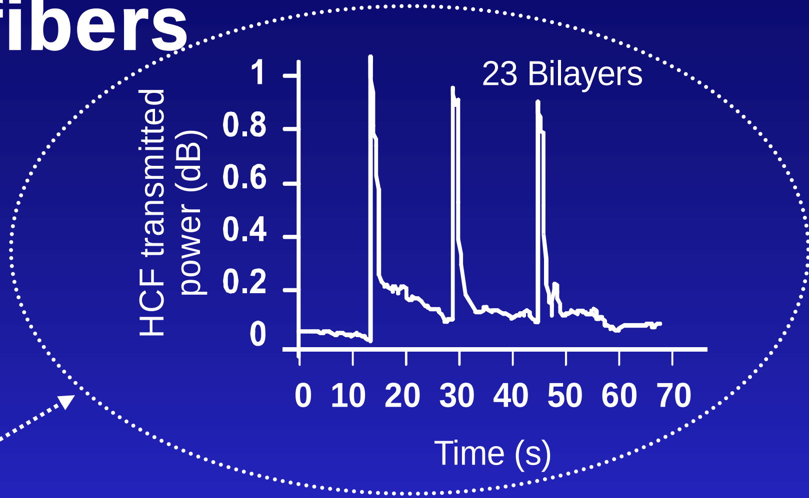
“Nanofilms on hollow core fiber-based structures: an optical study”. *IEEE J. of Light. and Tech.* Vol. 24 (5); pp. 2100-2107. May 2006

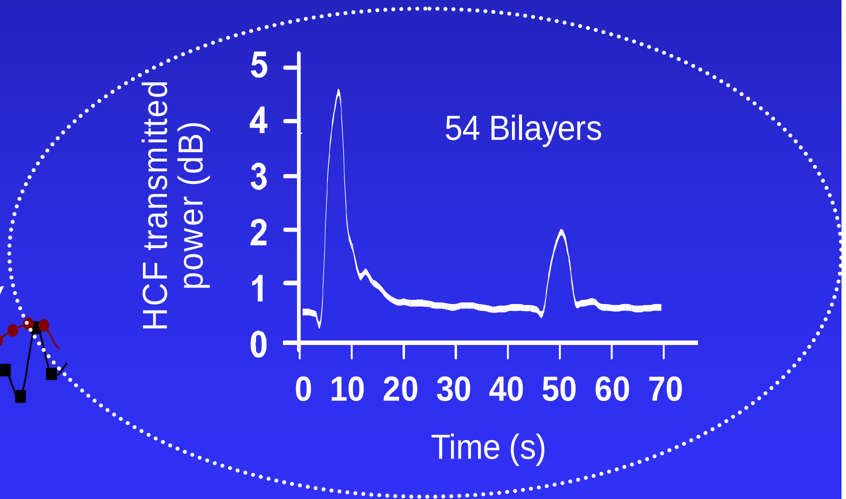
Sensors based on Hollow core fibers

Humidity sensing based on evanescent wave

breathing monitoring







Ignacio R. Matías et al. “Nanofilms onto a hollow core fiber”. *Opt. Eng. Letters.* Vol. 45 (5); 050503. May 2006

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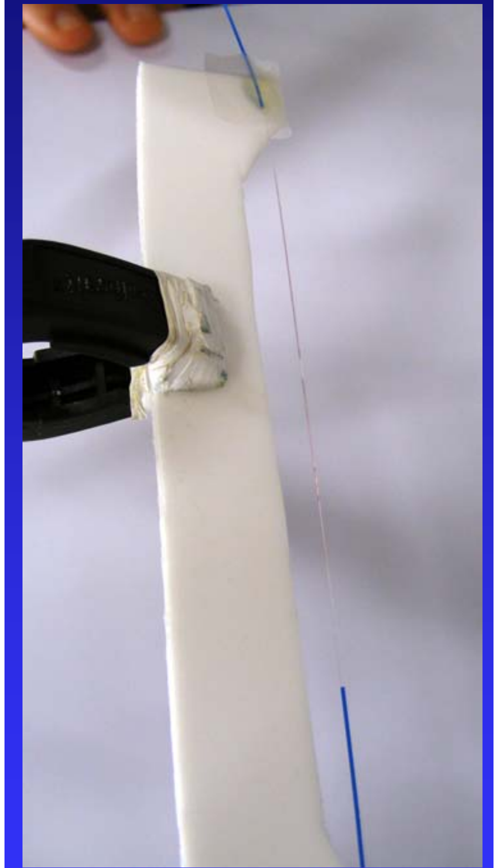
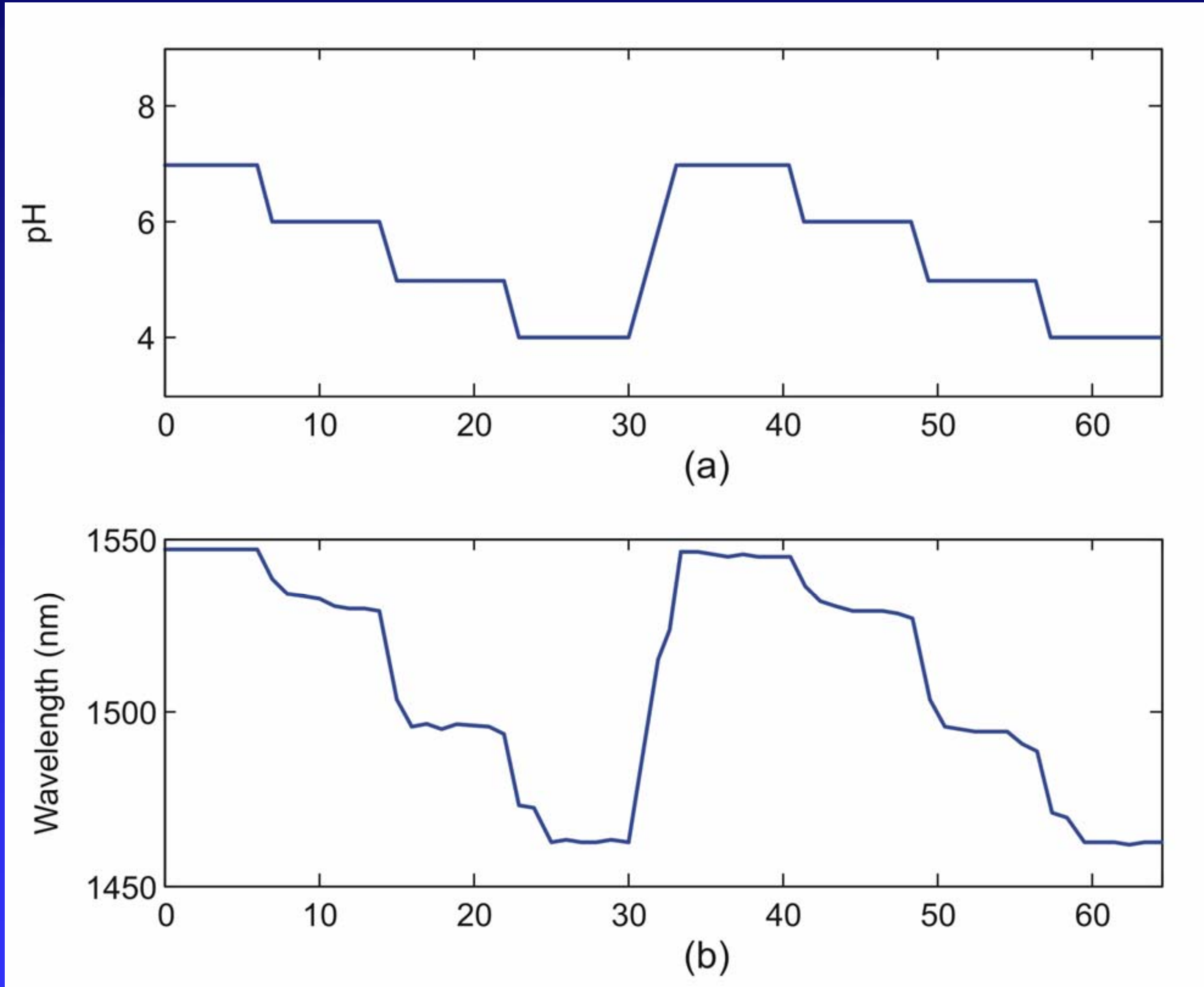
Nanostructured coatings on Long Period Gratings: a pH sensor

LPG overlays





Optical response of one of the attenuation bands of a LPG coated with [PAH/PAA] coatings when is submitted to pH changes

J. M. Corres, I. Del Villar, I. R. Matias, F. J. Arregui, Optics Letters, 32 (1), 29, 2007

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Optical fiber microgratings

gratings

Fabrication of Microgratings on the Ends of Standard Optical Fibers by the Electrostatic Self-Assembly Monolayer Process. *Optics Letters*, vol. 26 (3); pp. 131-133, 2001.

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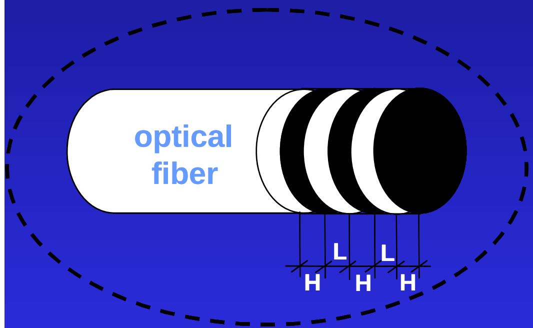
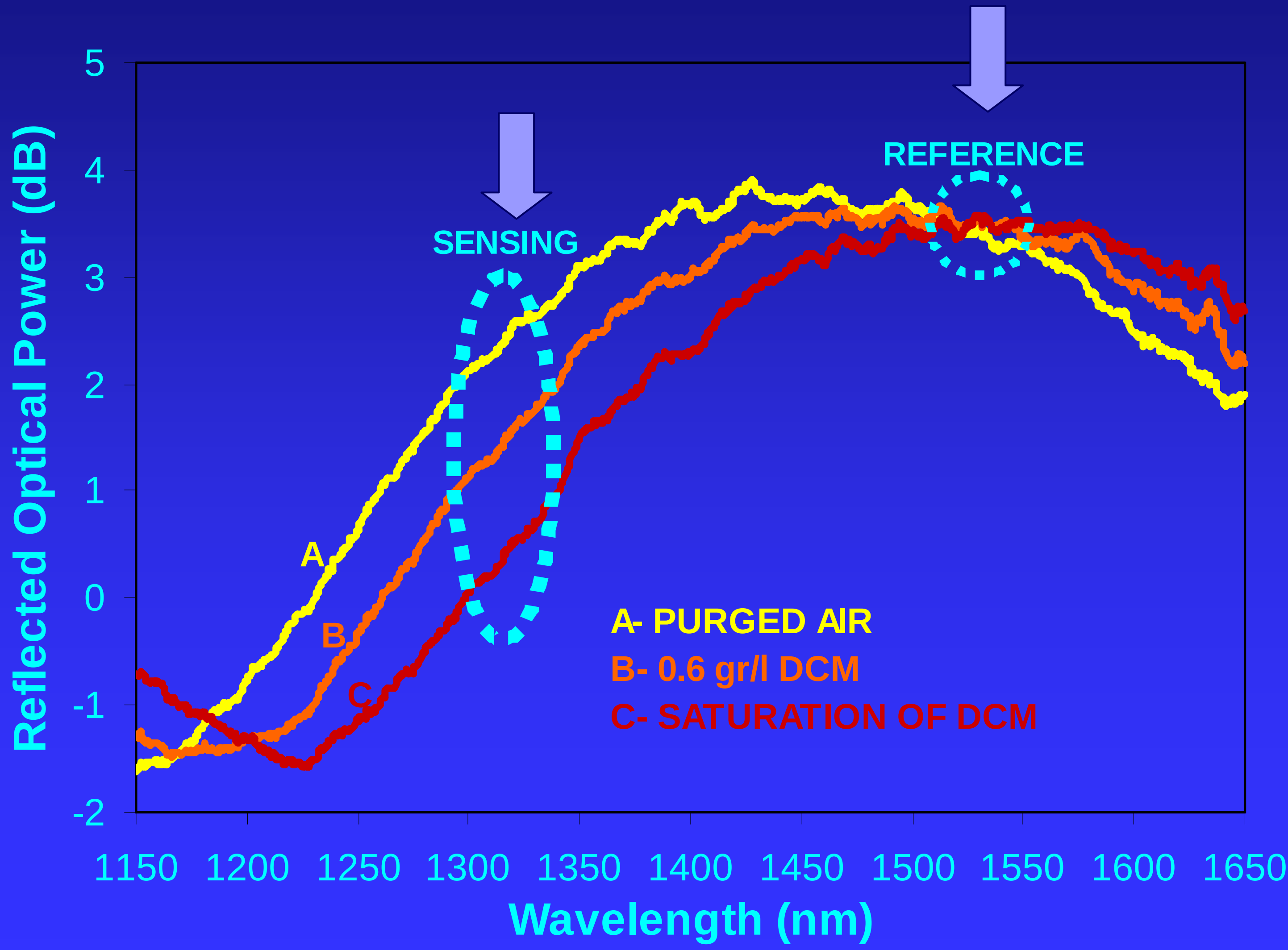
gratings

