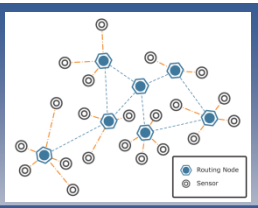
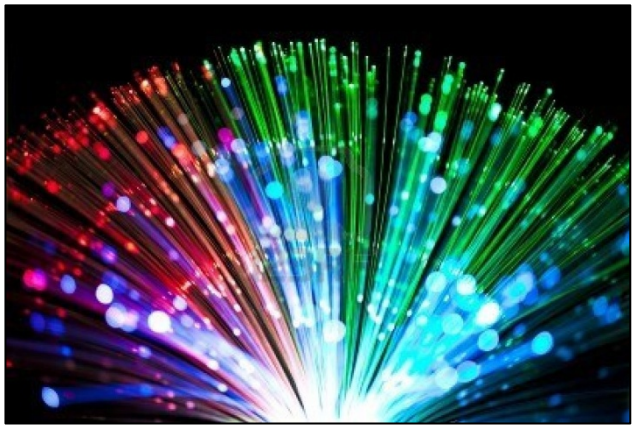
Optoelectronics Group, Engineering Department
University of Sannio, Benevento (Italy)

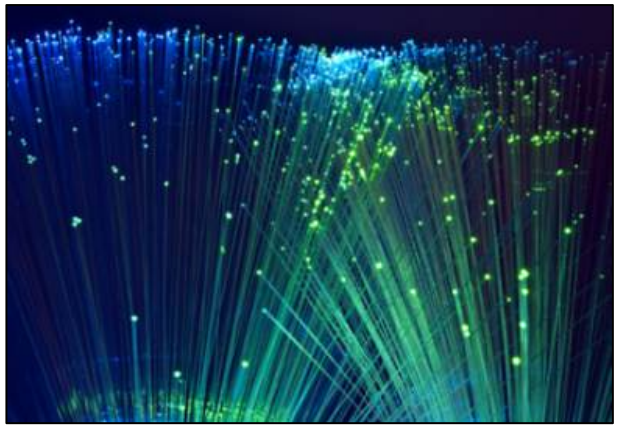


Fiber Optic Sensors for Industrial Applications

Perspectives, Challenges and New Trends

Andrea Cusano, Optoelectronic Division
University of Sannio



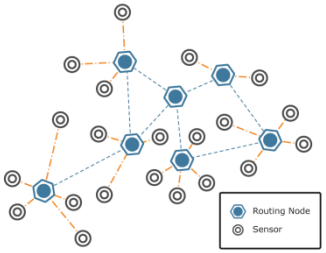


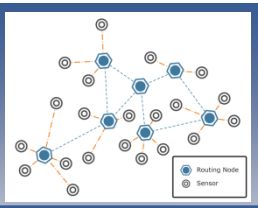
University of Padova, Dept. of Information Engineering

2013 Summer School of Information Engineering

Bressanone (Brixen, BZ), Italy -- June 30 – July 6, 2013

Sensors and sensors networks



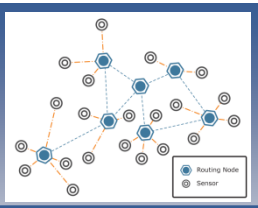


Outline

- *Introduction*
- *Fiber Optic Sensors*
- *Fiber Bragg Grating Sensors*
- *Industrial Applications: Case Studies*
- *A new Vision: Lab on Fiber Technology*
- *Conclusions*

OPTOELECTRONICS group
University of Sannio

University of Sannio
Department of Engineering
BENEVENTO



Optoelectronics Group Members

Full Professor

- Prof. Antonello Cutolo

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- Prof. Giovanni Vito Persiano
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- Dr. Alessio Crescitelli
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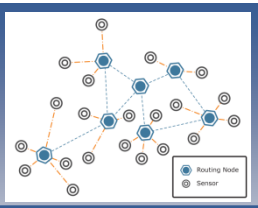
- Ing. Alberto Micco (1rd year)
- Ing. Gaia Berruti (1rd year)
- Ing. Antonella Chiuchiolo (1rd year)

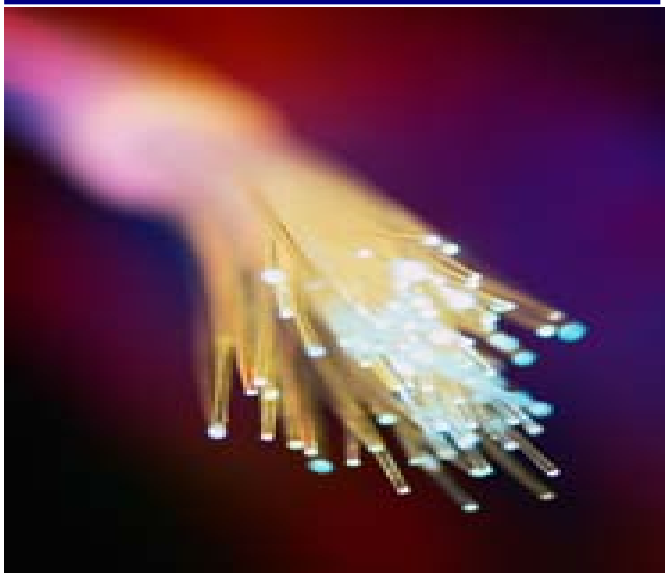
Administrative

- Dott. Paola Ambrosino



Spin-off Companies

NAME	YEAR	CORE BUSINESS
Optosmart s.r.l.	2005	Design and development of fiber optic sensor systems for structural and environmental monitoring applications.
Optoadvance s.r.l.	2011	Design and development of fiber optic sensors for musical and biological applications.



Optical Fiber

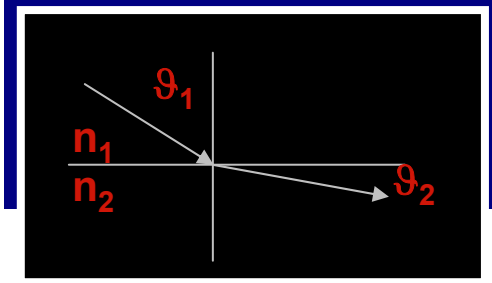
- a filament of transparent dielectric material, glass or plastic
- usually cylindrical in shape
- a guidance system for light

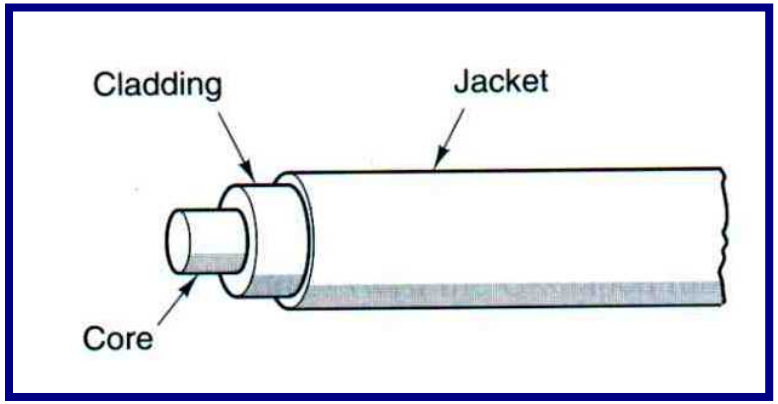
Optical Fiber

- Guidance is achieved through total internal reflection at the core-cladding interface
- Core, transparent dielectric material, surrounded by another dielectric material with a lower refractive index called cladding. ($n_1 > n_2$)
- In practice, there is a third protective layer called jacket.

SNELL'S LAW:

$n_1 \sin \vartheta = n_2 \sin \vartheta$
where n is the refractive index

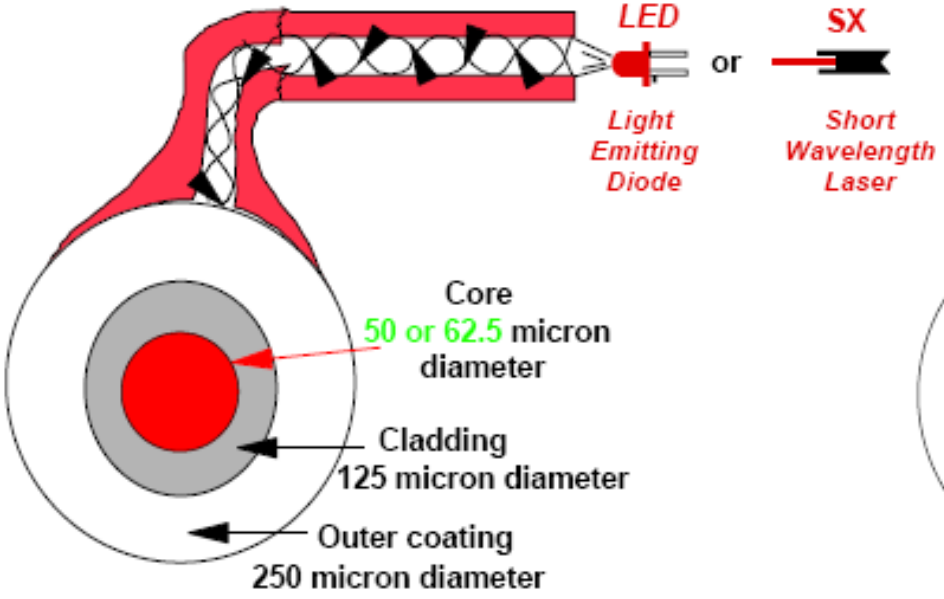




Fiber Optic Technology

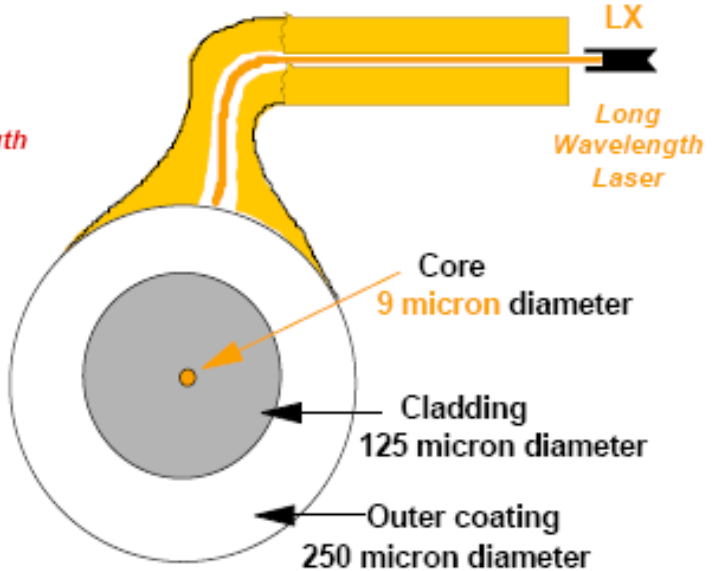
Multimode (MM) fiber

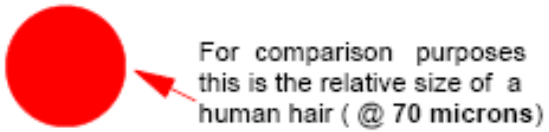
" Multiple paths" for the light to travel

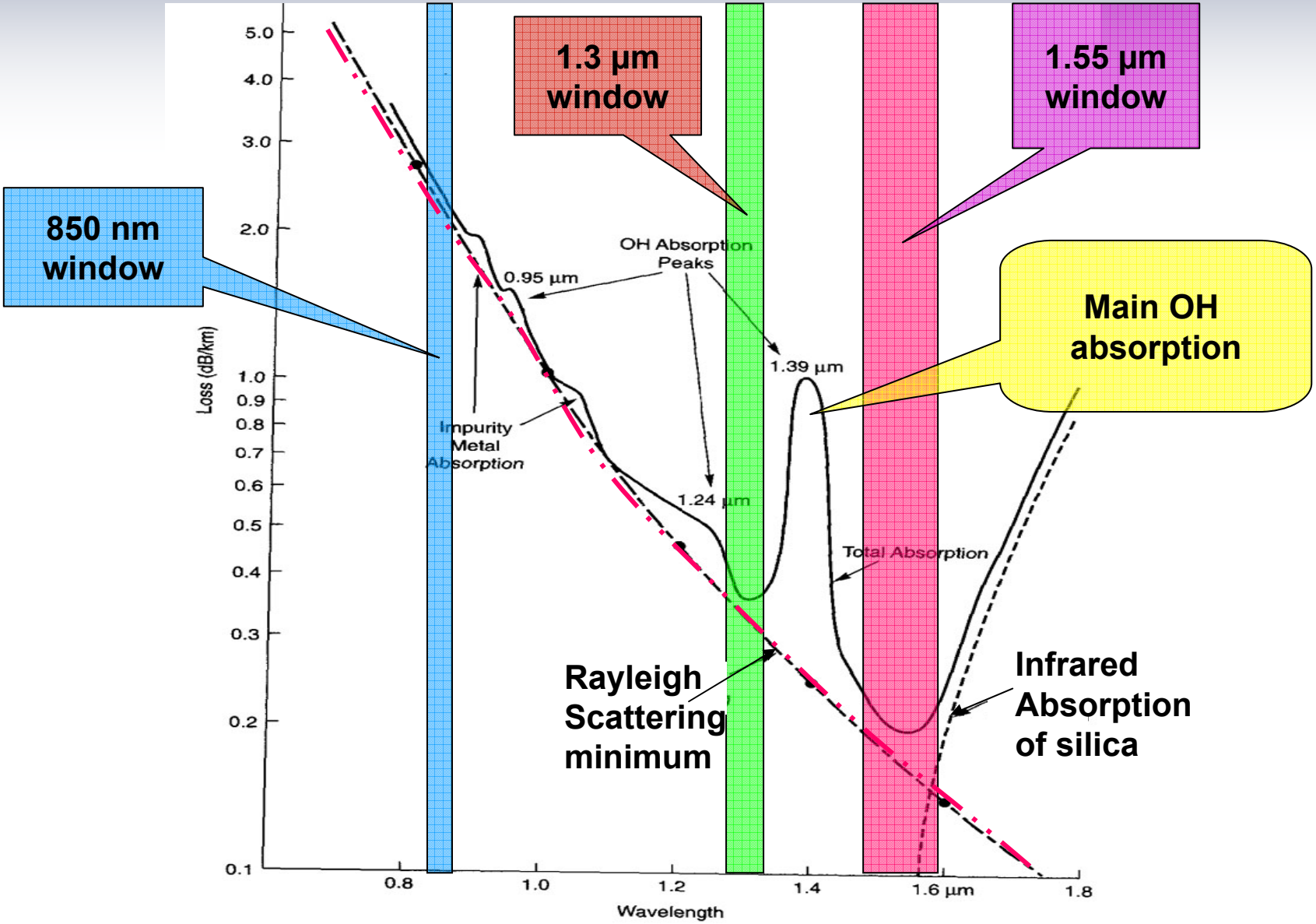


Single mode (SM) fiber

"Single path" for the light to travel

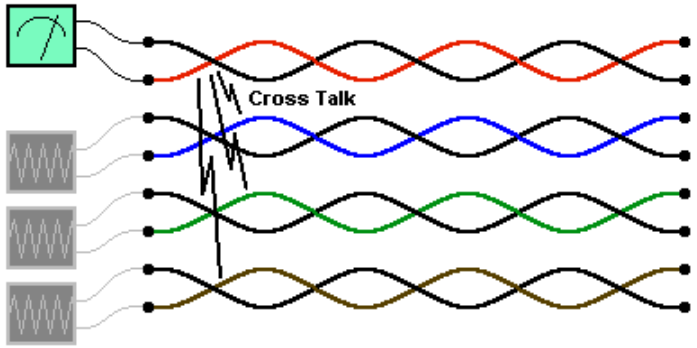





1.3 µm window
1.55 µm window
850 nm window
Main OH absorption
OH Absorption Peaks
0.95 µm
1.39 µm
1.24 µm
Impurity Metal Absorption
Total Absorption
Rayleigh Scattering minimum
Infrared Absorption of silica
Loss (dB/km)
Wavelength
5.0
4.0
3.0
2.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.8
1.0
1.2
1.4
1.6 µm
1.8

Optical Fiber Advantages

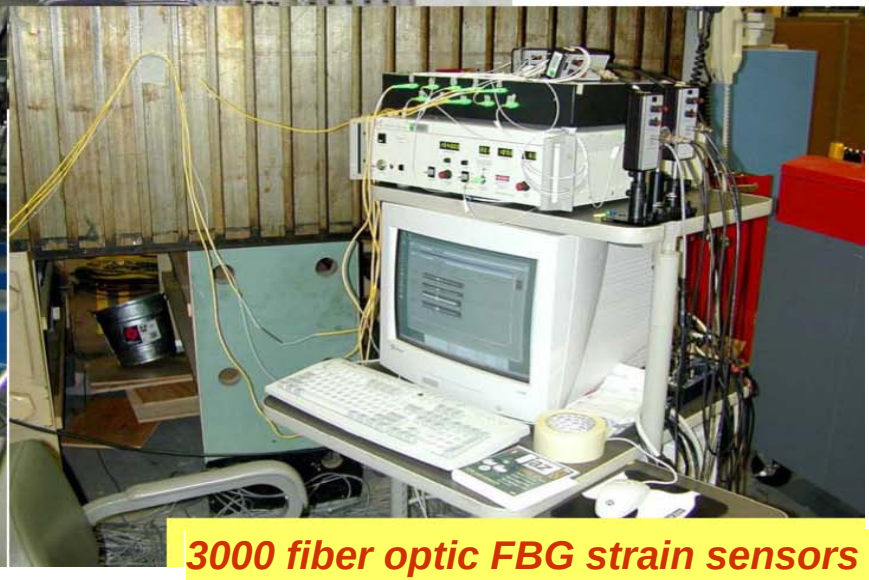
- Capacity: much wider bandwidth
- Crosstalk immunity
- Immunity to static interference
  - Lightening
  - Electric motor
  - Fluorescent light
- Higher environment immunity
  - Weather, temperature, etc.
- Safety: Fiber is non-metallic
  - No explosion, no shock
- Longer lasting
- Security: tapping is difficult
- Economics: Fewer repeaters
  - Low transmission loss (dB/km)
  - Fewer repeaters
  - Less cable



Why Fiber Optic Sensors?

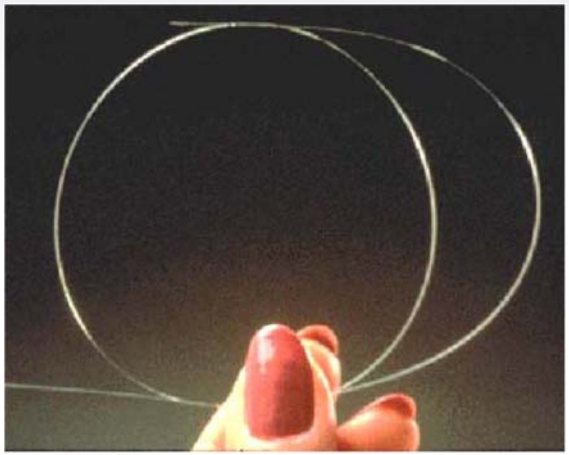
Source: NASA Langley
Composite wing IVHM testing

400 conventional strain gauge sensors



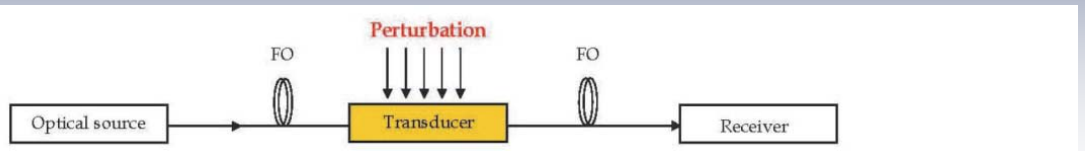
3000 fiber optic FBG strain sensors

Advantages of Fiber Optic Sensors



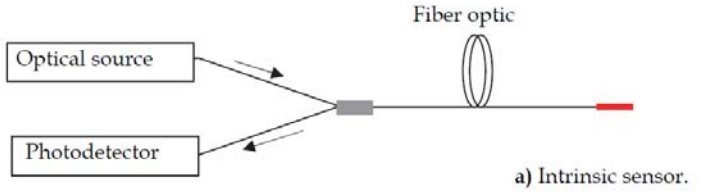
- *Galvanic isolation*
- *EMI immunity*
- *Intrinsically safe*
- *Passive: no need for electrical power*
- *Possibility of remote, multiplexed operation*
- *Small size and lightweight*
- *Integrated telemetry: fiber itself is a data link*
- *Wide bandwidth*
- *High sensitivity*

Fiber Optic Sensors: Fundamentals

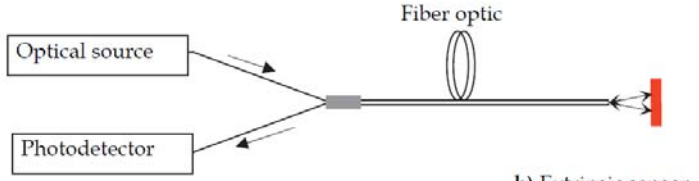


- **Optical source**
  - Laser
  - LED
- **Transducer:**
  - Optical fiber
    - Single-mode
    - Multimode
    - Doped
  - Bulk material
- **Modulation:**
  - Intensity:
    - Transmission
    - Absorption
    - Reflection
    - Scattering
    - Microbend
    - Wavelength
    - Transmission
    - Reflection
    - Refraction index

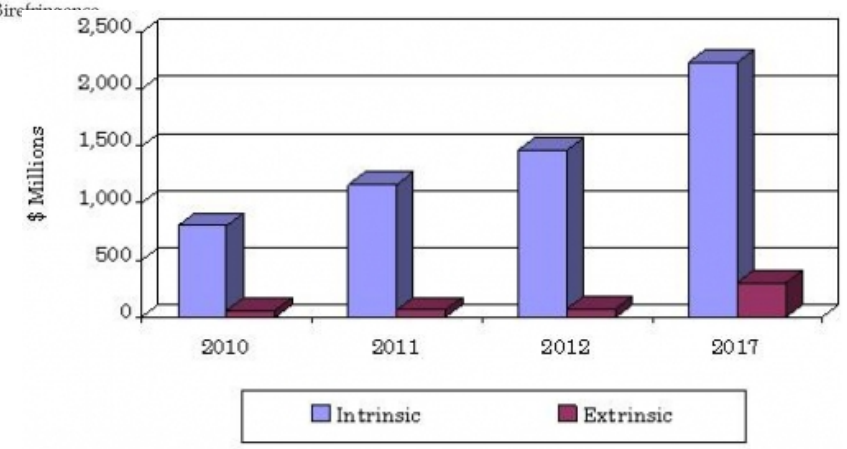
    → Fibers Bragg and Long Period Fiber Grating
  - Phase:
    - Optical frequency
    - Wavelength
  - Color:
    - Absorption
    - Reflection
    - Luminescence
  - Polarization
- **Receiver:**
  - Photo-detector
  - Amplifier



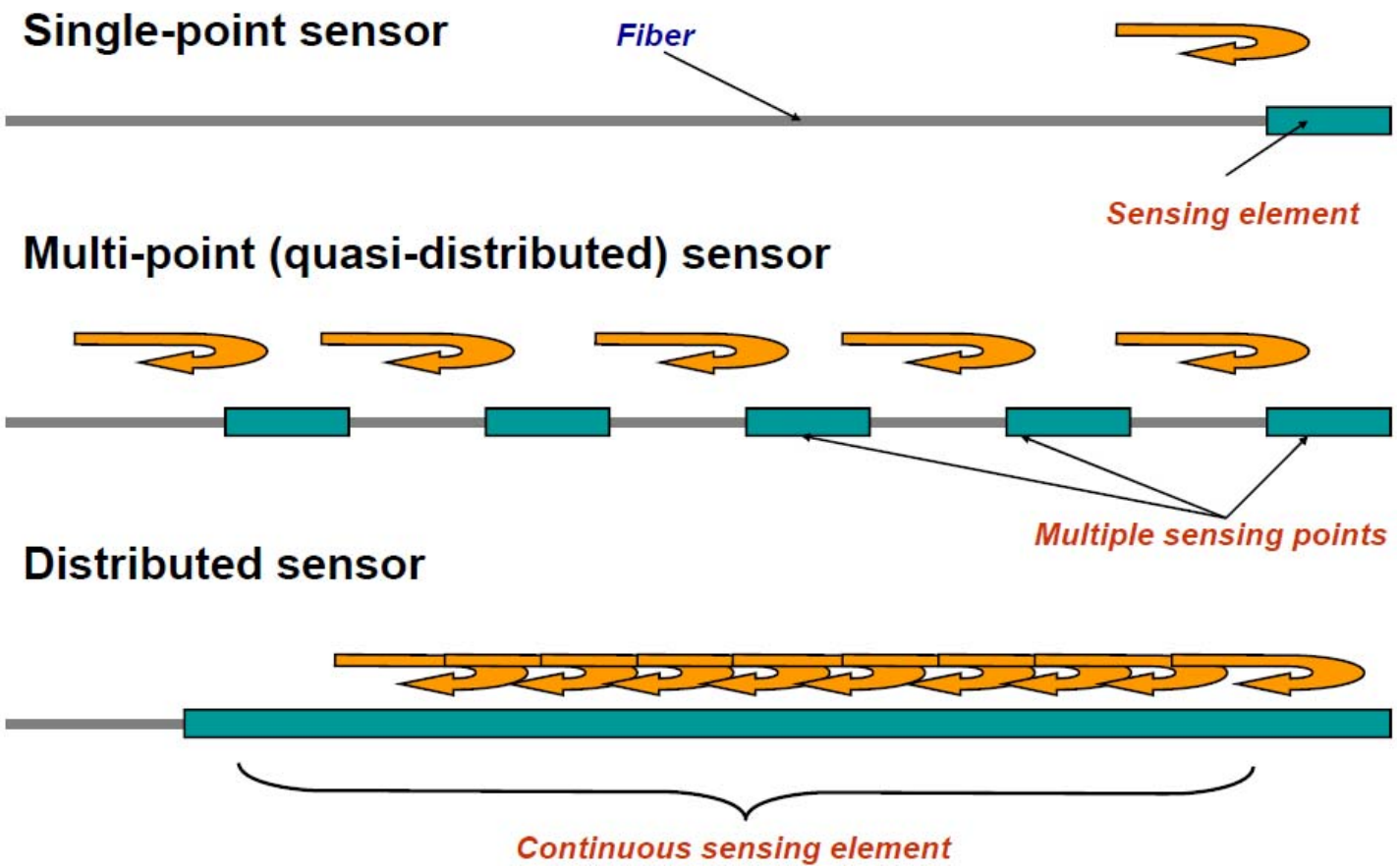
a) Intrinsic sensor.



b) Extrinsic sensor.



Fiber Sensors Configurations



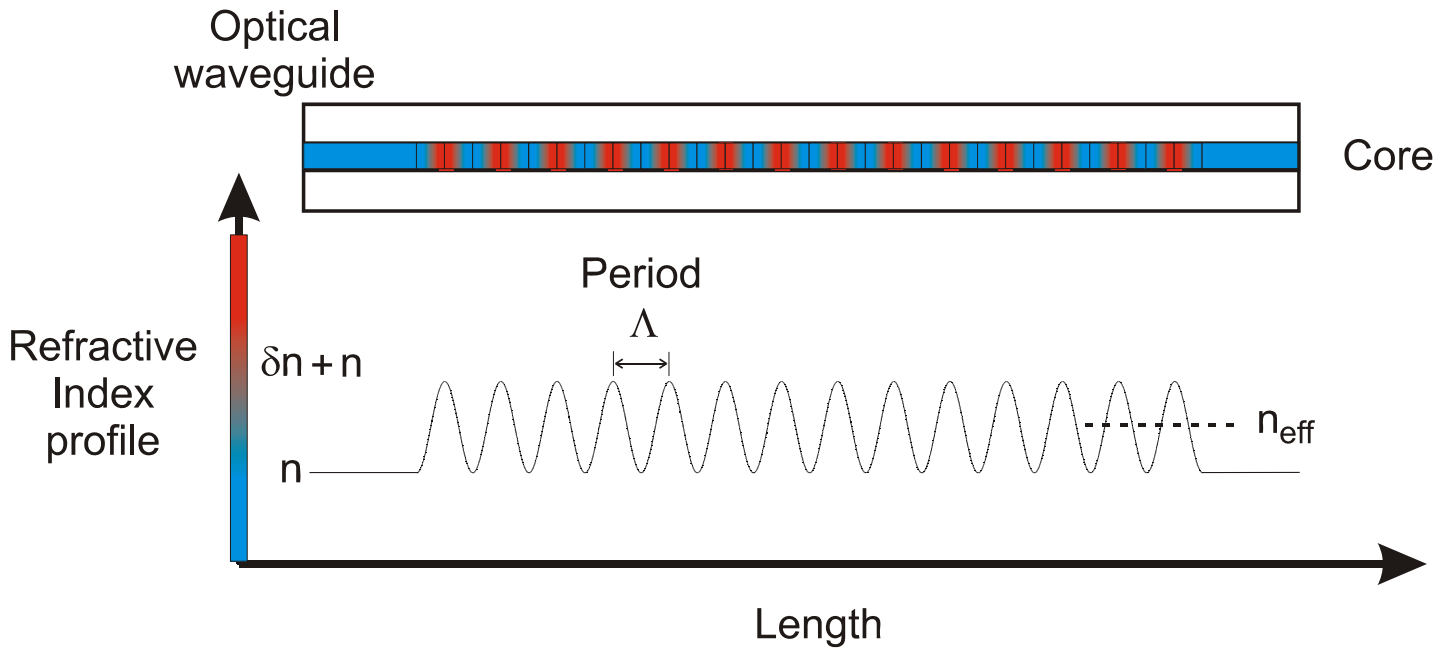
Extrinsic Optical Fiber Sensors (EOFS)

Intrinsic Optical Fiber Sensors (IOFS)

~ Bragg grating fundamentals ~

What is a Bragg grating?.

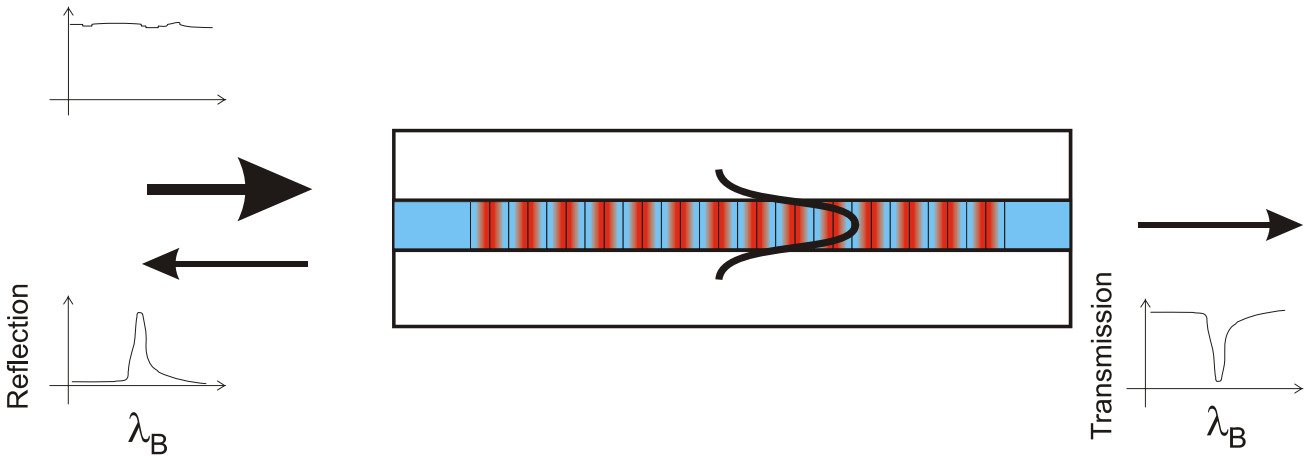
- A periodic or almost periodic structure consisting of a variation of for example the refractive index along the length of a waveguide.



~ Bragg grating fundamentals ~

What does it do?.

- Coupling of a forward propagating core-mode to a backward propagating core-mode.
- Acts as a band-rejection filter passing all wavelengths that are not in resonance with the grating and reflecting the wavelength that satisfies the Bragg condition.

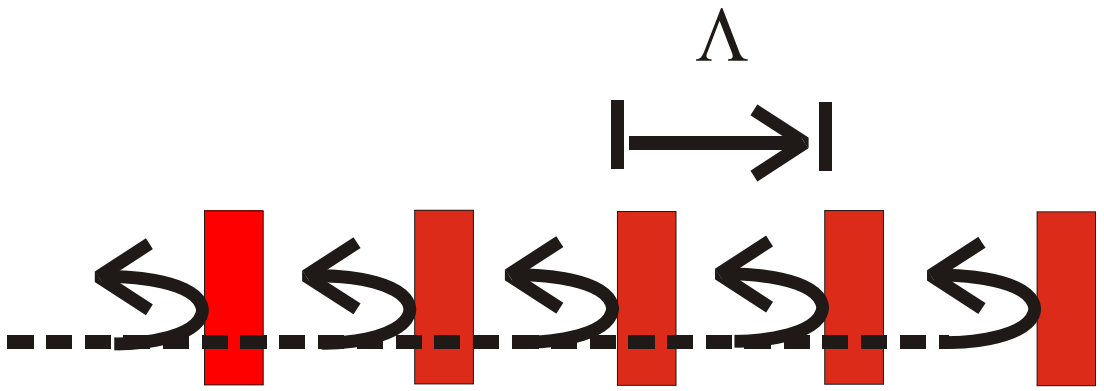


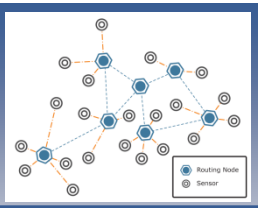
~ Bragg grating fundamentals ~

Why?.

- A small Fresnel reflection from each low-high, high-low refractive index transition.

$$r = \left(\frac{n - (n + \delta n)}{n + (n + \delta n)} \right)^2 = \left(\frac{\delta n}{2n + \delta n} \right)^2 \approx \underline{10^{-9}}$$





~ Bragg grating fundamentals ~

Parameters related to a Bragg grating.

- Strong overall reflection is achieved when each of the reflected contributions add in-phase (phase coherence/matching).

$$\beta = k \cdot n_{eff} = \frac{2\pi}{\lambda} \cdot n_{eff} \qquad \text{(Propagation constant)}$$

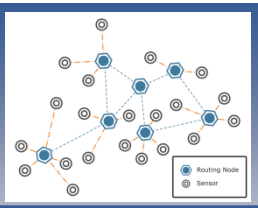
$$\delta = \beta \cdot \Lambda \qquad \text{(phase of the propagating wave)}$$

For each of the reflected contribution to add in phase

$$\delta = m \cdot 2\pi \qquad (m \text{ positive integer})$$

$$\Downarrow$$

$$\underline{\lambda_B \cdot m = 2 \cdot n_{eff} \cdot \Lambda} \qquad \text{(Bragg condition)}$$



BRAGG GRATINGS : Theory

- Grating couples two modes in a fiber
  - e.g: forward -> backward
  - Coupling strength given by k:

$$\kappa \propto \int E^*_n(x)\Delta n(x)E_m(x)dx$$

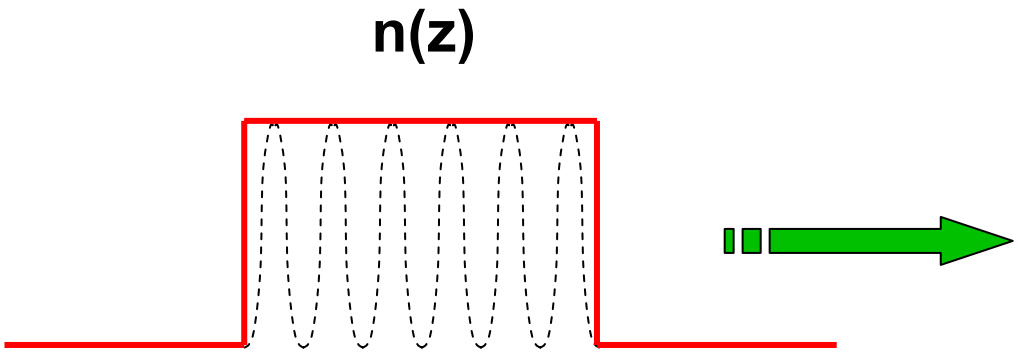
  - E_n and E_m are the electric fields related to mode n and m respectively
  - Grating length L, for complete power transfer

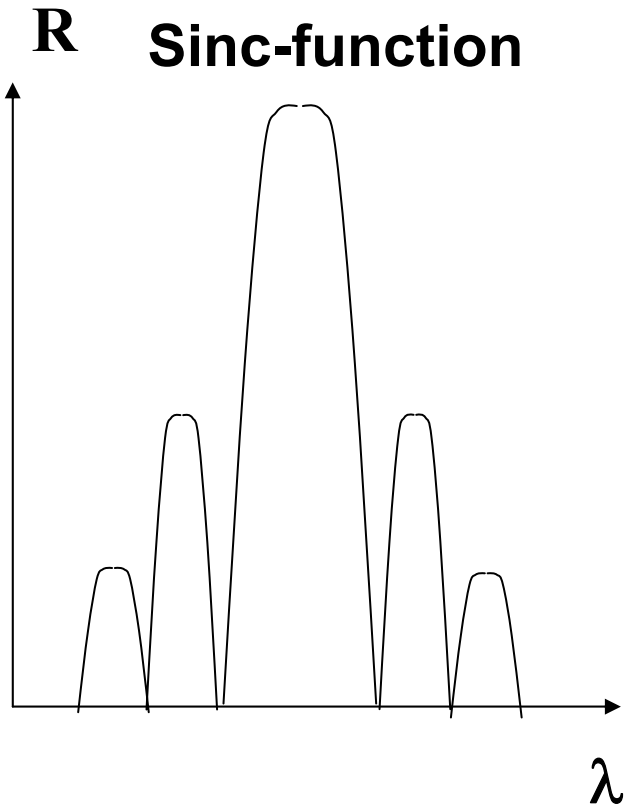
Maximum Reflectance Conditions

$$L = \frac{\pi}{2|\kappa|}$$

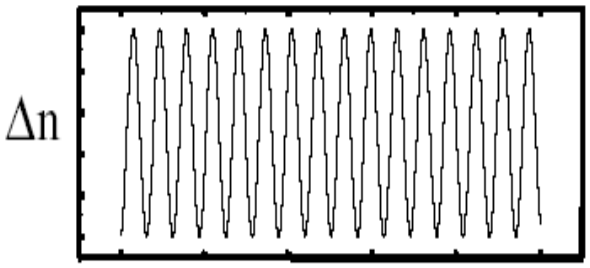
BRAGG GRATINGS APPROXIMATION

- Reflection spectrum a F. T. of the index profile
- Grating starts and stops abruptly
- F. T. of square function is a sinc function

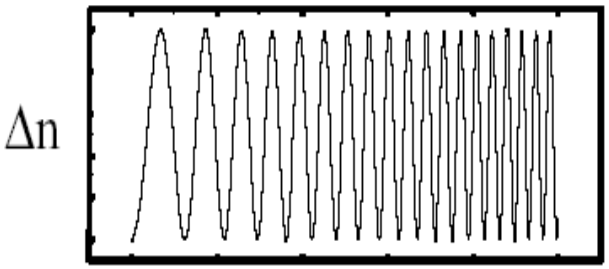




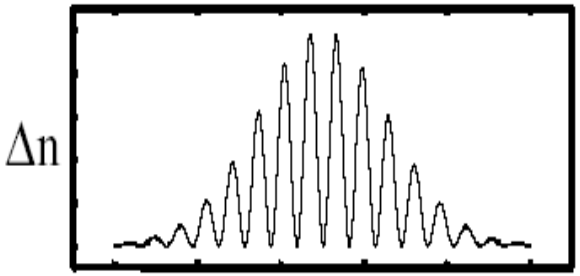
Suitable refractive index modulation can provide different spectral characteristics



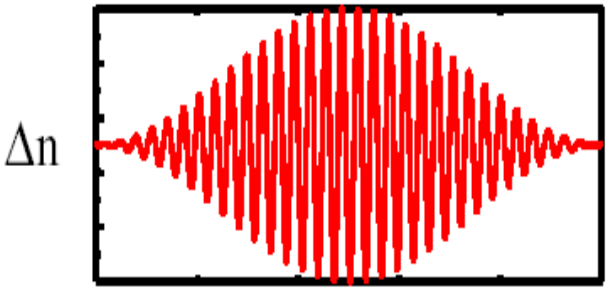
Uniform Profile : Uniform Bragg Grating Period (typical).



