CSMFO LAB. CHARACTERIZATION and DEVELOPMENT of MATERIALS for PHOTONICS and OPTOELECTRONICS Laboratory

Consiglio Nazionale delle Ricerche

DSFTM
Dipartimento di Scienze Fisiche e Tecnologie della Materia

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Unità di Trento
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FONDAZIONE BRUNO KESSLER

CENTRO FERMI
MUSEO STORICO DELLA FISICA E CENTRO STUDI E RICERCHE ENRICO FERMI

GLASS-BASED PHOTONIC STRUCTURES: ADVANCES AND PERSPECTIVES

Maurizio Ferrari *maurizio.ferrari@ifn.cnr.it*

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[4]Centro di Studi e Ricerche "Enrico Fermi", Piazza del Viminale 1, 00184 Roma, Italy
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[7]École Nationale d'Ingénieurs de Brest, CS 73862, 29238 Brest Cedex 3, France
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[17]MDF Lab. IFAC - CNR, Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy

University of Strathclyde Glasgow

AGH

AGH University of Science and Technology

IRB – Institute Ruđer Bošković

Swansea University
Prifysgol Abertawe

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HCMC University of Technology and Education
HCMUTE

PHOTOPTICS 2018 6th International Conference on Photonics, Optics and Laser Technology- Funchal, Madeira – Portugal 26 January 2018

OUTLINE

- ❖ WELCOME TO THE GLASS AGE
- ❖ GLASS CERAMICS AND ENERGY TRANSFER
- ❖ WHISPERING GALLERY MODES
- ❖ 1D MICROCAVITIES
- ❖ OPALS
- ❖ CONCLUSIONS AND PERSPECTIVES

The bright advancement of glass photonics

Welcome to the Glass Age

David L. Morse and Jeffrey W. Evenson - Corning

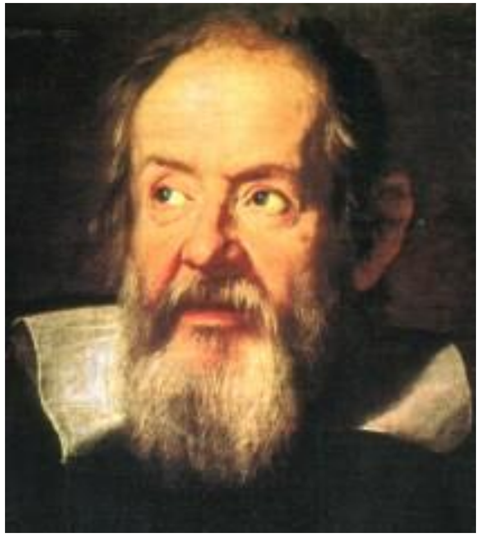
International Journal of Applied Glass Science, 7 [4] 409–412 (2016) DOI:10.1111/ijag.12242

- Glass is one of the world's most transformative materials.
- Featuring tremendous versatility and distinctive technical capabilities, glass has been responsible for numerous cultural and scientific advancements from windows to optical fiber.
- Today, the pace of glass innovation is accelerating, thanks to scientists' deep understanding of glass physics and chemistry, combined with modern analytic and control technologies.
- We believe that the world has entered the Glass Age.
- We have an unprecedented opportunity to harness the unique capabilities of glass to solve some of our world's most urgent challenges, such as more effective healthcare, cleaner energy and water, and more efficient communication.
- Realizing the potential of the Glass Age will require collaboration, resources, and support, but it is an opportunity we cannot afford to waste.

GLASS – BASED NANOTECHNOLOGIES

« …smaller objects in nature are not just scaled replicas of similar big objects and in fact they have improved properties…»

Galileo «Dialogue Concerning Two New Sciences» (1638)



- Light–matter interactions are stronger at small objects (micro- and nano-scale) PHOTONIC GLASS-CERAMICS
- High Q structures, with strong spatial localization of the field, well respond to this principle and receive a great attention in many fundamental processes in photonics. Great application potential in many areas including cavity QED, atom trapping, laser stabilization, microlasers, nonlinear optics, nonlinear-optical thin-film diagnostics, and evanescent-wave sensing. CONFINED STRUCTURES