EXPERIMENTAL RESULTS -VOLATILE ORGANIC COMPOUND SENSOR
DICHLOROMETHANE (DCM)

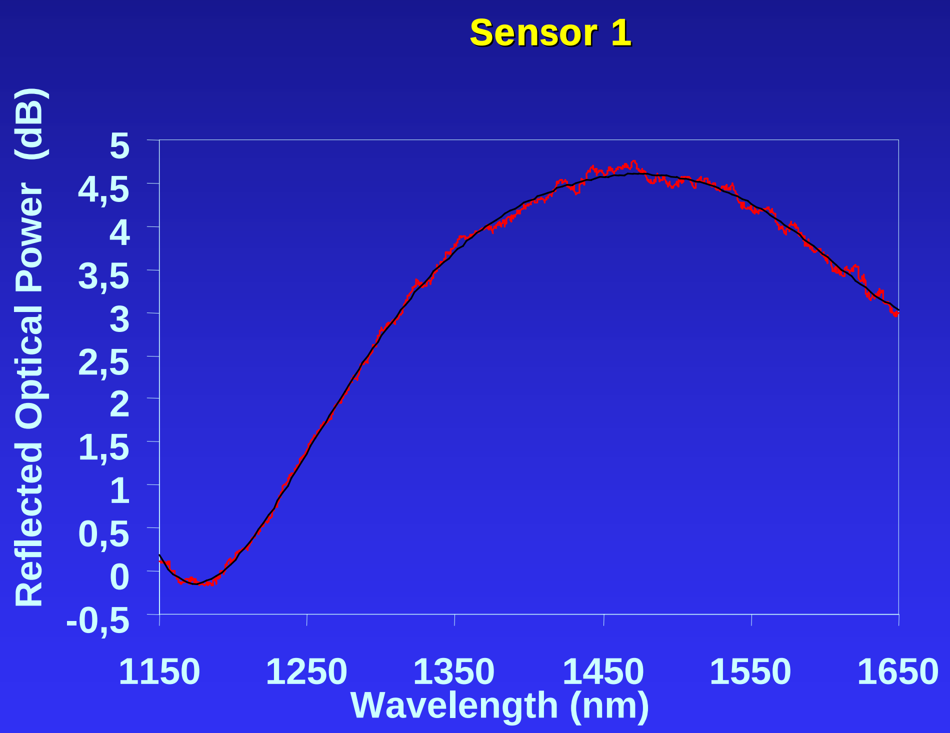
micrograting

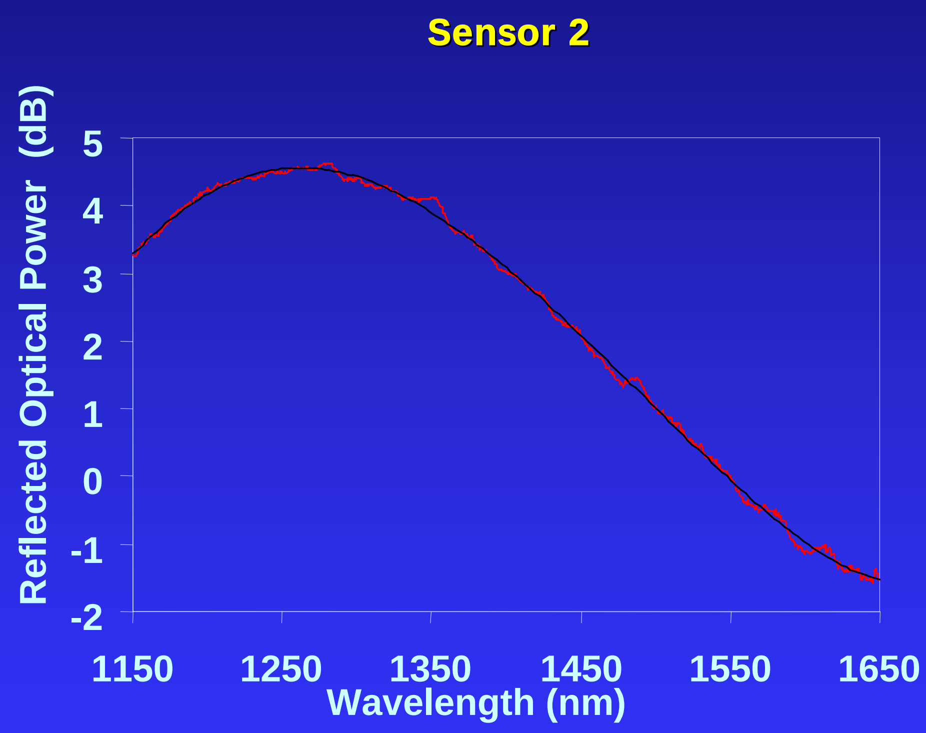




gratings

Different spectral responses



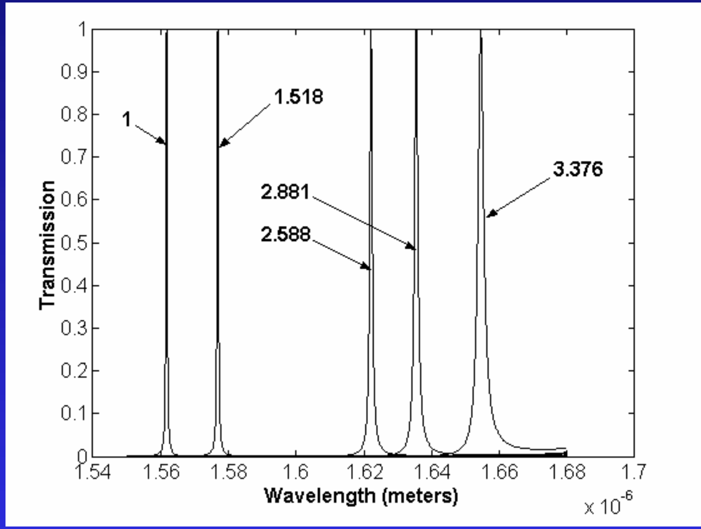


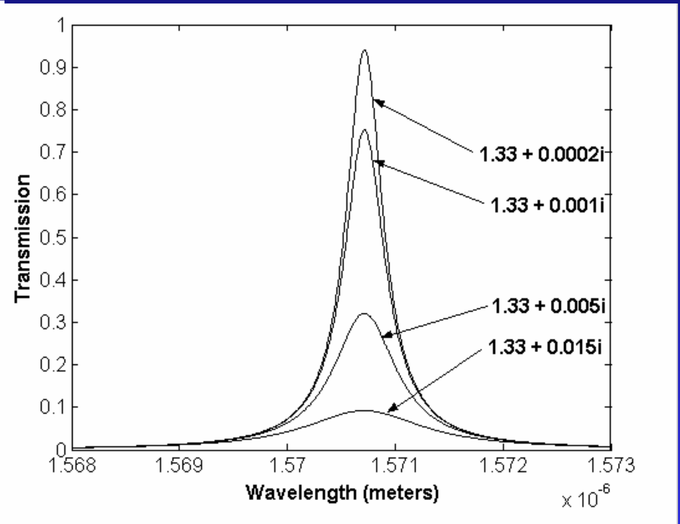
F. J. Arregui, Richard O. Claus, Kristie L. Cooper, Carlos Fdez-Valdivielso and Ignacio R. Matías. "Optical Fiber Gas Sensor Based on Self-Assembled Microgratings". *IEEE Journal of Lightwave Technology,* vol. 19 (12); pp. 1932-1937, 2001.

1D PBG with defects

others

Refractometer





Optics Letters. 28 (13), pp. 1099-1101, 2003

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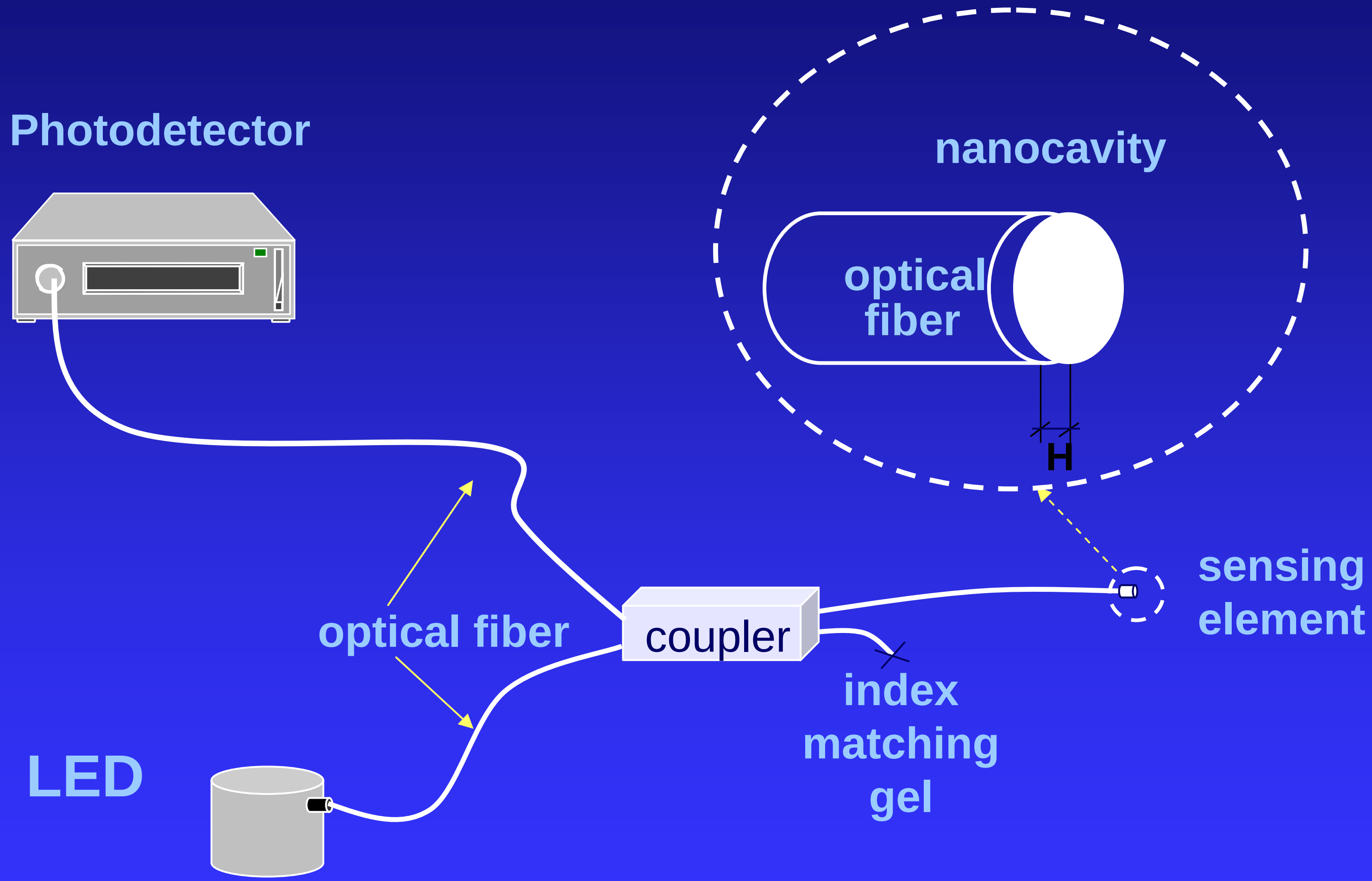
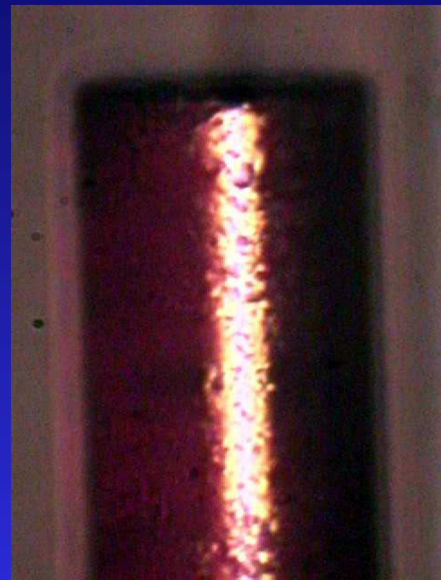
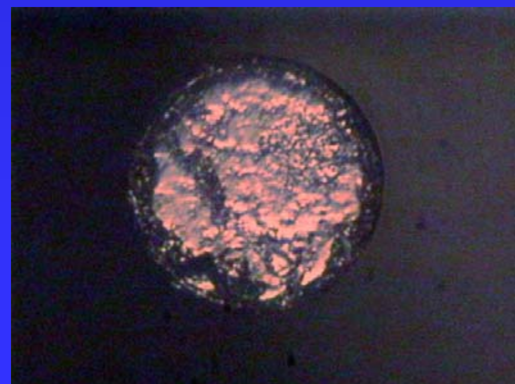
NFP Cavities. Experimental set-up