Chirp : Non-Uniform Bragg Grating Period.



Apodization : Tailored Spatial Exposure.

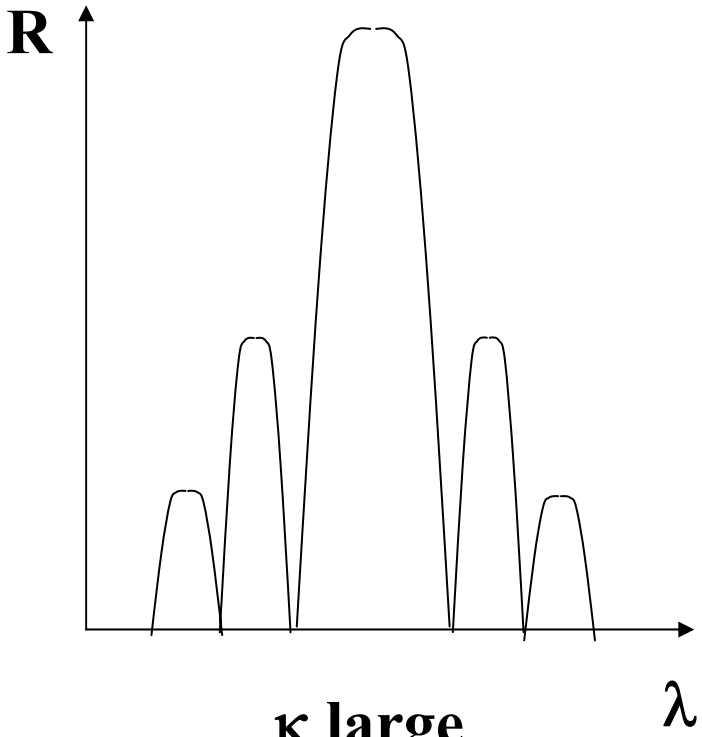


Apodization : Tailored Spatial Exposure.

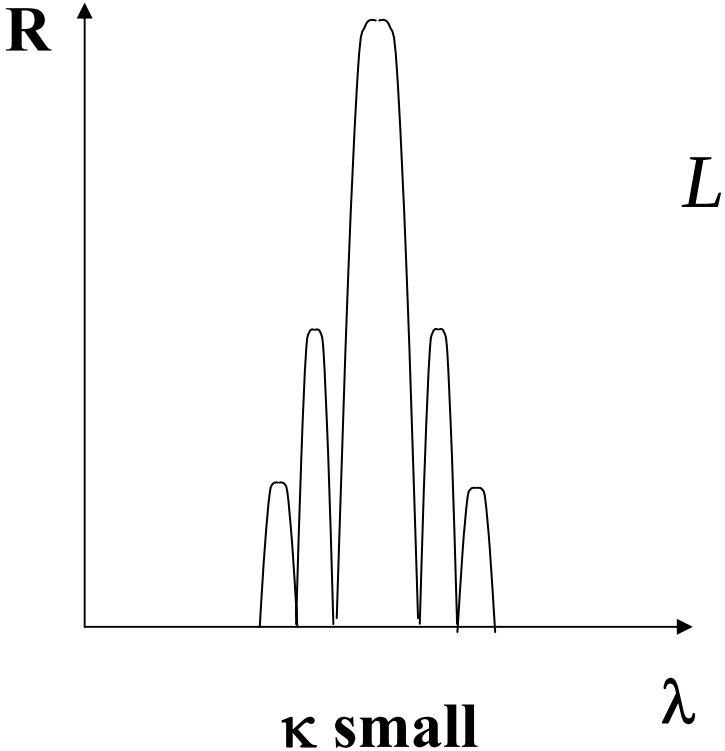
BRAGG GRATINGS : Bandwidth

Maximum Reflectance Conditions

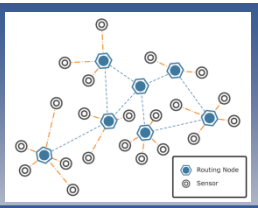
$$L = \frac{\pi}{2|\kappa|}$$



κ large
L short



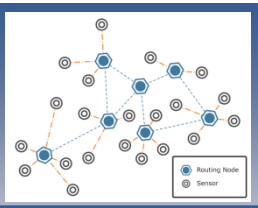
κ small
L long



Achieving Refractive Index Changes

- Create defects in glass
  - Increase absorption (in UV)
  - Affect the refractive index n through Kramers-Kronig relations
- Densification of glass
  - Increase the refractive index n directly

Both strategies can be implemented using light exposure



Photosensitivity in Germania doped silica fibers

Non linear effect which permits the index of refraction in the core of the fiber to be increased by exposure to intense laser radiation

Without Hydrogen

Index change: up to 10^{-3}

Defects absorb light and form new bonds

Writing by pumping defect bands: 240 nm, 330 nm, also 193 nm

Hydrogen loaded

Index change: up to 10^{-2}

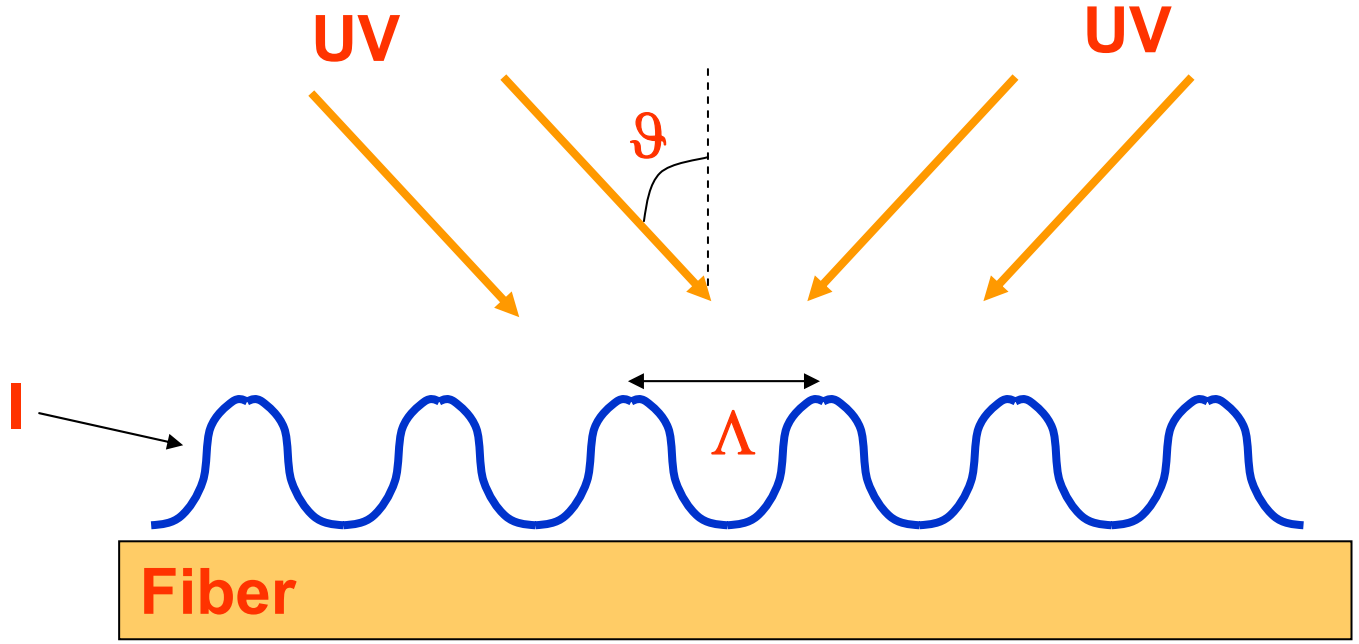
Photochemical reaction of hydrogen with Ge-O bonds

Edge of fundamental absorption: <310 nm (the shorter the better)

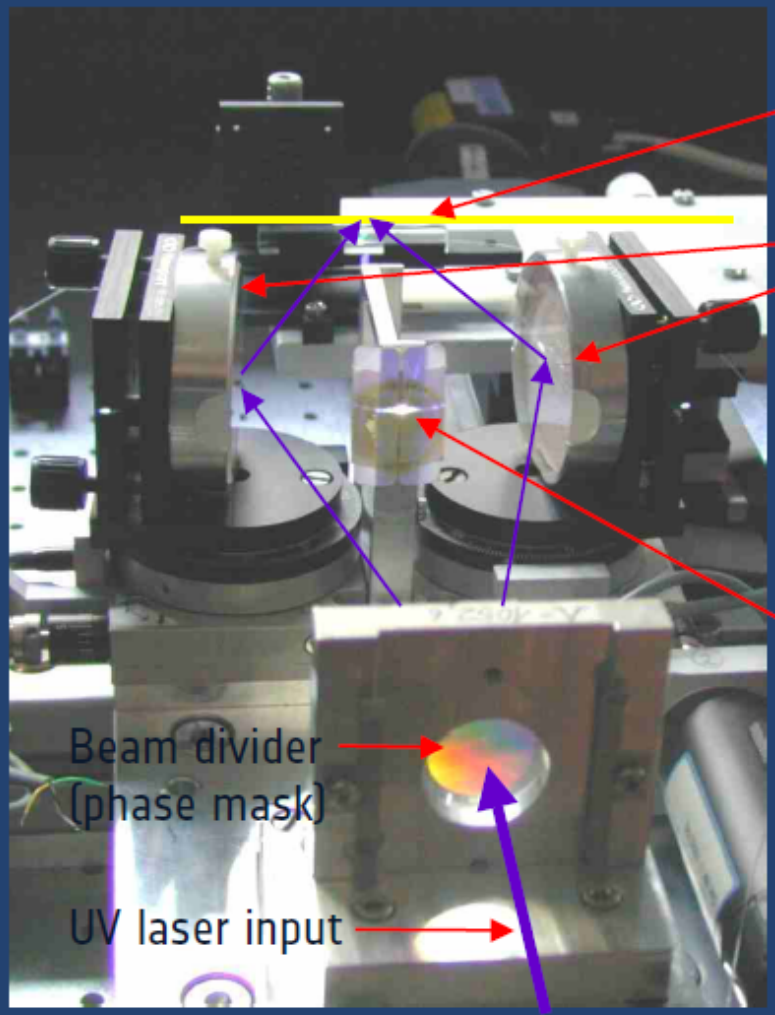
Gratings Manufacturing: The Holographic Method

- **Interfering UV beams:**
  - **Sinusoidal Δn**

$$\Lambda = \frac{\lambda_{uv}}{2 n_{uv} \sin\theta}$$



Talbot Interferometer



Optical fibre

2 mirrors (adjustable), directing diffracted beams of +1st and of -1st order, for superposition at optical fibre.

Blocking of 0th order

FABRICATION : Phase Mask

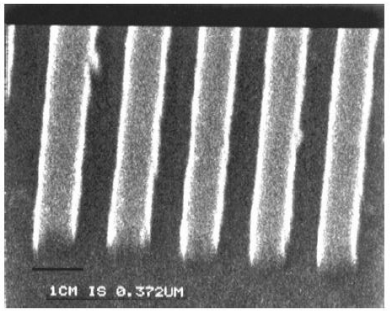
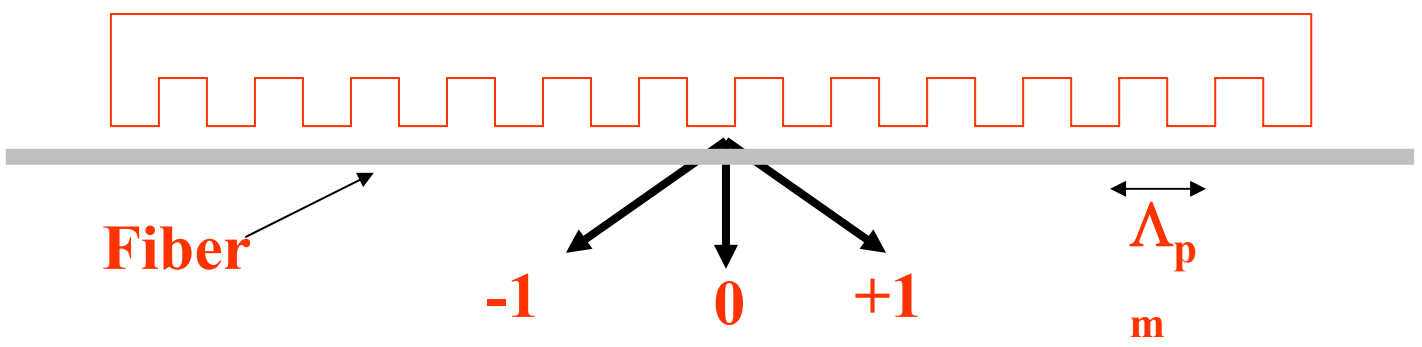


Figure 3.4 SEM photograph of a high-quality phase mask used for grating inscription of ~1060-nm Bragg gratings. (Courtesy Ian Lealman, BT Labs)

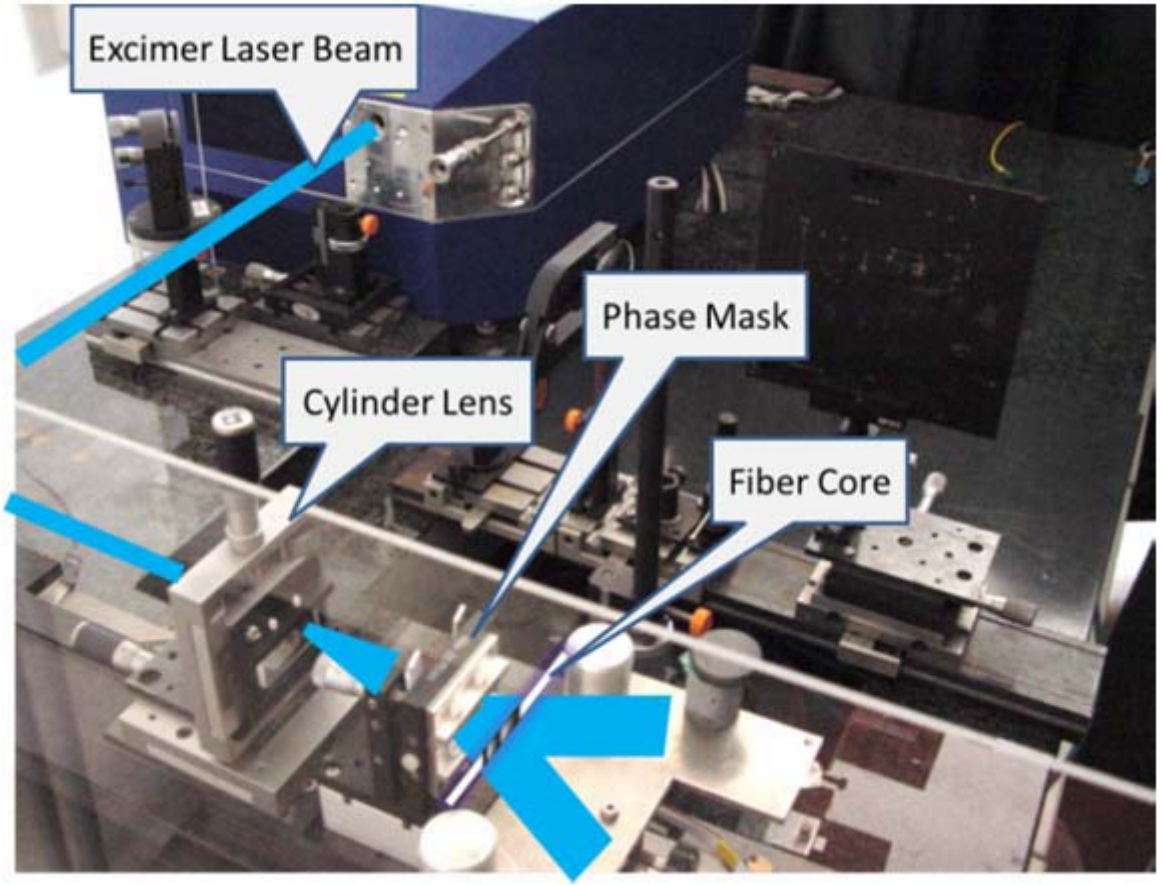
$$\Lambda = \frac{\Lambda_{pm}}{2}$$

Λ : Periodicity of the grating

Λ_{pm} : Periodicity of the phase mask



Phase Mask: A practical Set-up

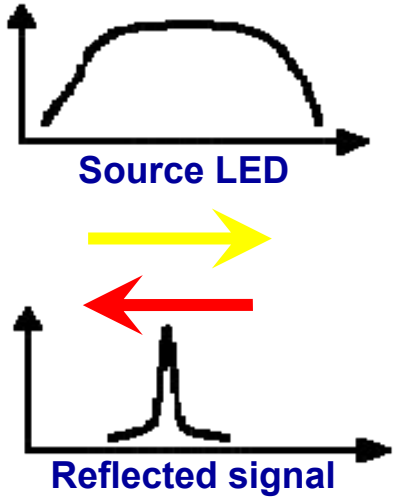


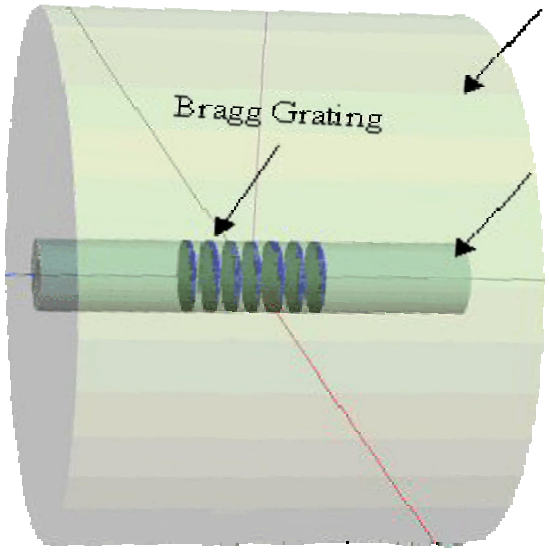
Fiber Bragg gratings in Single Mode Optical Fibers

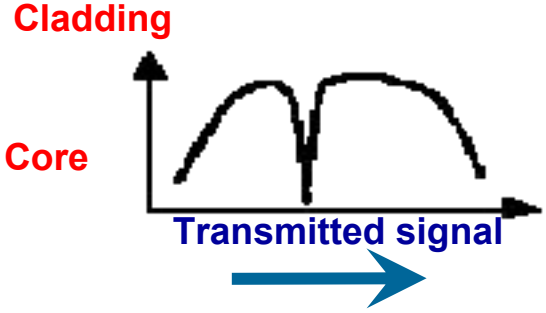
A. Cusano et al., «Fiber Bragg Grating Sensors: Recent Advancements, Industrial Applications and Market Exploitation», **Bentham Science Publishers**, 2011
ISBN: 160805084X,

Parameters related to a Bragg grating.

- n_{eff} ~ 1.455 in silica.
- "Short" period grating to operate in lowest order mode (m=1) with Bragg wavelength λ_B ~ 1550nm, Λ~500nm.
- Typical index changes, δn ~ 10^{-5} – 10^{-3}.
- Typical lengths, 1cm – 10cm, some types ~1m.



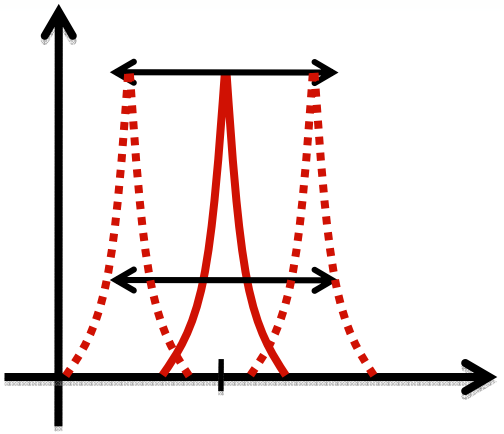




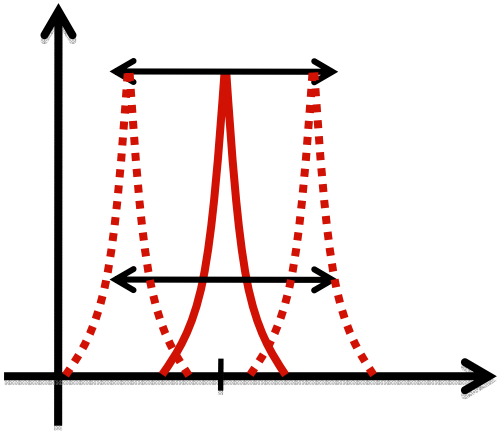
$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda$$

Temperature & Strain

Strain Changes Λ via direct deformation and n via elasto optic effect



Temperature Change n via thermo optic effect and Λ via thermal expansion



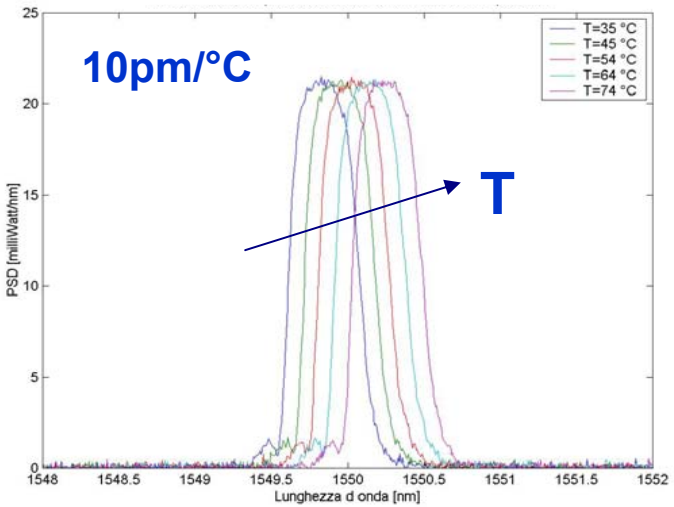
Temperature Sensitivity

$$\left(\frac{\Delta\Lambda}{\Lambda}\right)_T = \alpha\,\Delta T$$

Thermal Expansion Effect

$$\left(\frac{\Delta n}{n}\right)_T = \frac{1}{n}\cdot\frac{\partial n}{\partial T}\Delta T$$

Thermo Optic Effect



$$\left(\frac{\Delta\lambda_B}{\lambda_B}\right)_T = \left(\frac{\Delta\Lambda}{\Lambda}\right)_T + \left(\frac{\Delta n}{n}\right)_T = \left(\alpha + \frac{1}{n}\cdot\frac{\partial n}{\partial T}\right)\Delta T = S_T\,\Delta T$$

S_T: Temperature Sensitivity

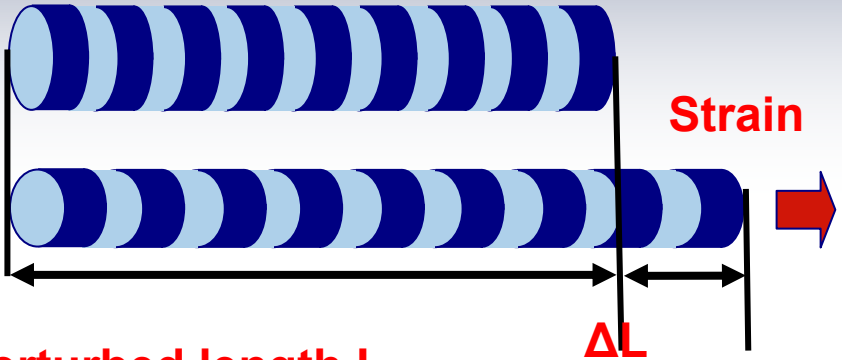
$5.8*10^{-6}/K^{-1}$@λ_B=1550nm

With :

- **α : Optical fiber core temperature expansion coefficient**
- **Λ : Periodicity of the grating**
- **n : Optical fiber core refractive index**

STRAIN SENSITIVITY

Axial Strain

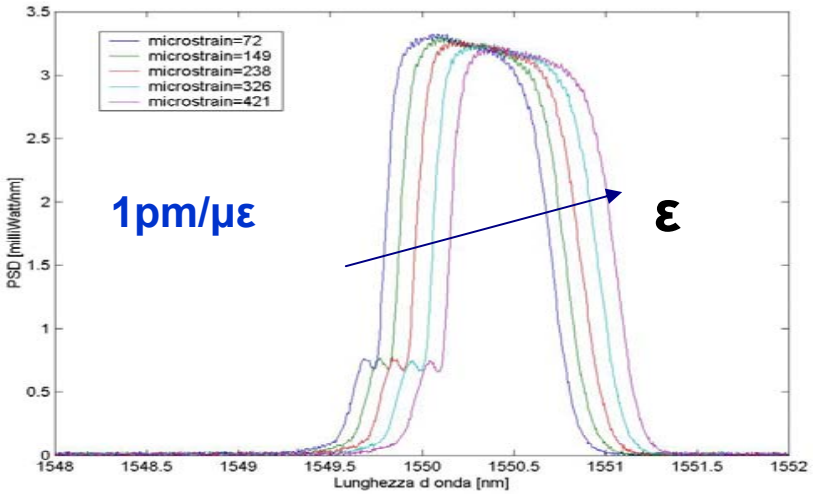


$$\begin{cases} \varepsilon_1 = \varepsilon \\ \varepsilon_2 = \varepsilon_3 = -\upsilon\varepsilon \end{cases}$$

υ: Poisson ratio

$$\left(\frac{\Delta\lambda_B}{\lambda_B}\right)_\varepsilon = \left(\frac{\Delta\Lambda}{\Lambda}\right)_\varepsilon + \left(\frac{\Delta n}{n}\right)_\varepsilon =$$

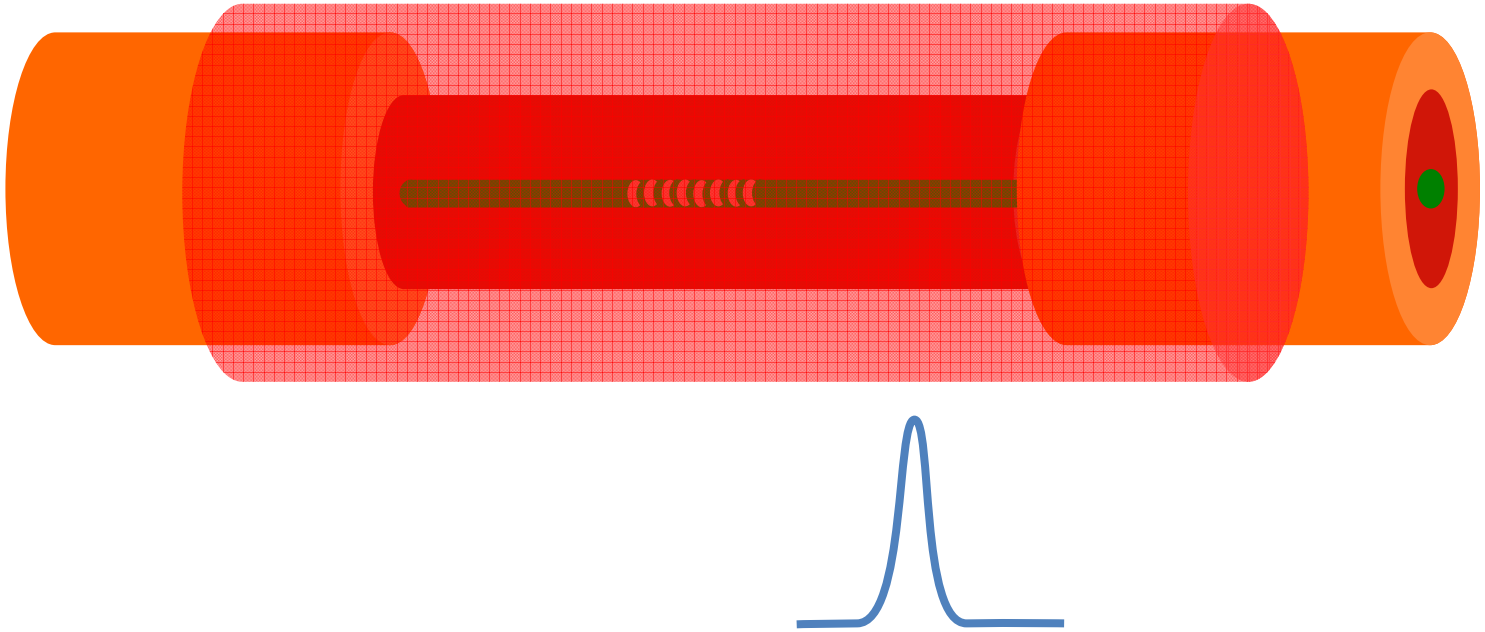
$$\left\{1 - \frac{n^2}{2}[p_{12} - \upsilon\cdot(p_{11} + p_{12})]\right\}\varepsilon_1 = S_\varepsilon\varepsilon$$



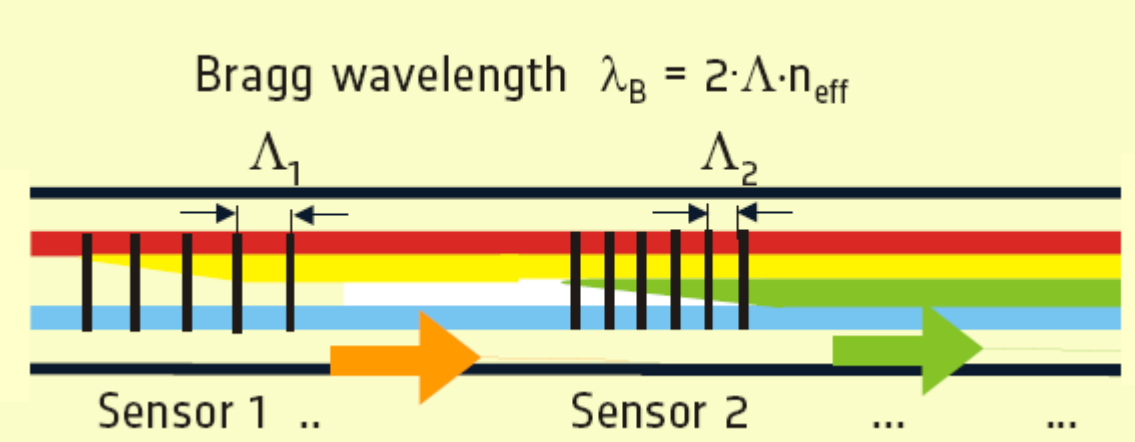
Strain Sensitivity $[(\Delta\lambda_B/\lambda_B)/\varepsilon]$:
$8{,}0*10^{-7}\mu\varepsilon^{-1}$ @ λ_B=1550nm

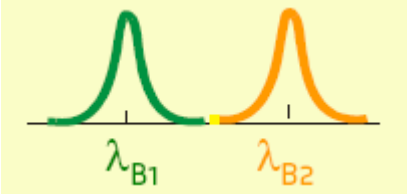
FBGs AS MULTIFUNCTIONAL SENSORS

- **Functionalization:** integration with appropriate materials and suitable packaging (i.e. mechanical packaging, magnetostrictive, polymeric coatings) to measure a number of physical, chemical and biological parameters (i.e. magnetic field, humidity, cryo temperatures, acoustic waves, weight, chemical and biological analytes)



Fibre Bragg Grating Sensor and Multiplexing Principle





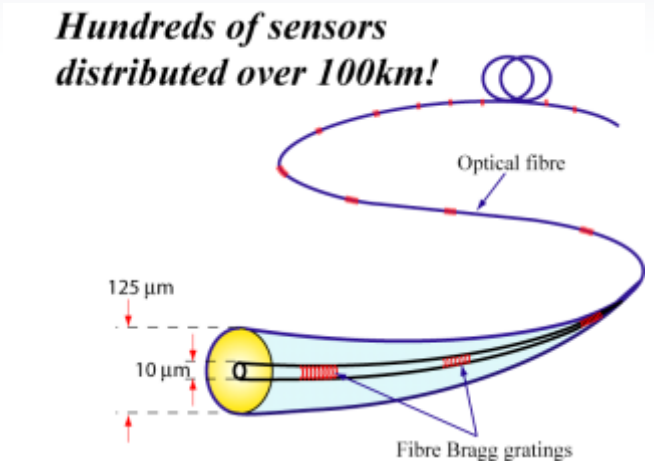
Hundreds of FBG sensors can be realized within a single optical fibers by changing the grating period

$$\lambda_{B\text{-}i}=2n\ \Lambda_i$$

Maximum number of sensors is ruled by taking into account the spectral range of the light source and the maximum expected wavelength shift of each sensor according to:

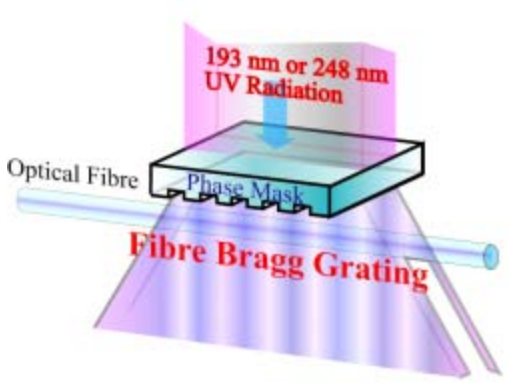
$$N< \Delta\lambda_{Source}/\ \Delta\lambda_{BMAX}$$

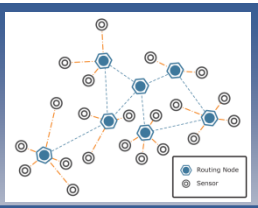
FBG Sensors: A Standardised Technological Platform



… An attractive sensing solution:

- *Wavelength Encoded*
- *Self Referencing*
- *Linear Output*
- *Small and Lightweight*
- *WDM & TDM Multiplexing*
- *Mass Producible*
- *Reflective & Transmission Operation*
- *Single & Multi Point Sensing*
- *Multi Parameter Sensing*
- *Long Range*
- *Reasonable Cost*
- *Durable*



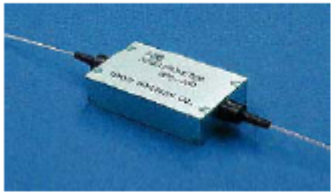


FBG TECHNOLOGY EVOLUTION: Major Milestones

1978	Discovery of photosensitivity in fibers (K.O. Hill)
1989	UV side-writing technique (Meltz, Morey & Glenn)
1993	Mask writing technique (K. O. Hill)
	Hydrogen loading photosensitization (Lemaire)
1995	Commercial FBG production (3M, Bragg Photonics, Innovative Fibers, Indx, etc…
	First commercial FBG interrogator (Electro-Photonics)
1997	Deployment of FBGs in WDM systems (Ciena)
2000	Advanced FBG instrumentation (Micron Optics)
2003	Commercial reel-to-reel FBG arrays (LxSix, Sabeus)
2007	First pre-packaged FBG strain gauge (Micron Optics)
	First strain gauge company to offer FBG sensors (HBM)
2009	Standardization efforts (W. R. Habel *et al.* BAM Institute-Jena Germany)
2010	First FBG sensors installation at CERN (University of Sannio & Optosmart)
2013	First Certified FBG Sensing System for Weighing in Motion (Ansaldo STS, University of Sannio & Optosmart)

FBG-Based Sensors & Arrays:

Multiple Parameters & Suppliers



Accelerometer

Displacement meter

Strain meter

Pressure meter

Thermometer

Tilt Meter

Reliability is the main commercial issue

IXSIX

FiberSensing

ofs

Avensys

insensys

aos advanced optics solutions

SMART FIBRES

FOS&S

MICRON OPTICS

FBGS TECHNOLOGIES

gavea sensors measurement solutions

sabeus

JENA IPHT

TeraXion

Applications: Segment Areas

Oil & Gas

- Reservoir monitoring
- Downhole P/T sensing
- Seismic arrays

Energy Industry

- Power plants
- Boilers & Steam turbines
- Power cables
- Turbines
- Refineries

Aerospace

- Jet engines
- Rocket & propulsion systems
- Fuselages

Underwater

- Leaks in subsea pipeline monitoring
- Flood detection
- Hydrophone

Civil

- Bridges
- Dams
- Road
- Tunnels
- Land slides

Transportation

- Rail monitoring
- Weight in motion
- Carriage safety

Optoelectronics Group, Engineering Department
University of Sannio, Benevento (Italy)

Smart Railways Using Fiber Optic Technology

AnsaldoSTS

Università degli Studi del Sannio

CM

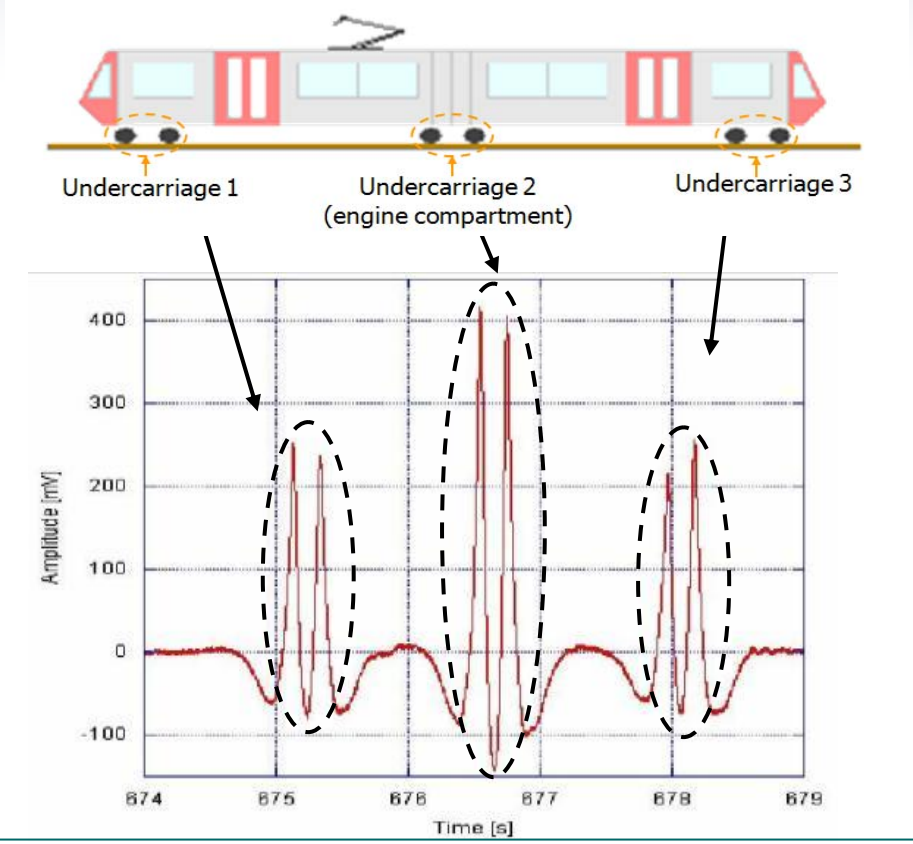
optoXsmart
OPTOELECTRONIC AND SMART SYSTEMS

Needs and Requirements

- Increasing need for improved safety, reliability and efficiency in the worldwide railway industry;
- Monitoring of railway traffic and in particular rail truck integrity;
- Require the Development of smart monitoring systems for real-time and continuous monitoring of the structural and operational conditions of rail tracks;
- Advantages for railway industry: reduced maintenance costs, optimized performance and capacity;
- Railway monitoring requires extensive sensor networks (1,000s of sensors) for multifunctional measurements (strain, vibration, velocity, temperature, acceleration, weighing in motion, traffic status, structural health …).