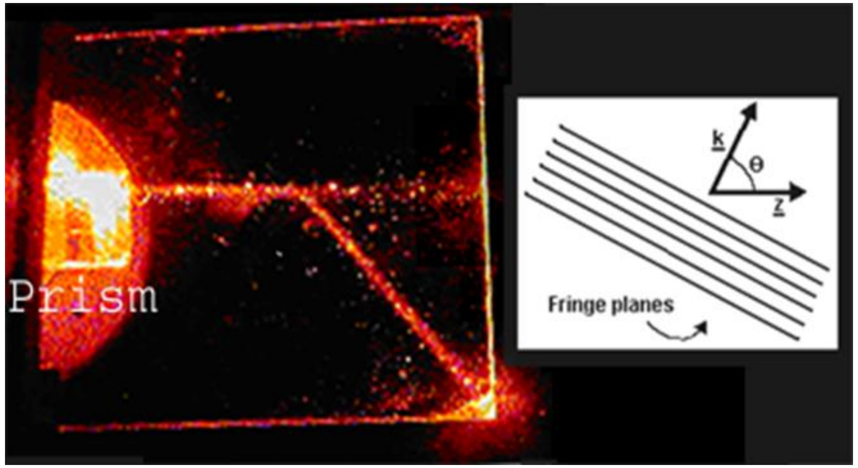
GLASS – BASED NANOTECHNOLOGIES

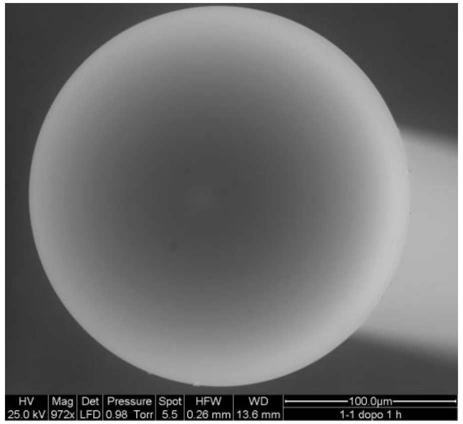
Nano scale confined structures

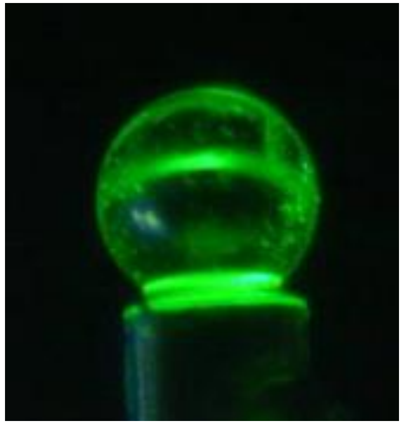
Micro scale confined structures

Light control

Photons management







You can save Energy reducing Energy consuming

Low threshold laser action

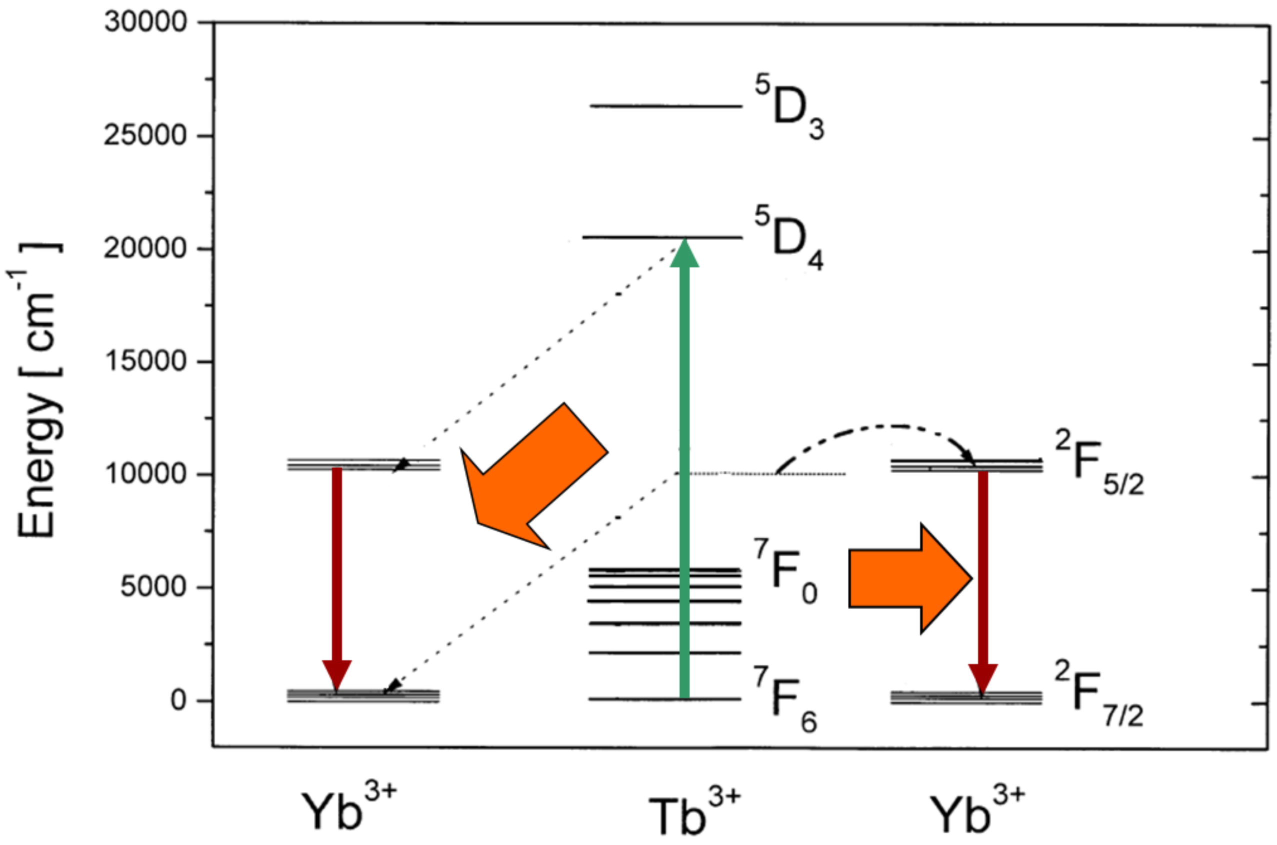
$$I_{th} = \frac{h\nu_p}{\sigma_p \tau}$$

Glass Ceramics and Energy Transfer

Lidia Zur

Thi Ngoc Lam Tran, Damiano Massella, Cristina Armellini, Yann G. Boucher, Alessandro Chiasera, Stefano Varas, Andrea Chiappini, Alessandro Carpentiero, Dominik Dorosz, Roberta Ramponi, Giancarlo C. Righini, James Gates, Pier Sazio, Brigitte Boulard, Anna Lukowiak, Daniele Zonta, Maurizio Ferrari

Down conversion with Tb^{3+}/ Yb^{3+}



One green photon @ 488nm **Two red photon @ 980 nm**

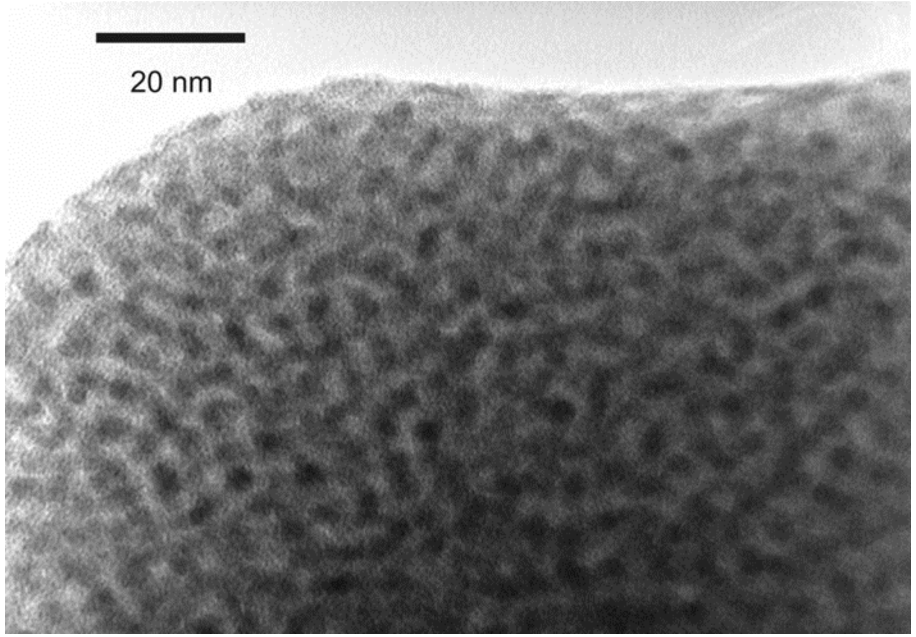
DOWN-CONVERTERS SILICA-HAFNIA GLASS CERAMICS

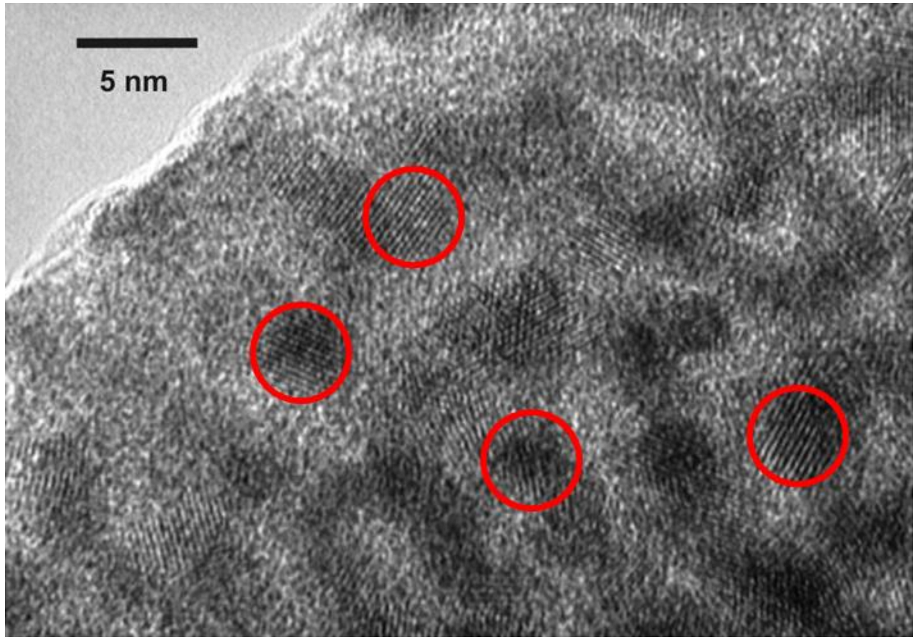
- ❑ **Low phonon energy (~ 700 cm^{-1})**
- ❑ **Rare earth solubility**
- ❑ **Combine spectroscopic properties of the crystal with optical properties of the glass**

- ❑ **Determine the efficiency of the process**
- ❑ **Optimize the rare earth ions content**

Glass Ceramics as a class of Nanocomposite Photonic Materials

✓ Nanoscale structural and optical fluctuation





Validation of the process: hafnia nanocrystals activated by rare earth ions embedded in waveguides – **Energy transfer efficiency enhanced by HfO_2 NCs**