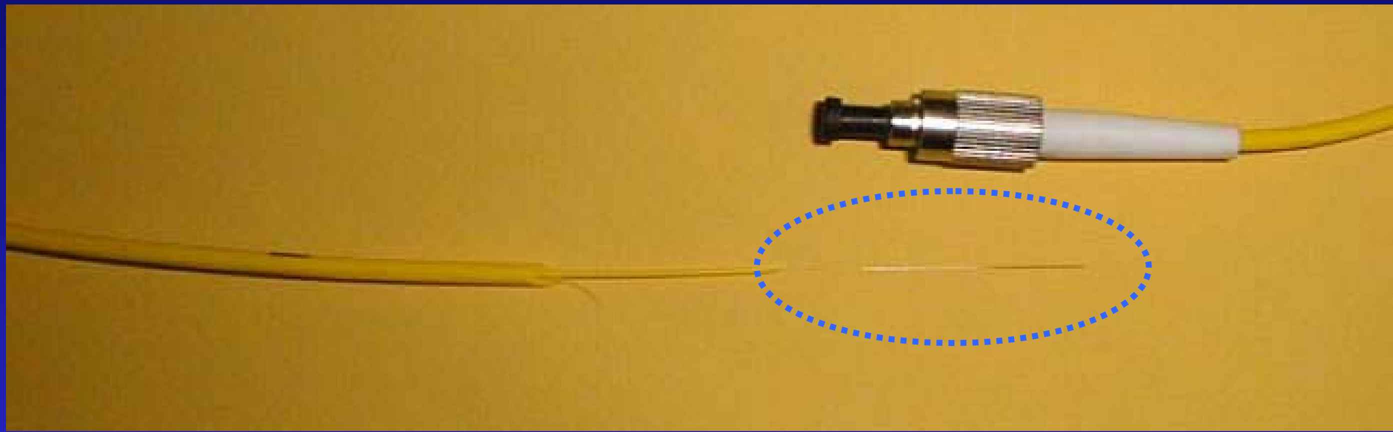






nanoFabry-Perots

Novel fiber optic sensing architectures based on sensitive nanofilms



nanoFabry-Perots

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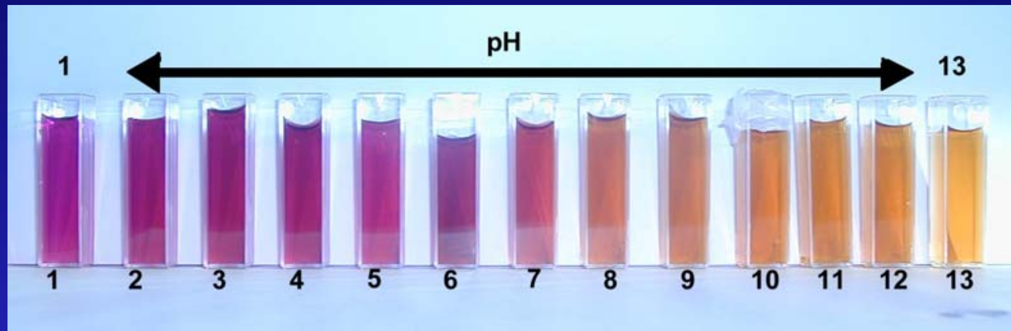
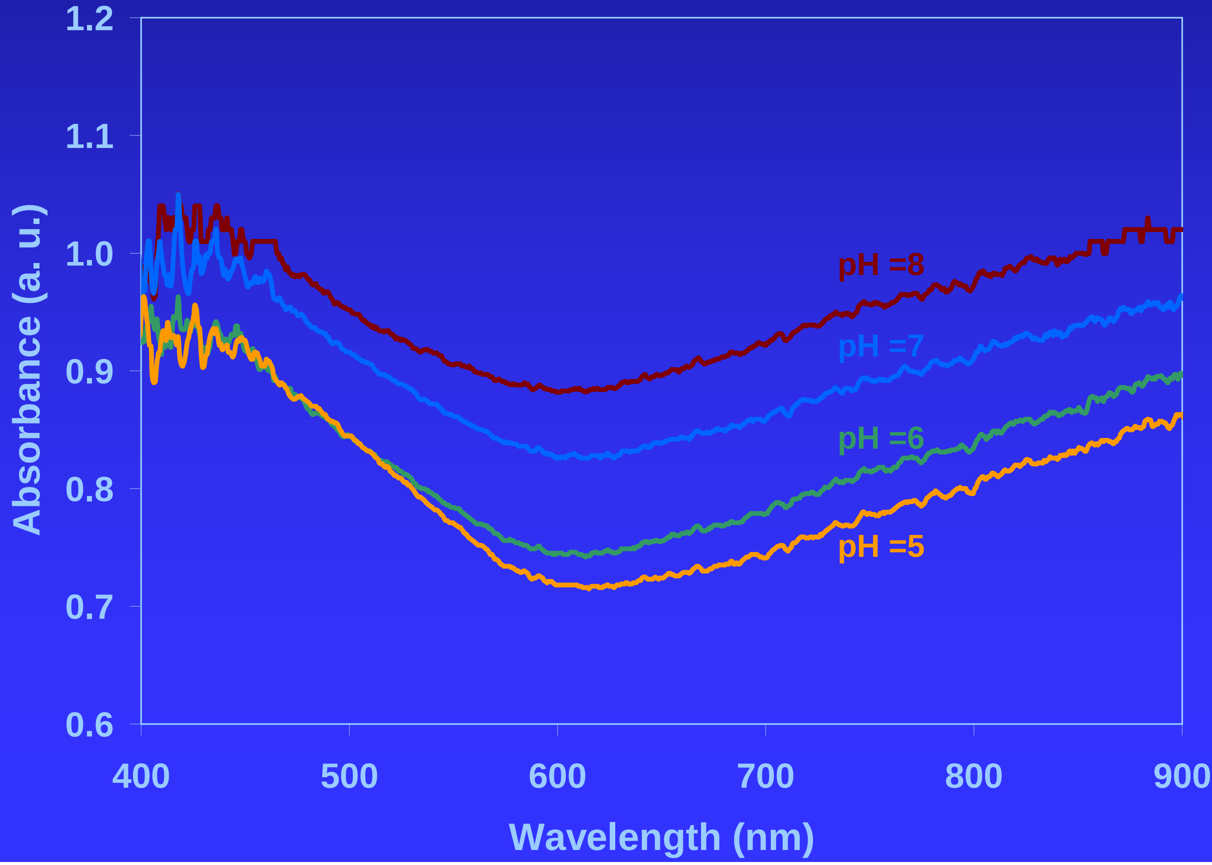
NFP Cavities. pH Sensors