Feasibility: Year 2007 "Tel Station (Bz)

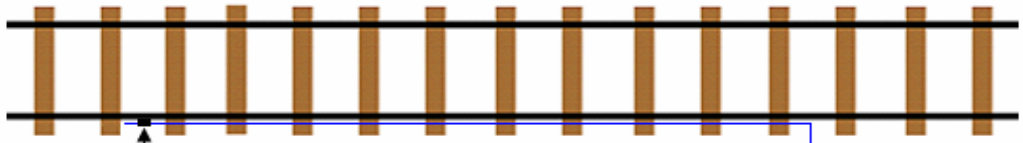
"Bare FBG" glued to the rail



A Single FBG glued to the rail, can provide useful information about:

•occupation state, train, velocity, acceleration, axle counting, weighing in motion,

December 2007 - June 2008: "Nervi (Ge) Station"
First Packaged Sensors



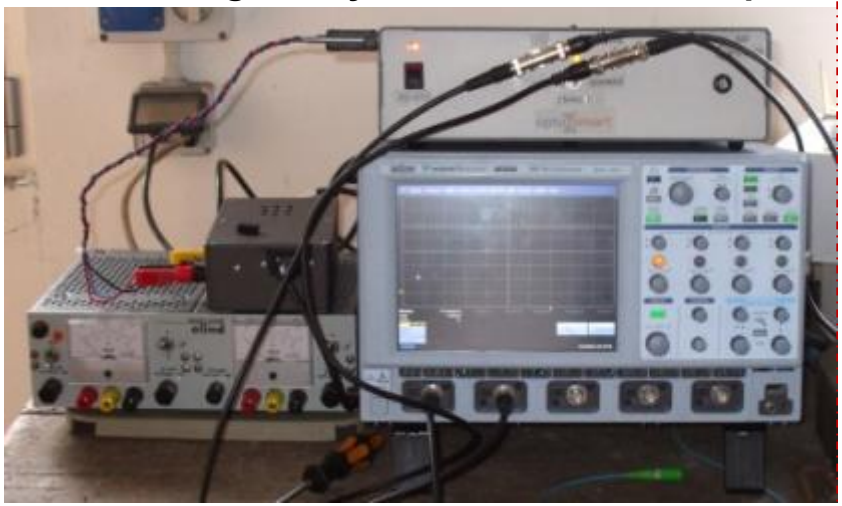
FBG

Bare FBG

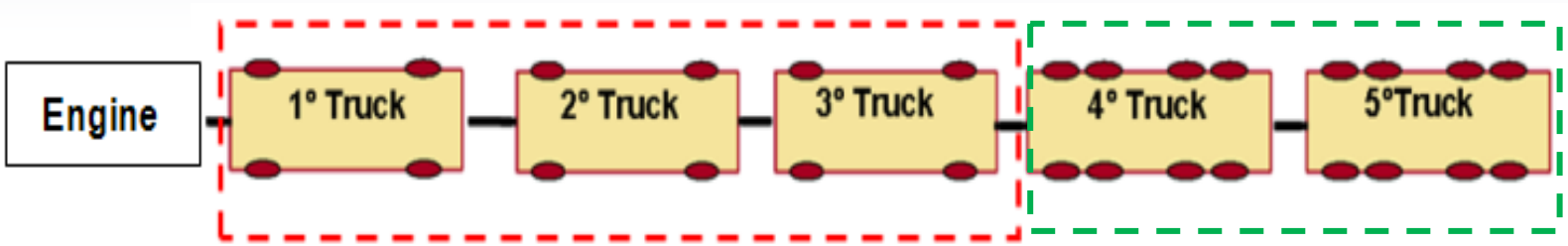
Package FBG

CONTROL ROOM

Interrogator system & measure setup

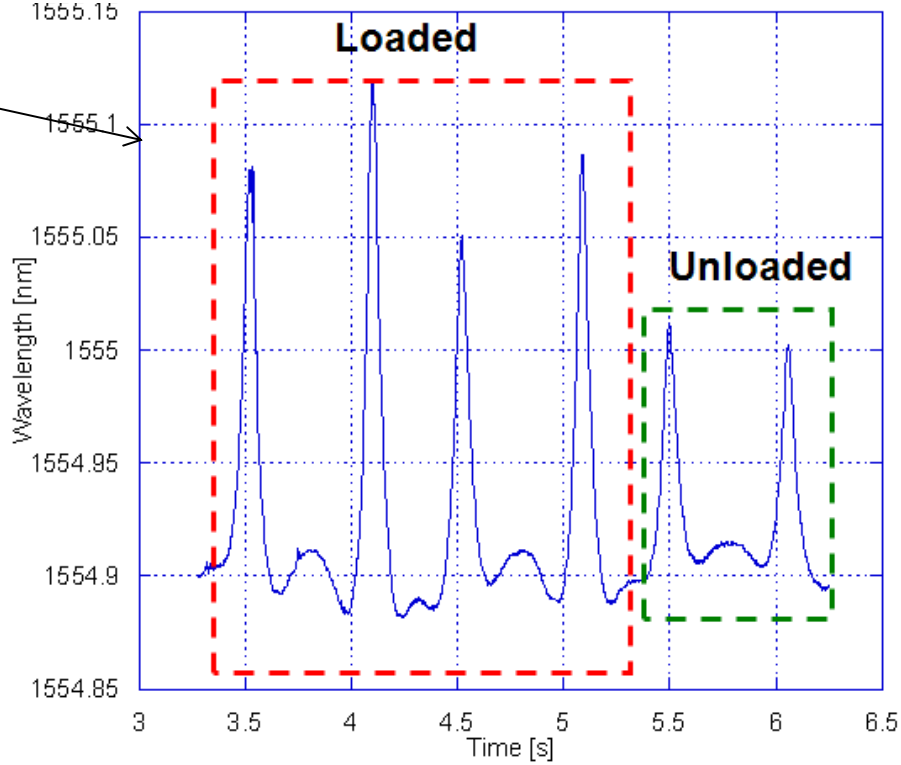


Test train with loaded and unloaded trucks



Truck loaded with concrete cube

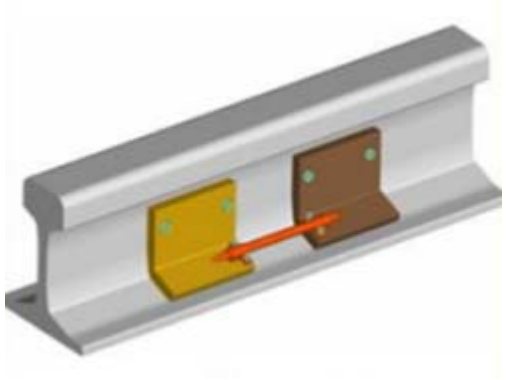
FBG soldered on the rail



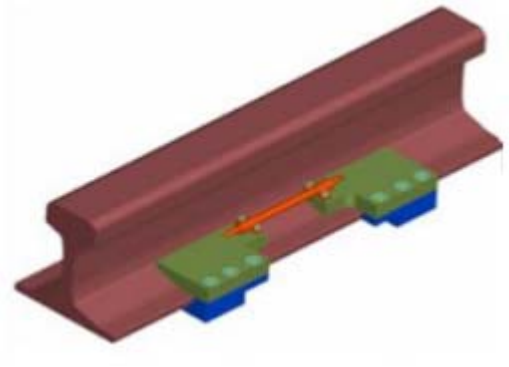
Sensors Packaging Engineering: November 2008 - December 2010 “Sezze Romano (LT) Station”

FBGs anchored to the rail, using customised metallic kit

Anchor solution A



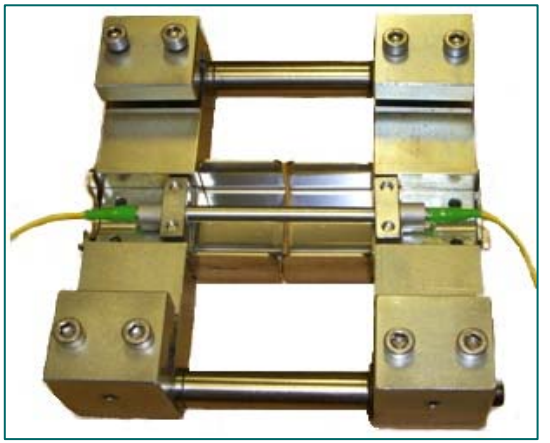
Anchor solution B



Anchor solution C

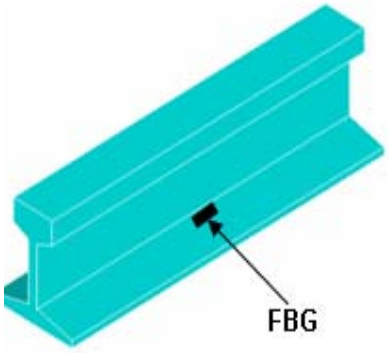
March 2011 - September 2012 :"Marcianise Station": Optimised Packaged Sensors

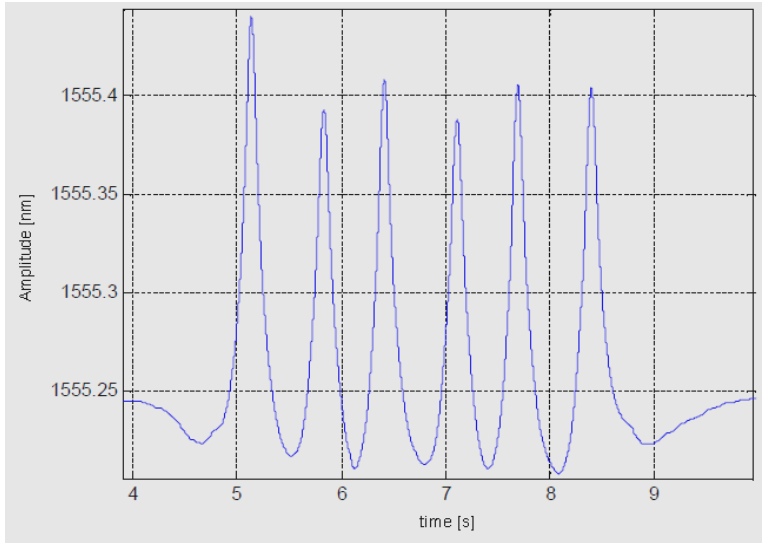
- Noninvasive
- No drilling of the rail
- Reduced installation time
- Easily removable



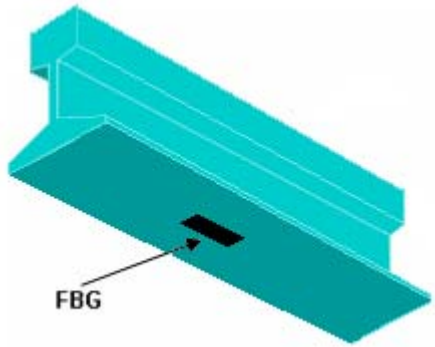
Improved Performances

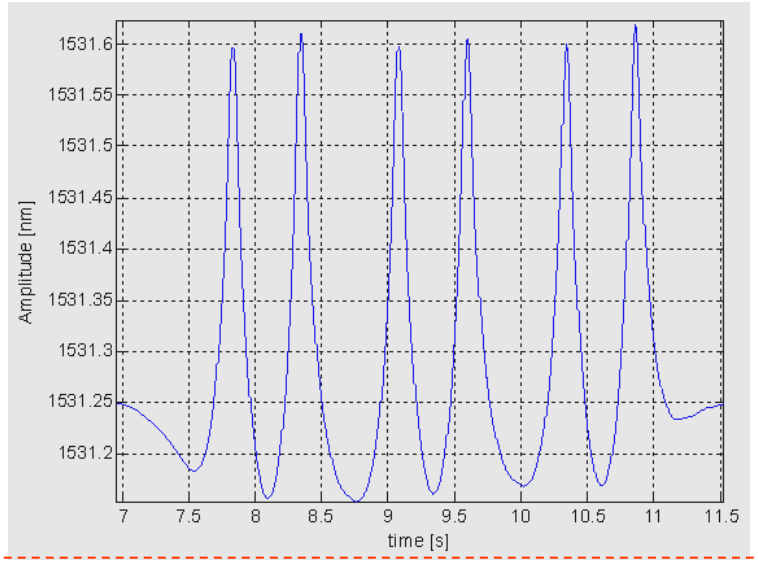
TWBCS packaging and positioning doubles sensitivity





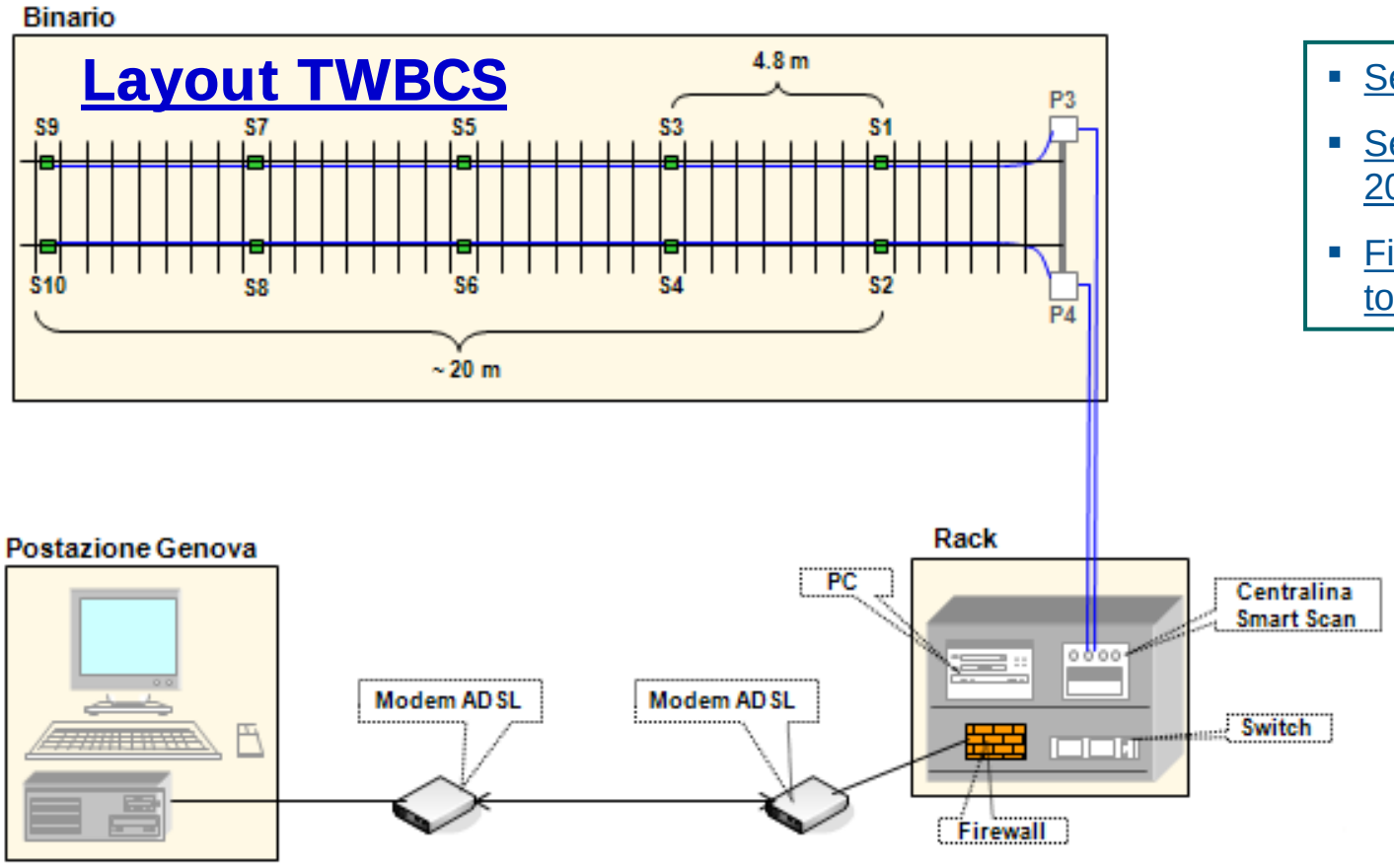
shift: ~ 200 pm per pulse





shift: ~ 400 pm per pulse

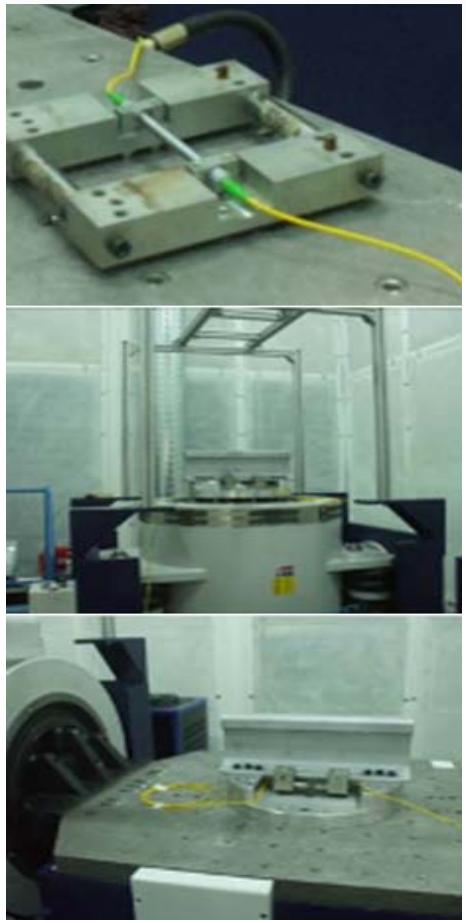
Year 2013 :TWBCS First Industrial Release



- Sensors Number: 10
- Sensorised Section length: 20m
- Fiber optic cabling ensures total electrical insulation

Certification Tests

Mechanical tests



- Vibrations: up to 280 m/s^2
- Shock: 2500 m/s^2/1ms

Solar irradiation tests

Maximum level of solar radiation : 1120 W/m2.
Temperature:60°C

Climatic tests

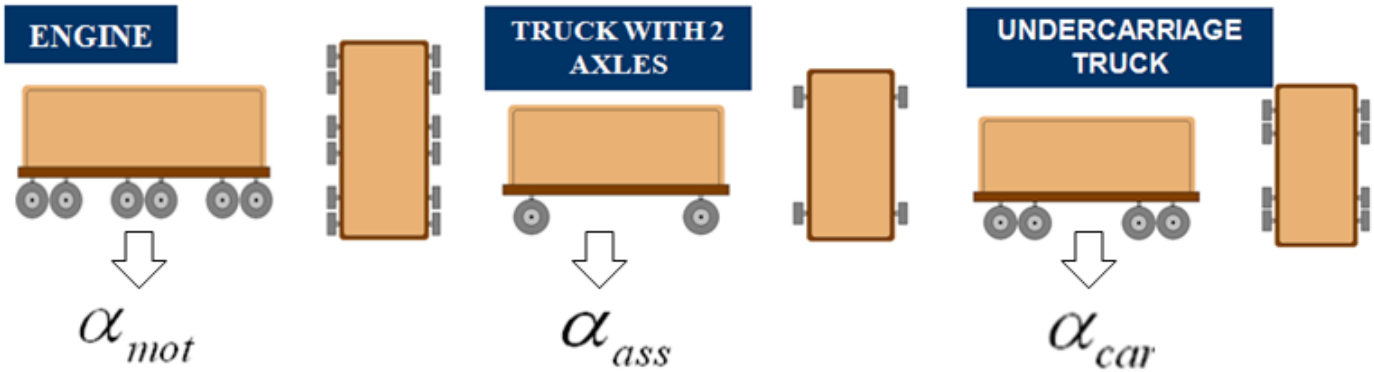
- Temperature changes : -40°C ÷ +85°C
- Hot dry test: 70°C, U.R. ≤ 60%
- Hot wet test: 55°C, U.R. 95%
- Cold test: -25°C

Immersion tests in sand and water

300 liters of water (h 50 cm) – 75 kg of sand (h 30 cm)

On line calibration

❑Calibration of FBG using all the typologies of trucks



To determinate the weight of the engine compartment :

$$P_{mot} = \alpha_{mot} * \sum_{i=1}^{6} A_i$$

To determinate the weight of axles :

$$P_{ass} = \alpha_{ass} * A_{ass}$$

To determinate the weight of undercarriages truck :

$$P_{car} = \alpha_{car} * \sum_{i=1}^{2} A_i$$

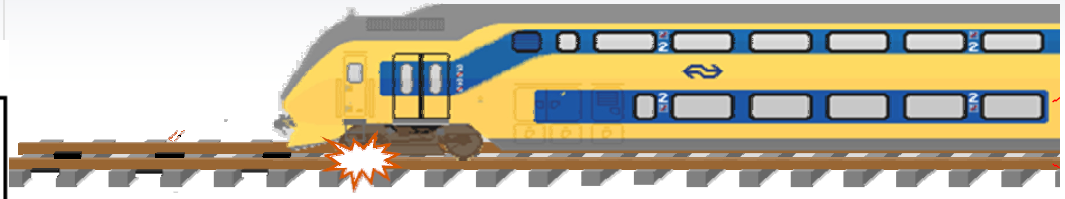
❑Calibration of FBG using only engine rail truck

α_{mot}

Optoelectronics Group, Engineering Department
University of Sannio, Benevento (Italy)

TWBCS (Train Weight Balance Control System)

Output



"A_110919_215919_total.html"

Risultato TWBCS

Scalo Merci Maddaloni/Marcianise

Data e Ora 110919_215919

Velocita 9[km/h]

Numero Vagoni 24

ID Vagone	Carrelli	Assi	Sbil. Longitudinale %	Sbil. Trasversale %	Carico [kg]
0	1	6	50	49	106890
1	2	4	52	48	57710
2	2	4	50	49	72364
3	2	4	46	50	57884
4	2	4	48	48	61336
5	2	4	49	49	70462
6	2	4	49	50	73094
7	2	4	49	51	63936
8	2	4	50	50	65042
9	2	4	49	53	70926
10	2	4	54	47	77308
11	2	4	52	47	74750
12	2	4	49	47	75178
13	2	4	49	48	58012
14	2	4	49	49	74880
15	2	4	49	50	71944
16	2	4	49	50	74254
17	2	4	50	53	64844
18	2	4	49	49	65300
19	2	4	49	48	71950
20	2	4	49	49	64818
21	2	4	51	49	59256
22	2	4	53	51	72226
23	1	6	50	48	106518

Peso Totale Convoglio 1710882 [kg]

"A_110919_215919_wheel.html"

Risultato TWBCS

Scalo Merci Maddaloni/Marcianise

Data e Ora 110919_215919

Velocita 9[km/h]

Numero Vagoni 24

ID Asse	Carico DX [kg]	Carico SX [kg]
0	9012	8803
1	9012	8803
2	9012	8803
3	9012	8803
4	9012	8803
5	9012	8803
6	7840	7426
7	7840	7426
8	7037	6552
9	7037	6552
10	9184	8918

Server TWBCS

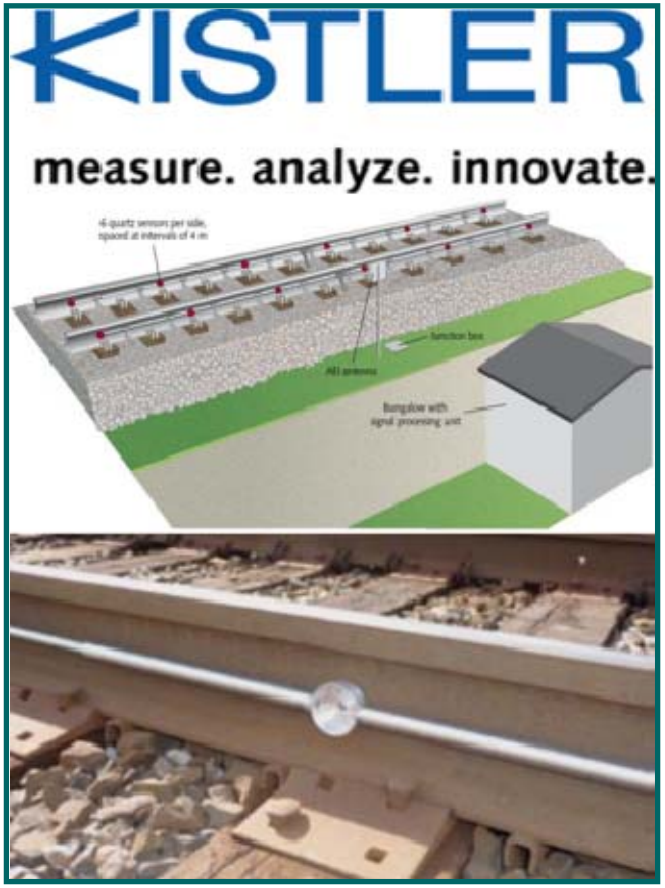
- **Weight for Wheel;**
- **Weight for Wagon;**
- **Type of wagon;**
- **Info about train composition**

TWBCS : Performances and Certification

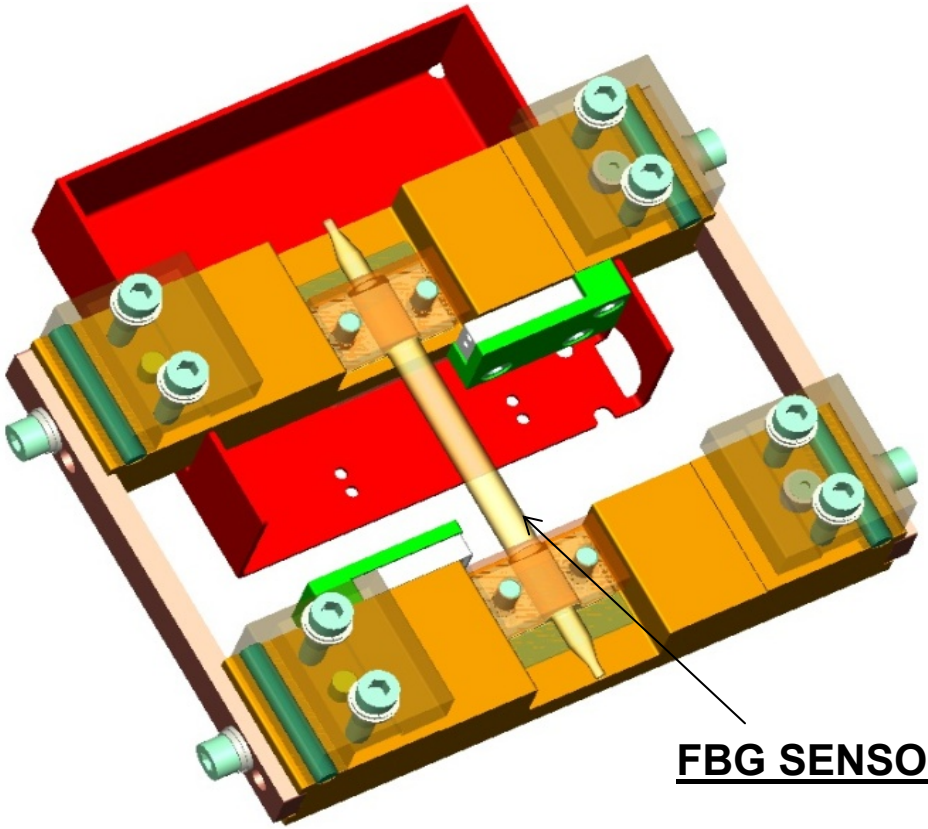
- Number of transits examined : 100

	|Error| Mean %	
Typology	FBG	KISTLER
Engine Truck	1	8
Undercarriages Truck	6	4
Truck with 2 axles	2	7

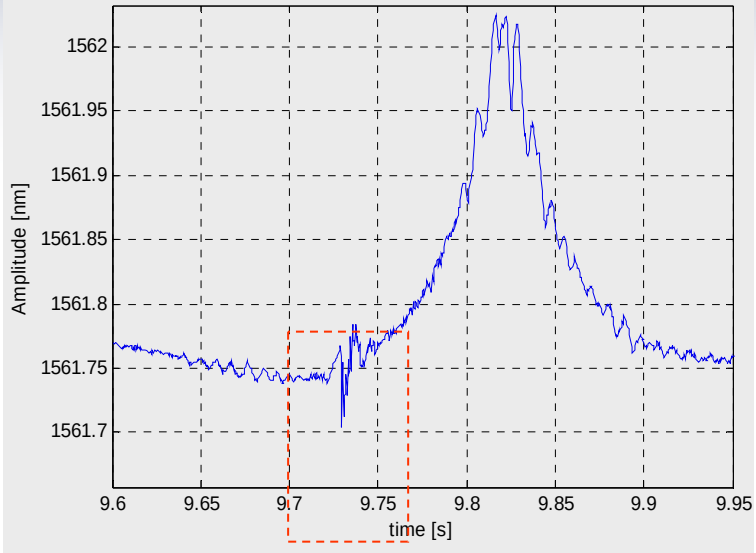
KISTLER USES QUARTZ SENSOR, INSTALLED BY DRILLING OPERATIONS



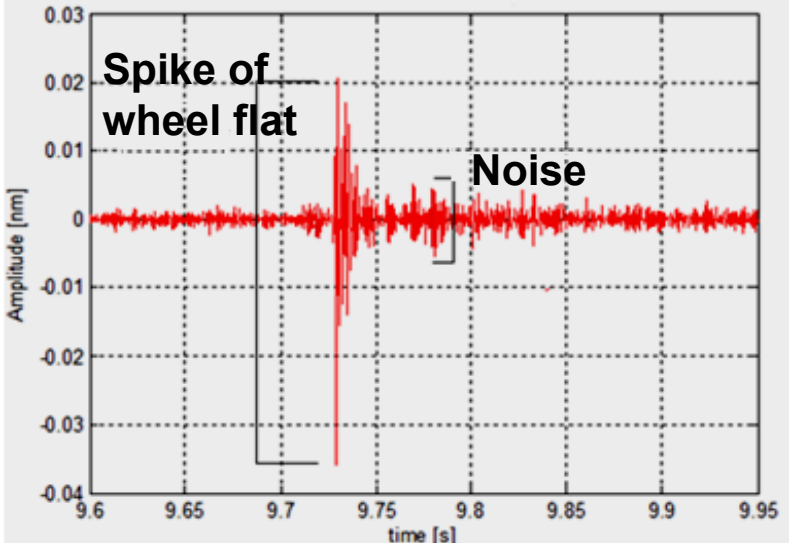
Add Functionality: Wheel flat detection



FBG SENSOR RESPONSE: RAW DATA



AFTER ELIMINATING STATIC CONTRIBUTE



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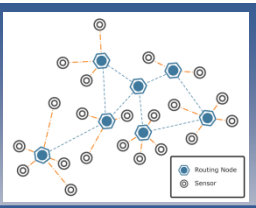


Sicurfer
Tecnologie per la Sicurezza Ferroviaria

UNIONE EUROPEA
Fondo europeo di sviluppo regionale
PON Ricerca e Competitività 2007-2013
Ministero dell'Istruzione, dell'Università e della Ricerca
Ministero dello Sviluppo Economico
investiamo nel vostro futuro

Innovative Technologies for Safety and Security of Railway Systems

PON Ricerca: 2012-2015
10MEuro

Main Partners

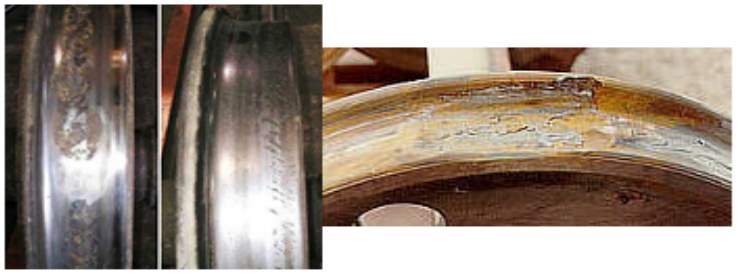
AnsaldoSTS
Università degli Studi del Sannio
softeco sismat information technology
RFI RETE FERROVIARIA ITAL
GRUPPO FERROVIE DELLO STATO ITALIANE
ISARail
CIRCUMVESUVIANA
SELEX ELSAG
Secure Networking Solutions
A Finmeccanica Company
Contact Srl
STRACO
intecs
the Brainware company
3F & EDIN

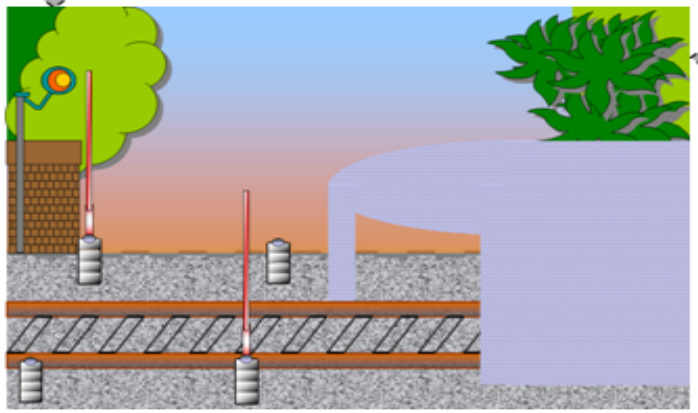
Optical Fibers: A Unique Multifunctional Technological Platform

sicurfer
Tecnologie per la Sicurezza Ferroviaria

Weight in motion

Wheelflat detection





Landslide

Temperature monitoring (rail/tunnel)

Anti – intrusion system

Optoelectronics Group, Engineering Department
University of Sannio, Benevento (Italy)

RESEARCH PROJECT "ASSO"

- *Supported by Italian Ministry of University and Research*
- Funding : 7 M€
- Duration: 3 years

In collaboration with:

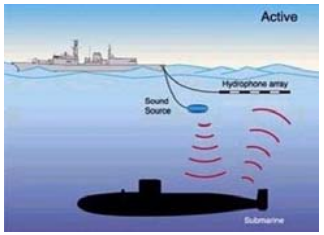
WASS
A Finmeccanica Company

optoXsmart
OPTOELECTRONIC AND SMART SYSTEMS

CENTRO REGIONALE
INFORMATION COMMUNICATION TECHNOLOGY
CERICT SCRL

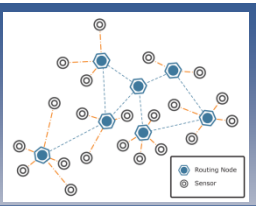
Aim: *To get high-performance opto-acustic antennas, based on Fiber Bragg Grating (FBG) technology, for military, environmental and industrial underwater applications*

Military applications



Marine environmental monitoring

Medical

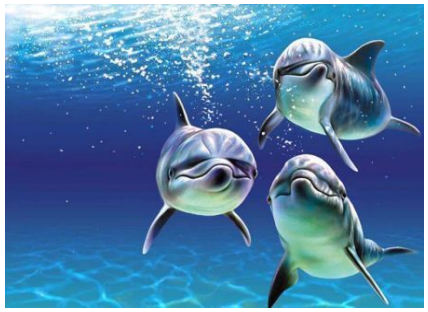


Comparison with Traditional Hydrophones

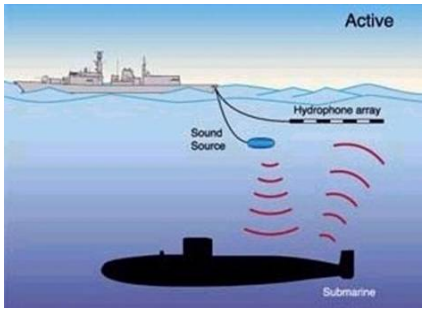
Traditional hydrophones

- *Electromagnetic sensitivity*
- *Water seepages*
- *Heavy and bulky*

Marine environmental monitoring



Military applications



Fiber optic hydrophones

- *Immunity to Electromagnetic Interferences*
- *Light and small*
- *No electric connections*
- *Remote monitoring*
- *Multiplexing capability*

Medical

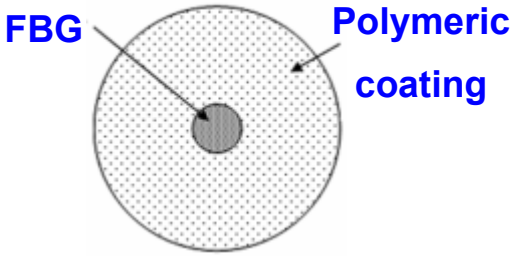
HYDROSTATIC ANALYSIS

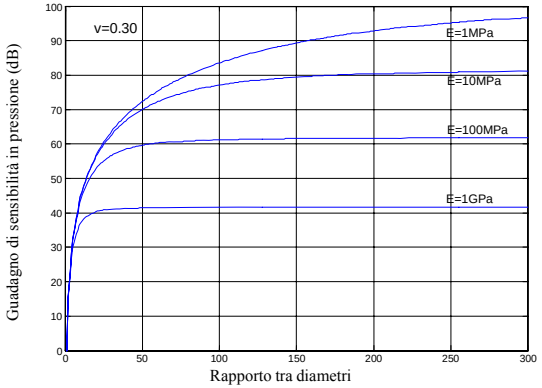
Pressure Sensitivity in FBGs

FBGs exhibit low pressure sensitivity essentially due to the high Young module of the optical fibre material (tens of GPa) which converts the effects of high pressures applied on the grating in weak deformations.