Tb^{3+}/Yb^{3+} DOWN CONVERSION EFFICIENCY

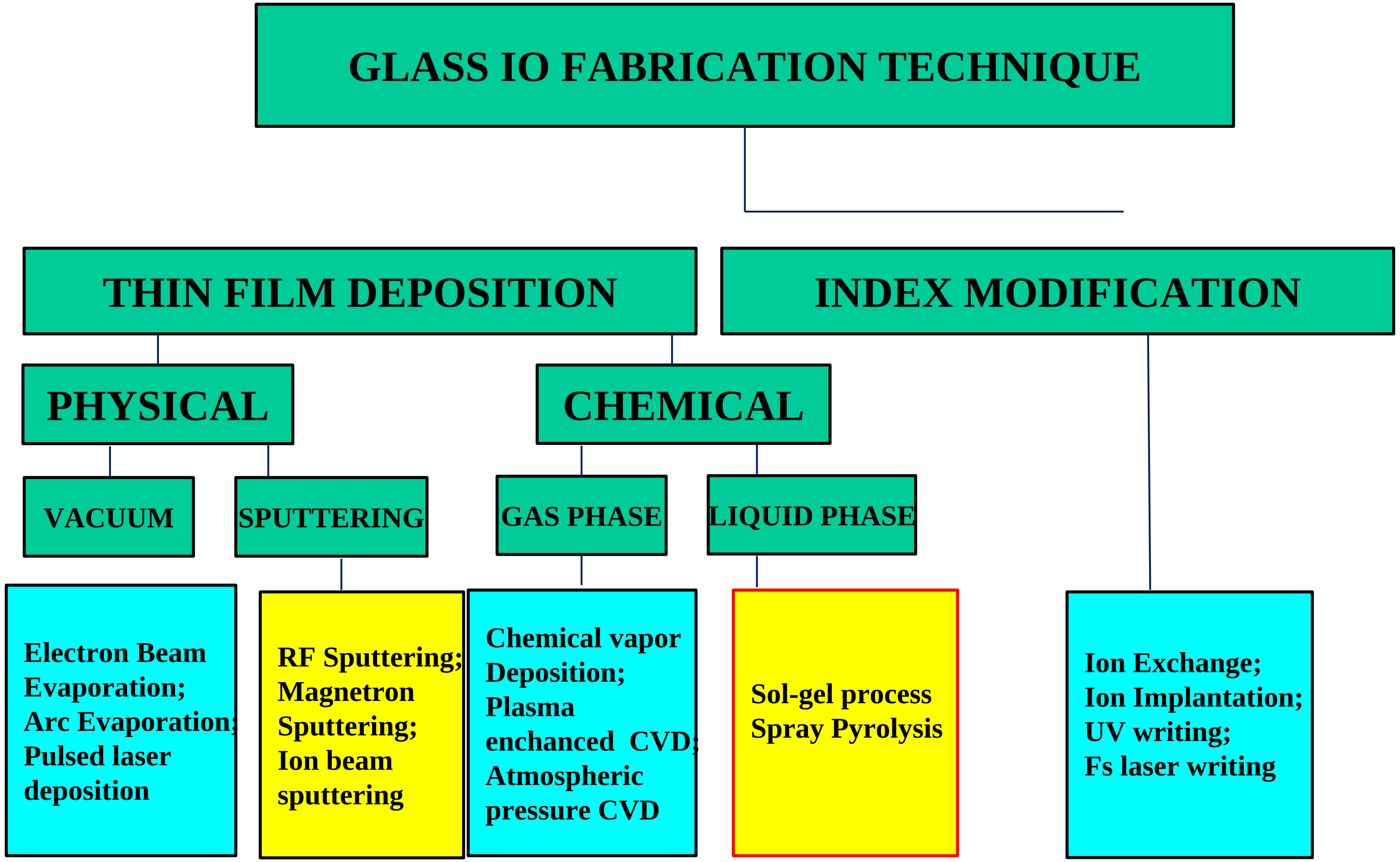
Composition (Yb concentration in mol%)	1%	2%	3%
Estimated transfer efficiency (in glass ceramic)	14%	24%	25%
Estimated effective quantum efficiency (in glass ceramic)	114%	124%	125%
Estimated transfer efficiency (in glass)	2%	4%	6%
Estimated effective quantum efficiency (in glass)	102%	104%	106%

Pr^{3+}/Yb^{3+} down conversion efficiency

$70ZrF_4–23.5LaF_3–0.5AlF_3–6GaF_3$	0.5% Pr^{3+}/10 Yb^{3+}	191%

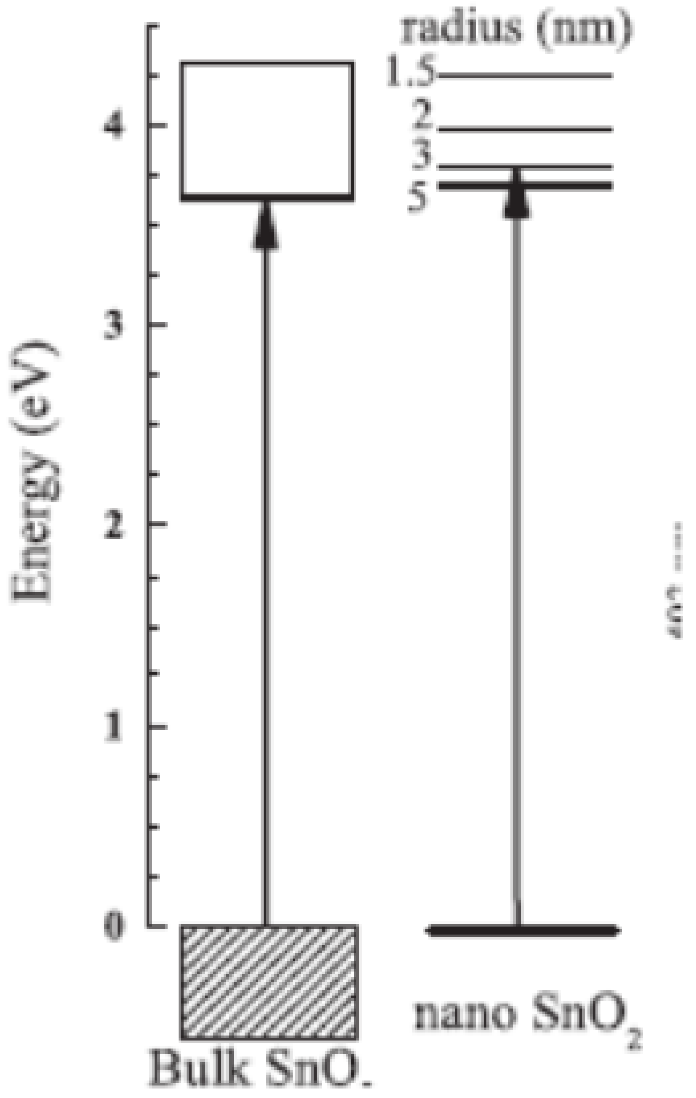
B. Dieudonné, B. Boulard, G. Alombert-Goget, A. Chiasera, Y. Gao, S. Kodjikian , M. Ferrari
"Up- and Down-conversion in Yb^{3+}-Pr^{3+} co-doped fluoride glasses and glass ceramics"
Journal of Non-Crystalline Solids 377 (2013) pp. 105-109. doi:10.1016/j.jnoncrysol.2012.12.025