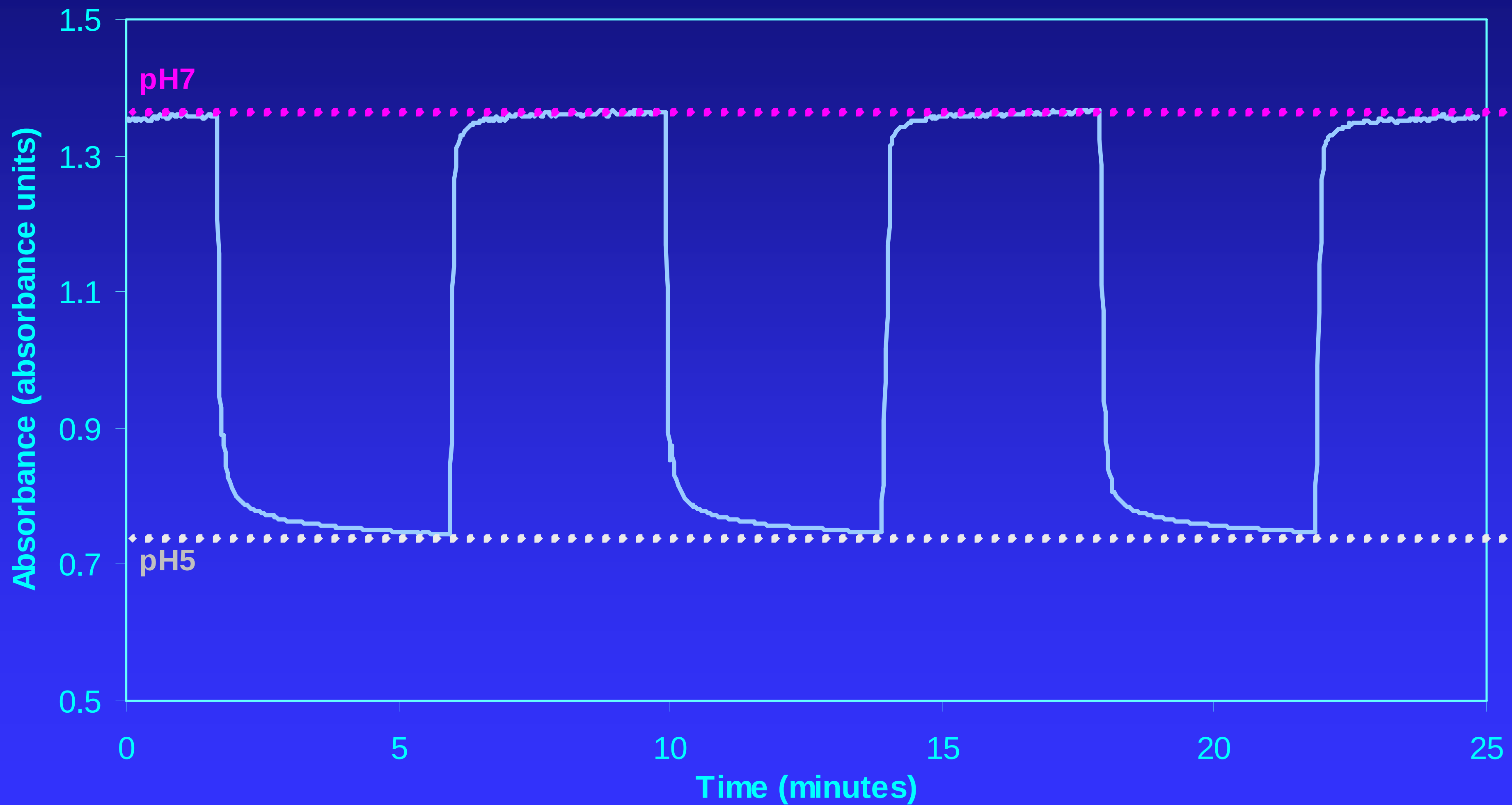




nanoFabry-Perots

Novel fiber optic sensing architectures based on sensitive nanofilms

NFP Cavities. pH Sensors



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NFP Cavities. pH Sensors

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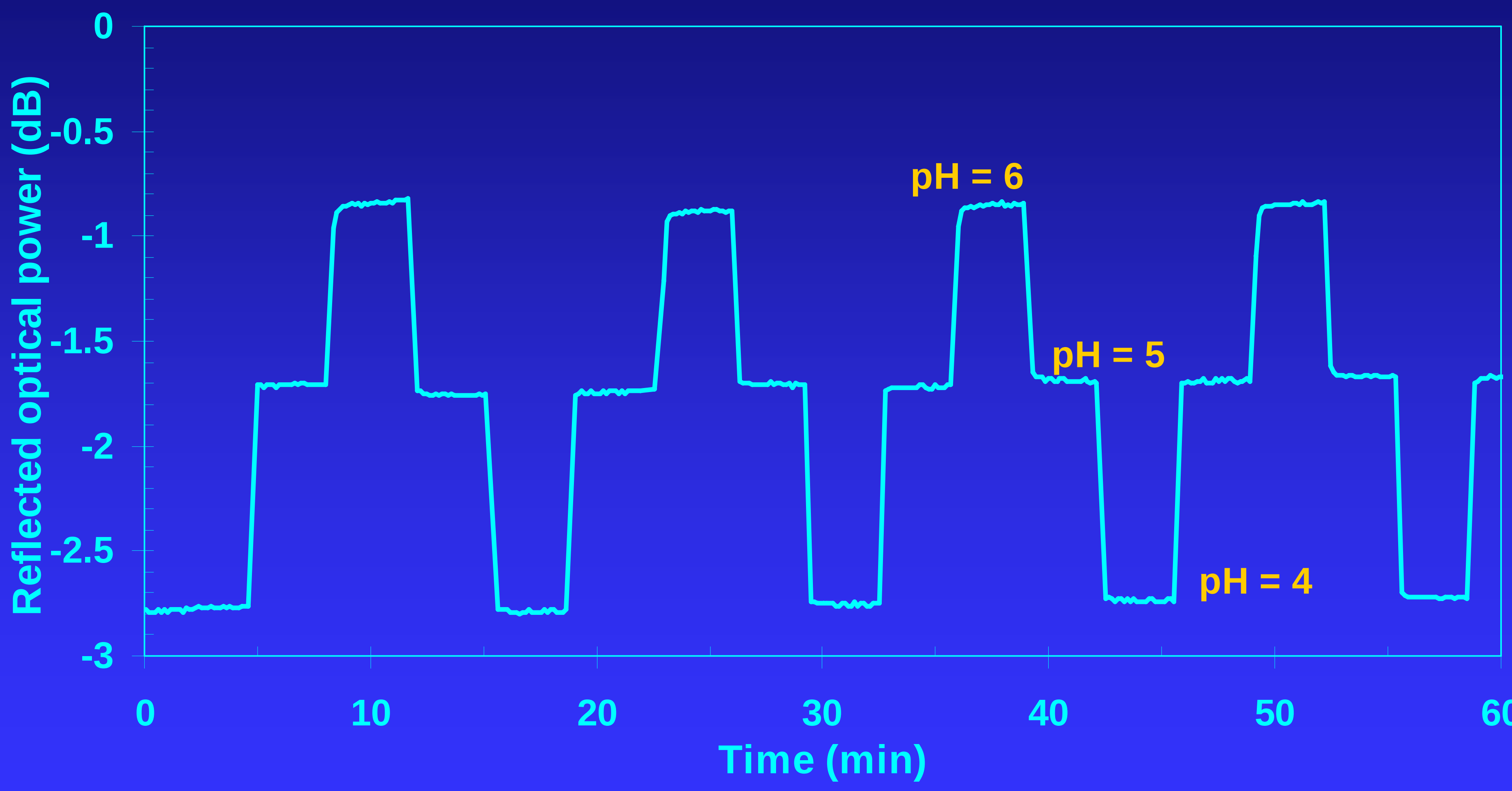
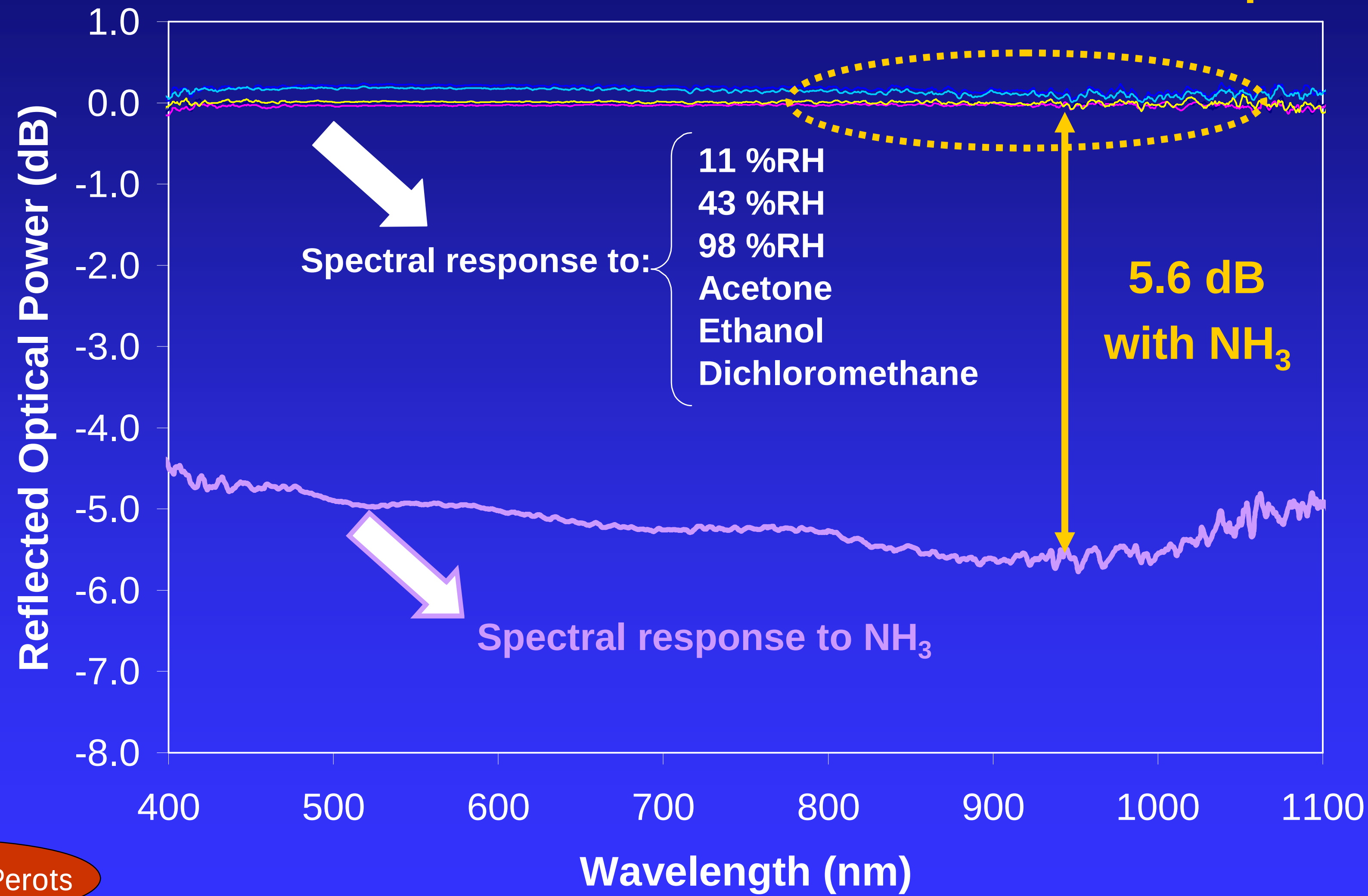


Novel fiber optic sensing architectures based on sensitive nanofilms

NFP Cavities. Ammonia sensors

< 4% of cross-sensitivity to other compounds



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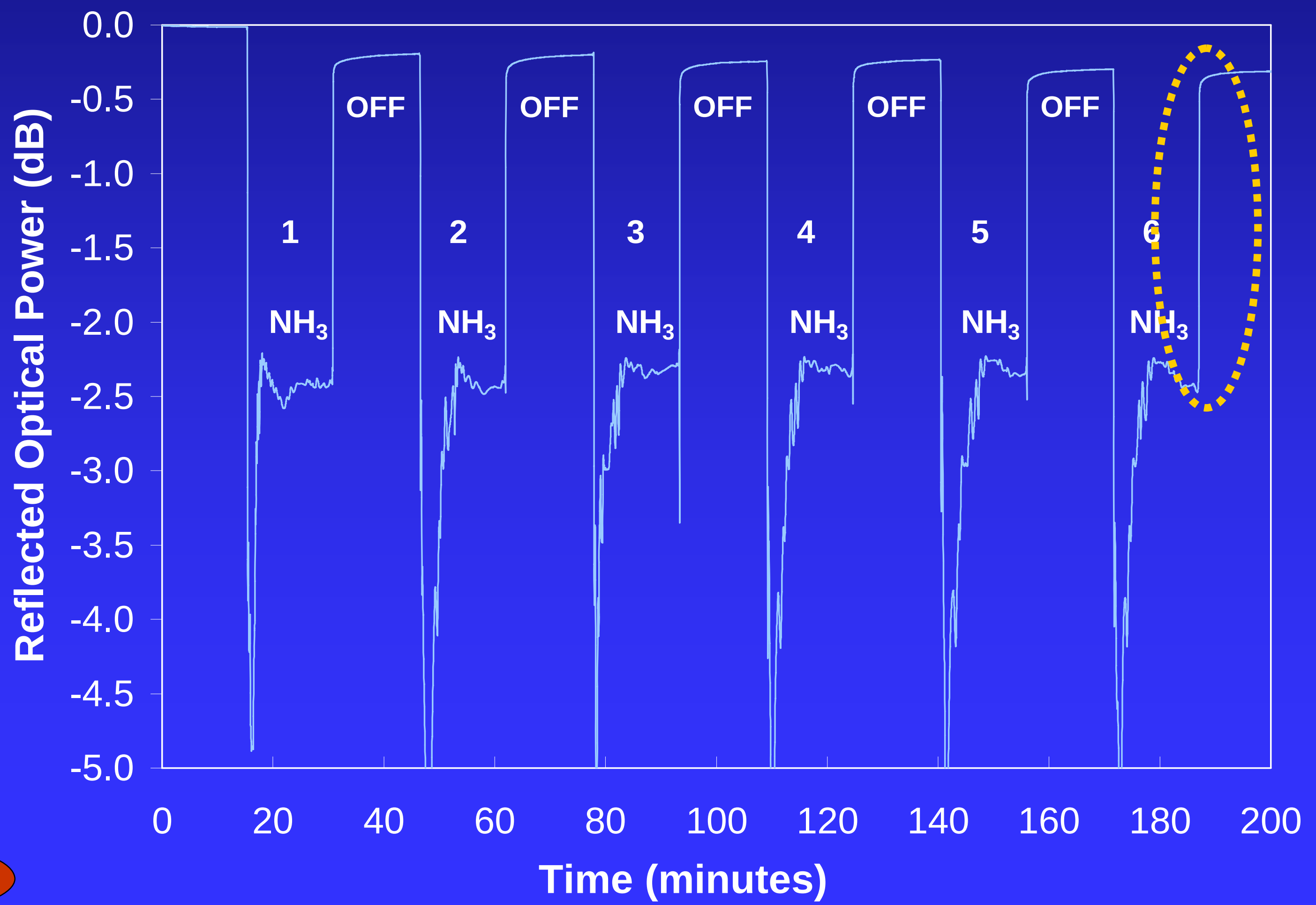
D. Galbarra, F. J. Arregui, I. R. Matias and R. O. Claus, Smart Materials and Structures, 14 (4), 2005