Solution

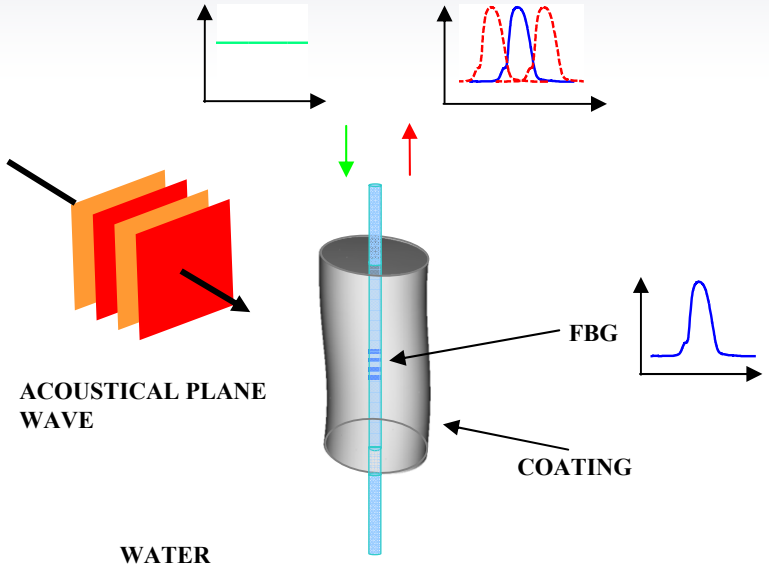
Fiber optic hydrophone: FBG coated with a polymeric coating





A proper choice of elastic and geometrical properties of the coating allows a significant sensitivity enhancement

DYNAMIC ANALYSIS: ACOUSTIC WAVE DETECTION



FBG hydrophones based on standard FBGs coated by a ring shaped overlay

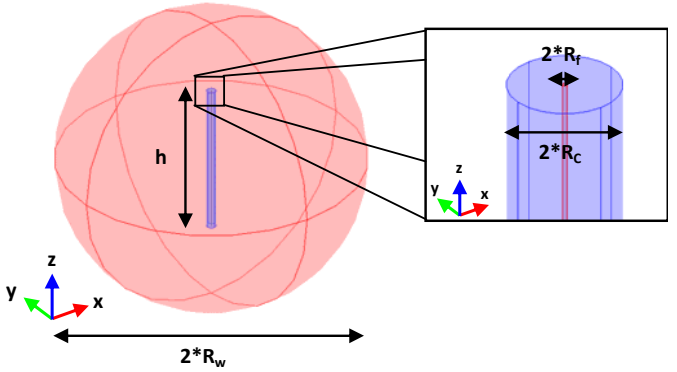
We studied, via full-wave numerical simulations, the complex opto-acousto-mechanical interaction among an incident acoustic wave traveling in water, the optical fiber surrounded by the ring shaped coating, and the FBG inscribed in the fiber

- COMSOL Multiphysics™ is used as FEM solver

  The 3D geometry is composed by an inner cylinder (*fiber*), an outer cylinder (*coating*) and a sphere (*truncated water domain*)

- The acoustical frequency range is 0.5 – 30 kHz

FEM geometry



M. Moccia, A. Cusano et al, **Opt. Express** 19, 18842-18860 (2011)
M Moccia, A. Cusano et al, ***Best Paper Award*** at the 21st International Conference on Optical Fiber Sensors, 2011

Optoelectronics Group, Engineering Department
University of Sannio, Benevento (Italy)

OPTO-ACOUSTIC-MECHANICAL: AN INTEGRATED DESIGN TOOL

COMSOL Multiphysics™ solve the problem with appropriate boundary conditions

Acoustics
(acoustic wave propagation)

$$\nabla^2 p + \left(\omega/c\right)^2 p = 0$$

ω angular freq., ***p* pressure**,
c sound speed

Mechanics
(elastic wave propagation)

$$\mu\nabla^2\mathbf{u} + \left(\tilde{\lambda} + \mu\right)\nabla\left(\nabla\cdot\mathbf{u}\right) + \rho\omega^2\mathbf{u} = -\tilde{\mathbf{f}}$$

***u* displacement**, $\tilde{f}$ load,
$\tilde{\lambda}$,μ Lamè const., ρ density

Optics
(Bragg wavelength shift with strain)

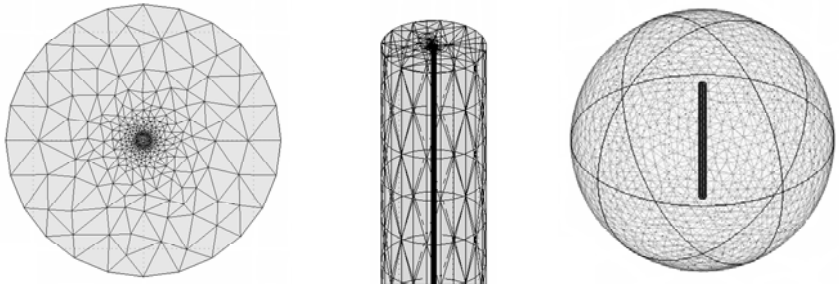
$$\frac{\Delta\lambda}{\lambda} = \varepsilon_z - \frac{n_{eff}^2}{2}\left(p_{11}\varepsilon_x + p_{12}\left(\varepsilon_z + \varepsilon_y\right)\right)$$

ε_i strain comp., **λ Bragg wavelenght**,
p_{ij} elasto-optic coeff., n_{eff} effective refr.ind.

Boundary conditions

- Inner/outer cylinder
  - Continuity of stresses and displacements
- Coating/water
  - Pressure in static equilibrium with stress normal to boundary
  - Normal displacement of solid and fluid are equal
  - No tangential stresses occurs
- Water sphere surface
  - No reflection of incident waves

Geometry discretization



MATERIAL SELECTION: LOW FREQUENCIES

Project "ASSO" defines among the needs and requirements two operating frequency ranges for the underwater acoustic sensors:

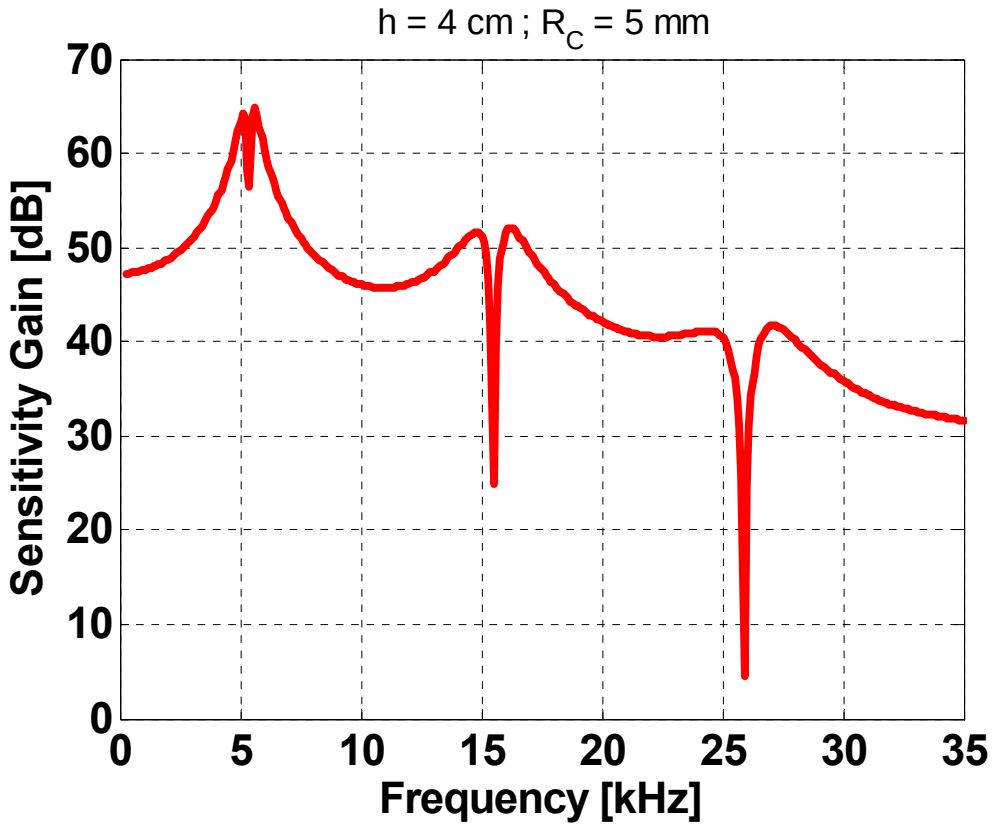
- **a "low" frequency range 0-15 kHz**
- **a "high" frequency range 15-30 kHz**

vonRoll

DAMIVAL 13650

E= 200 MPa
ν=0.4
ρ=1180 kg/m^3
η=0.1

- Thermosetting polyurethane resin
  - Perfect fiber bonding
  - Waterproof



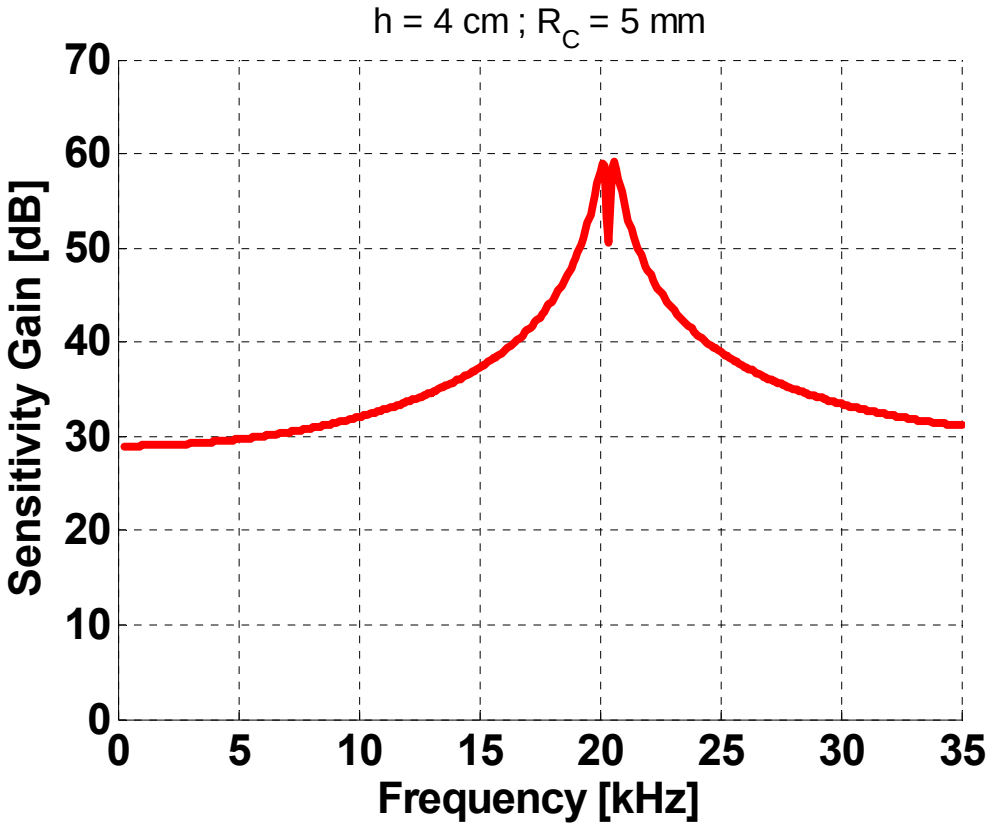
MATERIAL SELECTION: HIGH FREQUENCIES

HUNTSMAN

ARALDITE DBF

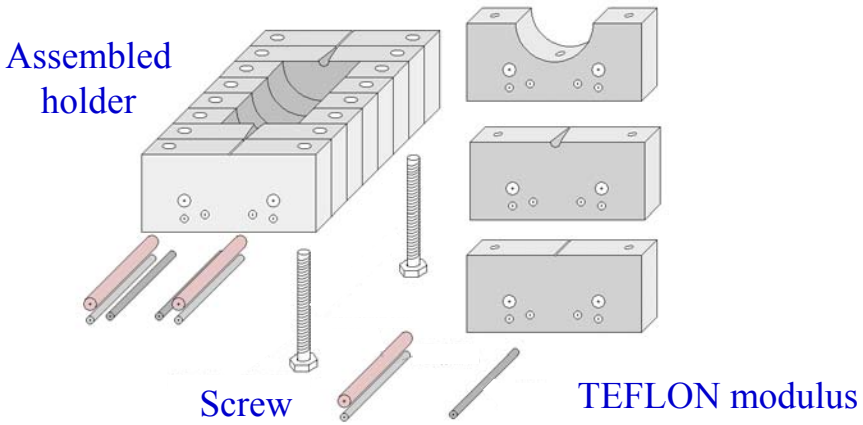
E= 2.9 GPa
ν=0.345
ρ=1100 kg/m^3
η=0.02

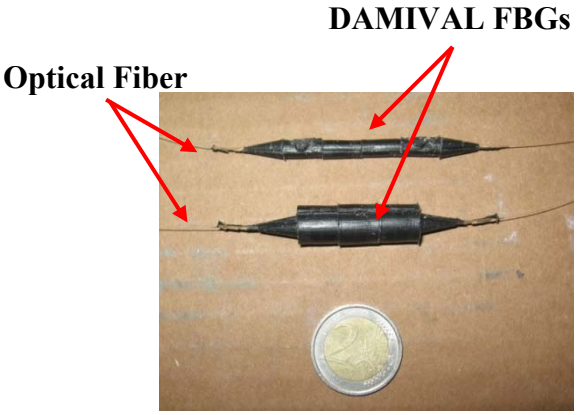
- Low viscosity epoxy resin
- Adhesive resin
- Perfect fiber bonding



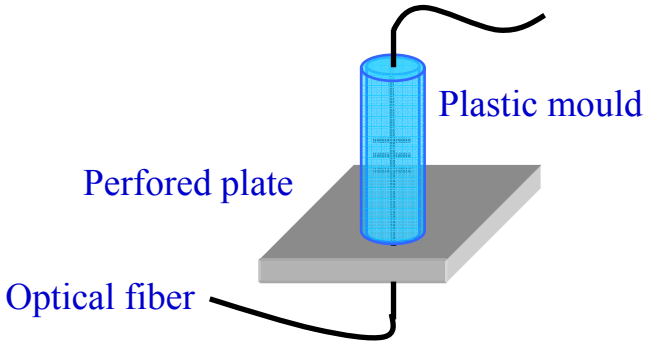
FIRST OPTO-ACOUSTIC ANTENNAS

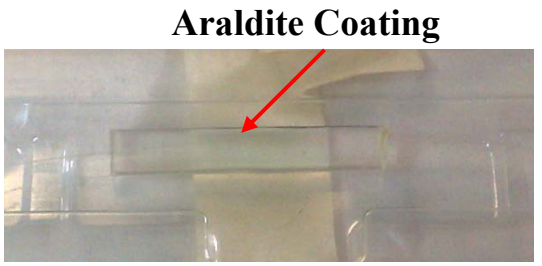
A TEFLON® modular holder was properly designed to fabricate DAMIVAL cylindrical coatings with different sizes.



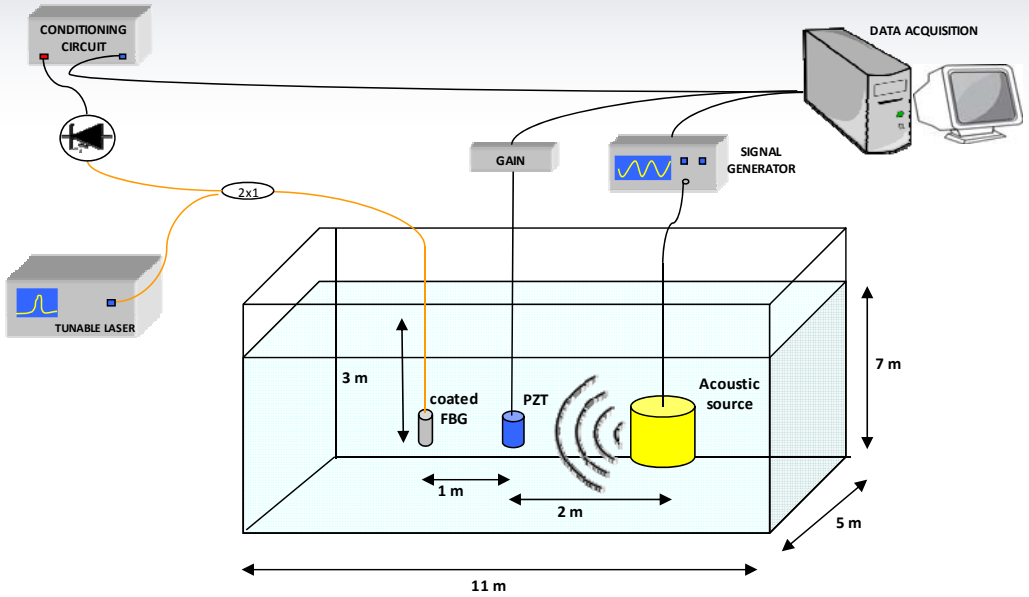


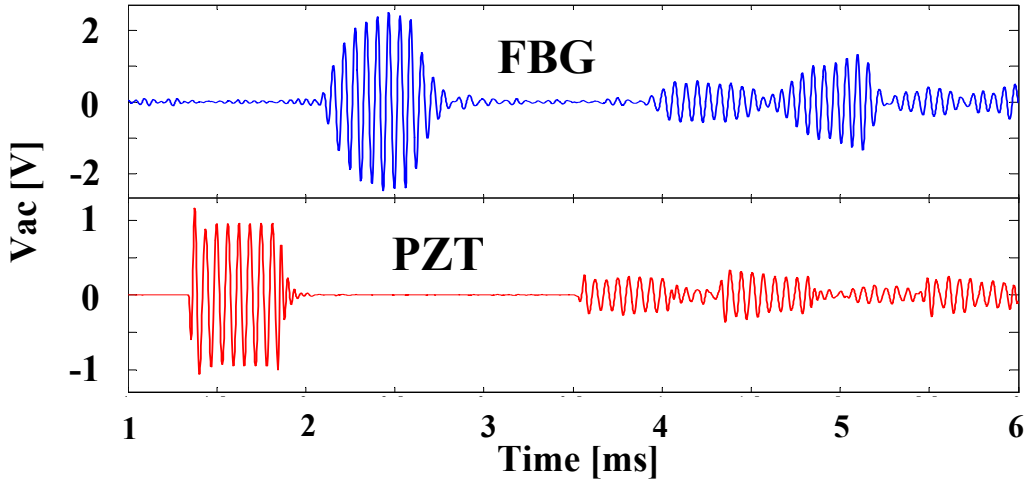
A cylindrical holder was properly designed to fabricate ARALDITE coatings.



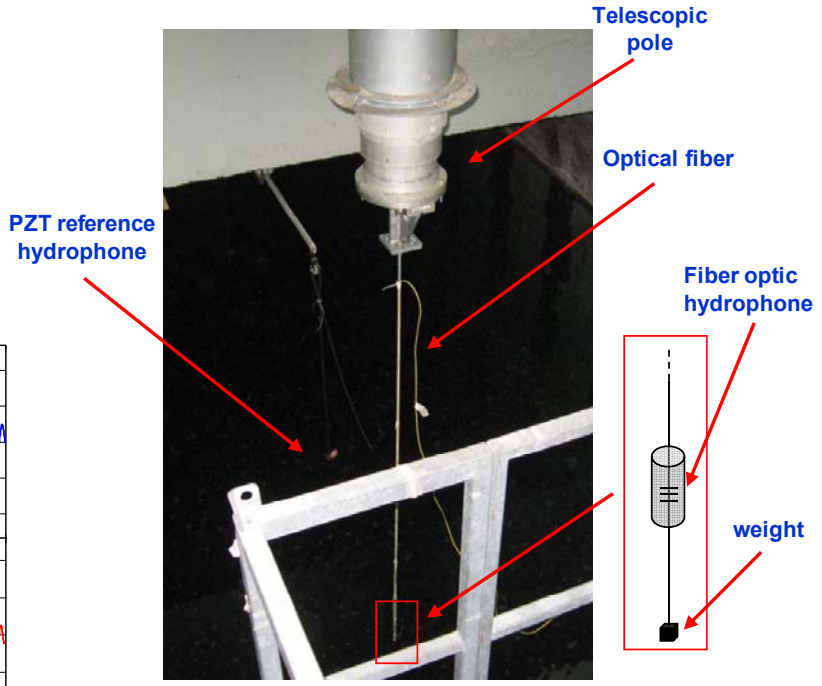


EXPERIMENTAL VALIDATION

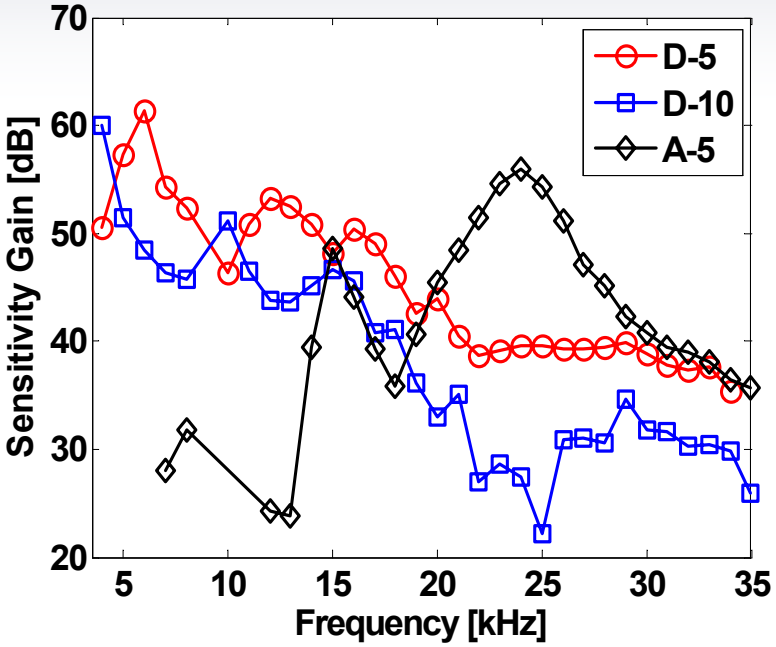


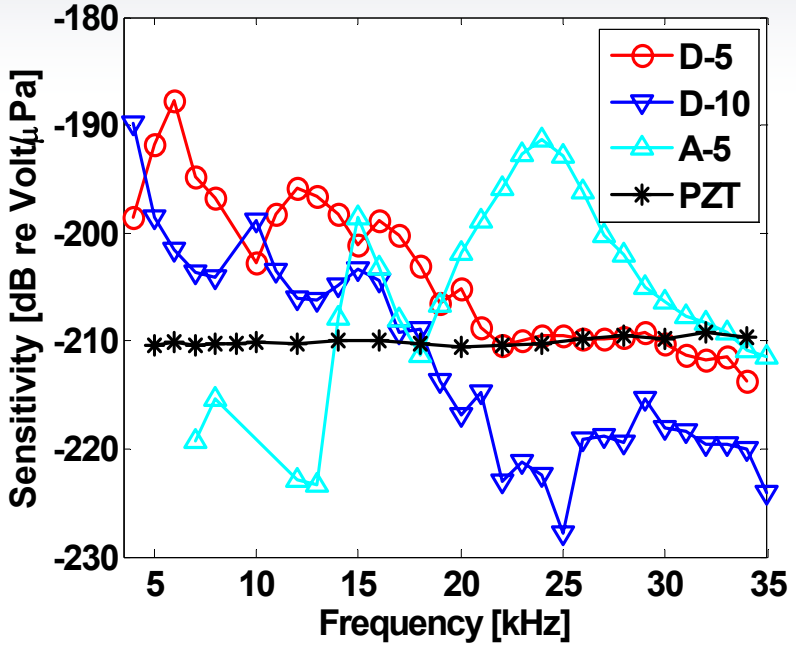


WASS
A Finmeccanica Company



SENSOR PERFORMANCES





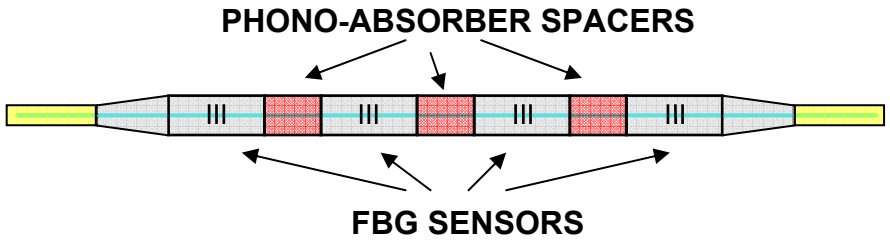
- **Sensors with Damival coating are more sensitive than PZT in the frequency range 4-20kHz**
- **Sensors with Araldite coating are more sensitive than PZT in the frequency range 15-35kHz**

- **Sensitivity improvement with respect to bare FBG of 2-3 order of magnitude**
- **Sensitivity comparable or higher than traditional PZT and other photonic technologies at the state of the art**

M. Moccia, A. Cusano et al, **Journal of Lightwave Technology**, 30 (15), 2472- 2481 (2012)

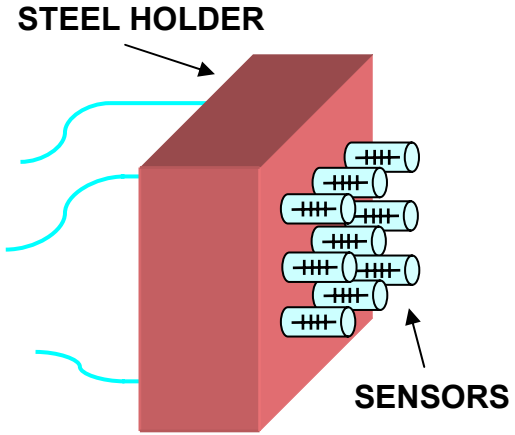
TOWARDS INDUSTRIALIZATION

Flexible array : **Material** : Damival **Array** : 4x1 **Sensors** : D-5



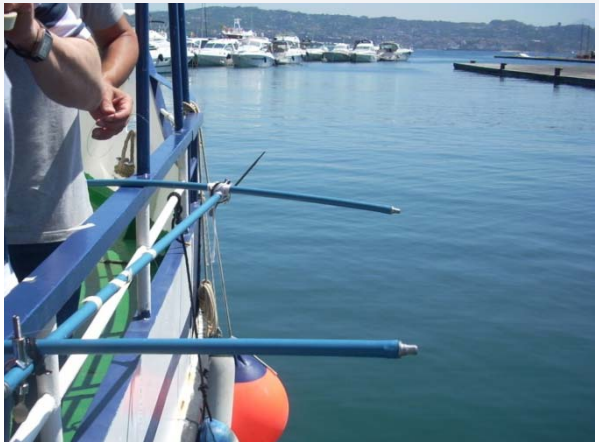
Phono-absorber spacers keep FBG sensors mechanically and acoustically separated

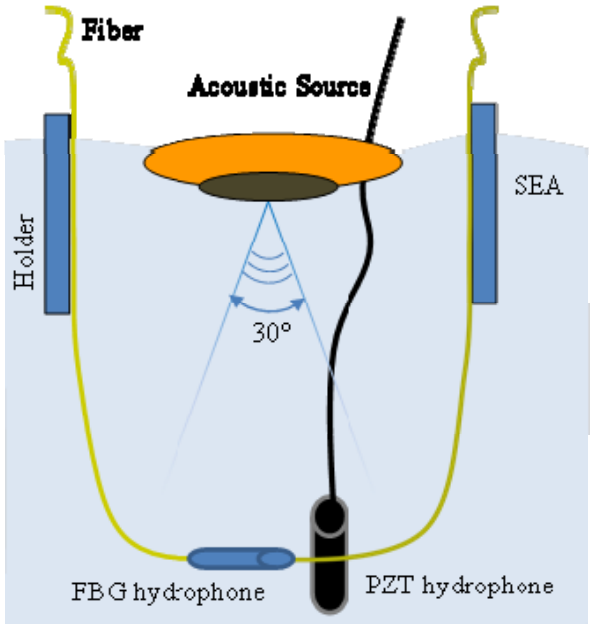
Rigid array : **Material** : Araldite **Array** : 4x4 **Sensors** : A-5



OFFSHORE PRELIMINARY TEST

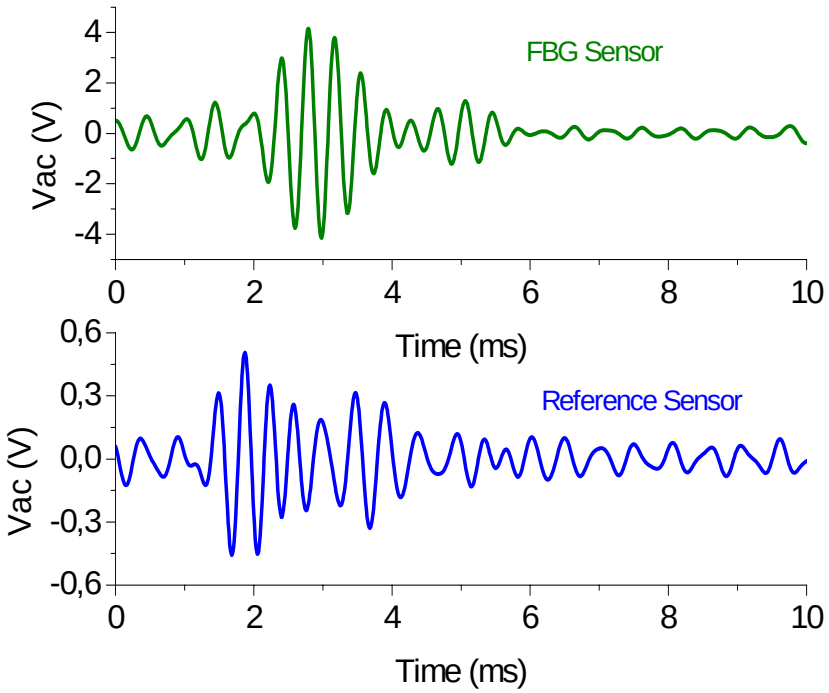
PZT





- Port of Baia, Napoli
- FBG Sensor: D-5
- Sea environment with high noise

Sensor time response



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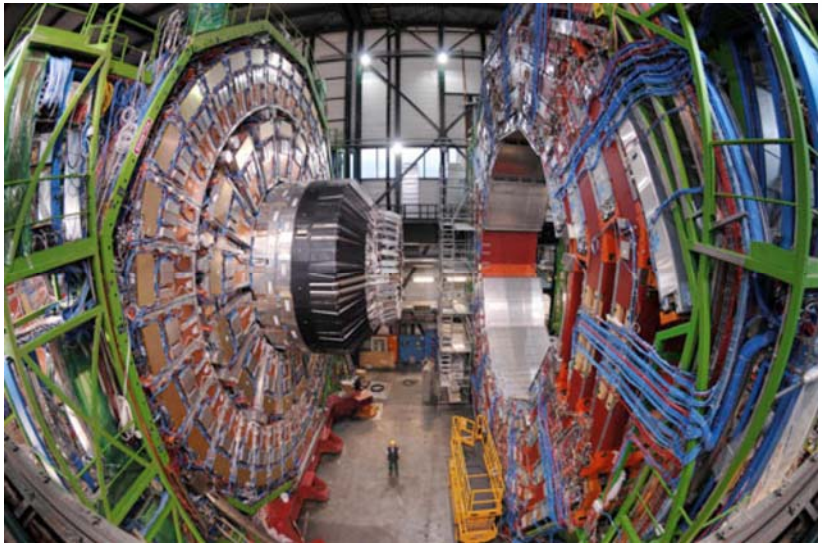
Fiber Optic Sensors for High Energy Physics Applications

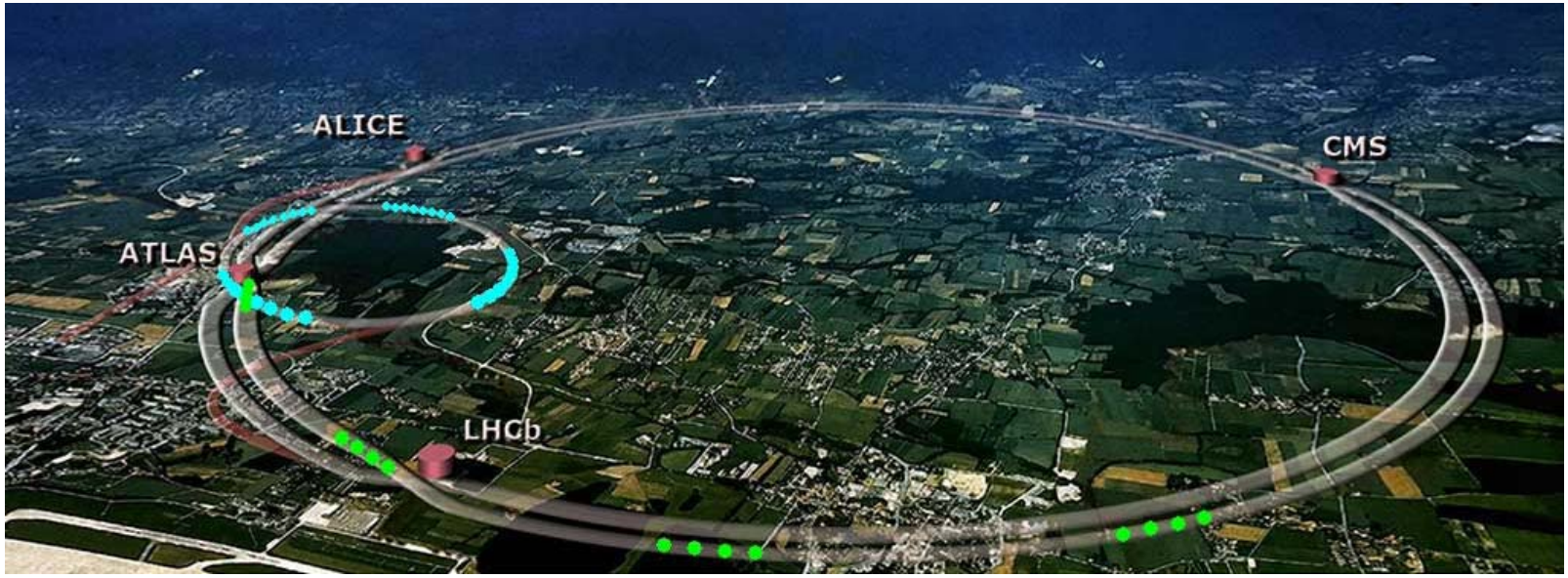


Fiber Optic Sensor Community
(academic and industrial partners)

CMS Collaboration @ CERN

FOS4HEP Project

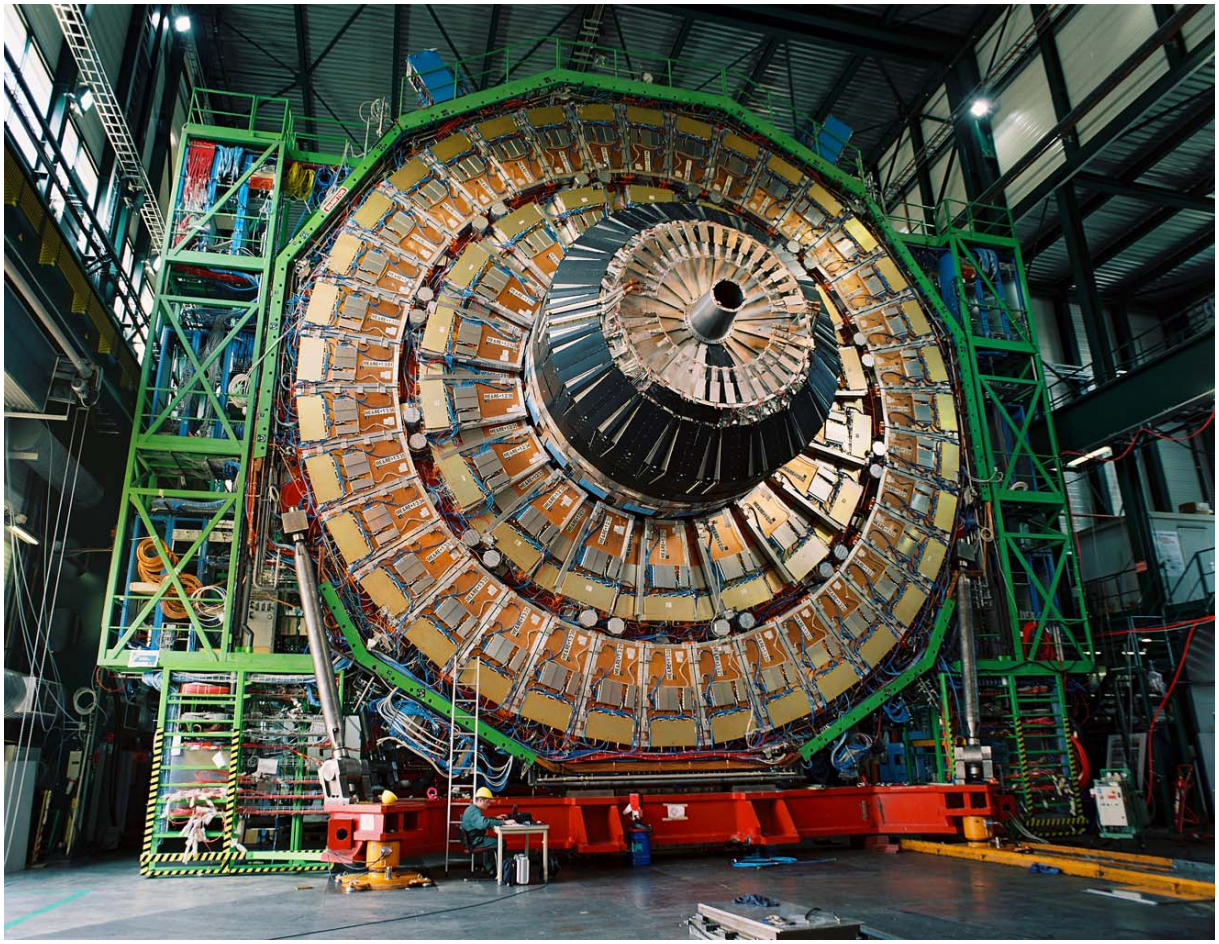
High Energy Physics at CERN



CERN (European Organization for Nuclear Research) from 1954
Large Hadron Collider (LHC) housed in a 27 km tunnel and 100 m underground
4 main experiments running

CMS: Needs and Requirements

Compact because it is "small" for its enormous weight, muon for one of the particles it detects, and solenoid for the coil inside its huge superconducting magnet.