GLASS - BASED INTEGRATED OPTICS TECHNOLOGIES

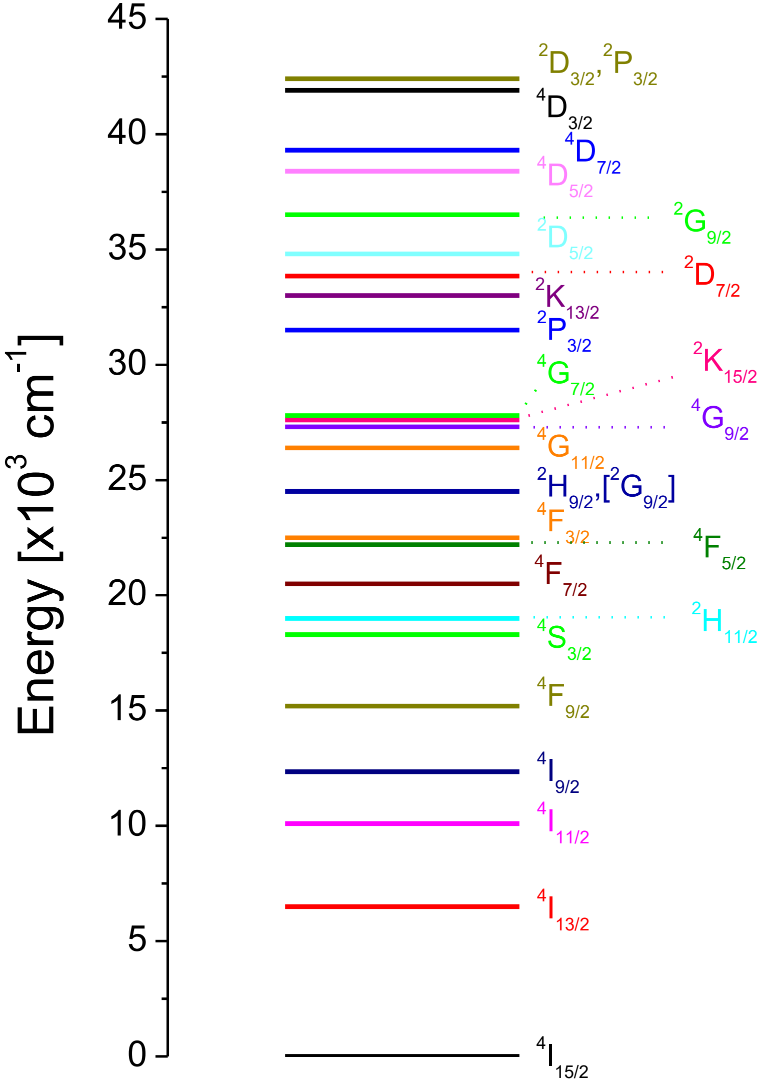


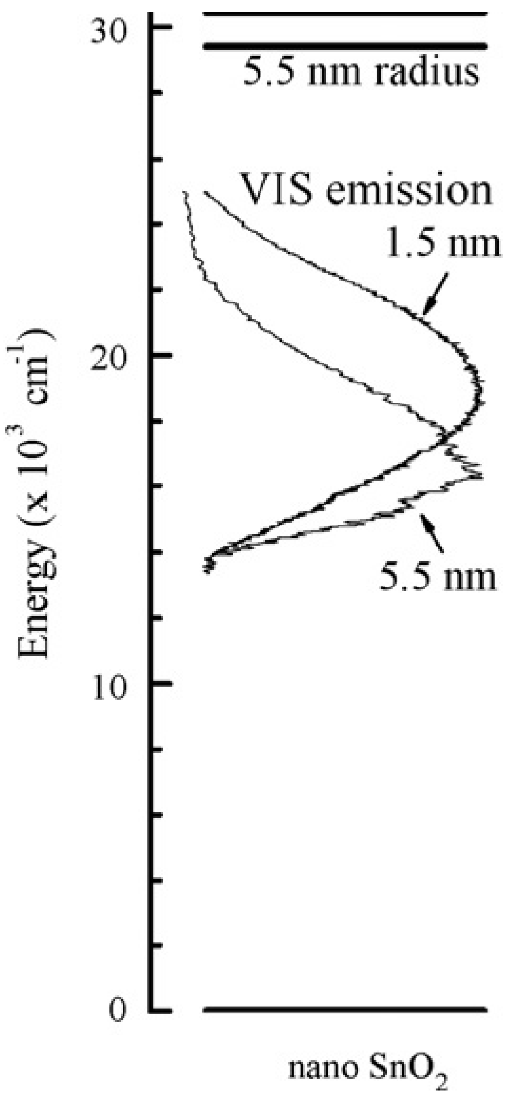
G.C. Righini, A. Chiappini “Glass optical waveguides: a review of fabrication techniques” Optical Engineering (2014)

SnO_2 nanocrystals



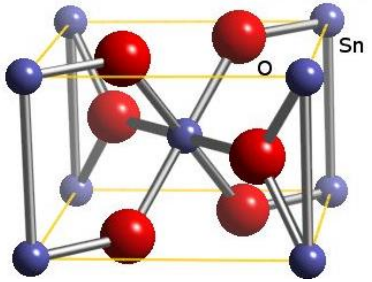
Innovative solution exploiting SnO_2 nanocrystals

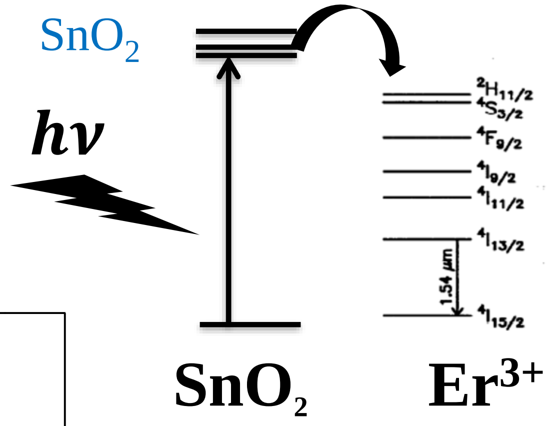


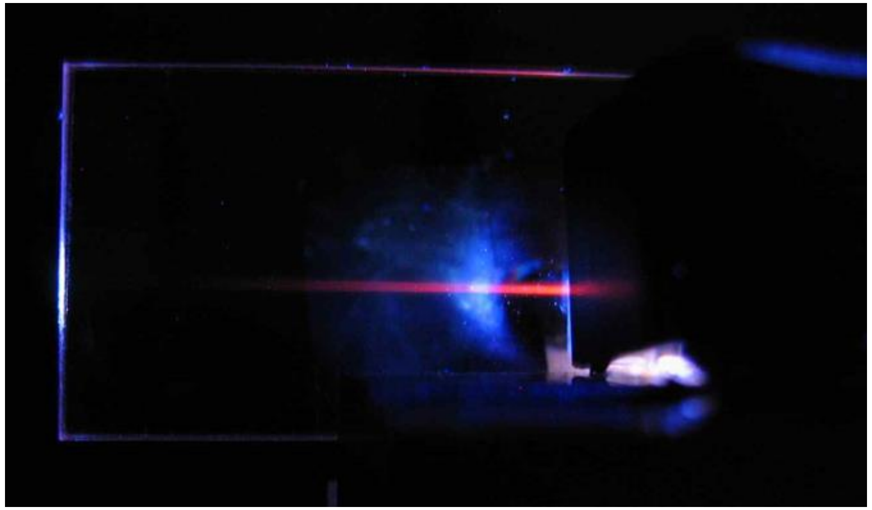


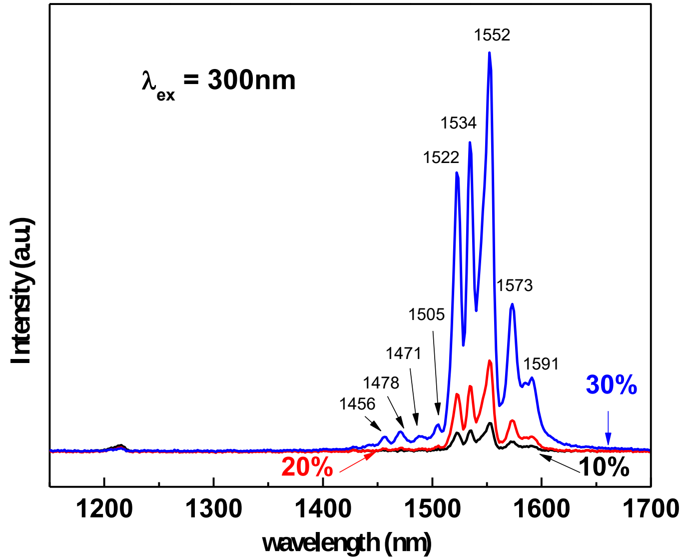
SnO_2 NCs as sensitizers for Rare Earth ions