NFP Cavities. Ammonia sensors

Dynamic response of a 25 bilayers sensor to Ammonia



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NFP Cavities. Ammonia sensors

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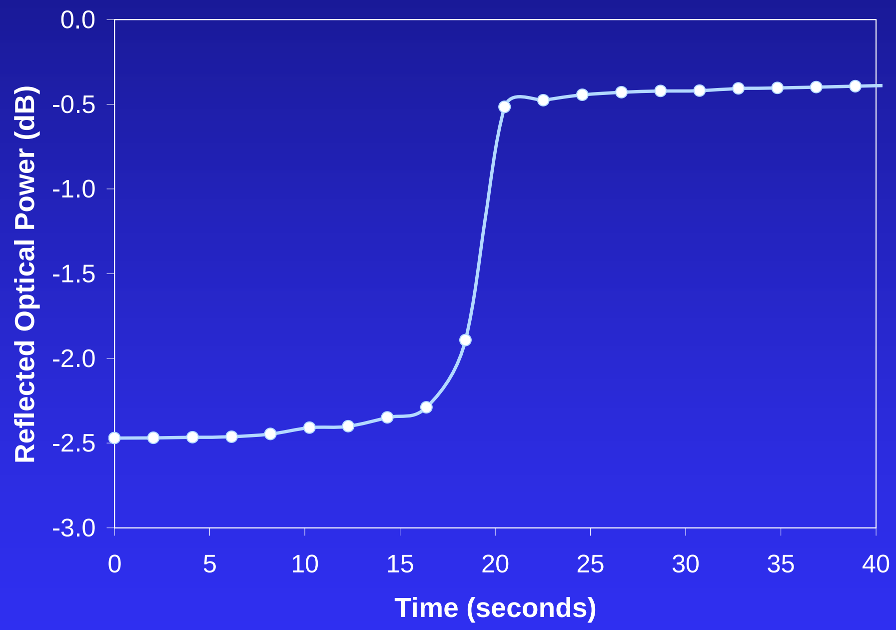
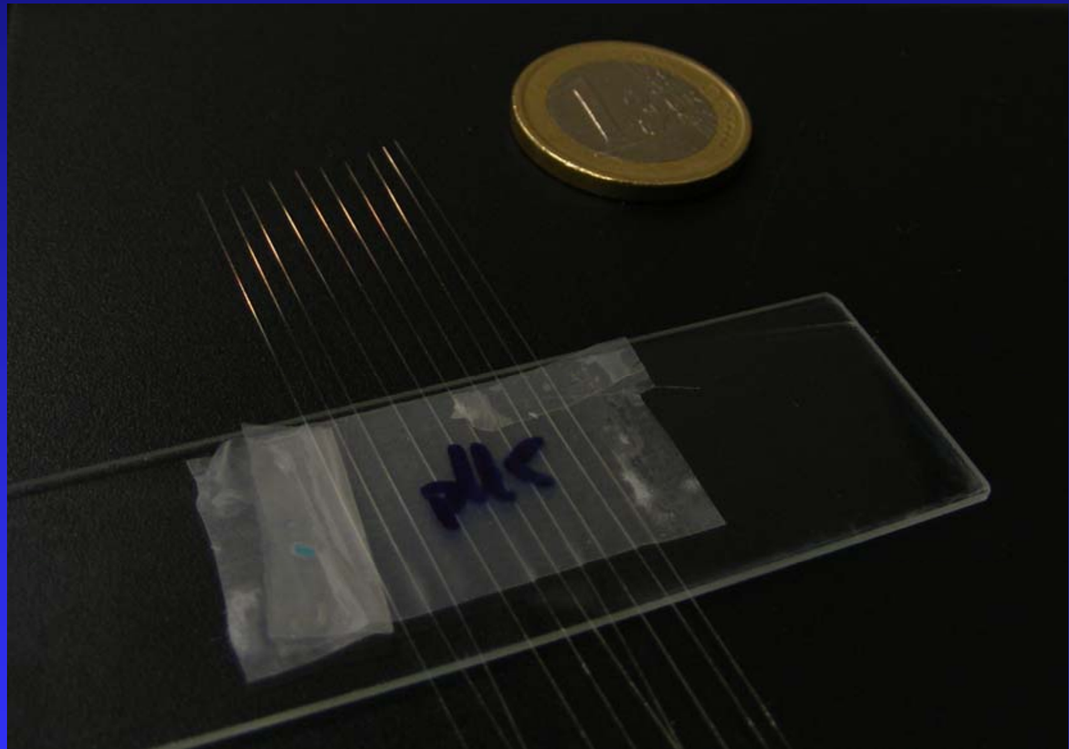
Recovery time < 4 seconds

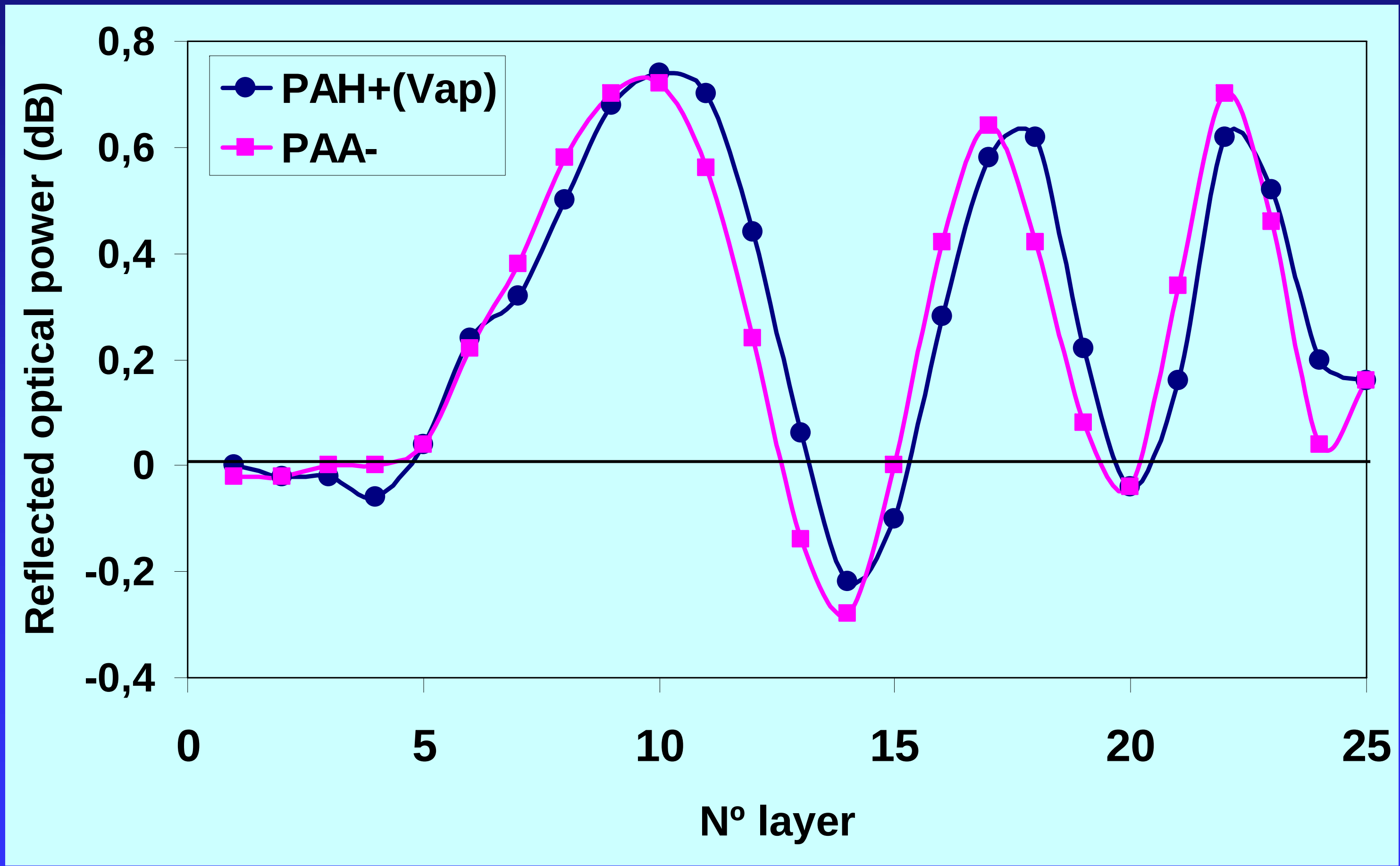




Smart Materials and Structures. Vol. 14; pp. 739-744, 2005.

NFP Cavities. Volatile organic compounds sensors

[Vap+PAH^+/PAA^-]



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Sensors and Actuators B. Vol. 115 (1); pp. 444-449, 2006