Needs:

Thousands of sensors for the monitoring and control of CMS operations

(SAFETY and SECURITY are fundamental in these types of experiments operating in extreme conditions)

Parameters to be detected:

Temperature, Humidity, pressure, magnetic induced strain, displacements magnetic field, gases, cryo sensors, and many others

Requirements:

Reduced cabling
Radiation Hardness
Electromagnetic immunity

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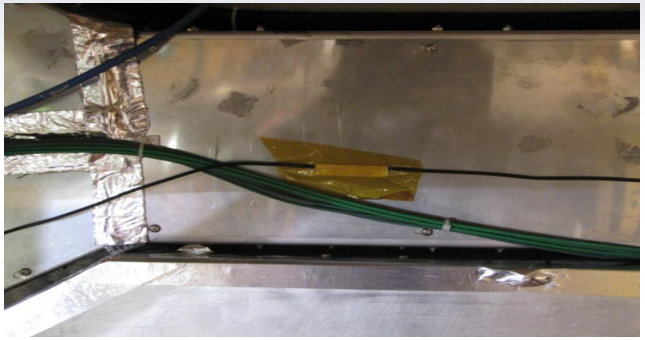
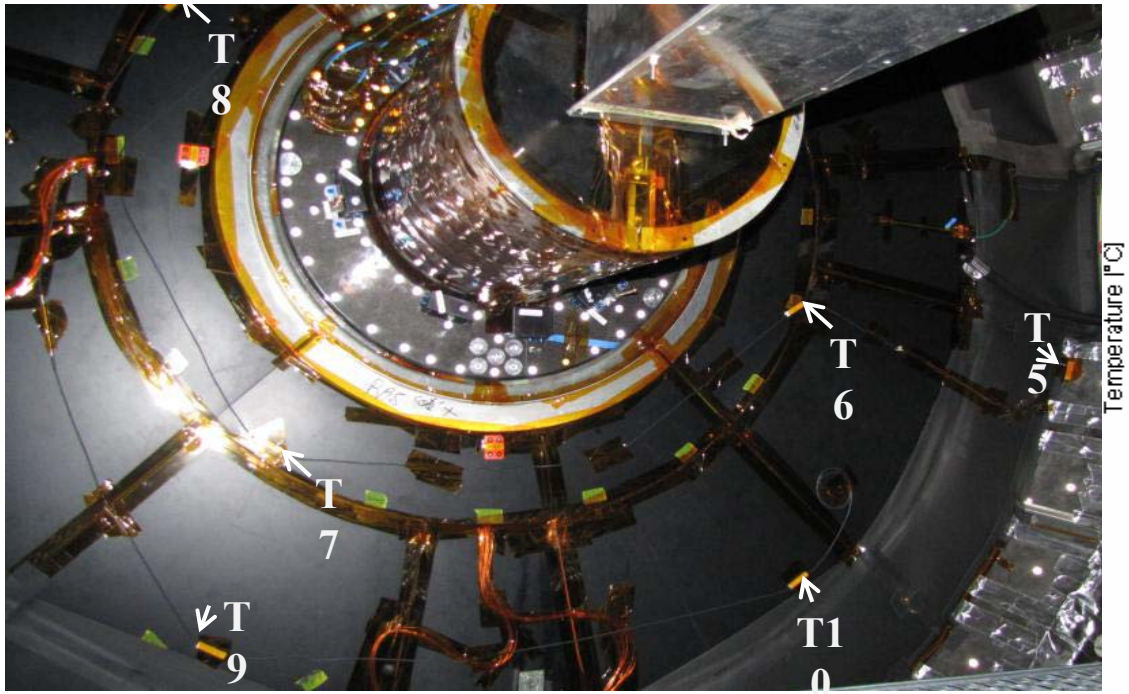
Fiber Optic Temperature Sensors at CMS

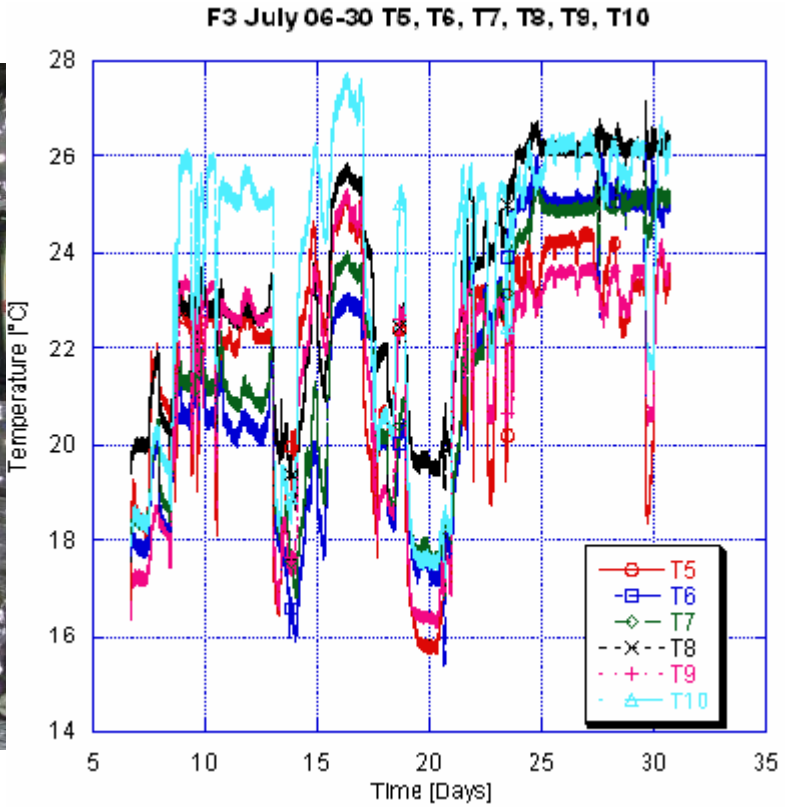


Ceramic packaging for radiation hardness

Coating absence on FBGs to avoid radiation induced craking and aging

A. Saccomanno, A. Cusano et al, **IEEE Sensors Journal**, 12(12), 3392- 3398 (2012)

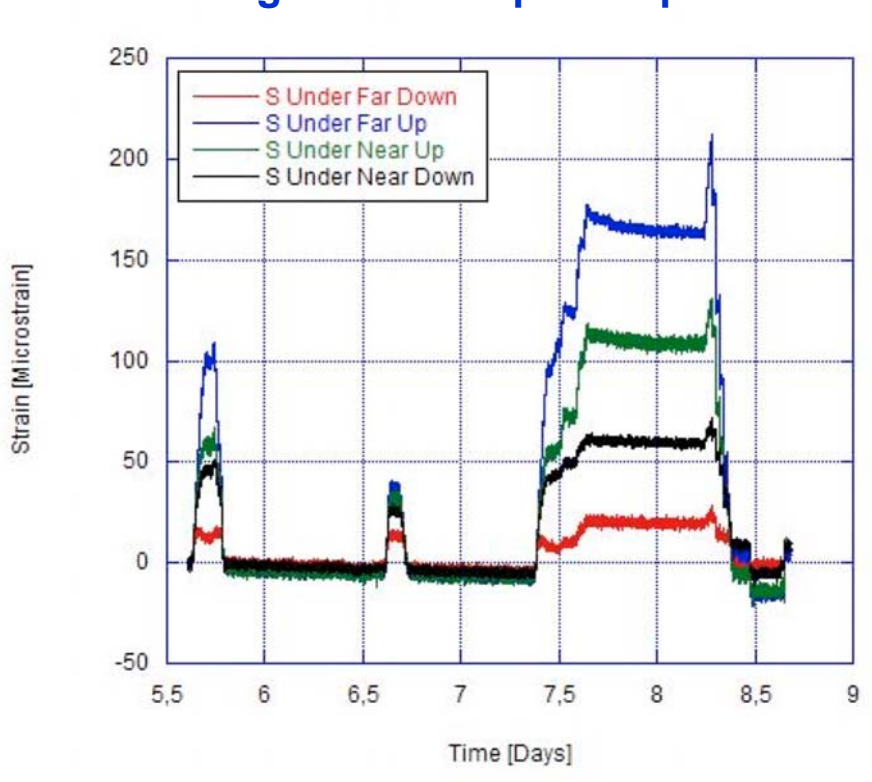




Strain Monitoring at CMS

High B field causes strain within iron structures leading to possible structure re-shaping

This effect is very dangerous since it can cause the damaging of the beam pipe leading to catastrophic explosions



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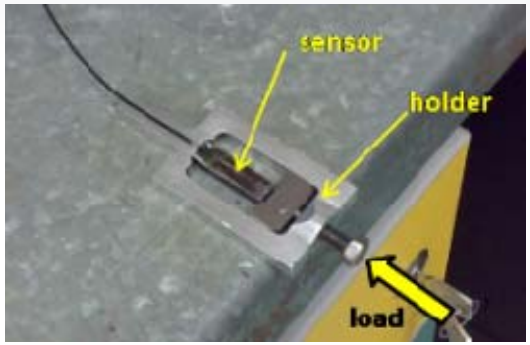
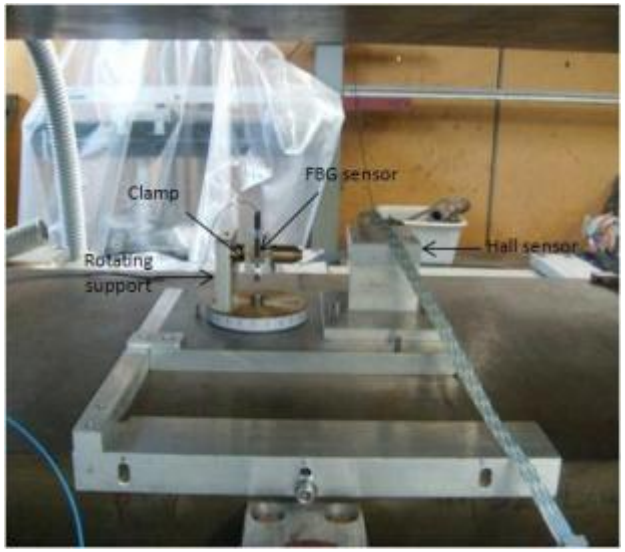
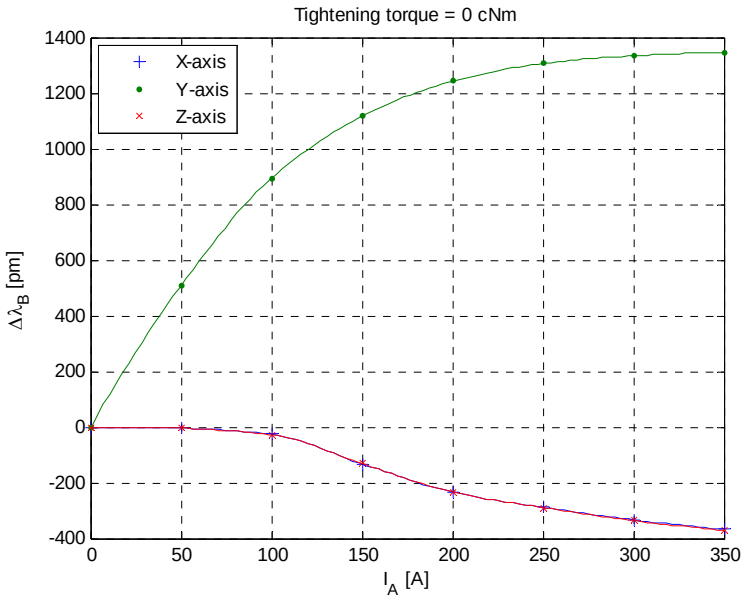
Fiber Optic Magnetic Field Sensors at CMS



Magnetic field measurement by magnetostrictive materials using.

They deform in the presence of magnetic field and an optical FBG converts mechanical deformations in optical signal; then, the optical interrogator replies the size magnetic measuring



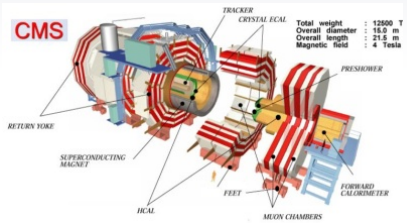


"Effect of the Anisotropic Magnetostriction on Terfenol-D Based Fiber Bragg Grating Magnetic Sensors," G. Lanza, G. Breglio, M. Giordano, A. Gaddi, S. Buontempo, A. Cusano, Sensors & Actuators: A. Physical 172 (2011) pp. 412-419

Optoelectronics Group, Engineering Department
University of Sannio, Benevento (Italy)

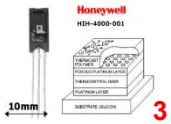
Humidity Sensors Issues in HEP Trackers

- ✓ Low mass and Small dimensions
- ✓ Insensitivity to magnetic field
- ✓ Operation at temperature down to -40˚C and response to the full range [0, 100]% RH
- ✓ Reduced number of wires
- ✓ High long term stability and/or possibility of an easy remote recalibration
- ✓ Radiation resistance to dose up to 1 Mgy



Miniaturized humidity sensors used at CERN

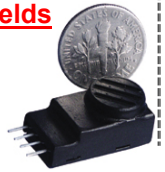
HIH 4000 series by Honeywell



Capacitive
Small Size
Inexpensive
3 wires for each RH measuring point
Accuracy of 3,5%RH
Response time 15s
Minimum operation temperature -40°C
NOT Radiation hard

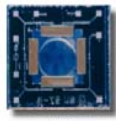
Precon HS2000

Pin #	1	2	3	4
Pin 1	Temperature Out (0 to Vsupply)			
Pin 2	Power (2 to 5.5 volt)			
Pin 3	RH Out (0 to Vsupply)			
Pin 4	Ground			



Capacitive
Small Size
Easy in use
Direct reading of Dew Point
NOT radiation hard
Sensitive to B fields

Hygrometrix HMX



Resistive
Small size
Tolerant to radiations
Extremely low response
Complex chain of read-out
over long distances
Highly not linear signal
NOT AVAILABLE on the market any more

For HEP detectors, multi-point distributed measurements and insensitivity toelectro-magnetic noise and resistance to ionizing radiations are a MUST.

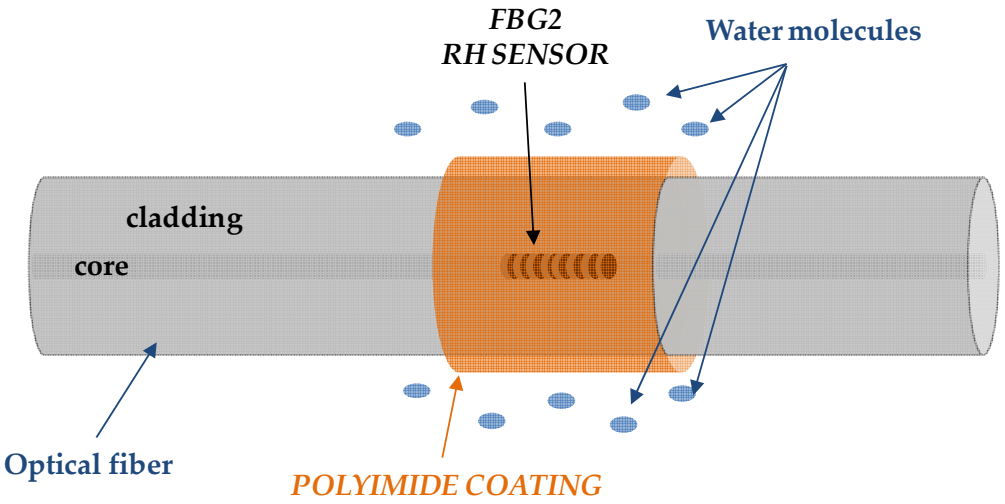
NOWADAYS THERE IS NO MINIATURIZED HUMIDITY SENSOR ON THE MARKET WELL SUITED FOR HEP DETECTOR APPLICATIONS

FBG as Humidity Sensor

- Bare FBGs are insensitive to humidity.
- Use of a sensitive material as coating of the FBG to induce a mechanical effect.
- Hygroscopic polymers swell upon adsorption of water molecules.

Development of humidity sensor by coating the FBG with a polyimide film.

Water molecules absorbed by the hygroscopic coating → **Coating expansion ("Swelling")** → **Strain induced on the FBG** → **Bragg wavelength shift ($\Delta\lambda_B$)**

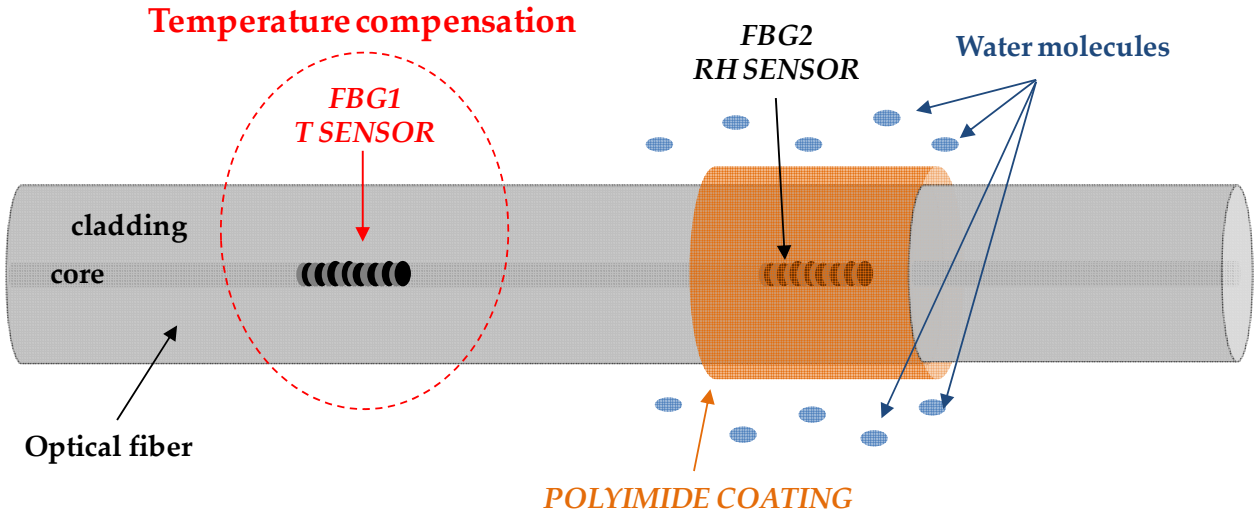


Temperature compensation

Polyimide-coated FBGs are also sensitive to temperature:

$$\Delta\lambda_B = f(\Delta T, \Delta RH) = S_T(T, RH)\cdot\Delta T + S_{RH}(T, RH)\cdot\Delta RH$$

- A temperature compensation scheme is required to extract RH measurements from the sensor readings, that can be simply accomplished by using an uncoated FBG (on the same fiber)



2011: FBGs as humidity sensors in HEP applications

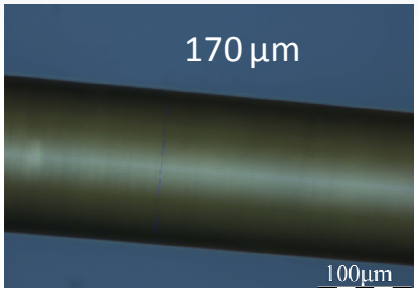
FBGs coated by a Polyimide (PI) layer

Sensors and Actuators B 177 (2013) 94–102

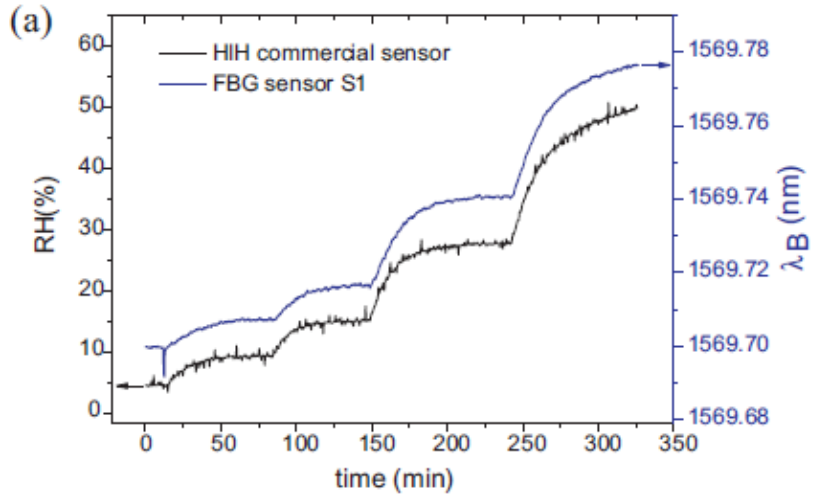
Radiation hard humidity sensors for high energy physics applications using polyimide-coated fiber Bragg gratings sensors

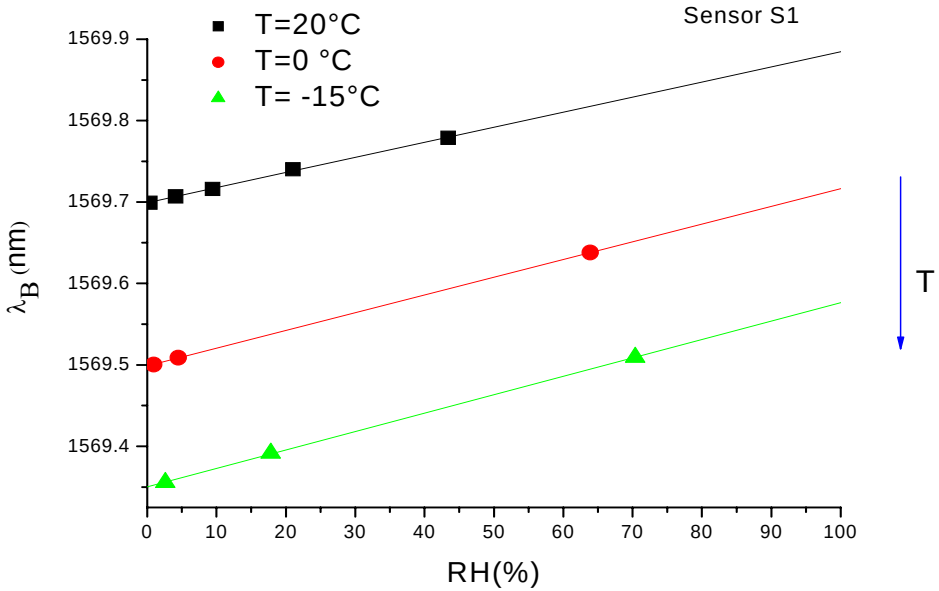
G. Berruti[a], M. Consales[a], M. Giordano[b], L. Sansone[b], P. Petagna[c], S. Buontempo[d], G. Breglio[e], A. Cusano[a,*]

[a] Optoelectronic Division, Department of Engineering, University of Sannio, Benevento, Italy
[b] Institute for Composite and Biomedical Materials, CNR, Portici, Italy
[c] European Organization for Nuclear Research CERN, Genève, Switzerland
[d] Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, Via Cinthia, 80126 Napoli, Italy
[e] Department of Biomedical, Electronic and Telecommunication Engineering, University of Naples Federico II, Napoli, Italy

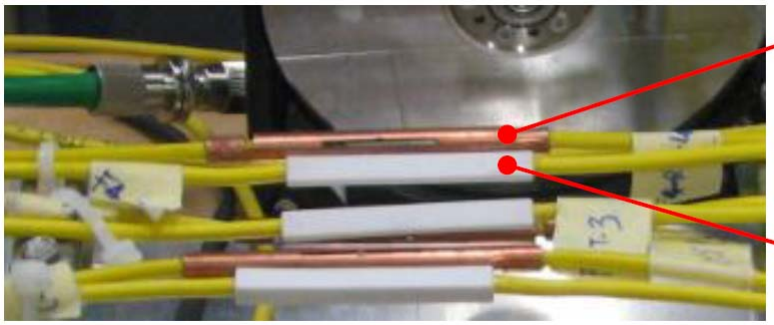


Optical microscope image of a FBG sensor coated by a ~23µm-thick PI layer





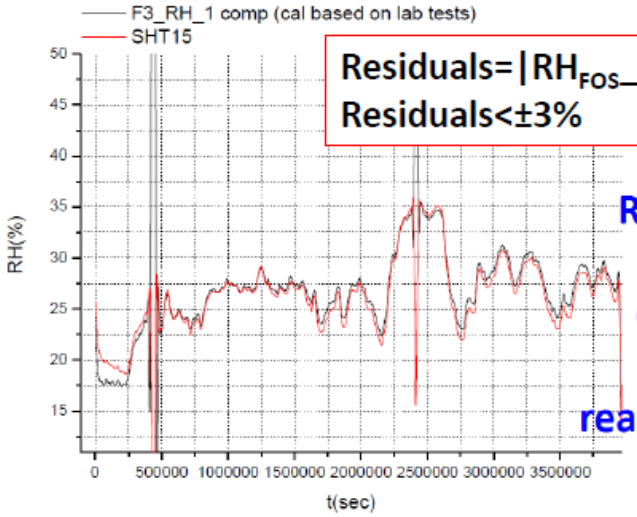
R&D PROGRAMME@CERN



RH-FOS SENSOR

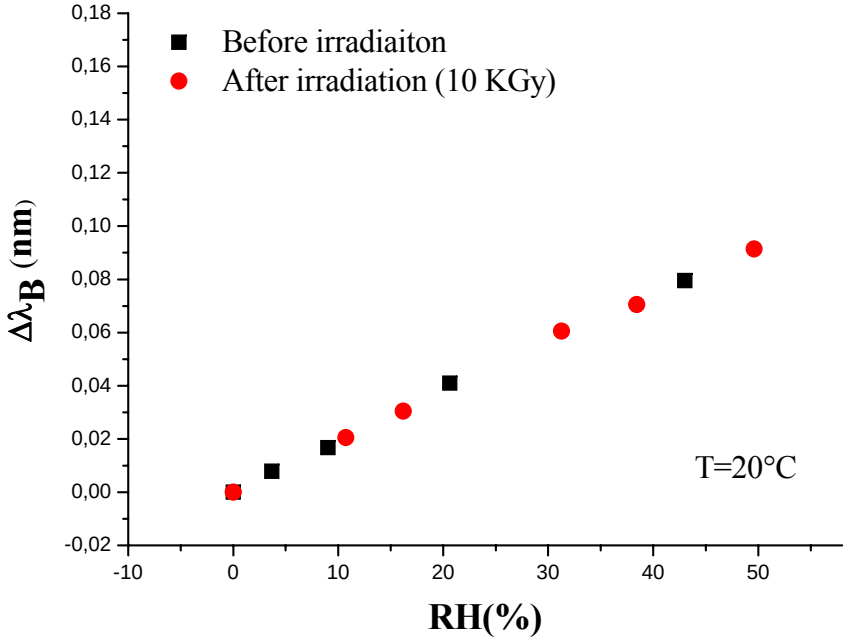
T-FOS SENSOR

- Arrays pre-irradiated at 10 kGy ionizing irradiation dose
- FBG conveniently protected in a special casing
- Calibration of the arrays performed in the climatic chamber using a special cylindrical support
- After the calibration, arrays installed in CMS as first application of this technology to the "real world"

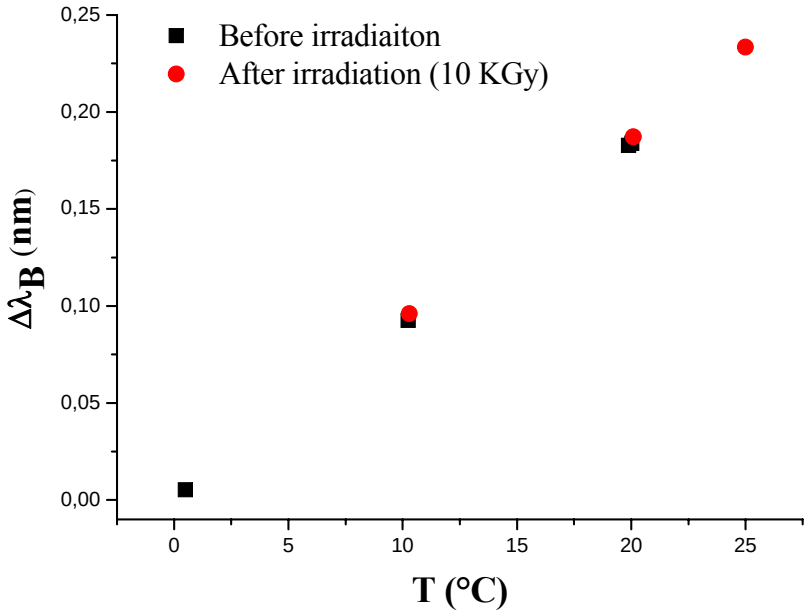


Results seem to be very compatible to RH analogic sensor readings present in the same box!!!

Pre and Post irradiation characteristic curves (after a 10kGy dose)

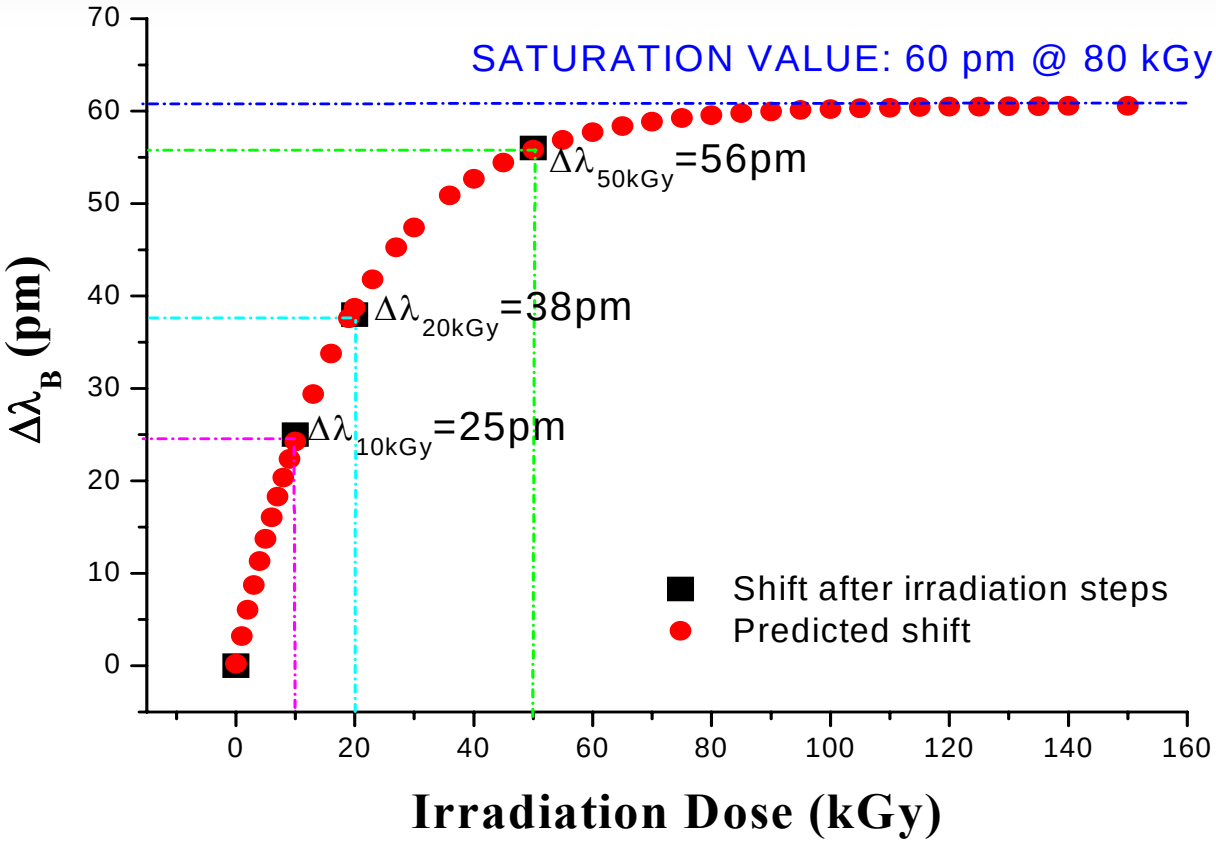


$\Delta\lambda_B$ vs RH before and after the irradiation process



$\Delta\lambda_B$ vs T before and after the irradiation process

$\Delta\lambda_B$ vs Irradiation dose

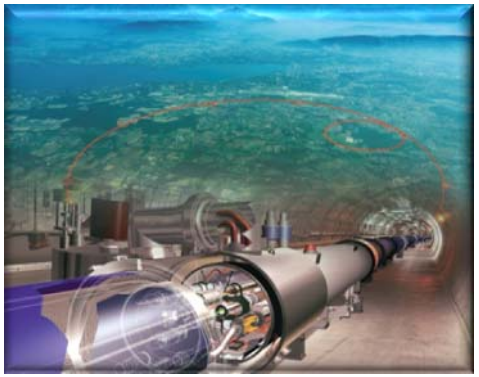


Commercial electronic hygrometer resulted definitely damaged after the 10 kGy dose.

Cryo-Sensors for superconductiong magnets
Needs and requirements

A large number of sensors and electronic devices located inside the 27- km LHC tunnel able to withstand the radiation and cryogenic environment:

Cryogenic Thermometers
to monitor and to control the temperature in the wide range 1.9 – 300 K



Electrical Strain Gauges
to monitor and to control the stress profile from the assembly to the operation of the magnet

A lot of wires needed!

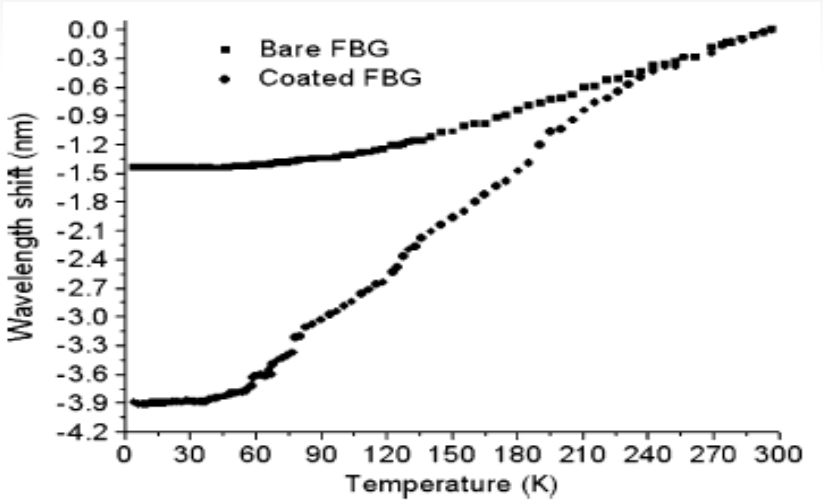
Potentials for the use of fibers for temperature and strain

- **Immunity to electromagnetic interference in high field environment**
- **reduction of instrumentation (wires, connections, read out system)**
- **low heat in-leak into the bath**
- **improvement of workplace safety in the upgraded tunnel by monitoring the temperature over long length (Wavelength Division Multiplexing)**

Temperature sensors: working principle

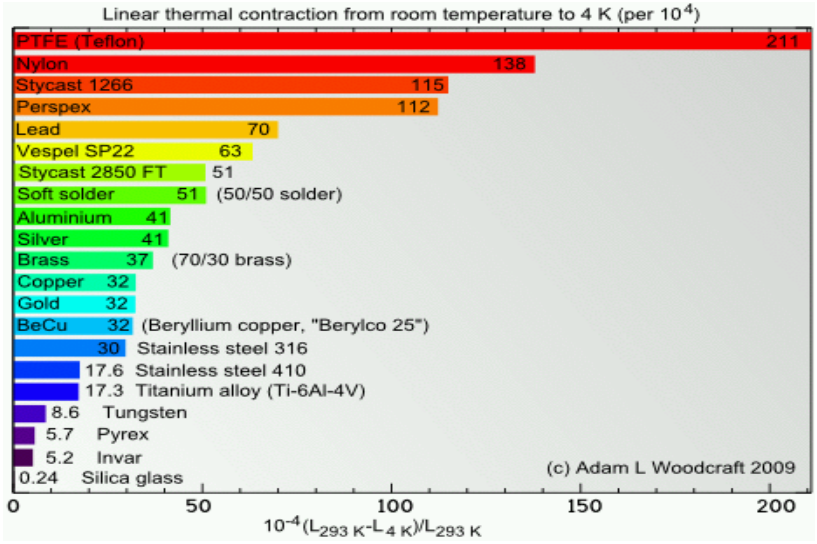
Poor FBG sensitivity at Cryo Temperatures

8 - 12 pm/K @ room T
< 0.1 pm/K below 40 K



Hongjie Zhang, Fanping Deng, Qiuliang Wang, Luguang Yan, Yingming Dai, and Keeman Kim, Development of Strain Measurement in Superconducting Magnet Through Fiber Bragg Grating, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 18, NO. 2, JUNE 2008;

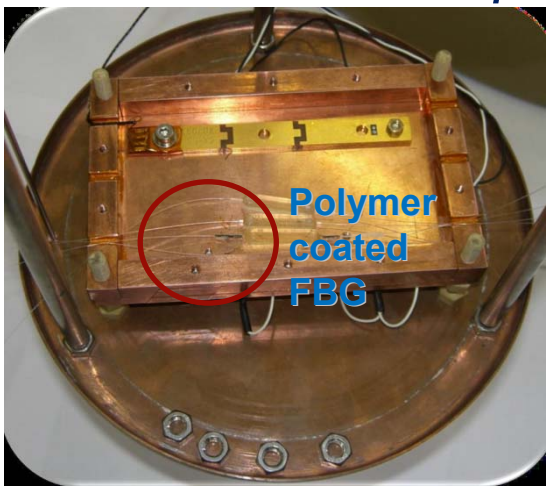
A suitable material with a **large thermal expansion coefficient** at cryogenic temperature is needed

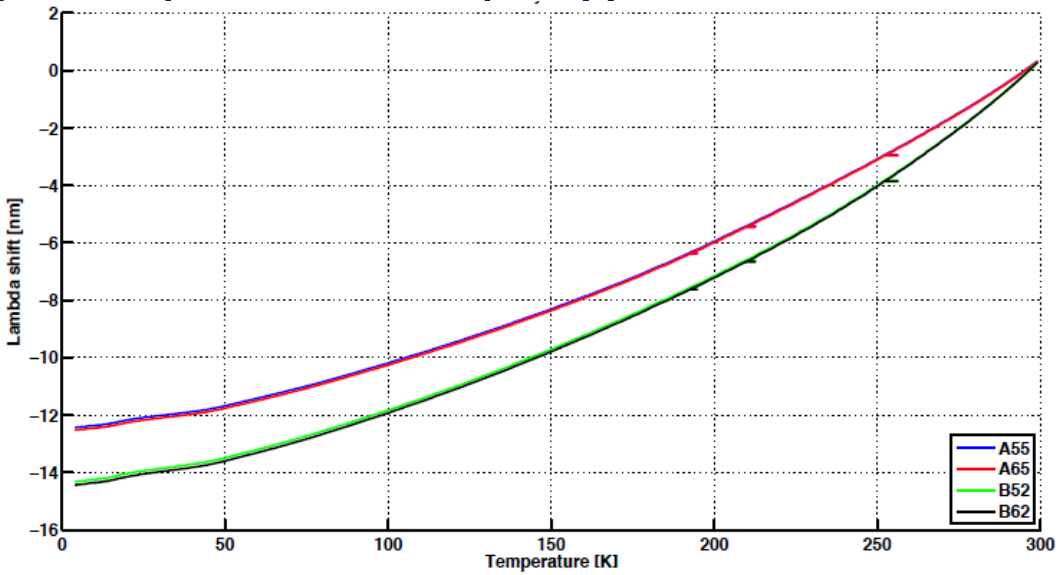


Embedded Temperature sensors

Polymer coating can be easy and cheap, it makes the FBG sensors very competitive in terms of fabrication and production

Tests at 4.2 K have been carried out on FBGs coated with different polymers (PMMA and Epoxy)





- **The analysis shows a strong non linearity within the range 4-10 K but a good feasibility of the coating technique up to 10 K**

M. Esposito, A. Cusano et al, **Sensors and Actuators A**, 189, 195–203 (2013)

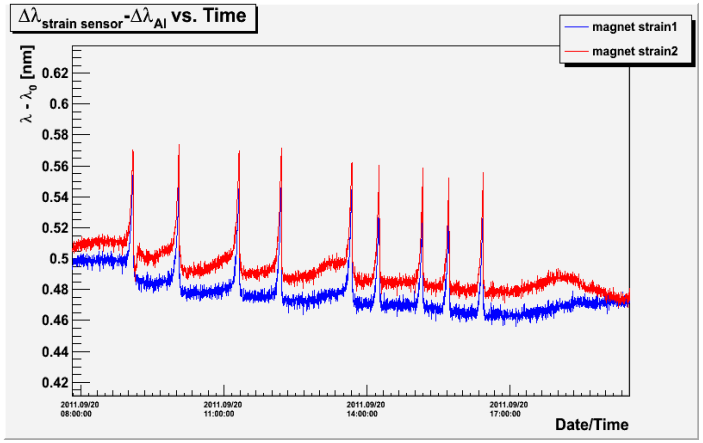
Optoelectronics Group, Engineering Department
University of Sannio, Benevento (Italy)

Strain Cryo-Sensors: Feasibility study

Preliminary tests have been carried out gluing the FBGs on the Aluminum structure of the magnet and comparing them with resistive strain gauges:

- **Cooldown: the magnet is lowered inside the cryostat and cooled down up to 1.9 K**
- **Training: the magnet is powered with high current in order to investigate the strain when quenches (transition from superconducting to resistive state) occur.**

Magnet fixed to the insert of the cryostat

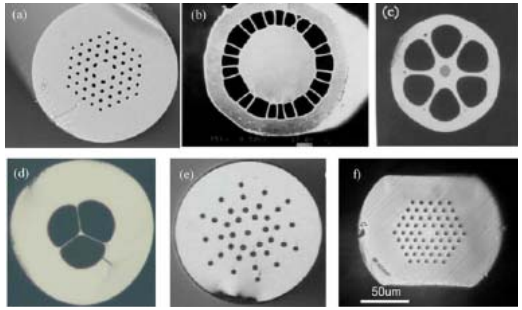


All quenches are clearly seen on the FBG strain sensors: the quench monitoring can help in preventing damages of the magnet due to the high temperature reached during the phenomena

ADDING FUNCTIONALITIES
Microstructured Fiber Bragg Gratings Sensors for Chemical and Biological Applications

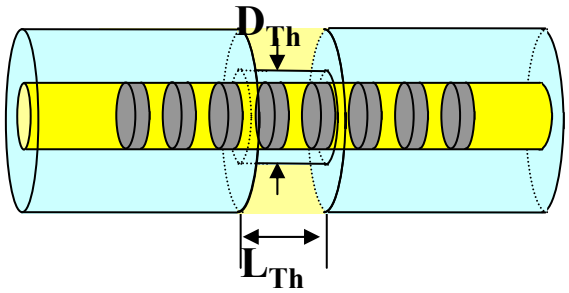
1) FBG realization within unconventional fiber structures

- Microstructured Optical Fiber (MOFs)



J. Canning *et al.*, Laser Chemistry 2008, 239417 (2008)

2) Conventional FBGs post-processed for structuring the host fiber in localized micro-sized regions: sensitization to surroundings



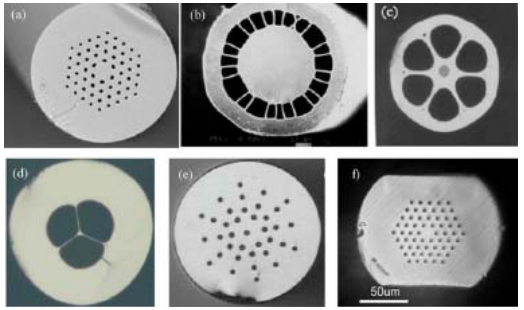
A. Cusano *et al.*, Journal of Lightwave Technology 27, 1663 (2009)