Tin dioxide









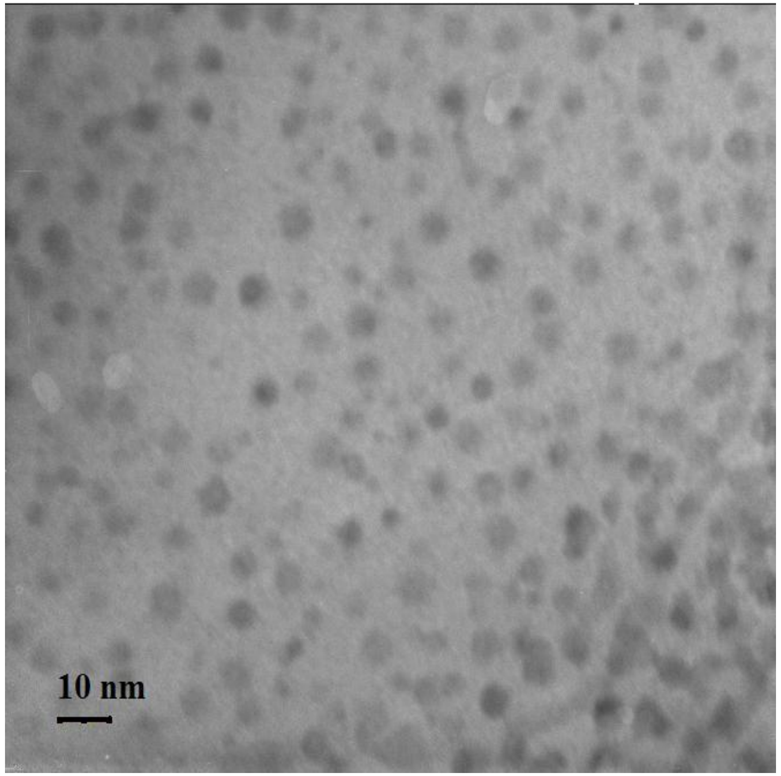
Photoluminescence spectra of $xSnO_2$-(100-x)SiO_2 doped with 1 mol% of Er^{3+} (x= 10, 20, 30 mol%)

1) Energy transfer from SnO_2 into Rare-Earth ions ***increases the luminescence*** of Rare-Earth ions
2) SnO_2 has a low phonon energy (630cm^{-1}) that **reduces losses** from non-radiative relaxation
3) SnO_2 has **transparency** in range from visible to NIR
4) SiO_2-SnO_2 exhibits **photorefractivity** **(Δn ~ -10^4** allowing writing of integrated circuits by UV and visible light

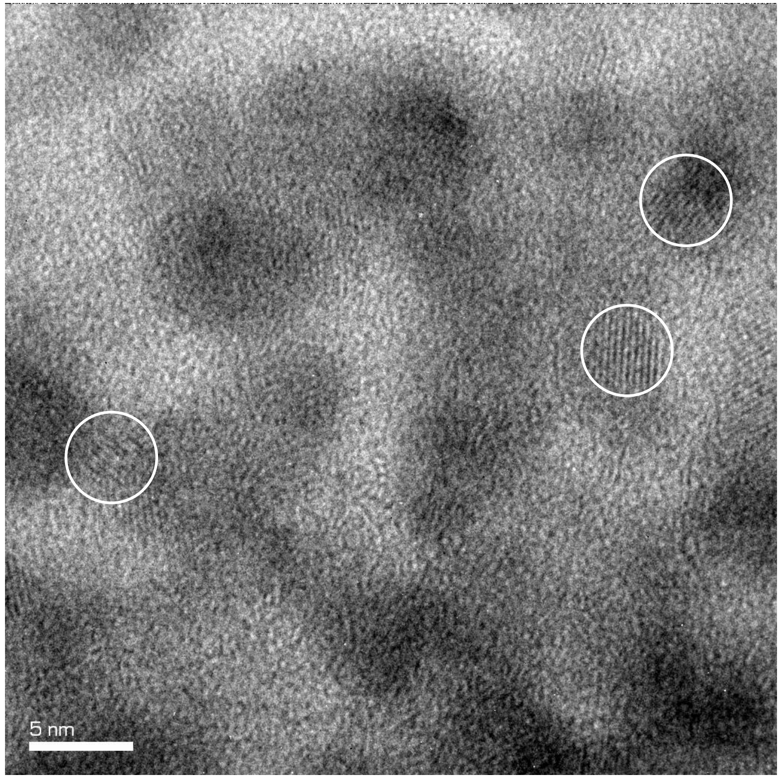
Lidia Zur, Thi Ngoc Lam Tran, Marcello Meneghetti, Thi Thanh Van Tran, Anna Lukowiak, Alessandro Chiasera, Daniele Zonta, Maurizio Ferrari, Giancarlo C. Righini
"Tin-dioxide nanocrystals as Er^{3+} luminescence sensitizers: formation of glass-ceramics thin films and their characterization"
Optical Materials 63 (2017) pp.95-100 Special Issue to Celebrate G. Boulon doi: 10.1016/j.optmat.2016.08.041