NFP Cavities. Volatile organic compounds sensors

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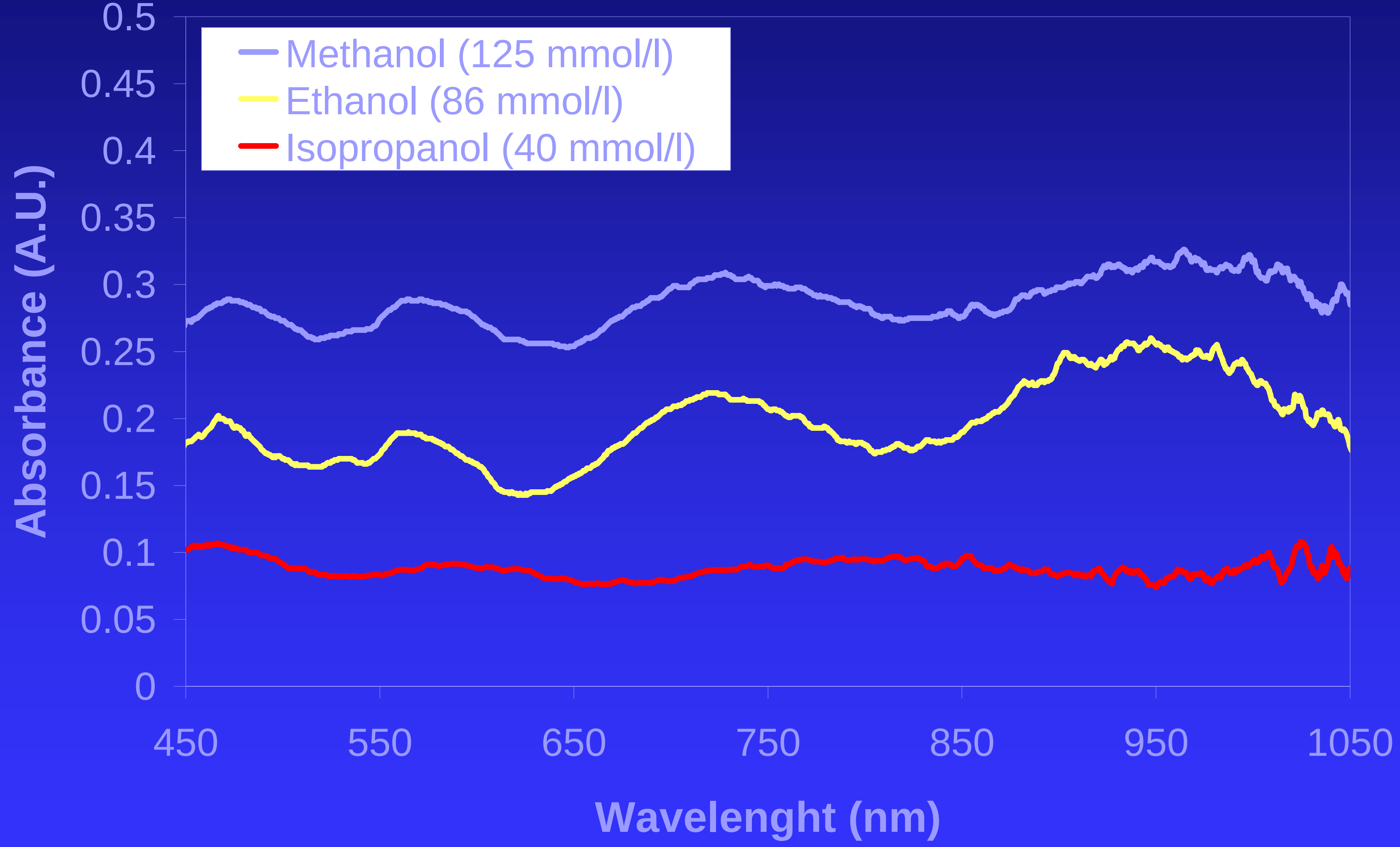

Absorbance spectra of the sensor after 40 minutes exposure

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NFP Cavities. Volatile organic compounds sensors

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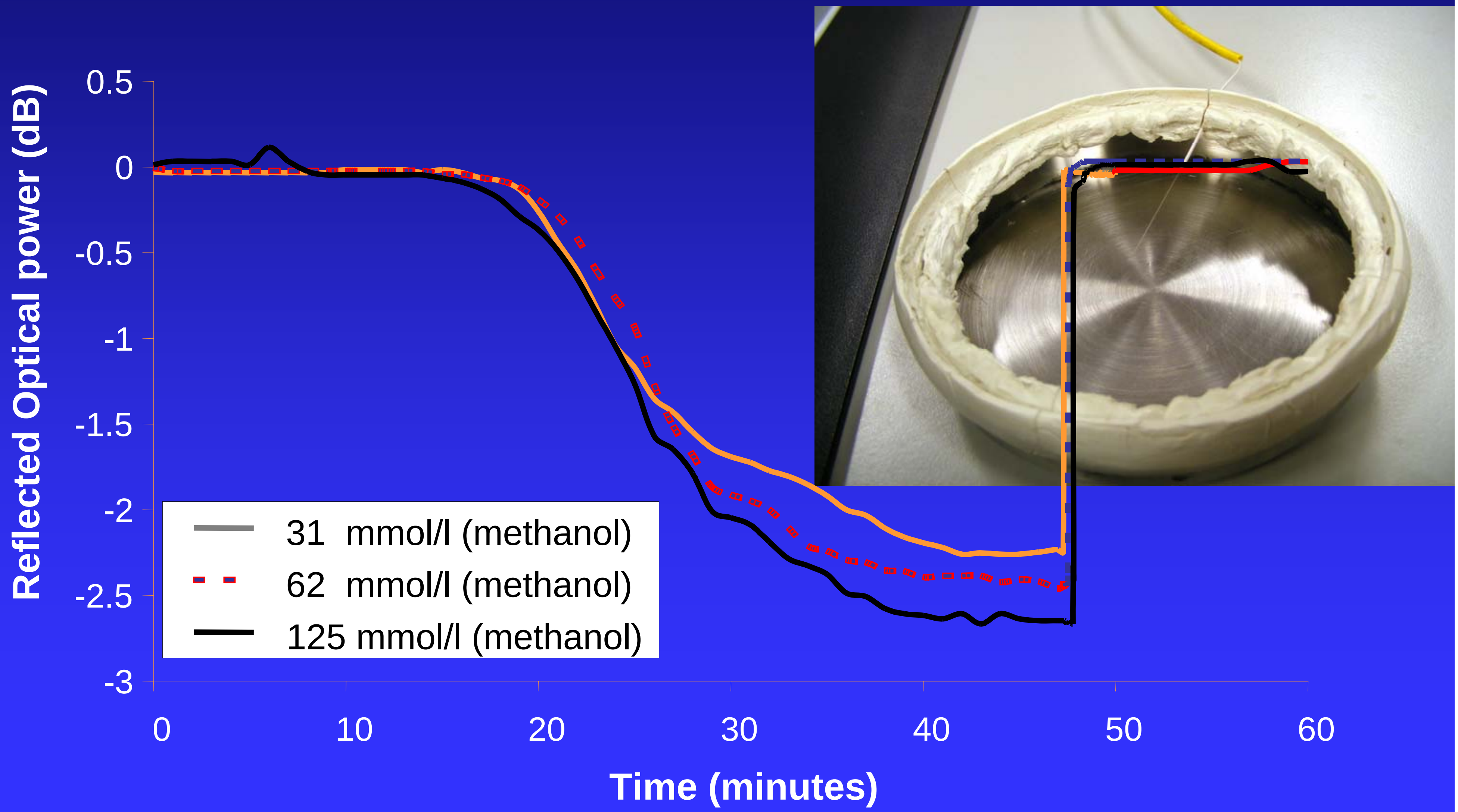
Response of the sensor for different methanol concentrations



Novel fiber optic sensing architectures based on sensitive nanofilms

NFP Cavities. Volatile organic compounds sensors

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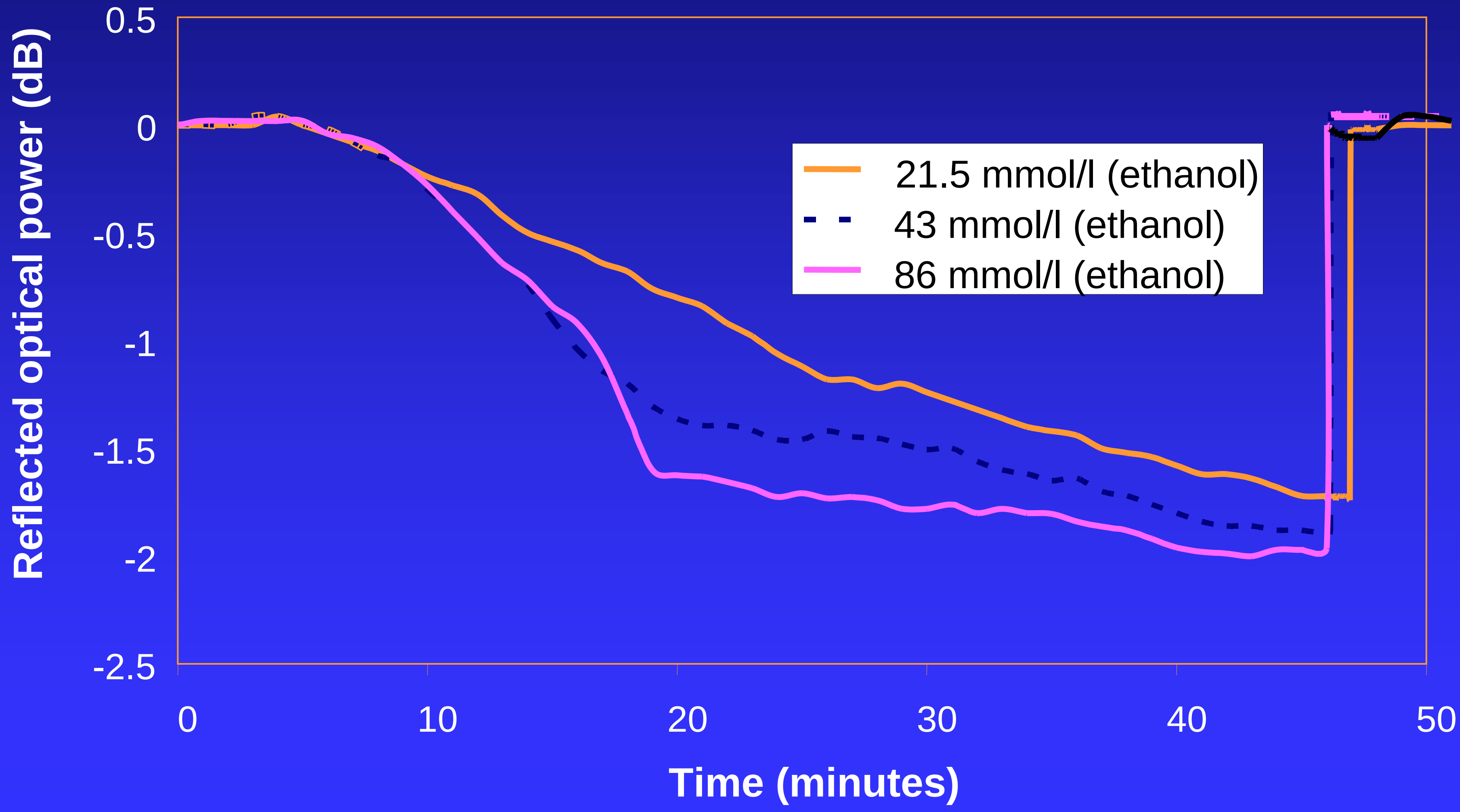
Response of the sensor for different ethanol concentrations