Microstructured Optical Fibers

- **1974: Kaiser and Astle Proposed for the First Time MOFs**

P. V. Kaiser and H. W. Astle, Bell System Technical Journal 53, 1021 (1974)

- **1996: Knight *et al.* Reinvigorated This Area of Research:**
  - **Peculiar Holey Structure**
  - **New Degrees of Functionality**



October 1, 1996 / Vol. 21, No. 19 / OPTICS LETTERS

All-silica single-mode optical fiber with photonic crystal cladding

J. C. Knight,* T. A. Birks,* P. St. J. Russell* and D. M. Atkin

Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK

Optoelectronics Group, Engineering Department
University of Sannio, Benevento (Italy)

FIRST DEMONSTRATION OF FBG WRITING IN MOFs

OPTICS LETTERS / Vol. 24, No. 21 / November 1, 1999

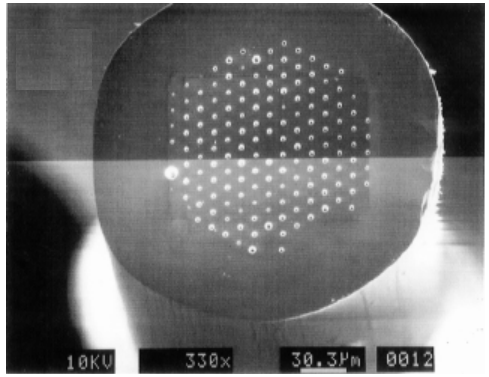
Grating resonances in air–silica microstructured optical fibers

B. J. Eggleton, P. S. Westbrook, R. S. Windeler, S. Spälter, and T. A. Strasser

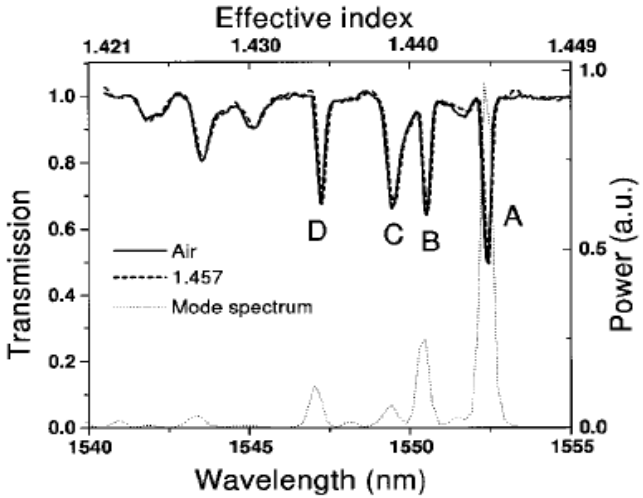
Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974

Single-photon writing at 242 nm: absorption band of the germanium-oxygen-deficient centers

- Conventional writing technique
- Scattered light from the holes
- Higher-Order Modes (HOMs)

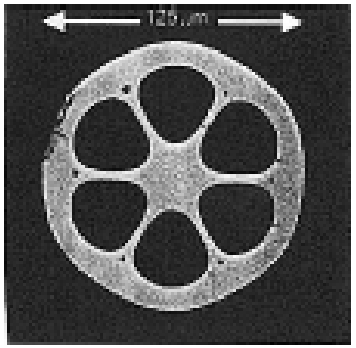


Ge-doped photosensitive solid core MOF



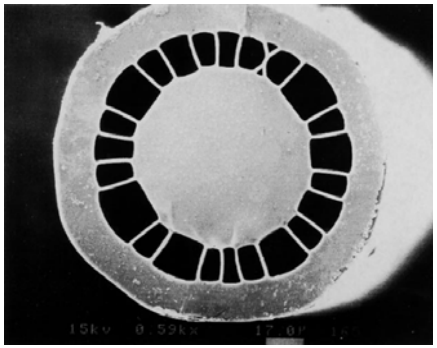
Other FBGs written Ge-doped core MOFs:

Grapefruit Fiber



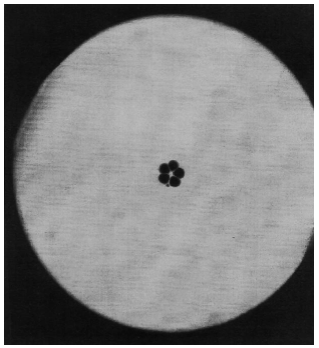
P. S. Westbrook *et al.*, IEEE Photonics Technology Letters 12, 495

Air-Clad Fiber



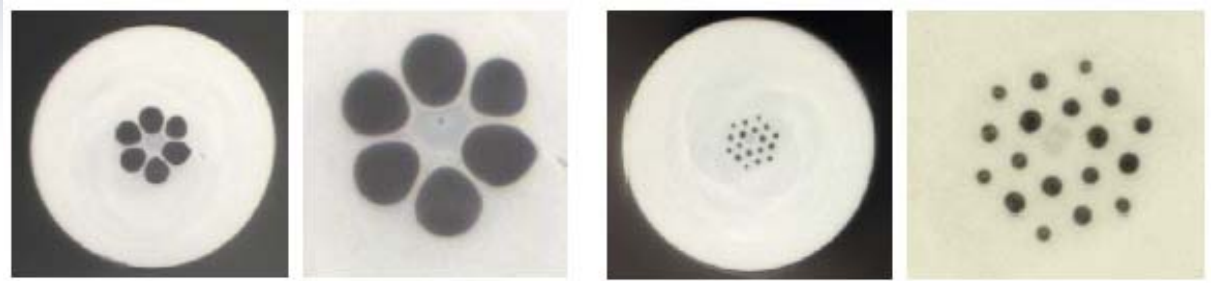
B. J. Eggleton *et al.*, Journal of Lightwave Technology 18, 1084

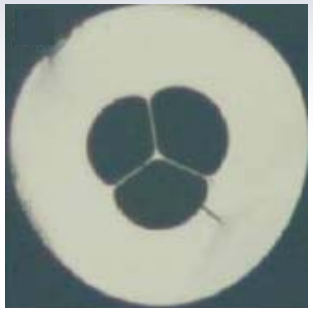
High-Delta MOF

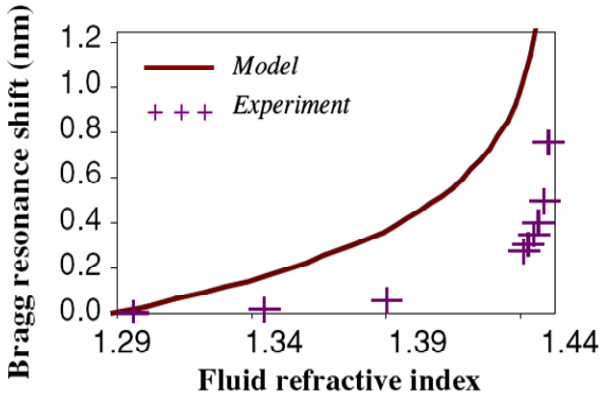


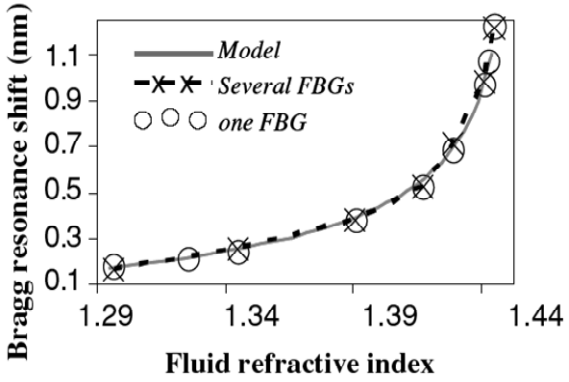
B. J. Eggleton *et al.*, Optics Express 9, 698 (2001)

MOF-BASED MSFBGs APPLICATIONS: RI Sensitivity

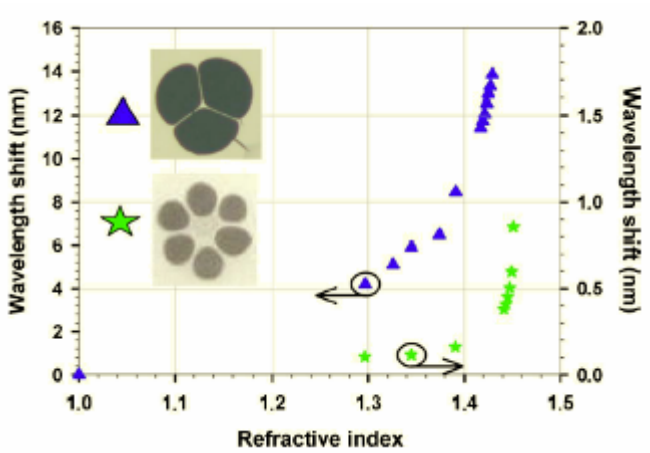








M. C. Phan Huy *et al.*, Measurements Science and Technology 17, 992 (2006)

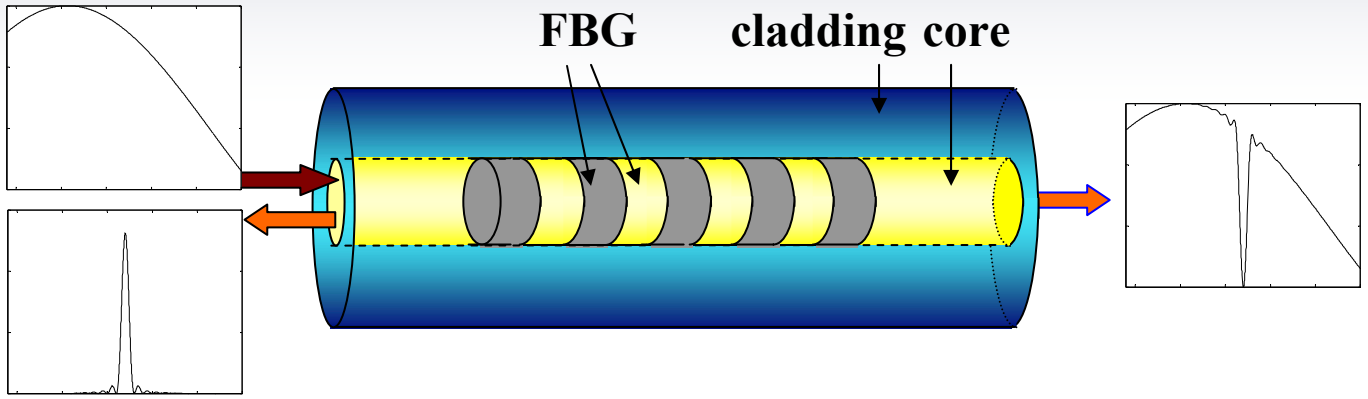


M. C. Phan Huy *et al.*, Optics Letters 32, 2390 (2007)

Δλ=1pm	Refractive Index Resolution		
RI	6-hole MOF	2-ring triangular MOF	3-hole MOF
~1.33	4×10^{-3}	7×10^{-4}	3×10^{-5}
~1.40-1.41	2.1×10^{-4}	1.8×10^{-4}	6×10^{-6}
~1.44	7×10^{-5}	2×10^{-5}	-
~1.45	6.8×10^{-6}	-	-

Resume of the different RI resolution with the assumption that 1 pm spectral variations are detectable

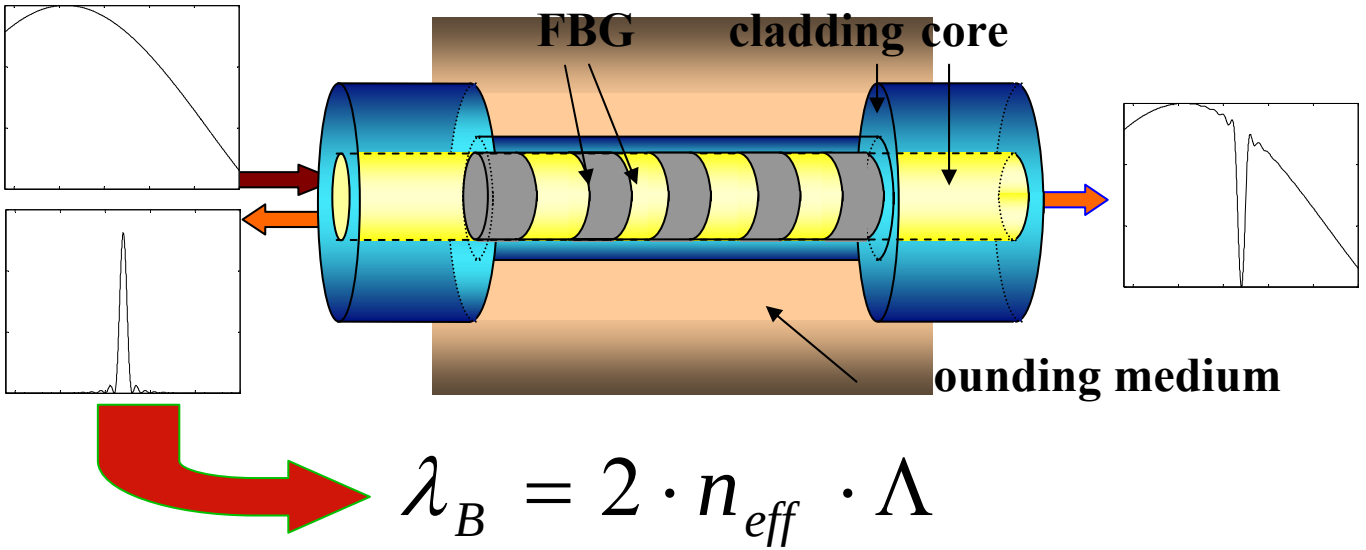
In Standard Fiber Bragg Grating (FBG):



$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda$$

The fundamental mode is well shielded from the environment through the cladding layer thus no sensitivity to external refractive index is expected

In Thinned Fiber Bragg Grating (ThFBG):

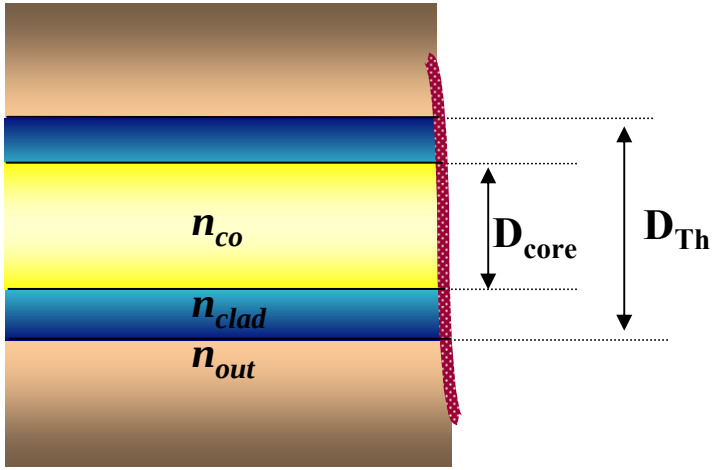


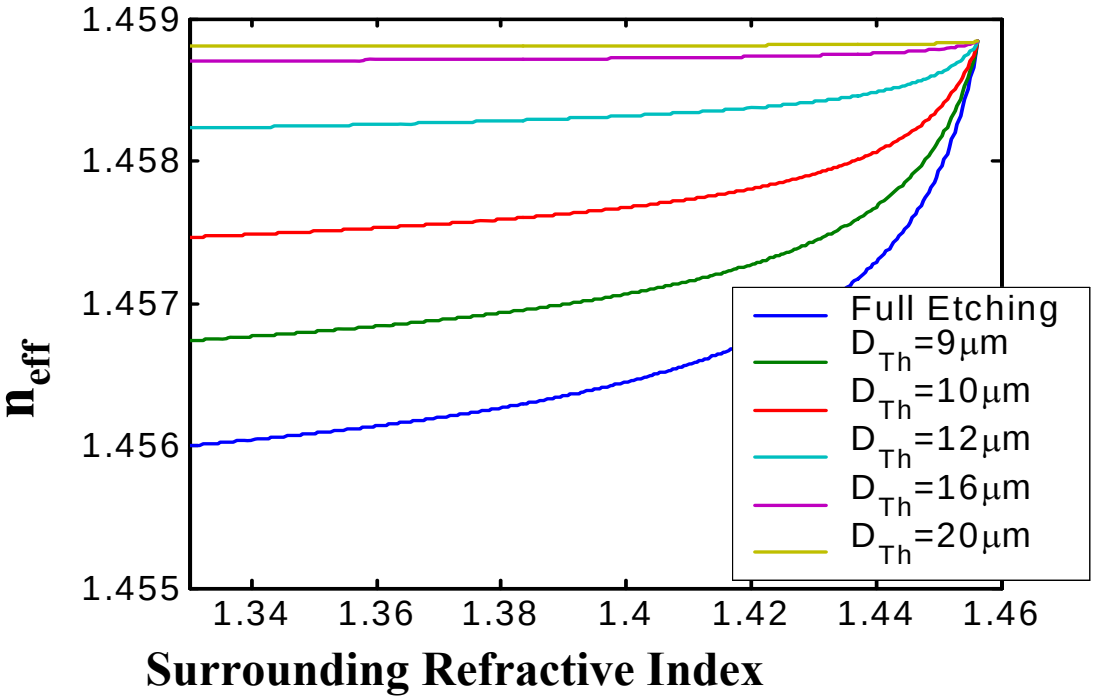
$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda$$

n_{eff} is significantly affected by surrounding medium refractive index

leading to a shift in the Bragg resonance

Effective Index Sensitivity

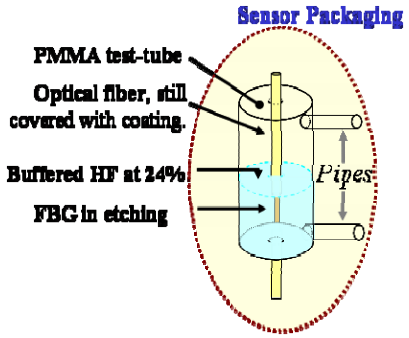


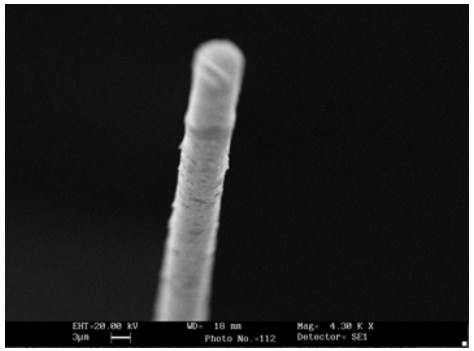


Maximum sensitivity is obtained by a complete removal of the cladding layer

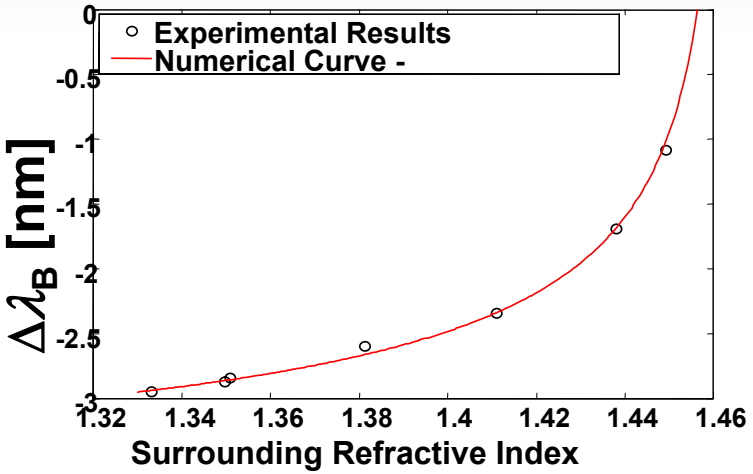
ThFBG demonstrations

A.Iadicicco, A.Cusano, A.Cutolo, R.Bernini, M.Giordano, IEEE Phot. Techn. Letters 16(4), 1149 – 1151 (2004)
A. Iadicicco, A. Cusano, S. Campopiano, A. Cutolo, M. Giordano, IEEE Sens. J. 5(6), 1288–1295, (2005)



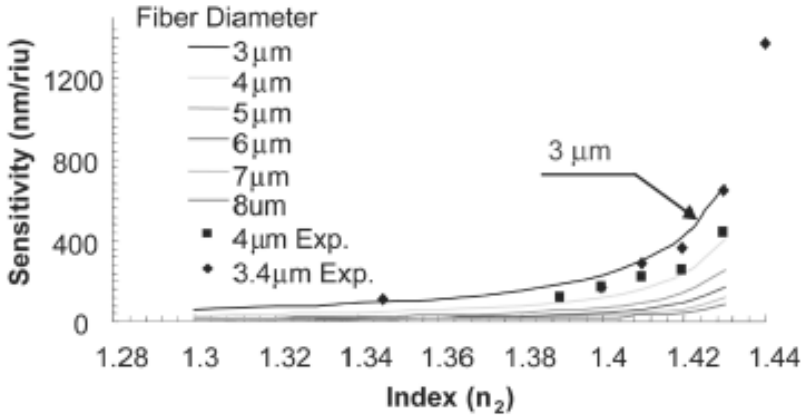


8.5 μ m thinned FBG was achieved in 2003.



Enhancement of sensor sensitivity by ultra-thinned FBGs was demonstrated

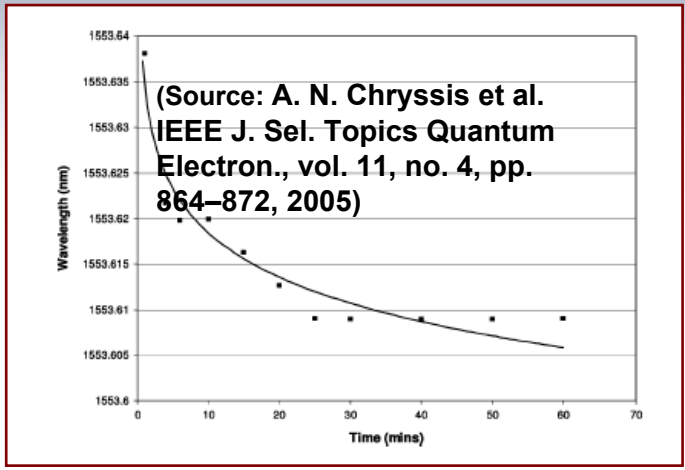
(Source: A. N. Chryssis, et al. IEEE Phot. Technol. Lett., vol. 17, no. 6, pp. 1253–1255, (2005)



ThFBG: Enhanced configurations

ThFBG based biosensor

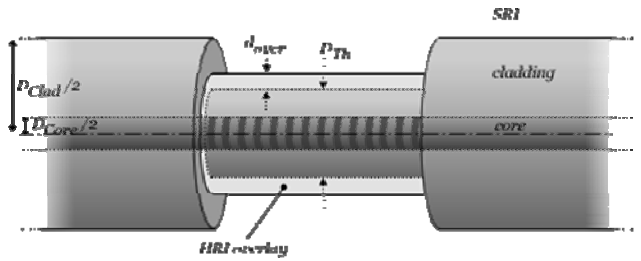
Single stranded DNA oligonucleotide probes of 20 bases were immobilized on the surface of the fiber grating using relatively common glutarahyldehyde chemistry. Hybridization of a complimentary target single strand DNA oligonucleotide was monitored in situ and successfully detected.



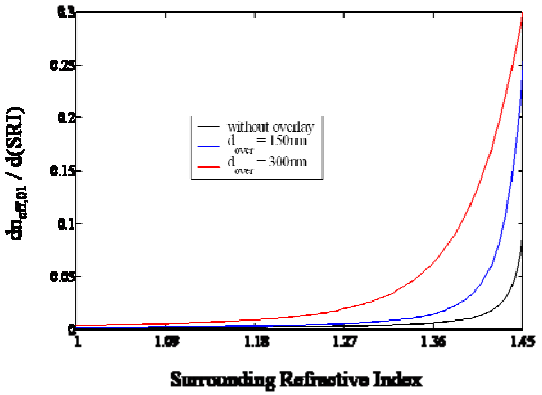
(Source: A. N. Chryssis et al. IEEE J. Sel. Topics Quantum Electron., vol. 11, no. 4, pp. 864–872, 2005)

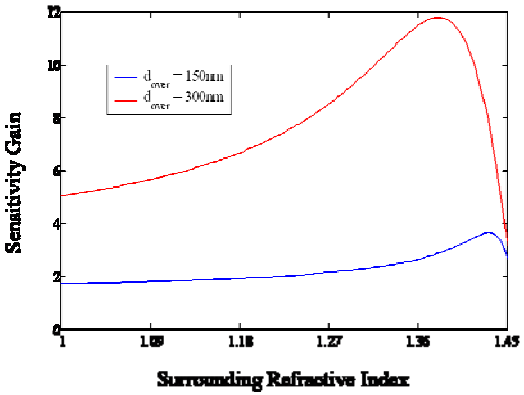
Bragg wavelength shift of a 5 μm core etched grating during the hybridization of the target

HRI coated ThFBG for enhancing sensitivity

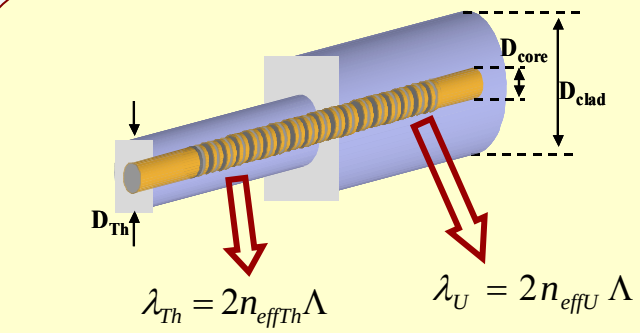


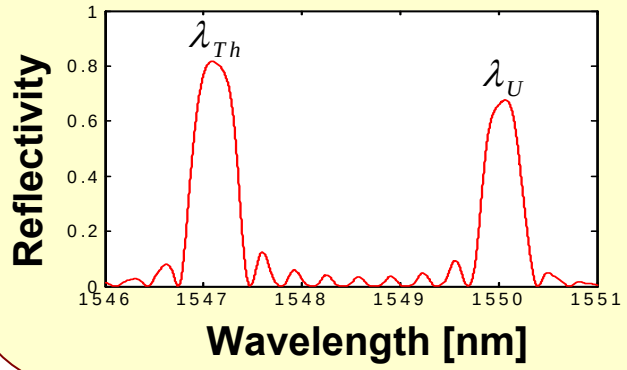
D. Paladino, A. Iadicicco, A. Cutolo, S. Campopiano, M. Giordano, A. Cusano, Proceedings of the 18th Optical Fiber Sensors Confer-ence SPIE Cancún, México (2006)



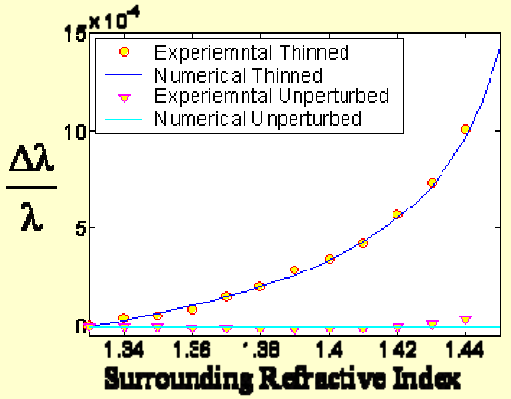


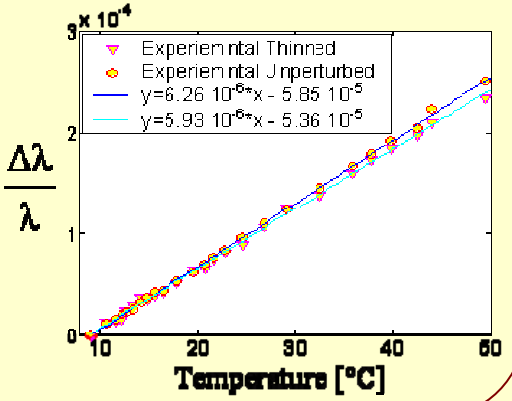
Self-temperature compensation



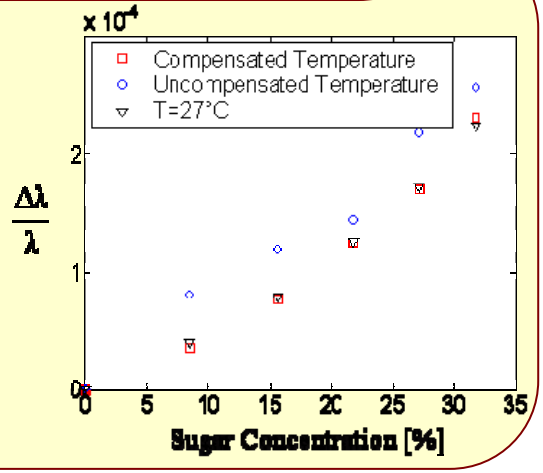


Relative Bragg wavelength sensitivity to surrounding refractive index and local temperature





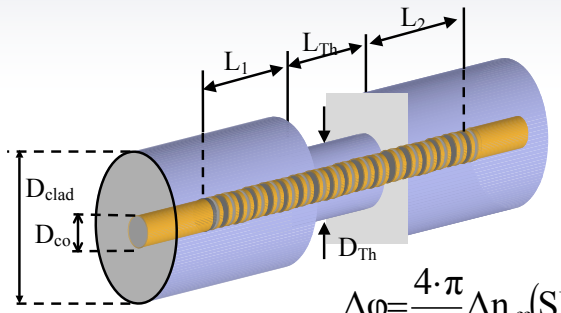
Sugar concentration measurements by non uniform ThFBGs with and without temperature self-referencing compensation



A. Iadicicco, S. Campopiano, A. Cutolo, M. Giordano, A. Cutolo, IEEE Photon Technol Lett, 17(7), 1495-1497 (2005).
A. Iadicicco, S.Campopiano, A. Cutolo, M. Giordano, A. Cusano, Sensors and Actuators B: Chemical 120(1), 231-237 (2006)
A. Iadicicco, S. Campopiano, A. Cutolo, M. Giordano, A. Cusano Proceedings of SPIE 5855, 479-482 (2005)

Optoelectronics Group, Engineering Department
University of Sannio, Benevento (Italy)

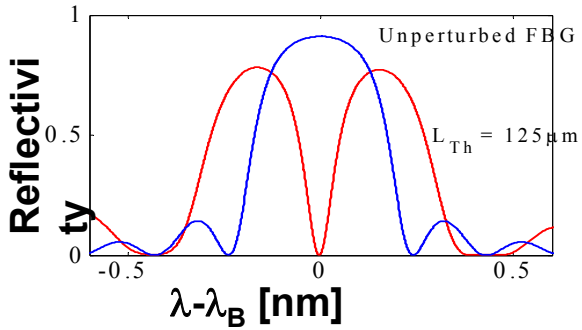
Micro-Structured FBGs

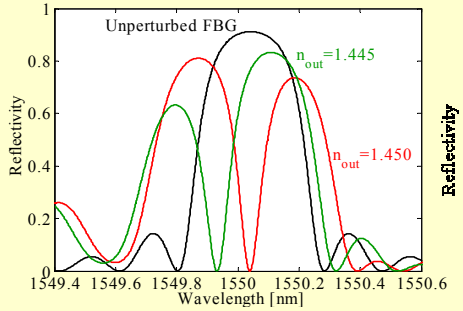


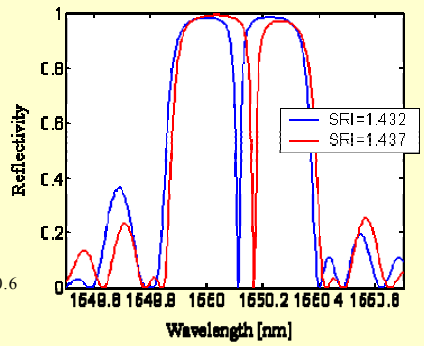
$$\Delta\varphi = \frac{4\cdot\pi}{\lambda}\Delta n_{eff}(SRI, D_{Th})L_{Th}$$

The main effects of the localized perturbation of the periodic structure are:

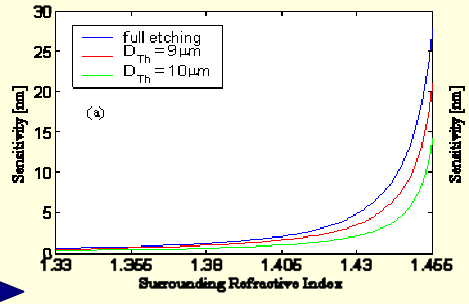
- **the increasing of the stop-band**
- **the formation on a narrow allowed band, or defect state.**

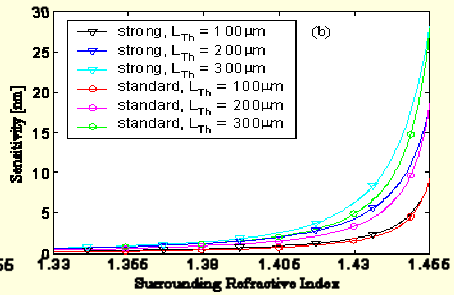






- **Defect state bandwidth depends on FBG reflectivity**
- **Defect state wavelength depends on SRI**



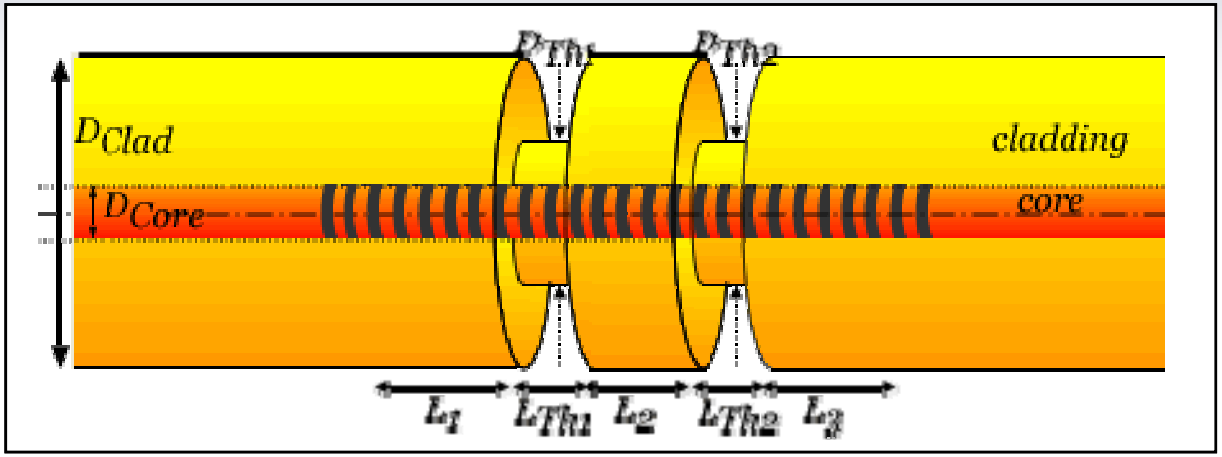


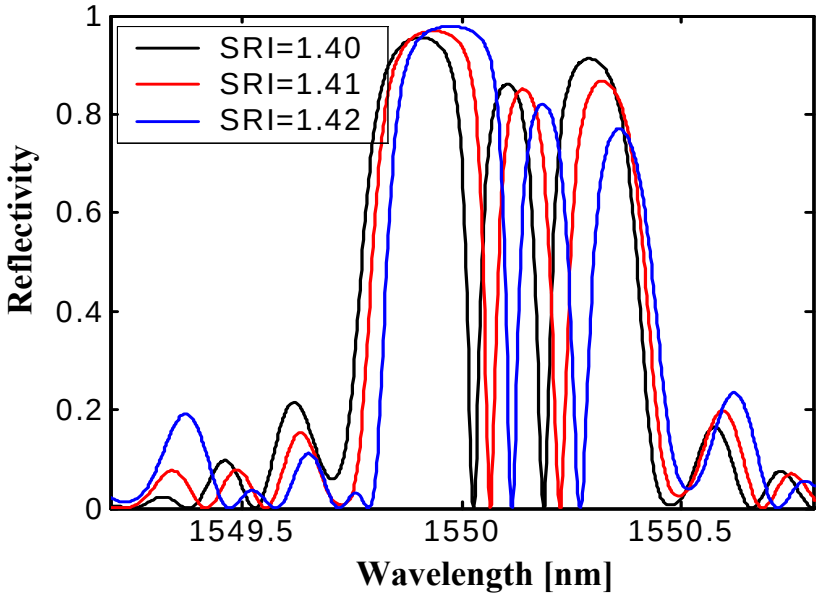
A.Iadicicco, A.Cusano, S.Campopiano, A.Cutolo, M.Giordano IEEE Electronics Letters 41(8), 466-468 (2005)
A.Iadicicco, A.Cusano, S.Campopiano, A.Cutolo, M.Giordano, IEEE Photonics Technology Letters 17(5), 1250-1252 (2005)
A. Cusano, A. Iadicicco, S. Campopiano, M. Giordano, A. Cutolo, J. of Opt. A: Pure and App. Optics 7, 734–741 (2005)
A. Cusano, A. Iadicicco, D. Paladino, S. Campopiano, A. Cutolo, M. Giordano, Optical Fiber Technology 13(4), 281-290 (2007)

MULTI-DEFECT STRUCTURE

A. Cusano *et al.*, Journal of Optics A: Pure and Applied Optics 7, 734 (2005)
A. Cusano *et al.*, Optical Fiber Technology 13, 291 (2007)

More structural defects can correspond to more allowed bands or defect states





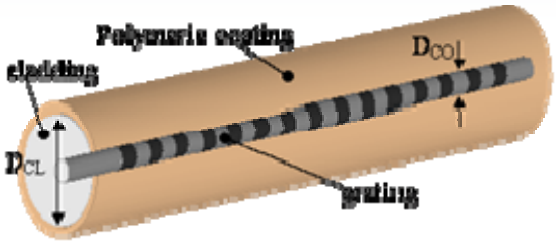
1. **Increasing sensitivity**
2. **Each allowed band results sensitive to the Surrounding RI (SRI) in correspondence of all the structural defects along the grating**

Lithographic Fabrication Procedure

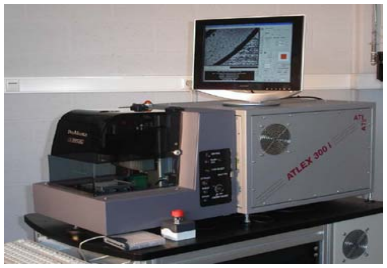
Three-steps procedure:

1. Uniform Coating Deposition

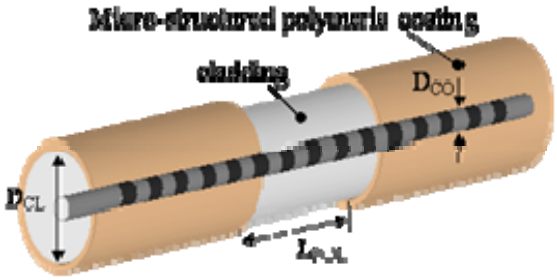
An uniform polymeric coating is cast on the grating fiber region by fiber recoater machine



2. UV Laser Micromachining (λ = 193 nm)

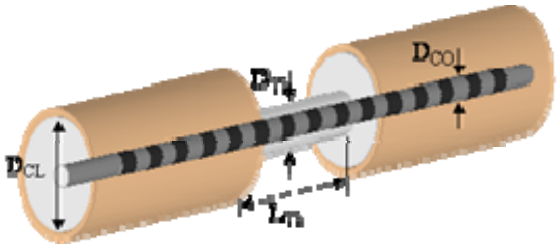


Excimer laser permits fine control of the polymeric coating microstructuring, controlling and accurately defining the etched region length



3. HF Based Etching

HF based wet chemical etching and consequent cladding thinning along the unmasked FBG region