TEM

Homogeneous distribution



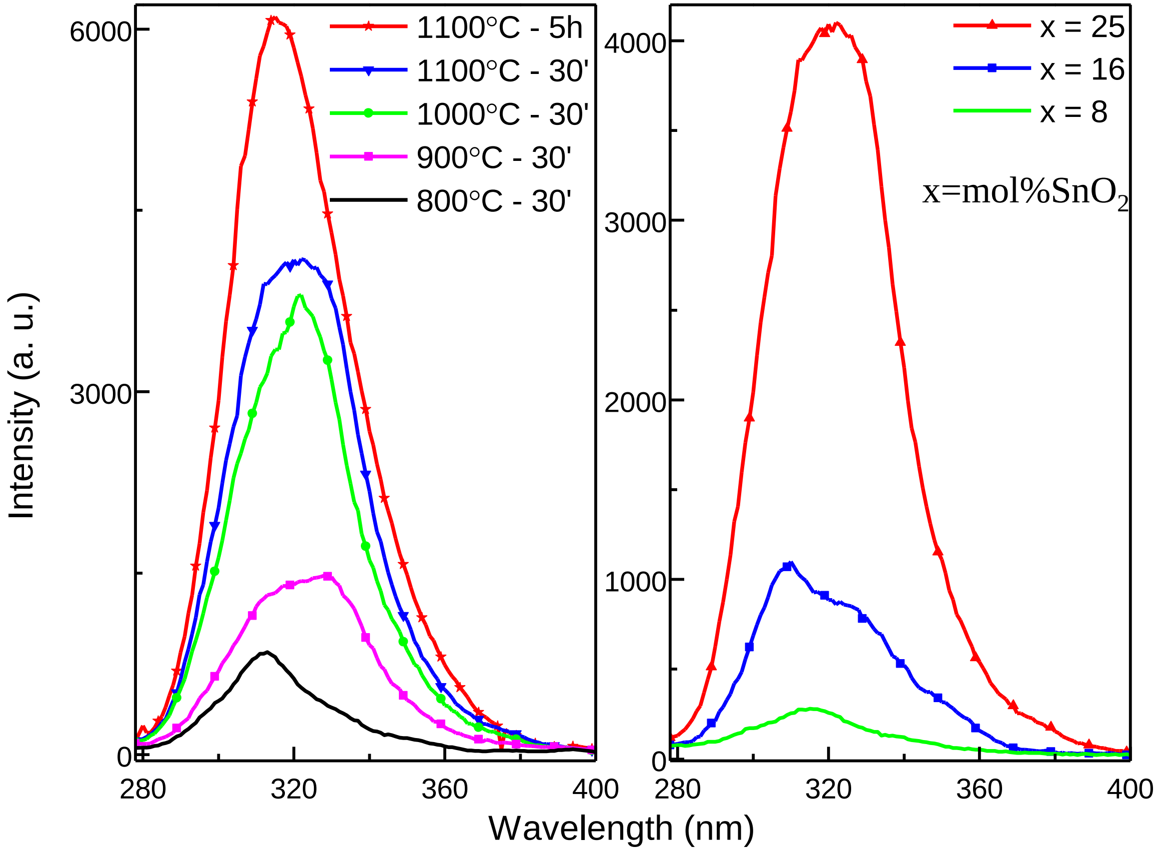
About 4 nm NCs



Tran T.T. Van, S. Turrell, B. Capoen, Lam Q. Vinh, O. Cristini-Robbe, M. Bouazaoui, F. d'Acapito, M. Ferrari, D. Ristic, A. Lukowiak, R. Almeida, L. Santos, and C. Kinowski "Erbium-doped tin-silicate sol-gel-derived glass-ceramic thin films: Effect of environment segregation on the Er^{3+} emission" Science of Advanced Materials 7 (2015) pp. 301-308 doi: 10.1166/sam.2015.2022

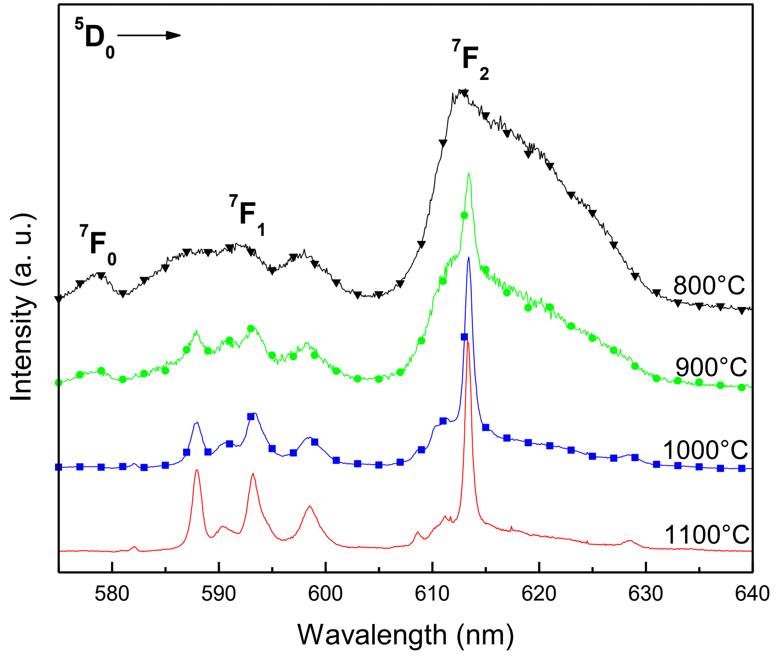
Excitation spectra

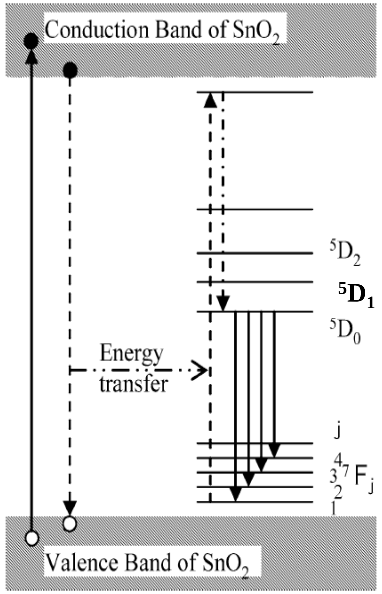
Room temperature excitation spectra of $^5D_0 \rightarrow {}^7F_2$ emission at 613 nm



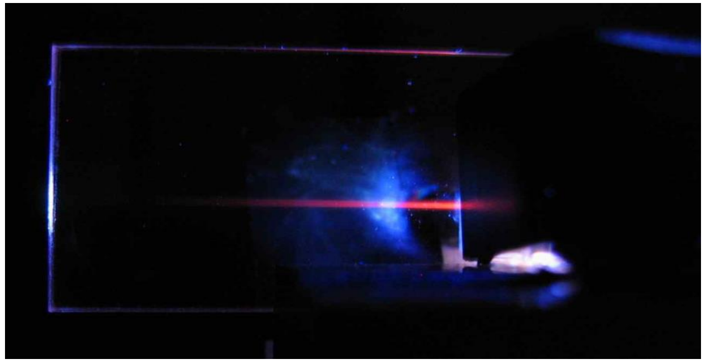
The broad and strong band observed at 310 nm (4.0 eV) corresponds to the SnO_2 band-gap energy.

PL spectra λ_{ex}=351nm





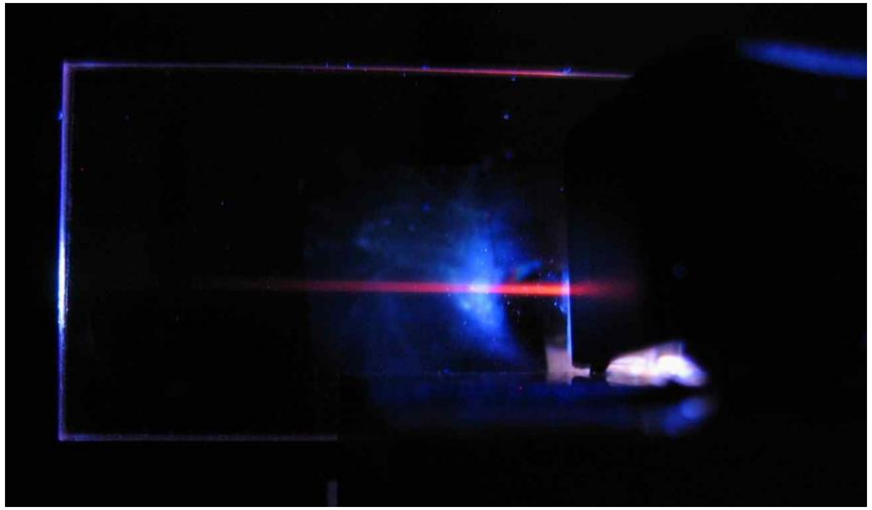
For annealing temperature higher than 900 °C the emission **features typical of Eu^{3+} ion in a crystalline like environment** are predominant, *indicating that most part of Eu^{3+} ions are embedded in SnO_2 nanocrystals*



Enhanced fluorescence from Eu^{3+} in low-loss silica glass-ceramic waveguides with high SnO_2 content