NFP Cavities. Volatile organic compounds sensors

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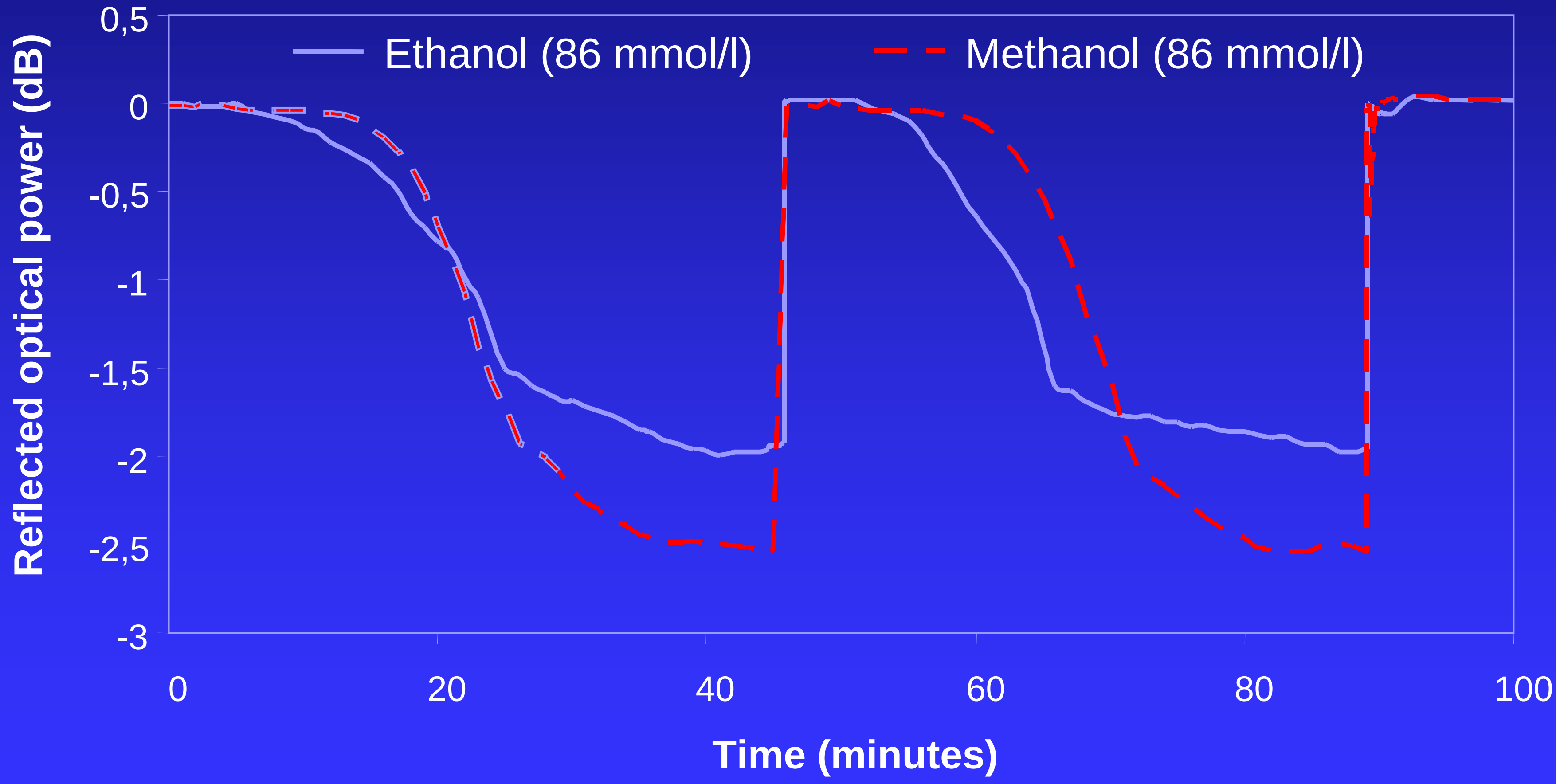
Comparison between ethanol and methanol



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NFP Cavities. Hydrogen peroxide sensor

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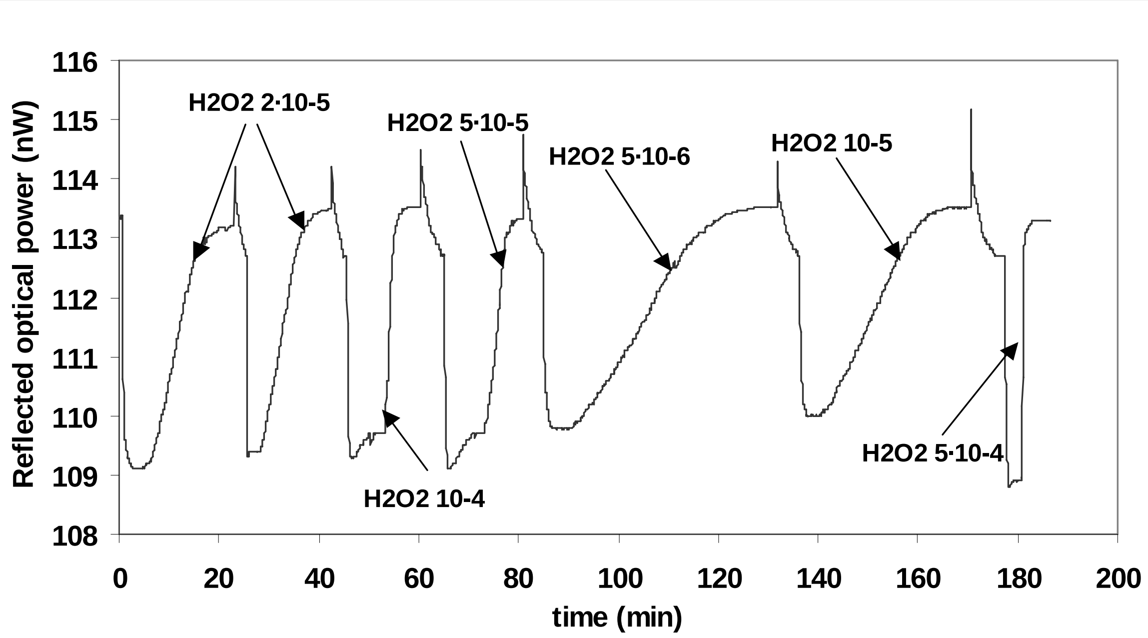
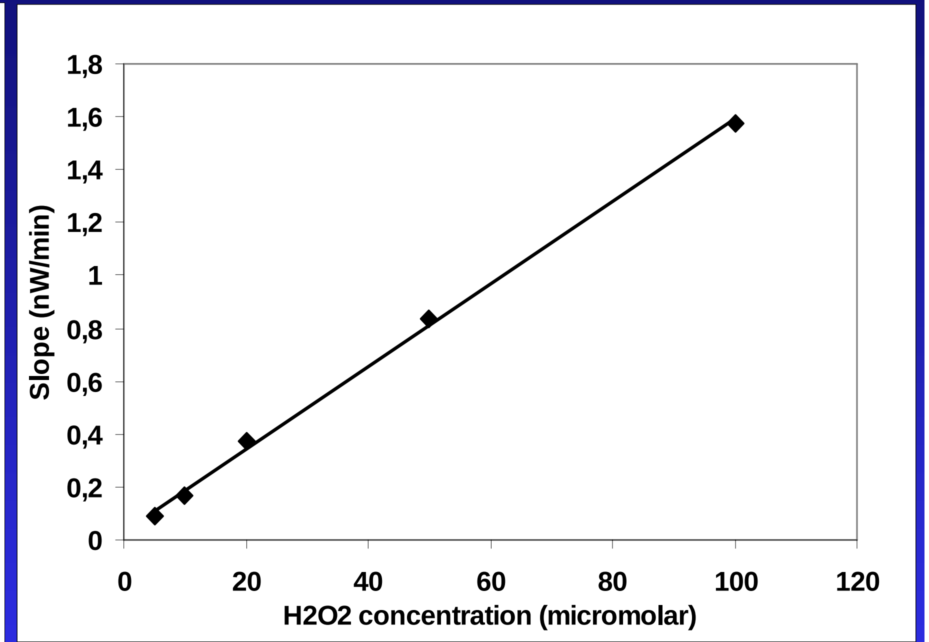
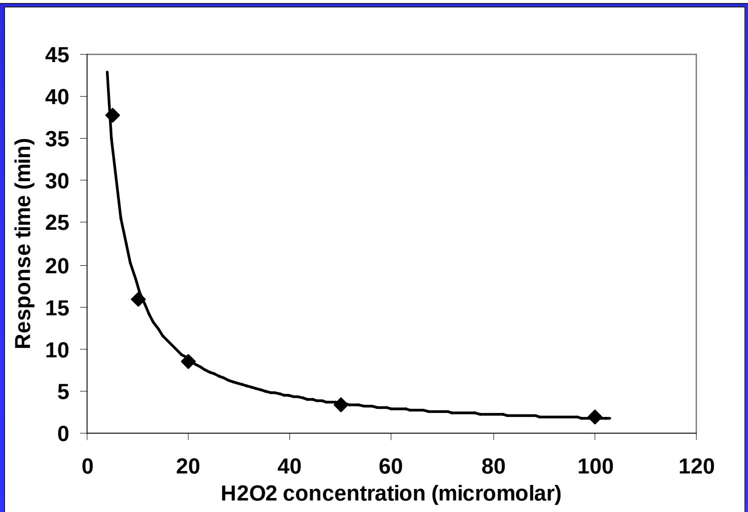






Response of the sensor for different concentrations of hydrogen peroxide at pH 4:

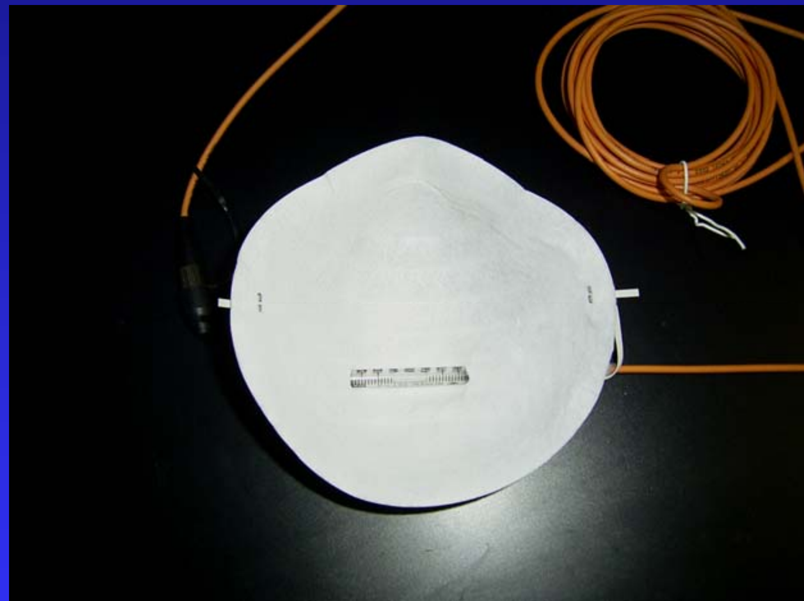
1.- Reflected optical power

2.- Slope of the change in the reflected power

3.- Response time

NFP Cavities. Human breathing

Sensor and opto-electronic units



Face mask and sensor

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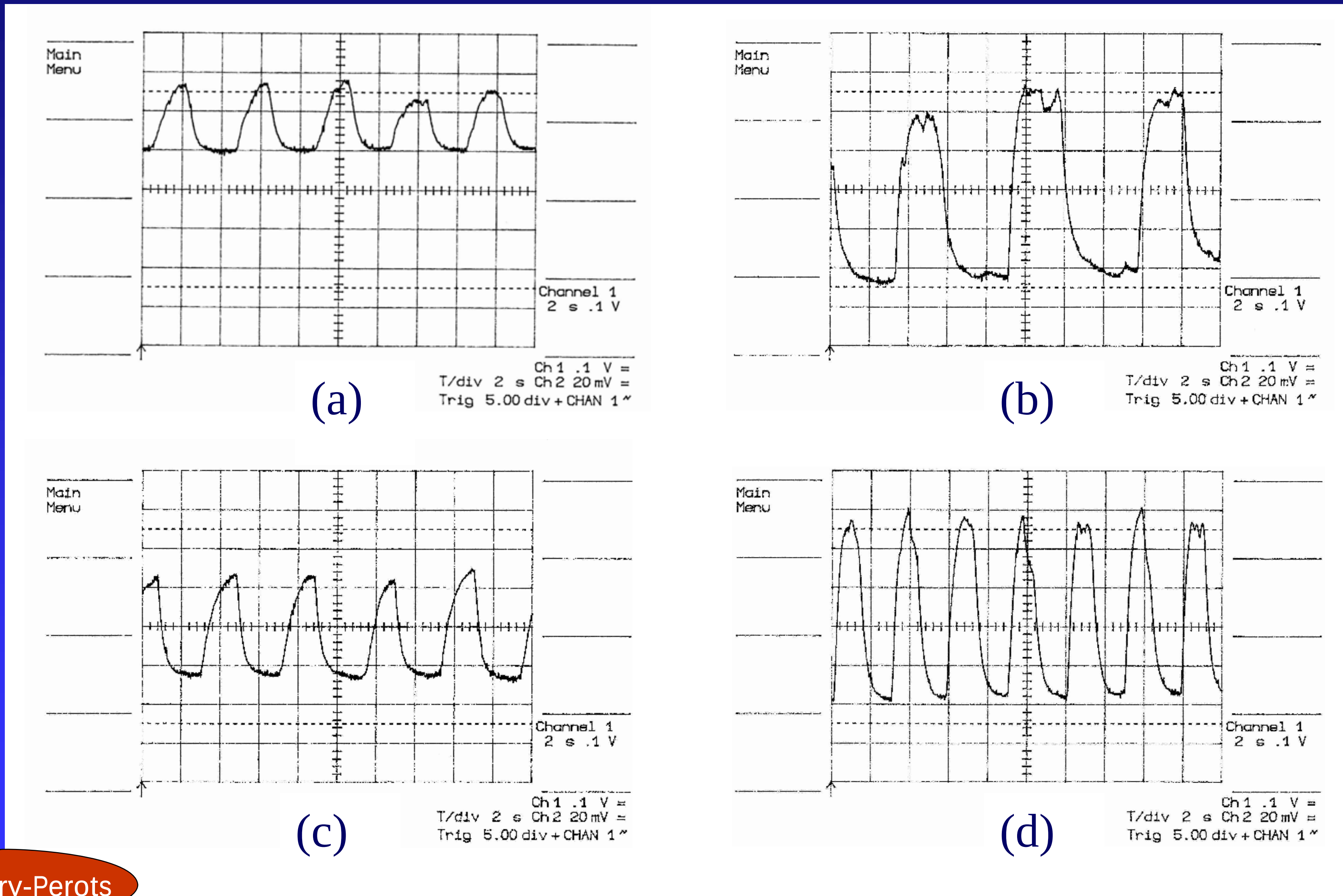
NFP Cavities. Human breathing