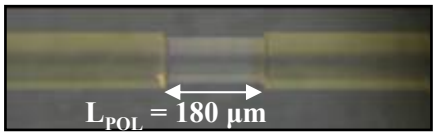


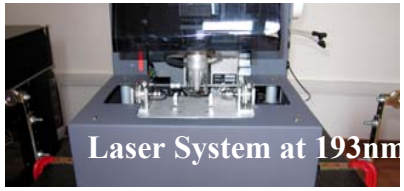
Optoelectronics Group, Engineering Department
University of Sannio, Benevento (Italy)

LITHOGRAPHIC FABRICATION PROCEDURE

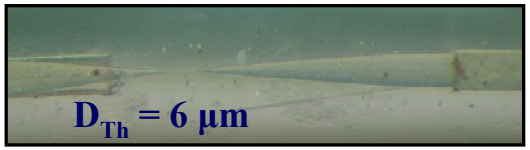
1. Uniform Overlay Deposition

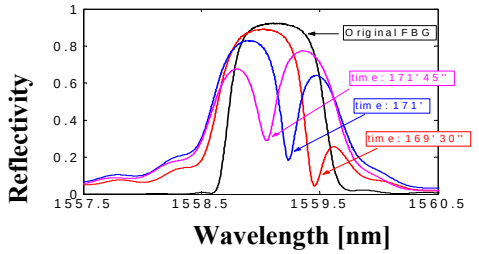
2. UV Laser Micromachining

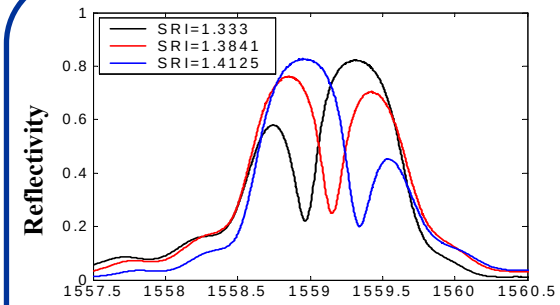


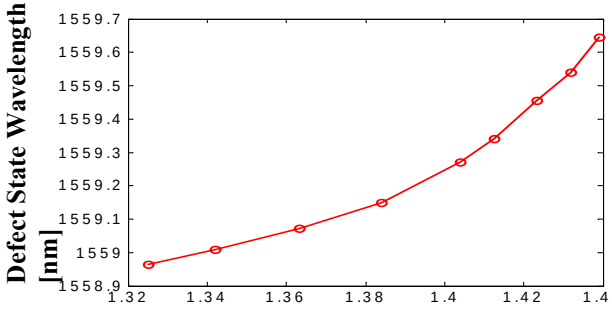


3. HF Etching









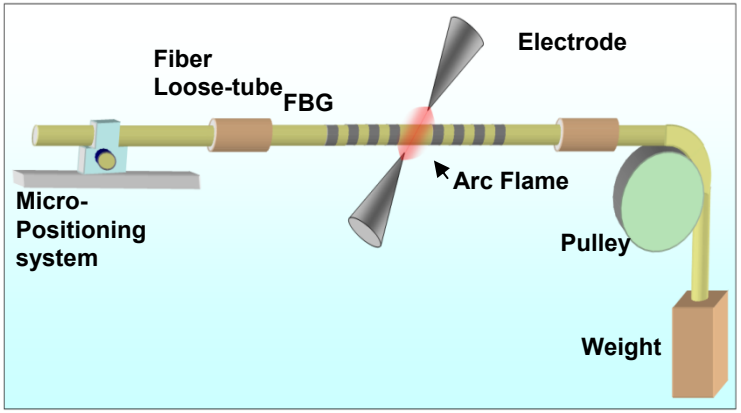
Sensitivity of:
2.5nm/RIU for SRI=1.33
14.5nm/RIU for SRI=1.44

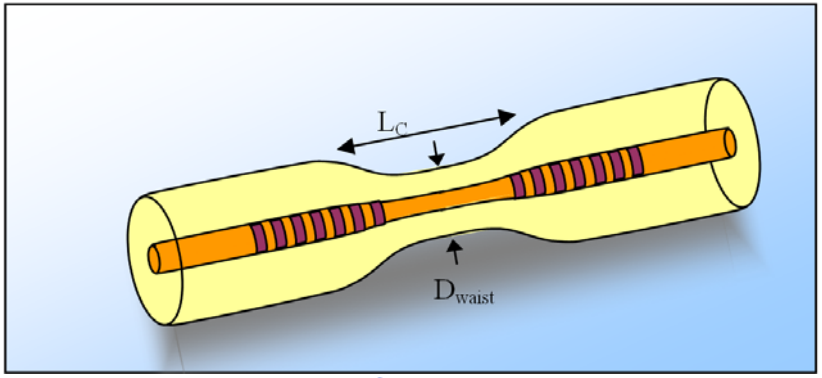
A. Iadicicco *et al.*, Optics Express 15, 15011 (2007)

Heat & Pulling Technique

Locally heating and contemporarily pulling it → **Non-adiabatic cavity tapering**

$$\phi(\lambda) = \frac{4\pi}{\lambda} n_C L_C$$



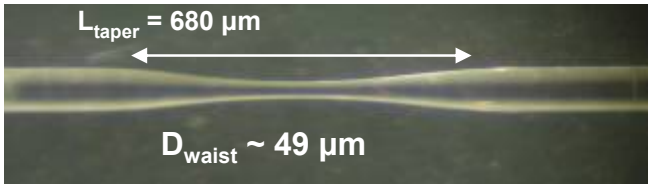


Biconical taper features are mainly determined by:

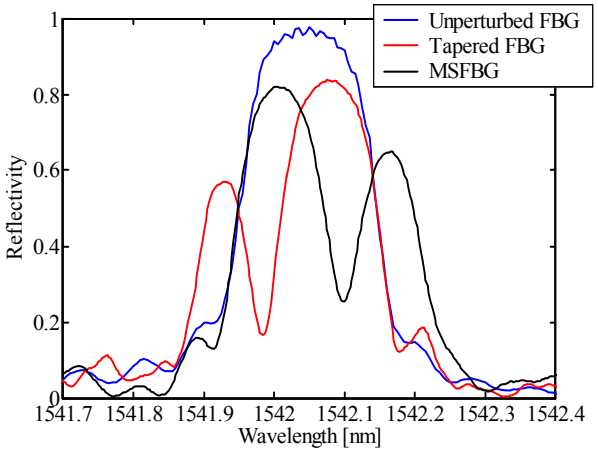
- ✓ **Arc Power (Arc Current)**
- ✓ **Arc Duration**
- ✓ **Pulling Weight (4÷20 g)**

NOT-LITHOGRAPHIC FABRICATION PROCEDURE

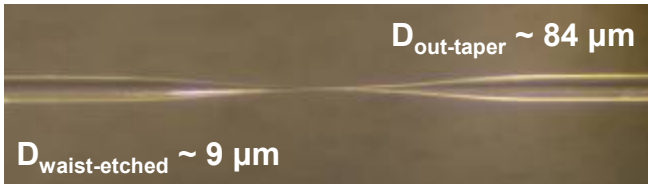
1. Biconical Taper by Electric Arc Discharge (EAD)



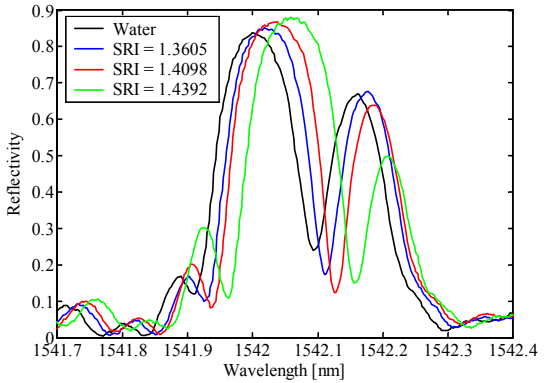
Here a diameter mismatch of 20 µm is requested

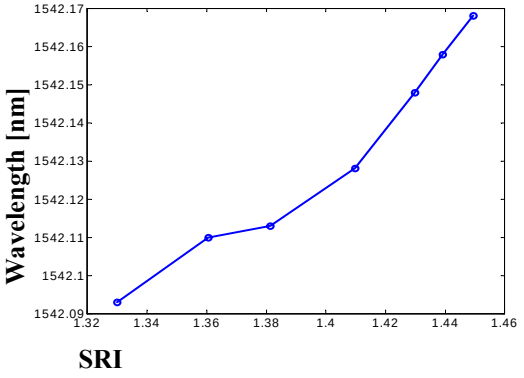


2. Maskless HF Etching



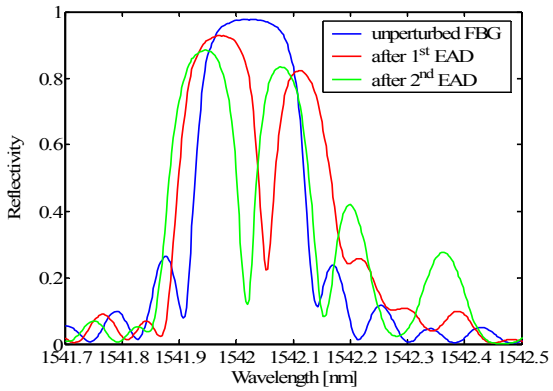
Wet chemical etching in HF allows a uniform fiber thinning

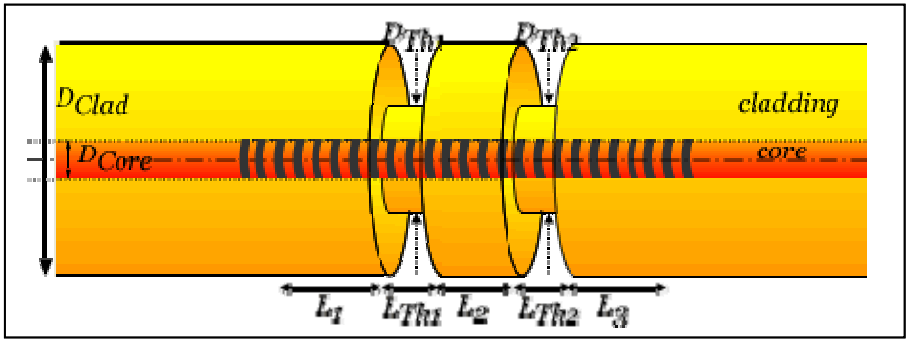


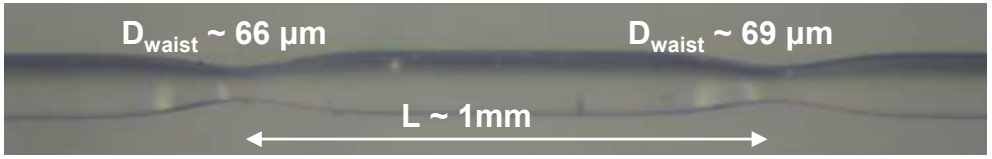


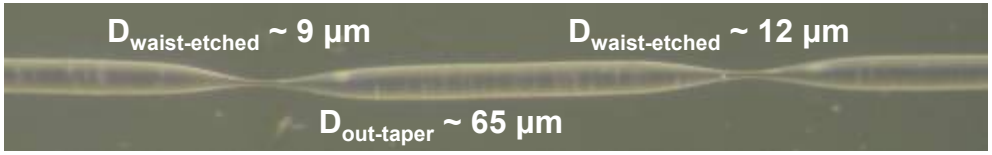
D. Paladino *et al.*, Optics Express 17, 1042 (2009)

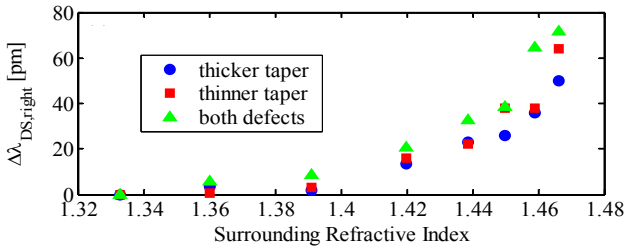
MULTI-DEFECT MSFBG

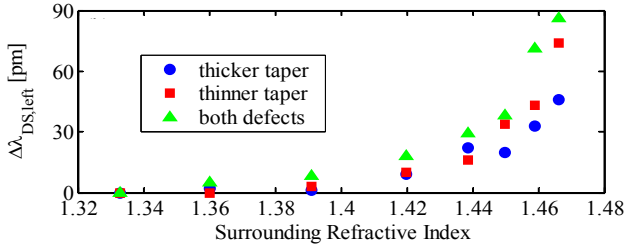








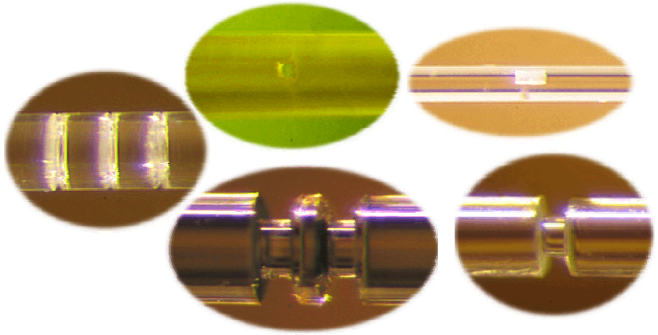


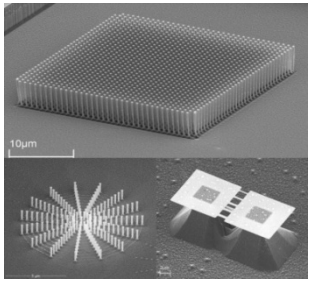


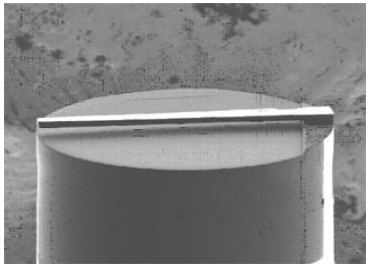
D. Paladino *et al.*, Optics Express 17, 1042 (2009)
A. Cusano *et al.*, Optical Fiber Technology 13, 291 (2007)

NEW TREND: LAB ON FIBER VISION
towards integrated and multifunctional micro and nanodevices

- **Integration and patterning (at the micro and nano-scale) of different functional materials with desired optical, mechanical, magnetic, electrical, acoustic, chemical and biological properties**

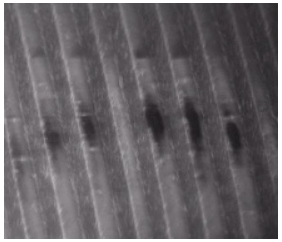


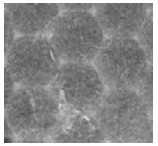


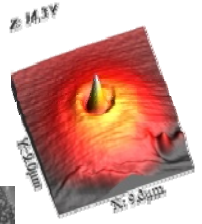


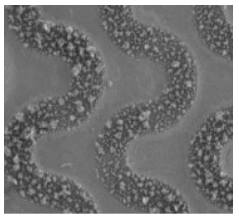
A. Cusano et al.,
"**Lab on fiber technology and related devices**",
Invited Paper
Proc. SPIE, vol. 8001
(**2011**)

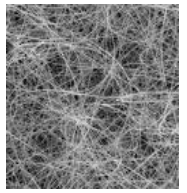
Increased light matter interaction and creation of a technological world completely integrated within optical fibers with significant advantages in terms of functionality, performances, miniaturization, robustness, cost effectiveness and power consumption

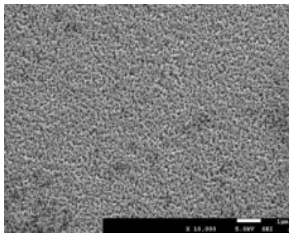










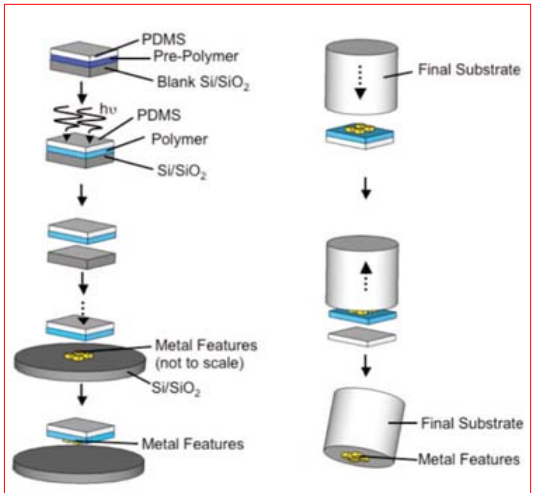


MAIN ISSUE: Definition of a reliable ***fabrication procedure able to integrate and process, at micro- and nano-scale,*** several materials onto unconventional substrates such as the optical fibers.

Integration with Optical Fibers

Nano-fabrication on planar substrates and transferring onto optical fibers

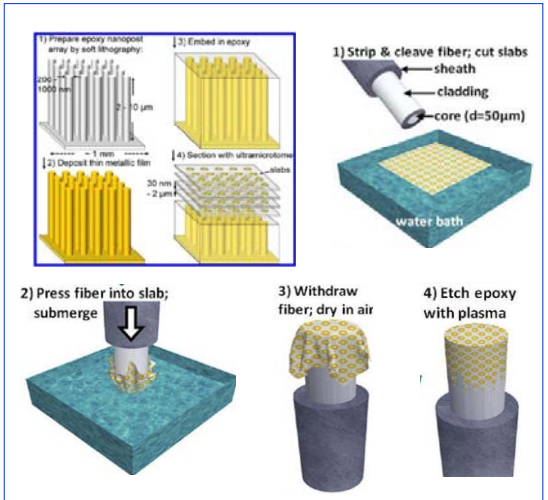
EBL and soft lithography



E. J. Smythe, F. Capasso et al.,
ACS Nano, 2009, 3 (1), 59-65

HARVARD UNIVERSITY

Soft lithography, nano-skiving and dipping



D. J. Lipomi, F. Capasso et al.,
Nano Lett. 2011, 11(2) 632-6

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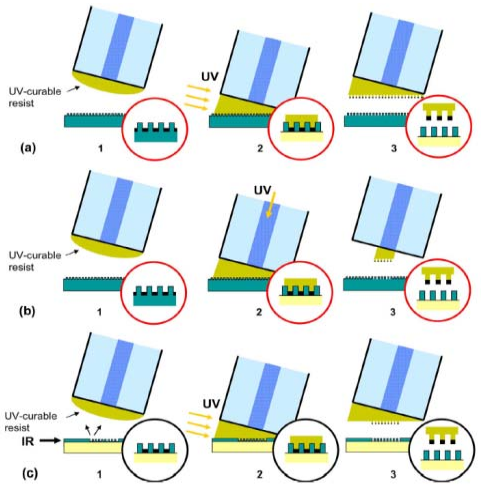
UV nano imprint and transfer lithography (NITL)



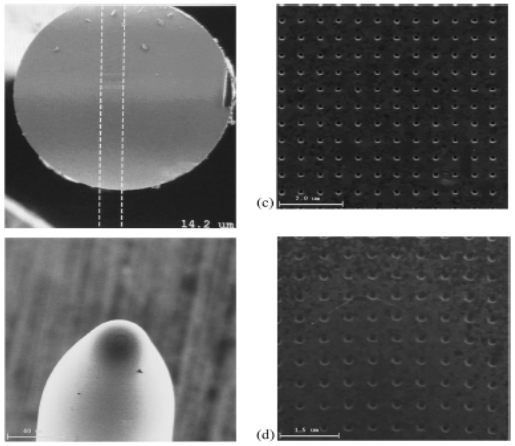
S. Scheerlinck , R. Baets et al., J.
Light. Tech., pp.1415-1420, 2009

UNIVERSITEIT GENT
Photonics Research Group

Integration with Optical Fibers

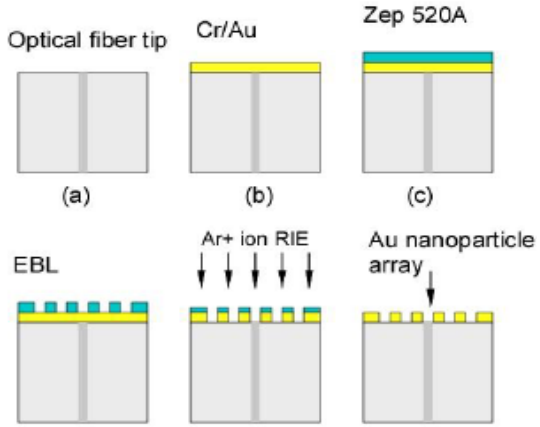
Direct-writing approaches

FIB milling



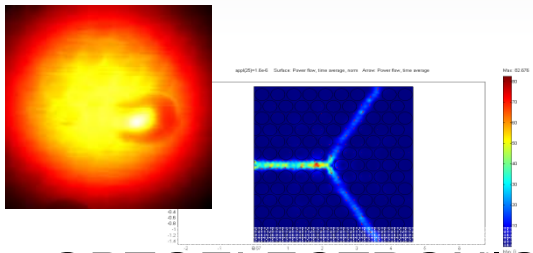
A. Dhawan et al., Sens. J. IEEE 2008, 8, 942-950

EBL and Reactive Ion Etching



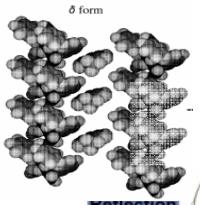
Y. Lin, R. G. Lindquist et al., Biomed Opt Express. 2011; 2(3): 478–484.

Multidisciplinary Approach

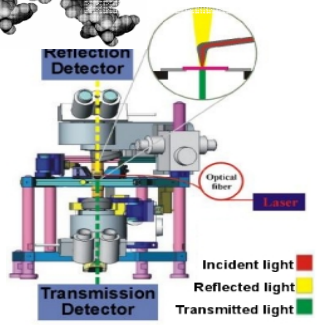


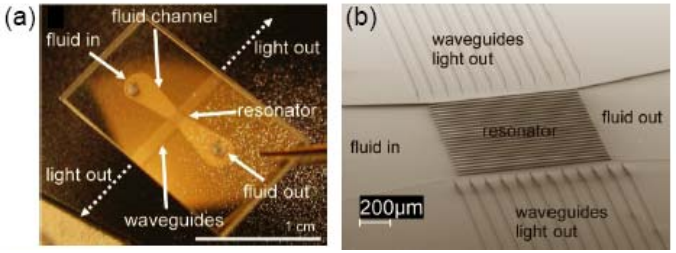
OPTOELECTRONICS

Simultaneous management of complementary disciplines and competencies is necessary to get the development of devices



MATERIALS





MANUFACTURING TECHNOLOGIES

Optoelectronics Group, Engineering Department
University of Sannio, Benevento (Italy)

Ente Nazionale per l'Energia e l'Ambiente, Portici (NA) Italy

Plasma Enhanced Chemical Vapor Deposition (PE-CVD)

Focused Ion Beam (FIB)

Excimer Laser Micromachining Systems (193 nm)

Excimer Laser Micromachining Systems (248 nm)

Optical Characterization

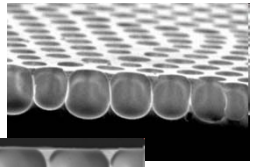
Modified Spin coater

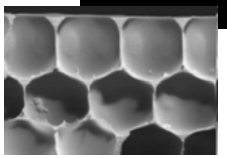
Istituto di Cibernetica "E. Caianiello", CNR, Pozzuoli (NA) Italy

Magnetron Sputtering System

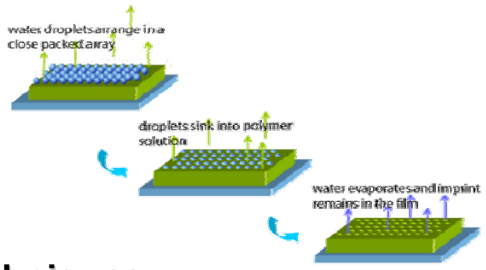
Electron Beam Lytography EBL RAITH 150

Monolayer





Multilayer



Self-assembling techniques

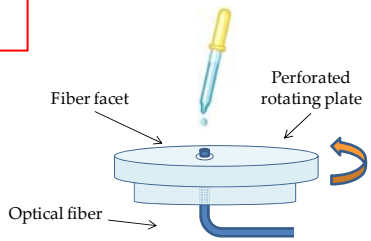
A New Fabrication Process

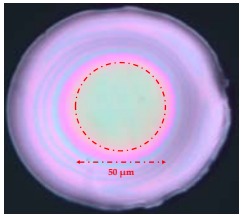
Direct fabrication of metallic and dielectric nanostructures on the optical fiber tip

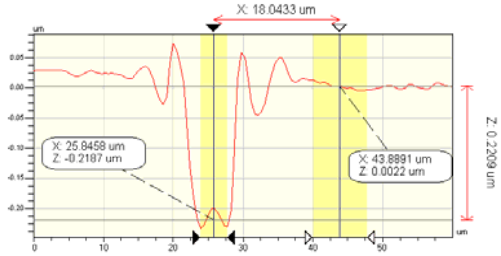
A. Cusano et al., **ACS Nano. 2012**, vol. 6(4), pp. 3163–3170.

1) Electron resist (ZEP520A) deposition

Customized spin coating for optical fibers



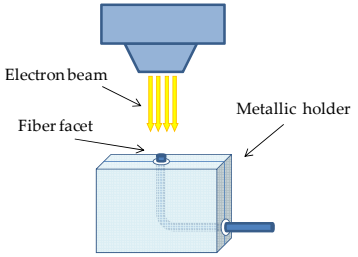


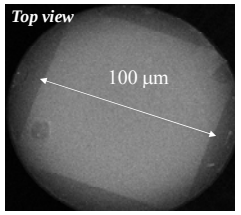


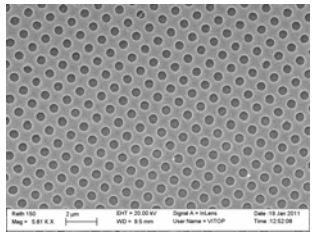
100-400nm thick (ZEP) overlay can be reproducibly obtained with high uniformity on the fiber core

2) Nano-scale patterning of the overlay

Customized EBL for optical fibers

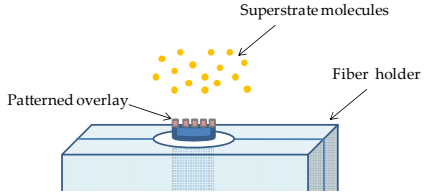


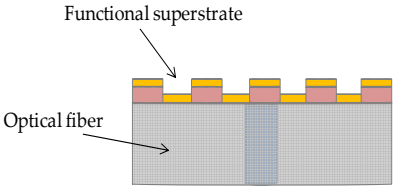




3) Functional superstrate deposition

Customized sputtering, thermal evaporation, etc.





Different functional materials (metallic or non-metallic) can be easily deposited by various techniques, properly customized to operate with optical fibers

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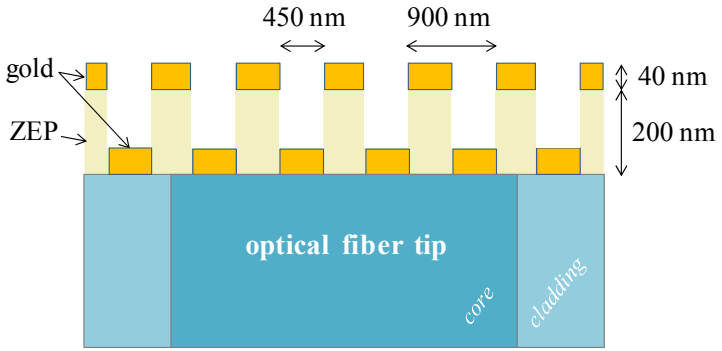
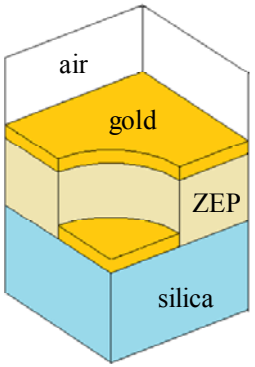
Nanoplasmonics within Optical Fibers

A first technological platform based on a 2D metallo-dielectric nanostructure





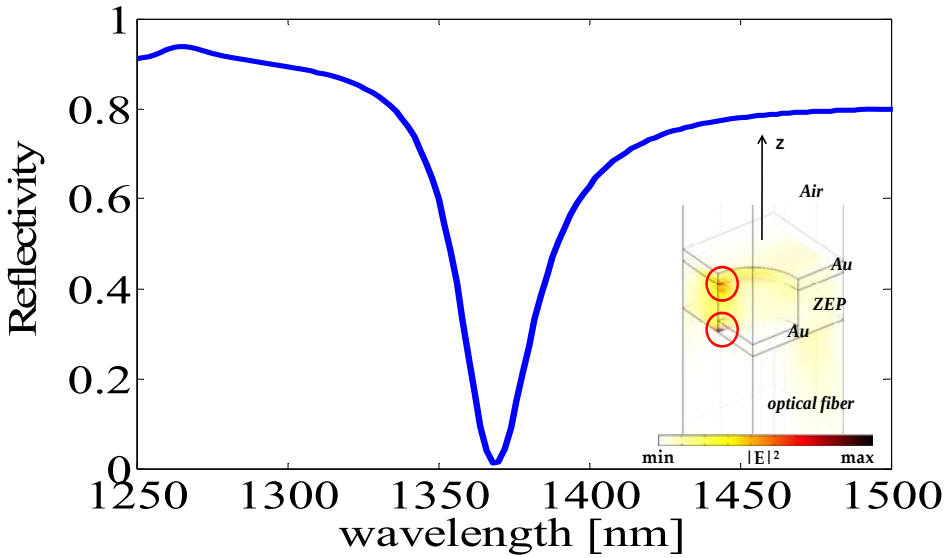
Full-wave simulations have been carried out via the finite-element-based commercial software package COMSOL Multiphysics

Refractive index at 1350 nm:

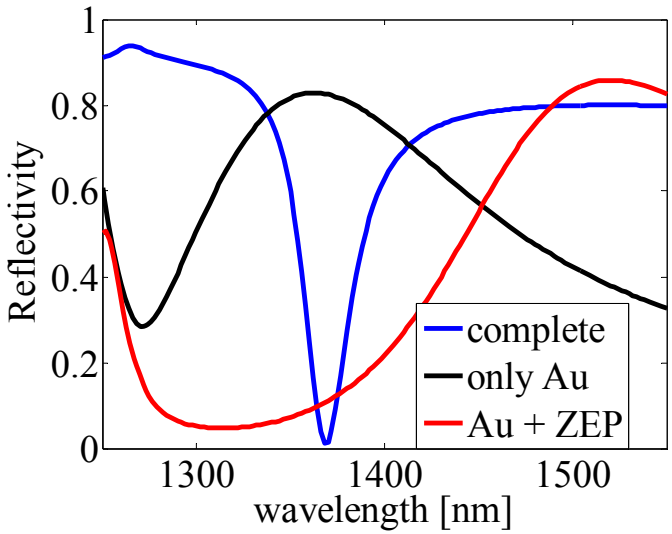
$n_{ZEP} = 1.54$ [from datasheet]

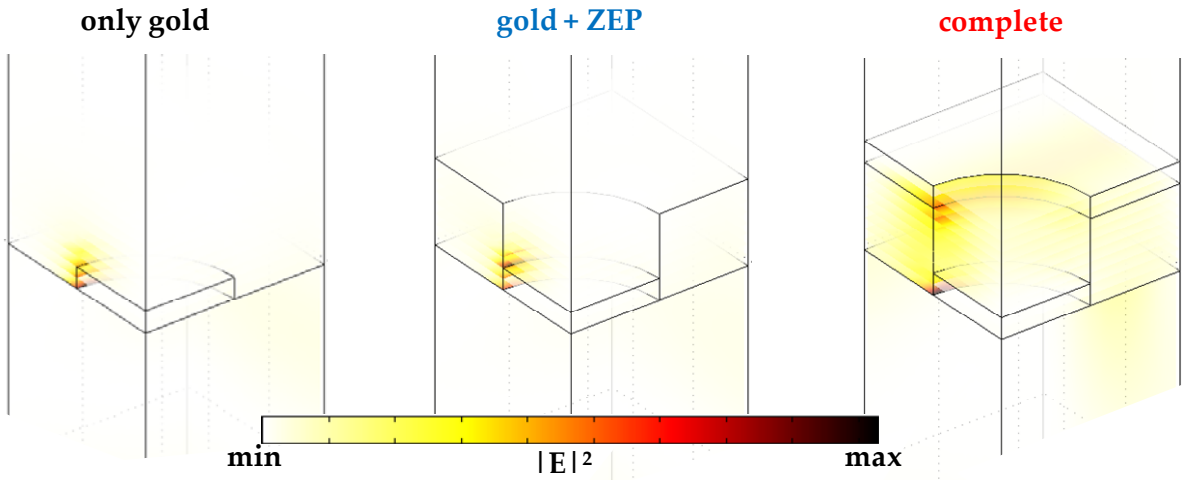
$n_{Au} = 0.5\text{-}7j$ [E.D. Palik, Academic Press, New York. 1985]

$n_{SiO2} = 1.44$

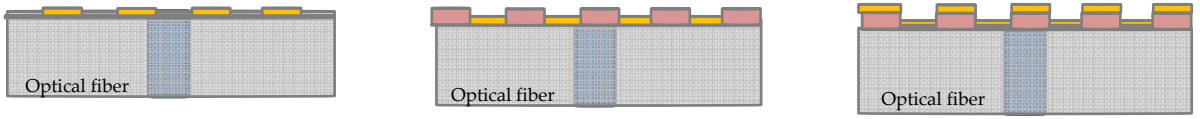


THE WHOLE IS BETTER THAN THE SINGLE PARTS

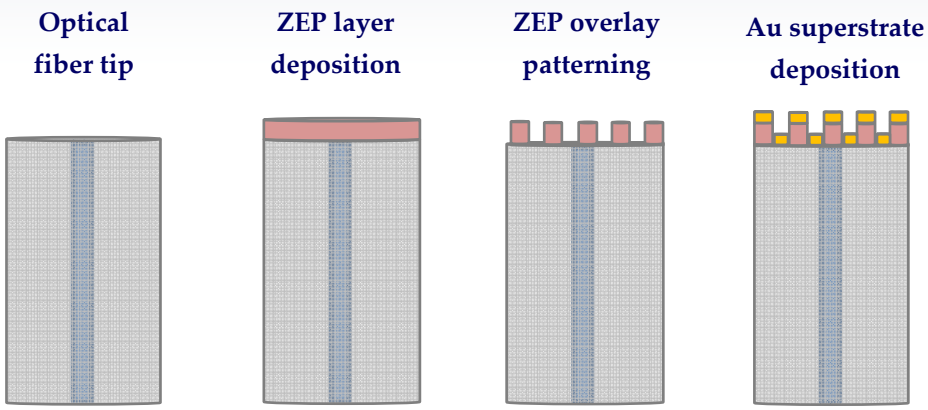


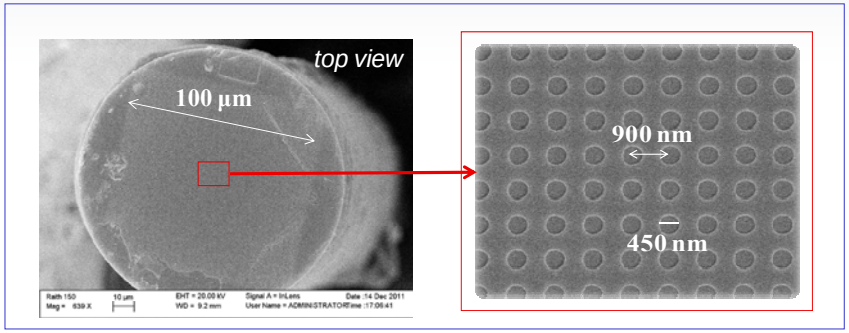


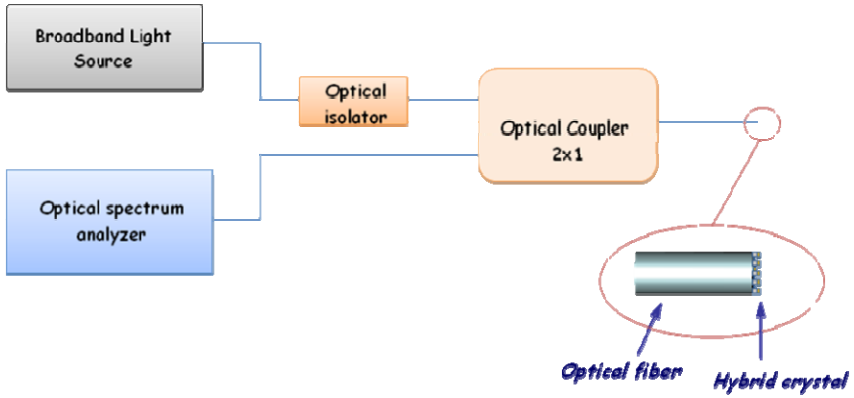
Enhancement of Field Intensity up to 7 times



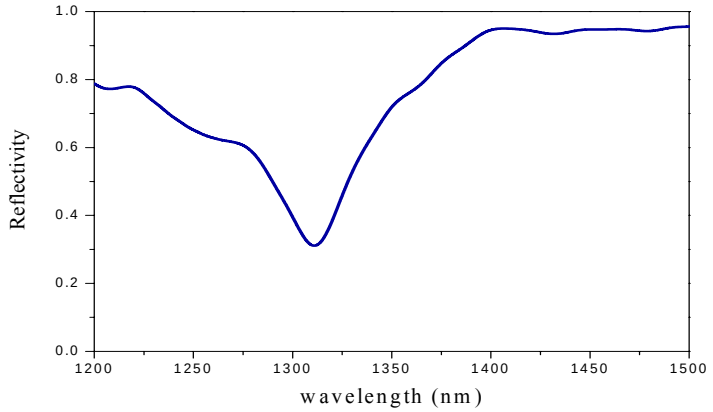
Device Fabrication







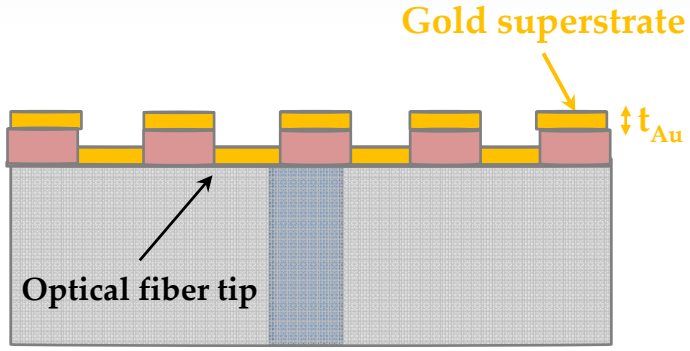
Experimental setup for spectral characterizations of fabricated samples

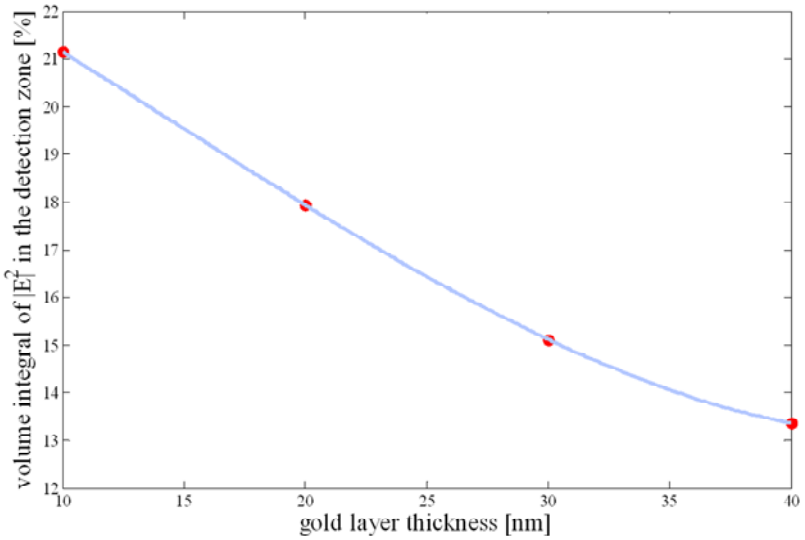


Reflectivity spectrum of a hybrid crystal with period a=900 nm (r/a=0.25)