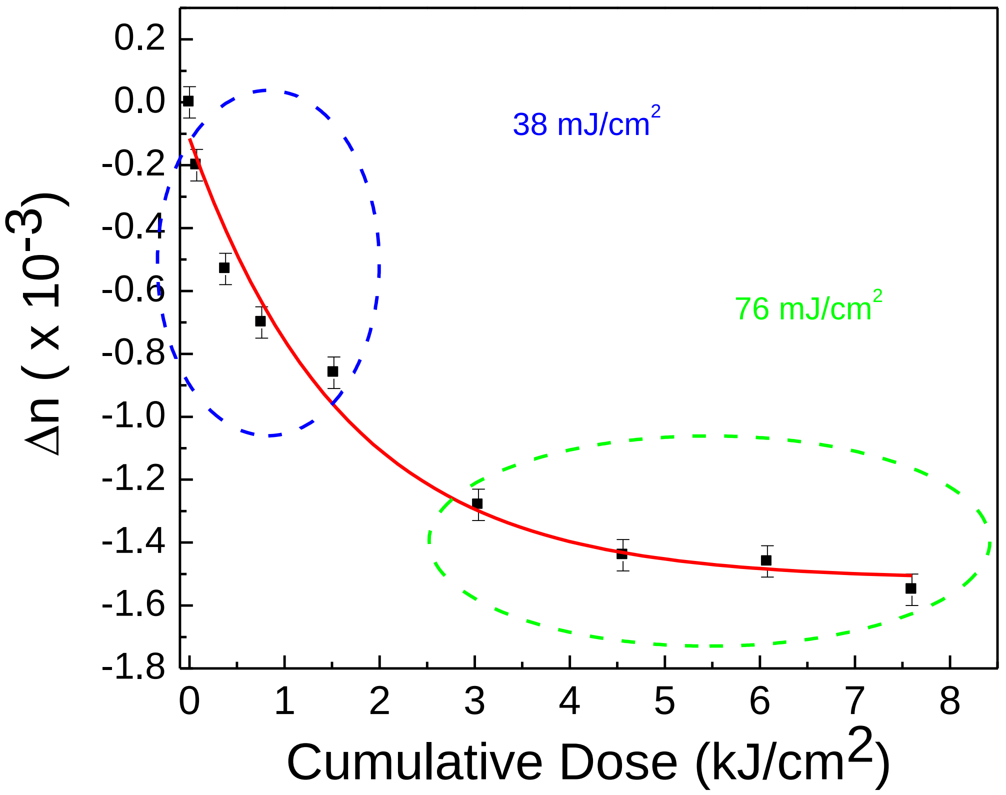
λ_{ex} = 351 nm

S.N.B. Bhaktha, F. Beclin, M. Bouazaoui, B. Capoen, A. Chiasera, M. Ferrari, C. Kinowski, G.C. Righini, O. Robbe, S. Turrell, “Applied Physics Letters 93 (2008) pp. 211904-1/3.



Crack-free and low loss glass ceramic waveguide $75SiO_2$-$25SnO_2$: Eu^{3+} fabricated by sol gel, dip-coating method. Losses remain below 0.8 dB/cm.

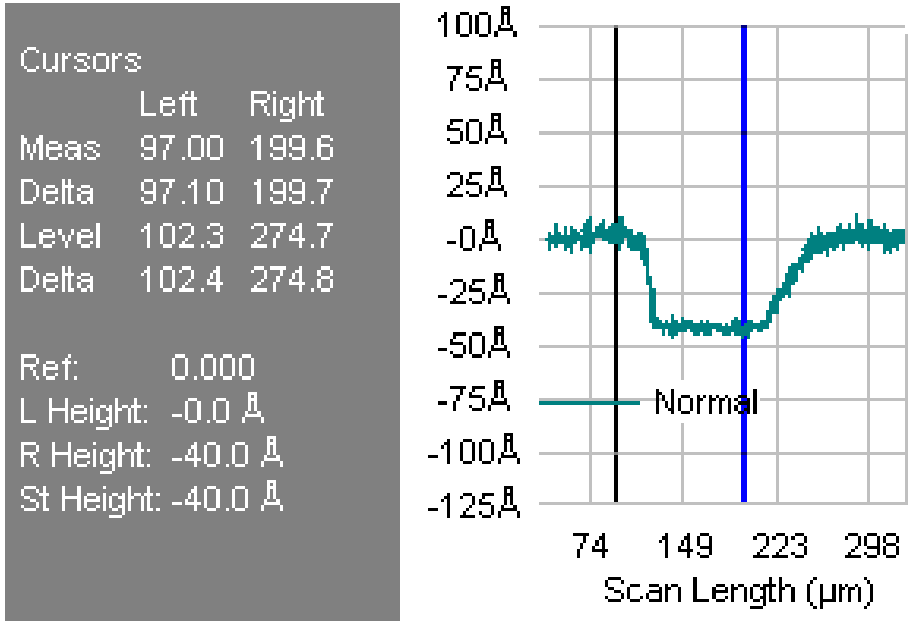
High photosensitivity in low-loss sol-gel SiO_2 – SnO_2 waveguides



Effective index change at 1550 nm for the single mode waveguide after the UV irradiation at 248 nm as a function of cumulative doses used. The solid line is an help for the eyes.

Anna Lukowiak, Lidia Zur, Thi Ngoc Lam Tran, Marcello Meneghetti, Simone Berneschi, Gualtiero Nunzi Conti, Stefano Pelli, Cosimo Trono, B.N. Shivakiran Bhaktha, Daniele Zonta, Stefano Taccheo, Giancarlo C. Righini, Maurizio Ferrari "Sol–Gel-Derived Glass-Ceramic Photorefractive Films for Photonic Structures"
Crystals 7 (2017) pp. 61_1/7 doi:10.3390/cryst7020061

High photosensitivity in low-loss sol-gel $SiO_2 - SnO_2$ waveguides

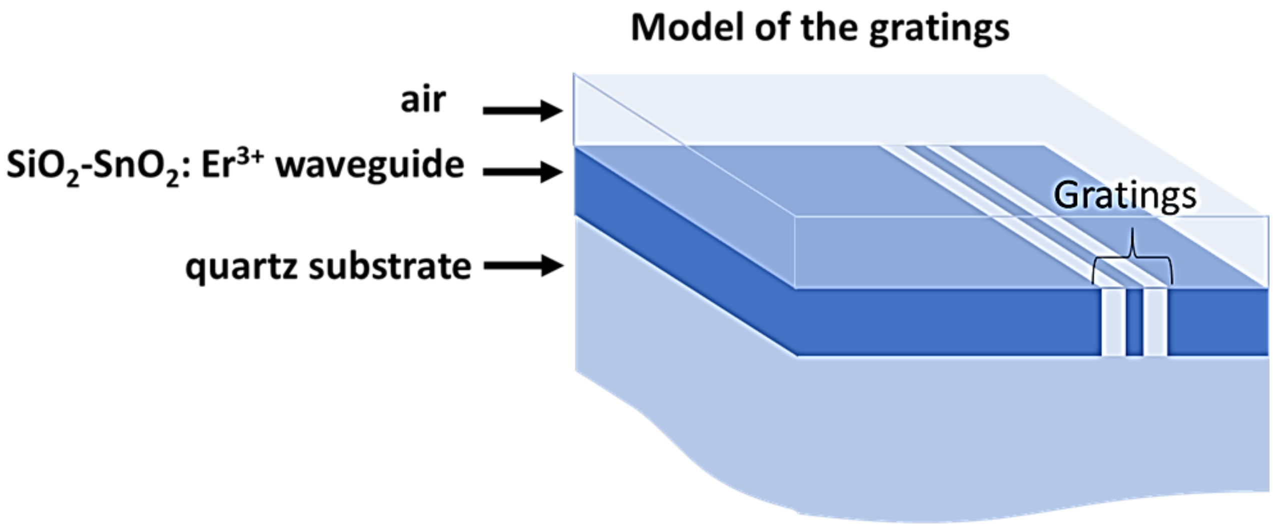


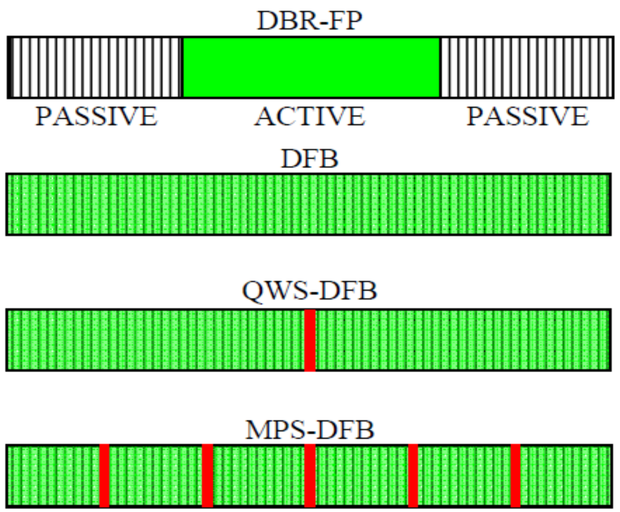
A swelling of about 4 nm was observed in UV exposed regions