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IEICE Transactions on Electronics, vol. E83-C (3); pp. 360-365, 2000

NFP Cavities. Interrogator system for NFP reflexive sensors

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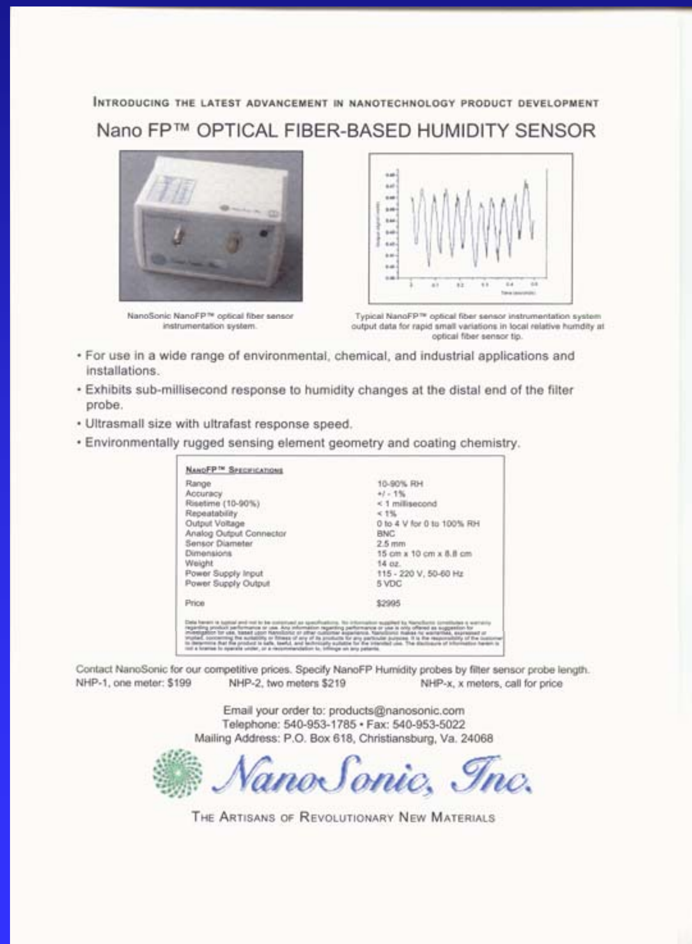

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Typical NanoFP™ optical fiber sensor instrumentation system output data for rapid small variations in local relative humdity at optical fiber sensor tip.

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- Ultrasmall size with ultrafast response speed.
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NANOFP™ SPECIFICATIONS

Range	10-90% RH
Accuracy	+/ - 1%
Risetime (10-90%)	< 1 millisecond
Repeatability	< 1%
Output Voltage	0 to 4 V for 0 to 100% RH
Analog Output Connector	BNC
Sensor Diameter	2.5 mm
Dimensions	15 cm x 10 cm x 8.8 cm
Weight	14 oz.
Power Supply Input	115 - 220 V, 50-60 Hz
Power Supply Output	5 VDC
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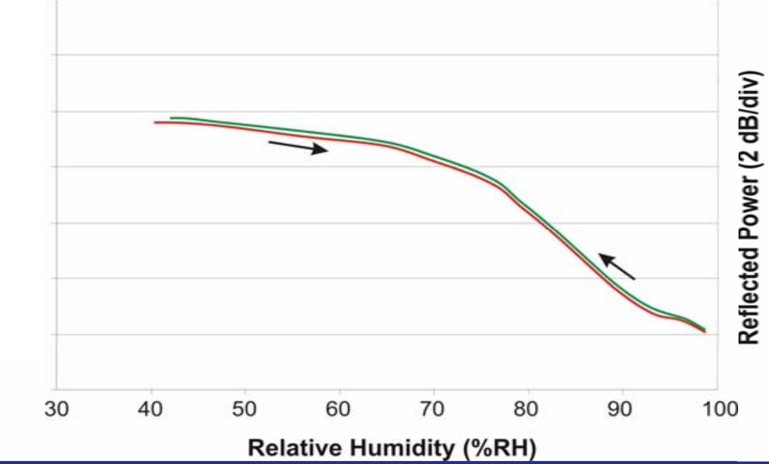
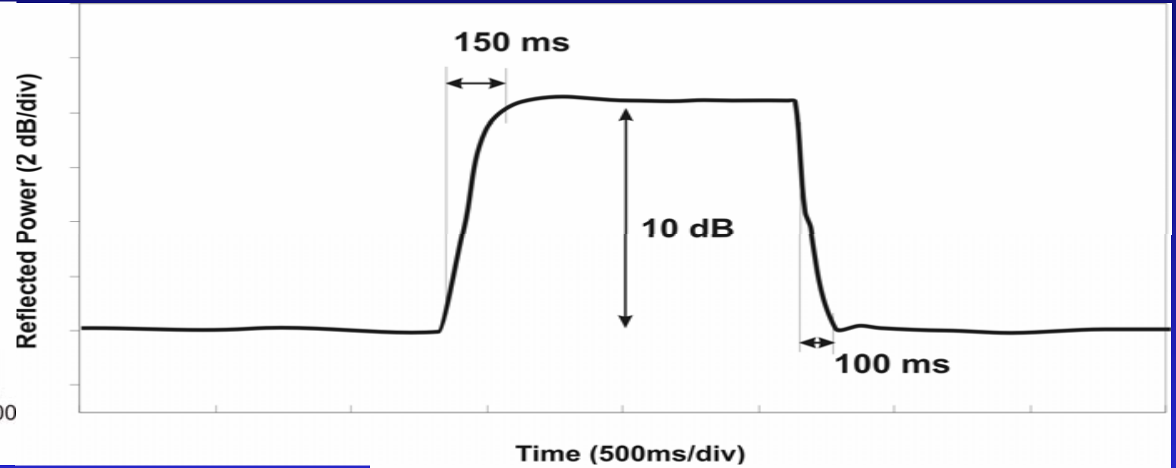
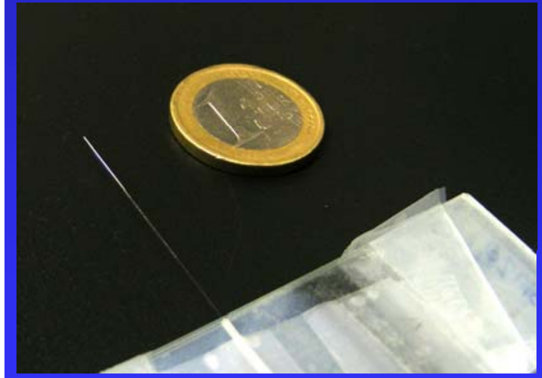
Novel fiber optic sensing architectures based on sensitive nanofilms

NFP Cavities. Humidity sensors using silica nano-spheres

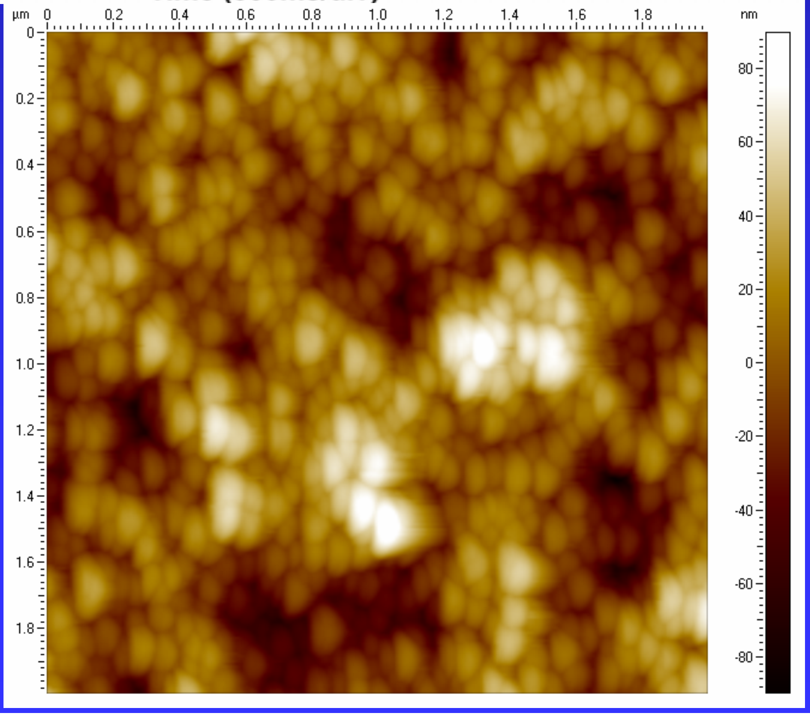






Caracterization (AFM)

50 nm SiO_2 nanoparticles
Contact angle: 5º
Surface: Silica



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Summary

- ❑ Introduction to the fiber optic sensor market
- ❑ Nanotechnology and fiber optic sensors?
- ❑ The Electrostatic Self-Assembled Monolayer Method
- ❑ Possible sensing architectures based on nano-films
  - ❑ Tapered ends
  - ❑ Tapered optical fibers
  - ❑ Hollow core fibers
  - ❑ Long period gratings
  - ❑ Optical fiber gratings
  - ❑ NanoFabry-Perot Cavities
- ❑ Conclusions

CONCLUSIONS

- The Layer-by-Layer Electrostatic Self-Assembly Method has been presented as a useful tool for fabricating nano-structured sensing coatings, not only fiber optic sensors.
- These coatings can be deposited on substrates of different shapes: flat, cylindrical or conical
- Different optical fiber sensors have been already experimentally demonstrated (humidity, volatile organic compounds, ammonia, glucose, etc.) and the possible applications of this technique in the sensing field are very promising.
- The sensors have a very fast response time, can operate at room temperature and it is possible to find a suitable architecture depending on the specific application.
- Several different optical fiber structures to fabricate sensors have been proposed: Tapered ends, Tapered optical fibers, Hollow core fibers, Long period gratings, Optical fiber gratings, NanoFabry-Perot Cavities, 1D PBG with defects, etc.). All of them are feasible to be implemented using ESA technique with different sensing properties and final performances.
- It is possible to design specific sensors for specific applications by varying any of the design parameters: materials, thickness, number of bilayers, structures, etc.

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This is the result of the contribution of many people

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