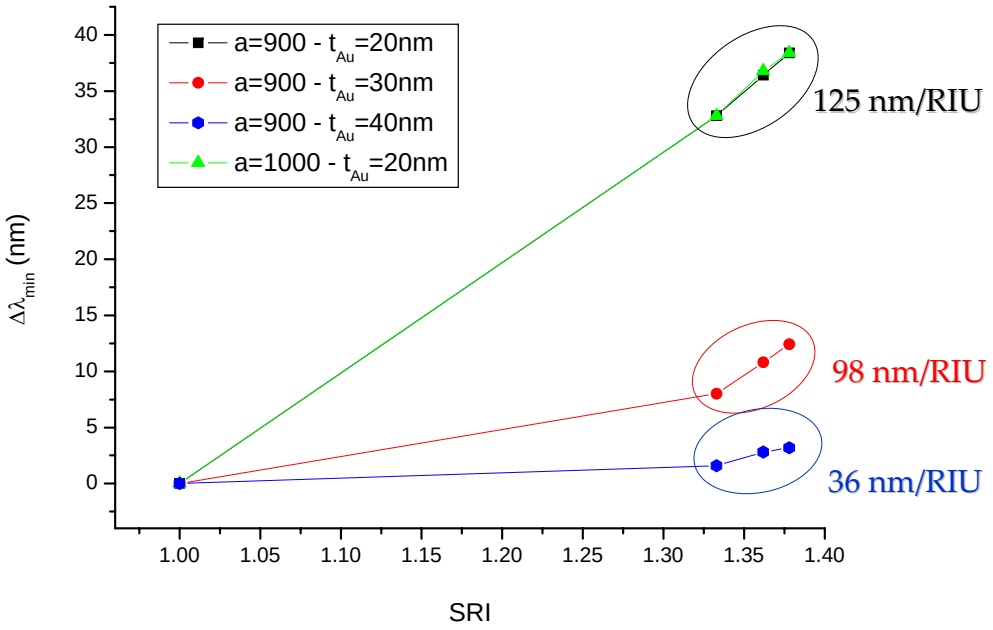
A resonance dip centered at 1311 nm was found with a Q-factor of ~23

LIGHT-MATTER INTERACTION ENHANCEMENT

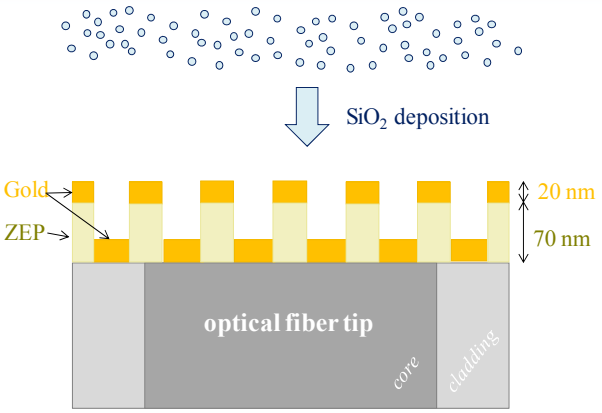




Decreasing gold thickness provides a useful tool to improve light matter interaction with the surrounding environment



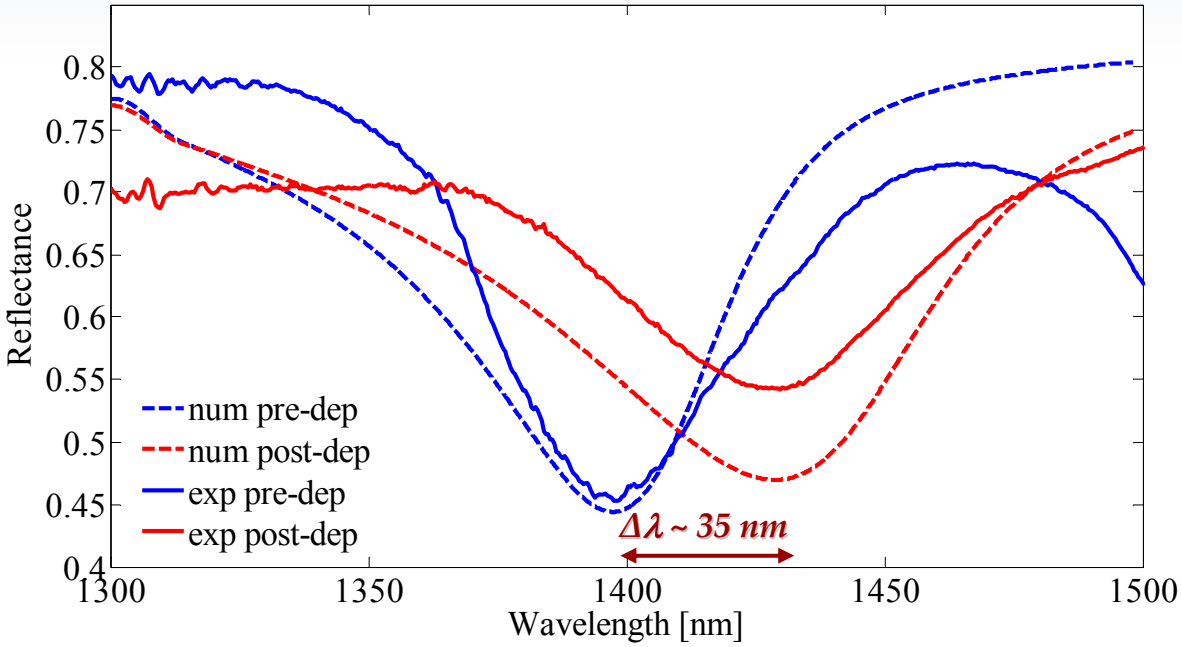
SURFACE REFRACTIVE INDEX SENSITIVITY



$d_{ZEP} = 70nm$, $d_{Au} = 20nm$

$d_{SiO2} = 100nm$

$n_{SiO2} = n_{biolayers}$ ~1.45



Numerical and experimental spectra before and after the deposition of a 100nm-thick SiO_2 overlay

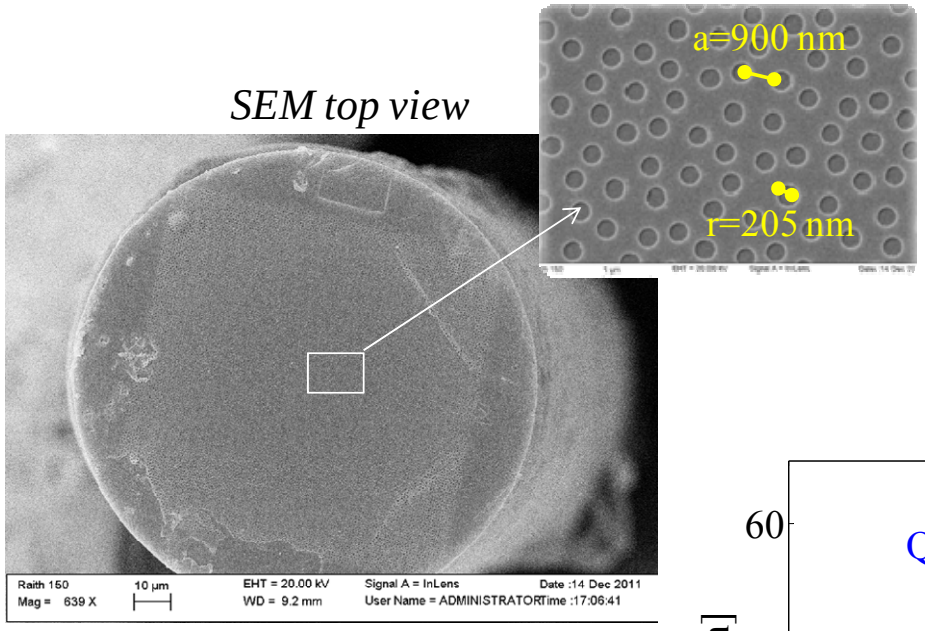
The surface sensitivities (in terms of resonance shift per nanometer of SiO_2 overlay) resulted as high as 0.35 nm /nm of deposited overlay

Further optimization margins exist taking advantages from the large set of degrees of freedom exhibited by the platform

Optoelectronics Group, Engineering Department
University of Sannio, Benevento (Italy)

REFRACTIVE INDEX SENSITIVITY ENHANCEMENT USING PALSMONIC RESONANCES IN HYBRID METALLO-DIELECTRIC QUAICRYSTALS INTEGRATED ONTO OPTICAL FIBERS

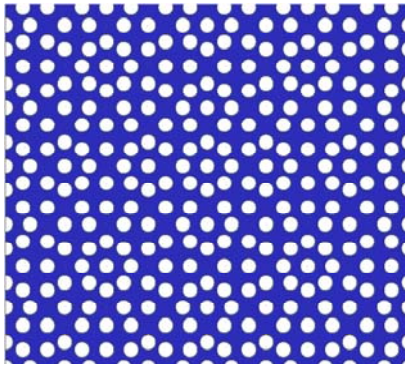
SEM top view



250nm ZEP

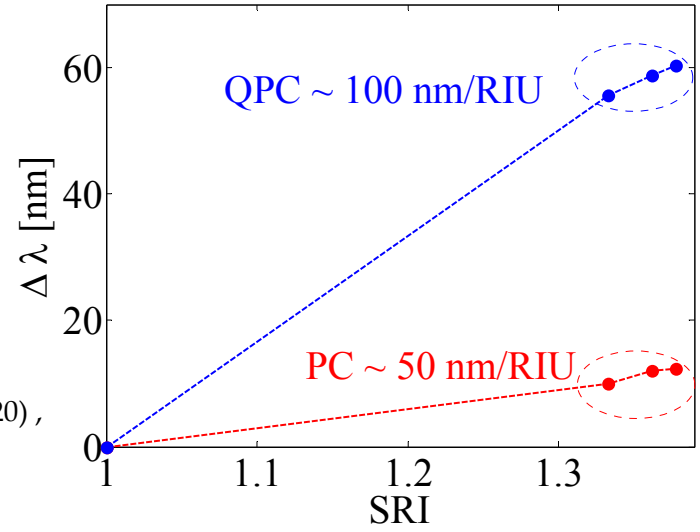
40nm Gold

Ammann-Beenker octagonal (8-fold symmetric) tiling



Rotational symmetry for $\varphi=2\pi/8$

Same filling factor

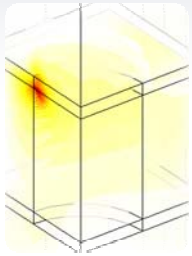


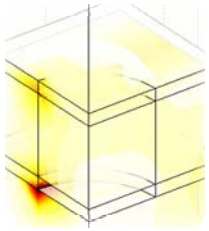
For a given filing factor QCs outperform the periodic counterpart

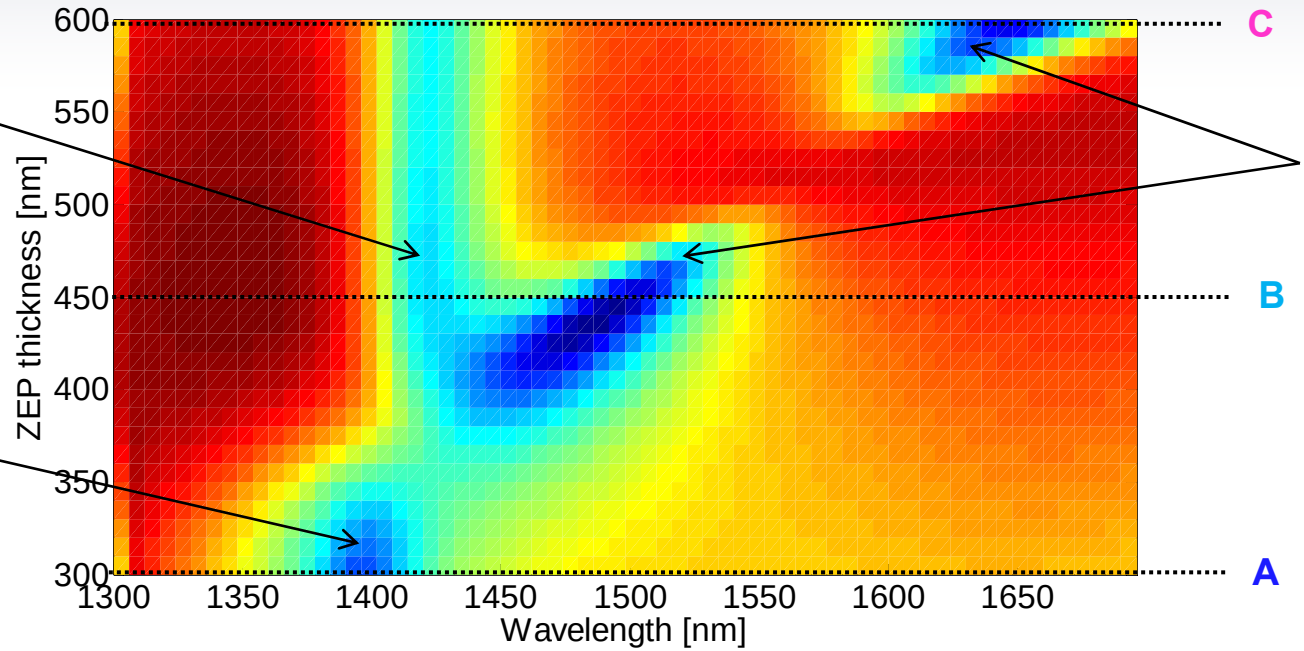
Using the large set of available parameters (gold and resist thickness, lattice tiling) SRI sensitivities of the order of 500nm/RIU are expected with active regions of less than 100 (µm)²

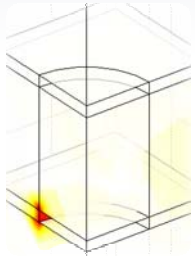
A. Cusano et al, **Advanced Functional Materials**, 22 (20) , 4389-4398 (2012)

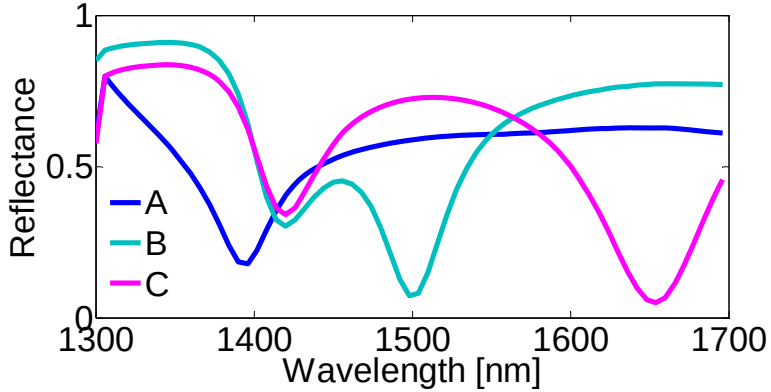
DIELECTRIC THICKNESS TUNING : TOWARDS RESONANCES ENGINEERING



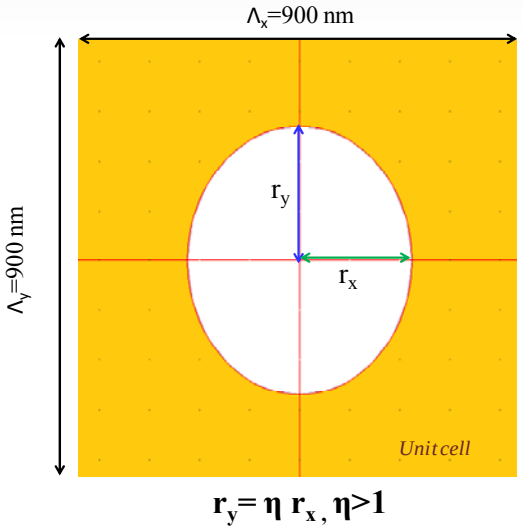








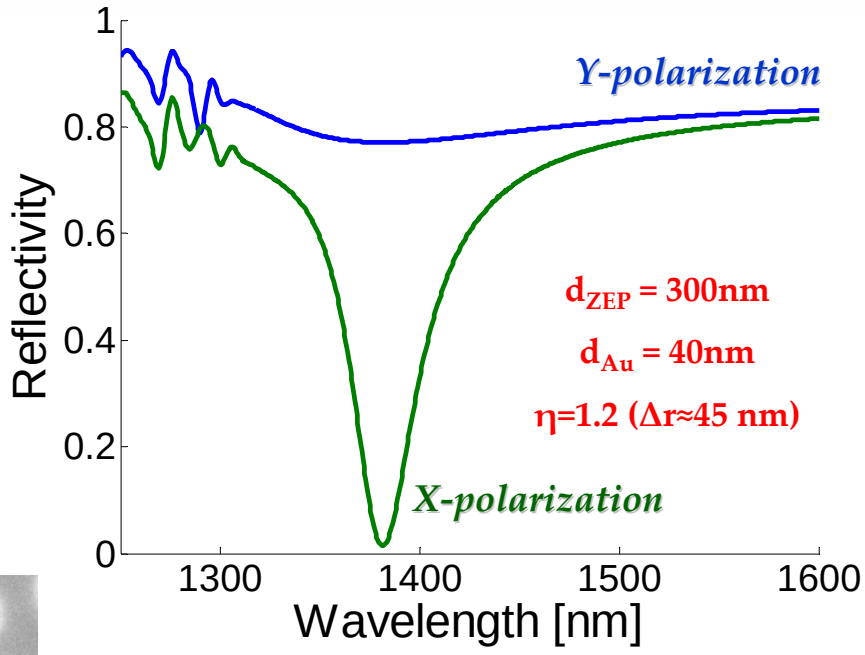
TOWARDS POLARIZATION DEPENDENCE-BASED DEVICES



$r_y = \eta\, r_x$, $\eta > 1$

Ellipticity

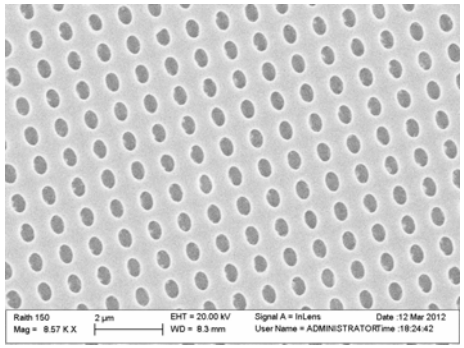
$\eta = r_y / r_x$

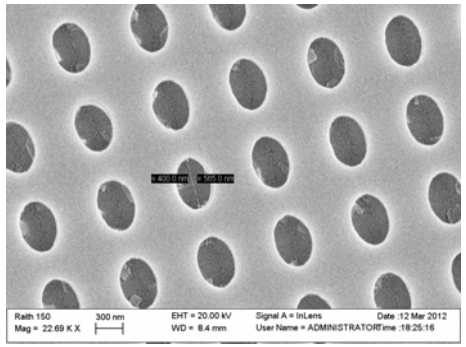


d_{ZEP} = 300nm

d_{Au} = 40nm

η=1.2 (Δr≈45 nm)





Numerical spectra of the two orthogonal polarization (X- and Y-polarizations) when η = 1.2 (Δr≈45 nm)

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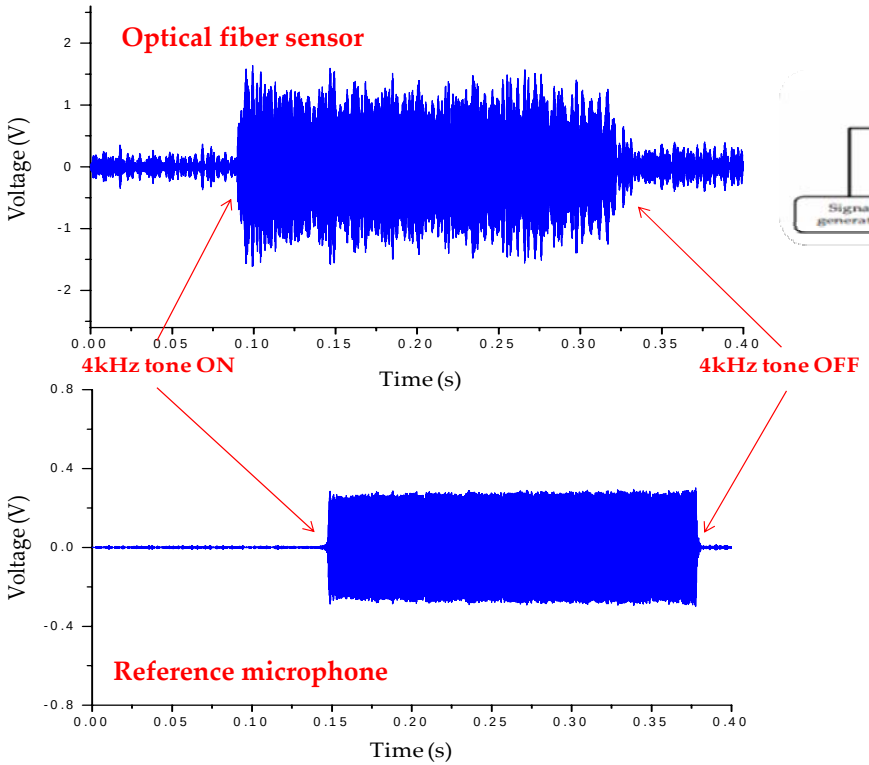
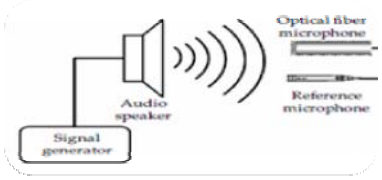
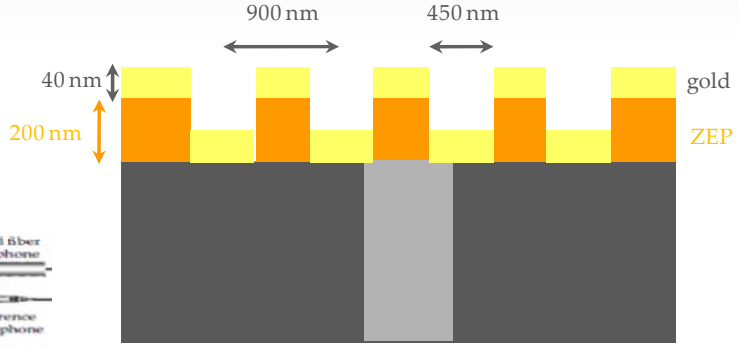
MULTIPARAMETER SENSING: ACOUSTIC WAVE DETECTION

Active role of the polymeric layer: Incident acoustic pressure wave modulates either the geometric features of the low elastic module polymer producing a resonance dip shift at the same frequency of the acoustic wave.

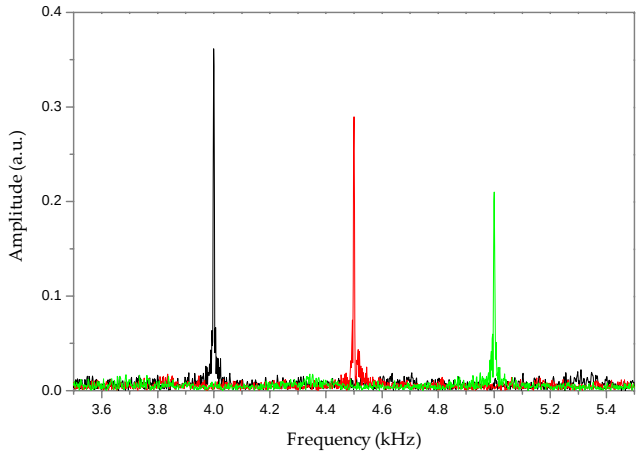


Typical time response for a 4kHz tone





optical fiber tip



Sensor response to tones having different frequency

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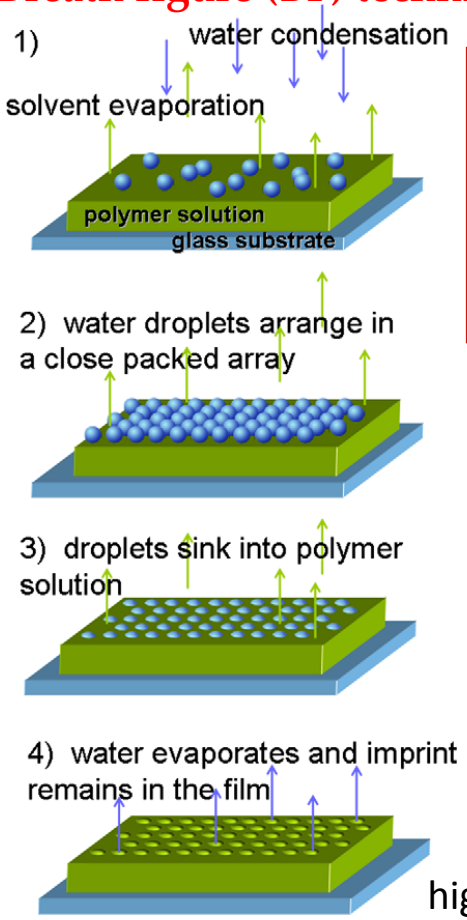
LAB ON FIBER BY SELF ASSEMBLY: BREATH FIGURE TECHNIQUE

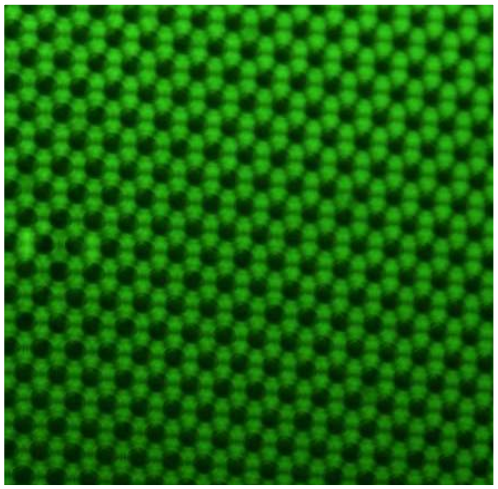
In collaboration with ISMAC

Self assembly techniques enable the deposition of polymeric periodic pattern on glass substrates

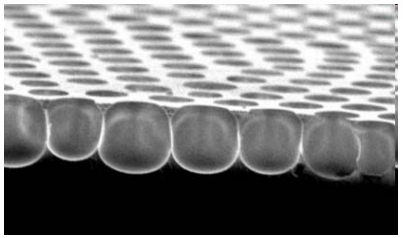
Breath figure (BF) technique



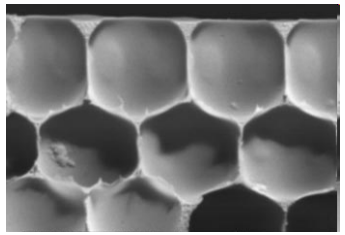
deposition conditions:
1.5-5 mg/mL polystyrene in CS_2
moist N_2: 60 % R.H. at 25 °C
2 L/min flow



highly ordered breath figure patterns



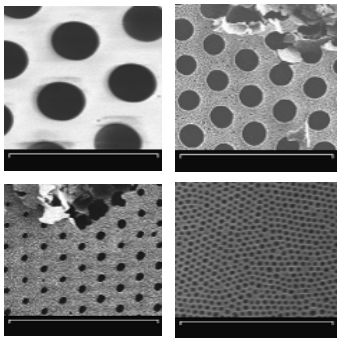
monolayer



multilayer

tunable structures

cavity size : nm → µm



scale bar is 10 µm

Galeotti F et al. Self-functionalizing Polymer Film Surfaces Assisted by Specific Polystyrene End-tagging. *Chemistry of Materials*, **2010**, 22, 2764-2769.

Galeotti F. et al, CdTe nanocrystal assemblies guided by breath figure templates. *Soft Matter*, **2011**, 7, 3832-3836.

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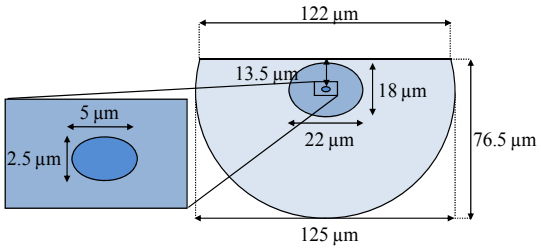
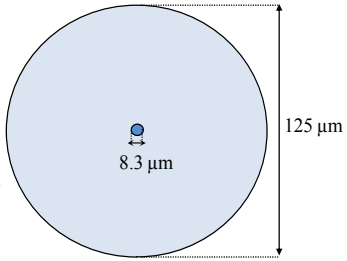
FIB-ASSISTED NANOFABRICATION FOR LAB-ON- FIBER TECHNOLOGY

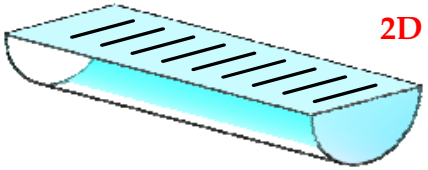
D-shaped fiber



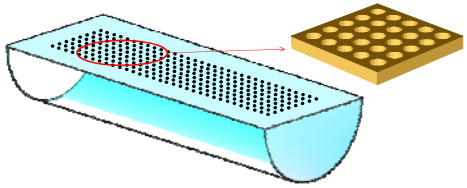
Standard fiber



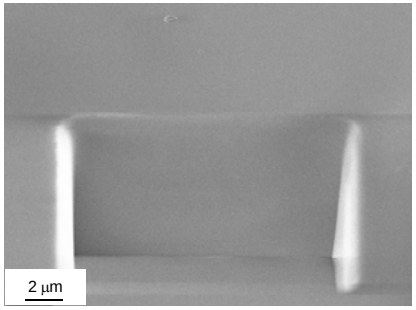
New Fiber Gratings (1D)

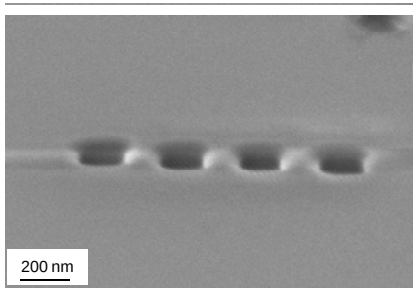


2D In-Fiber Photonic-Plasmonic Crystals

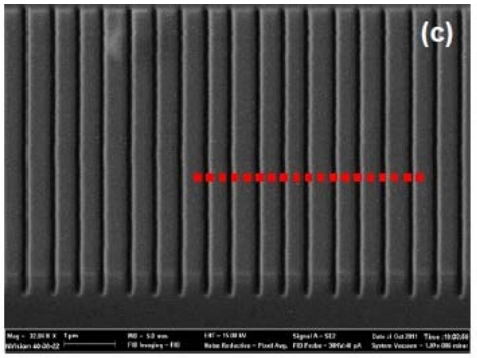


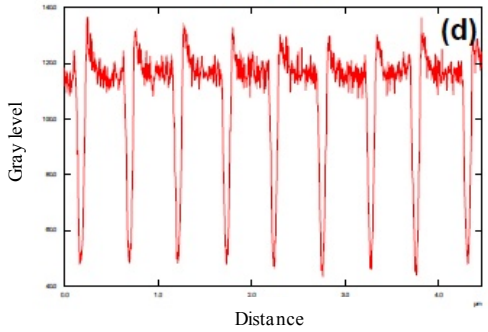
1D metallic (Pt) grating realized on the core of a D-shaped optical fiber (the grating period is 500 nm)





SEM images of a 13x13µm² dig (depth = 13.5µm) and of a row of 150x150 nm² holes FIB milled inside the fiber core.





SEM image of a Pt 1D grating created on the core of a D-shaped fiber by FIB. The contrast line-scan profile shows the regularity of the pattern.

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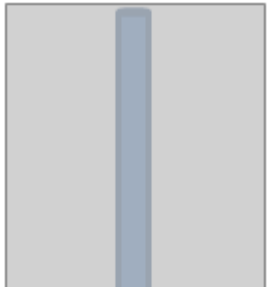
Lab on Fiber by Focused Ion Beam (FIB)

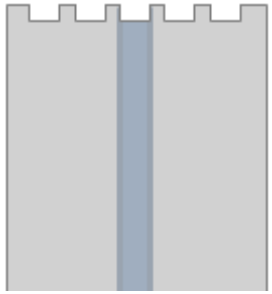
Fabrication steps for creating a photonic crystals slab on the fiber tip

Italian National Agency for New Technologies, Energy and Sustainable Economic Development

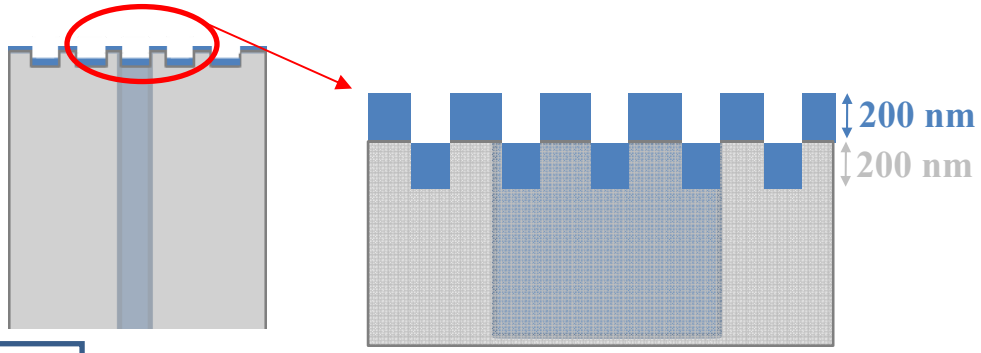
1. Optical fiber tip



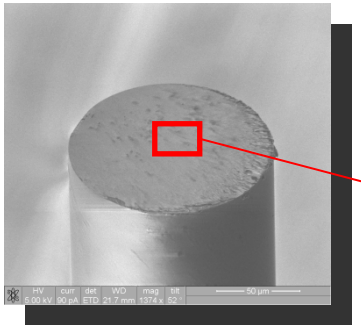
2. Optical fiber nano-pattern (FIB)



3. nSiO*x* deposition (PECVD)

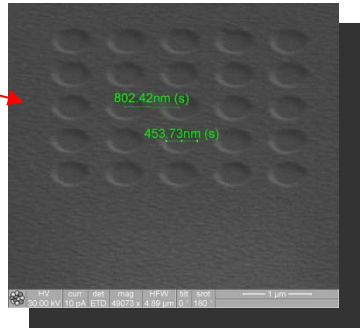


Preliminary experimental results

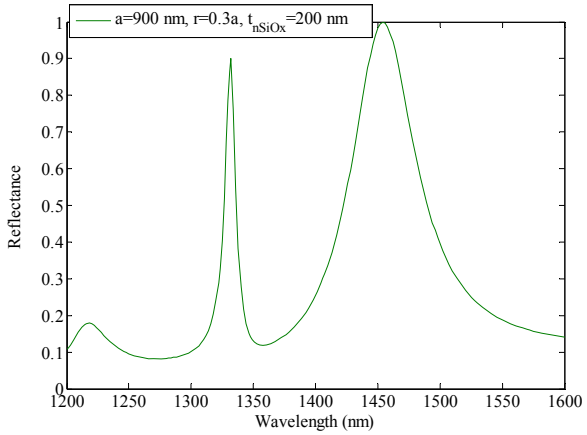


SEM image

Nano-pattern onto the optical fiber



Numeric Reflectance



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STARTING RESEARCH PROJECT: "SMART HEALTH 2.0"

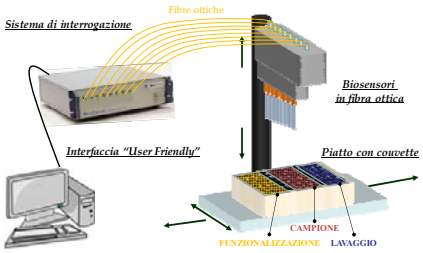
- *Supported by Italian Ministry of University and Research*
- Call: PON *Smart Cities*
- Funding : 30M€
- Duration: 3 years

Optoelectronics Framework

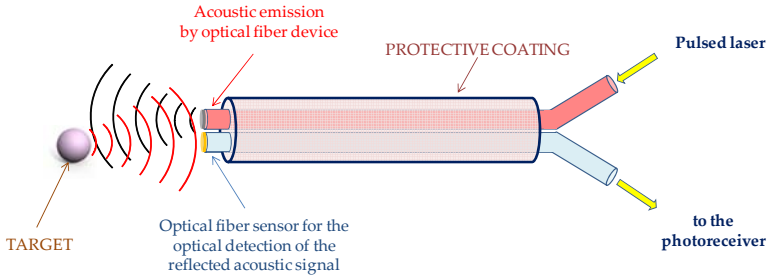
To develop innovative optical fiber sensors for real time and continuous detection of clinically relevant parameters for the invasive diagnostics

CENTRO REGIONALE INFORMATION COMMUNICATION TECHNOLOGY CERICT SCRL

Consiglio Nazionale delle Ricerche

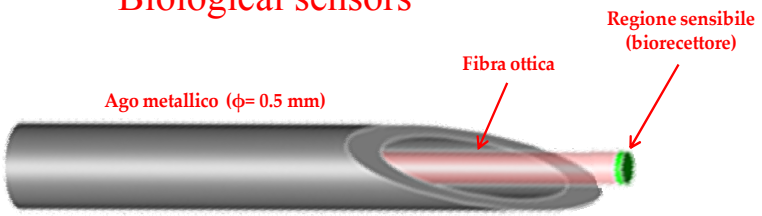


Acoustic Sensors



Magnetic sensors

Biological sensors



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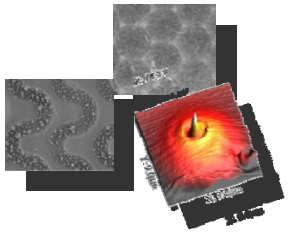
A NEW PUBLIC-PRIVATE AGGREGATION "TOP-IN"

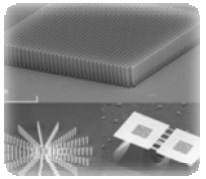
- *Supported by Italian Ministry of University and Research*
- Call: PON *LABORATORI PUBBLICO-PRIVATI E RELATIVE RETI*
- Funding : 20.6M€ for 3 Industrial Research Projects
- *Partners: 30 (industries, research centers, universities, SME)*

TOP-IN — *Tecnologie Optoelettroniche per l'Industria*

Mission: *Research and development of optoelectronic technologies for industrial applications*

Nanophotonics Laboratory



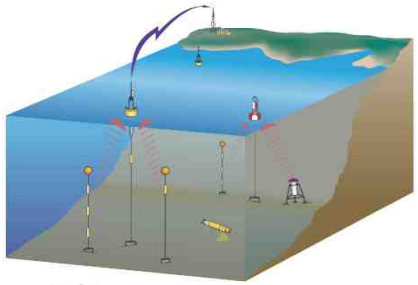


Main lines of action (priorities)

Railway monitoring

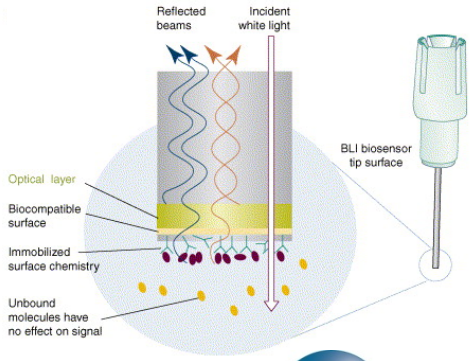

AnsaldoSTS
A Finmeccanica Company

Water monitoring



WASS
A Finmeccanica Company
Whitehead Sistemi Subacquei

Biomedical sensors



BTP tecno


THANKS FOR YOUR
ATTENTION