Lidia Zur, Thi Ngoc Lam Tran, Marcello Meneghetti, Maurizio Ferrari
"Sol-gel derived SnO2-based photonic systems"
in Handbook of Sol-Gel Science and Technology (2017) pp. 1-19, Springer International Publishing AG Eds. Lisa Klein, Mario Aparicio, Andrei Jitianu
Print ISBN: 978-3-319-19454-7 Online ISBN: 978-3-319-19454-7 doi: 10.1007/978-3-319-19454-7_116-1

S.Berneschi, S.N.B. Bhaktha, A. Chiappini, A. Chiasera, M. Ferrari, C. Kinowski, S. Turrell, C. Trono, M. Brenci, I. Cacciari, G. Nunzi Conti, S. Pelli, G. C. Righini "Highly photorefractive Eu^{3+} activated sol-gel $SiO_2 - SnO_2$ thin film waveguides"
Proceedings of SPIE Vol. 7604 (2010) pp. 76040Z-1/6

DESIGN FOR PLANAR PHOTONIC STRUCTURES

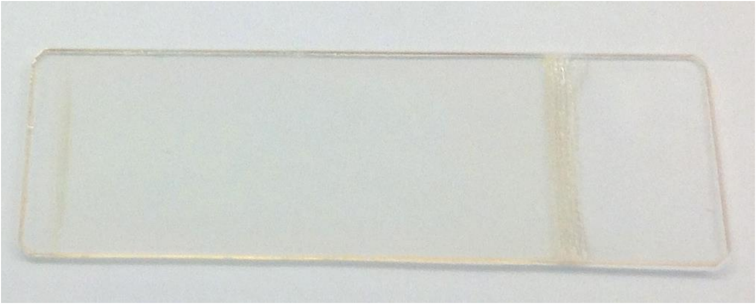




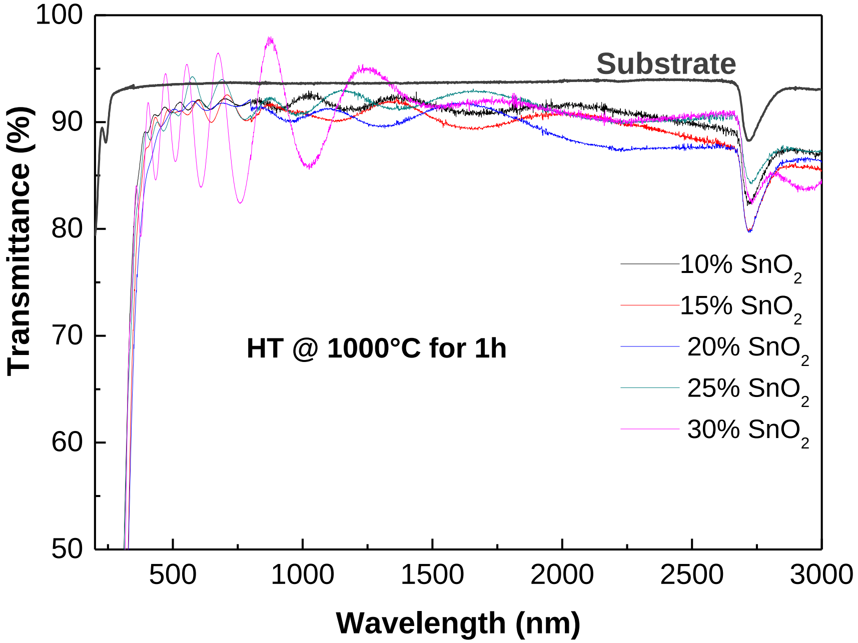
i. active Fabry-Perot cavity with passive Distributed Bragg Reflectors (DBR- FP);
ii. active Distributed-Feedback structure (DFB);
iii. DFB with Quarter-Wave phase Shift (QWS-DFB);
iv. DFB with Multiple Phase Shifts distributed along the cavity (MPS-DFB)

SnO_2-SiO_2:Er^{3+} PLANAR WAVEGUIDES

70%SiO_2-30%SnO_2-0.5%Er^{3+}, HT@ 1000°C for 1h

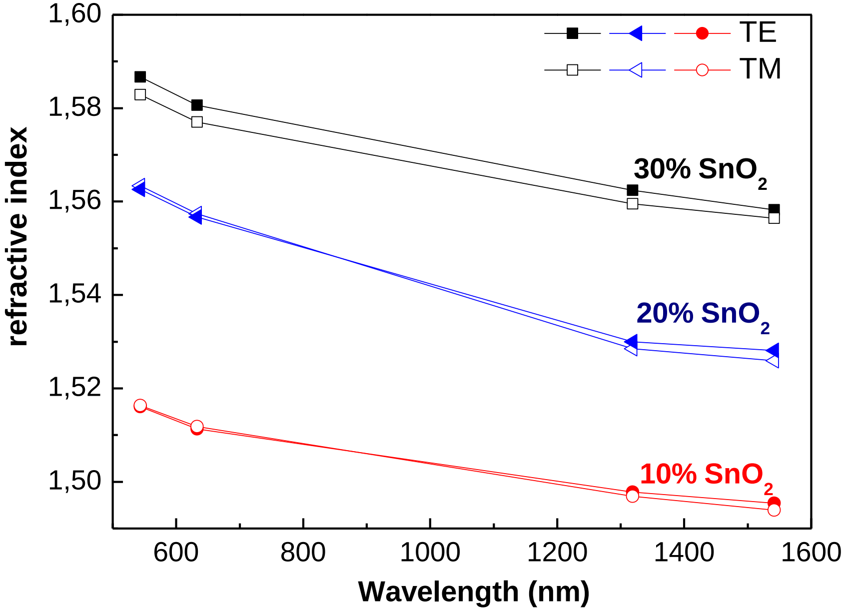


TRANSPARENT (UV-NIR)



Transmission spectra of xSnO_2-(100-x) SiO_2-0.5%Er^{3+}, HT@1000°C for 1h

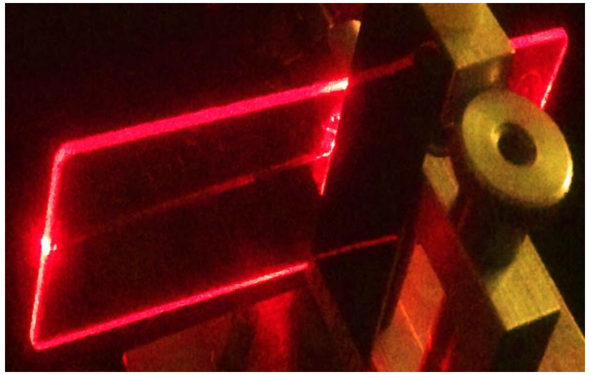
INCREASED REFRACTIVE INDEX

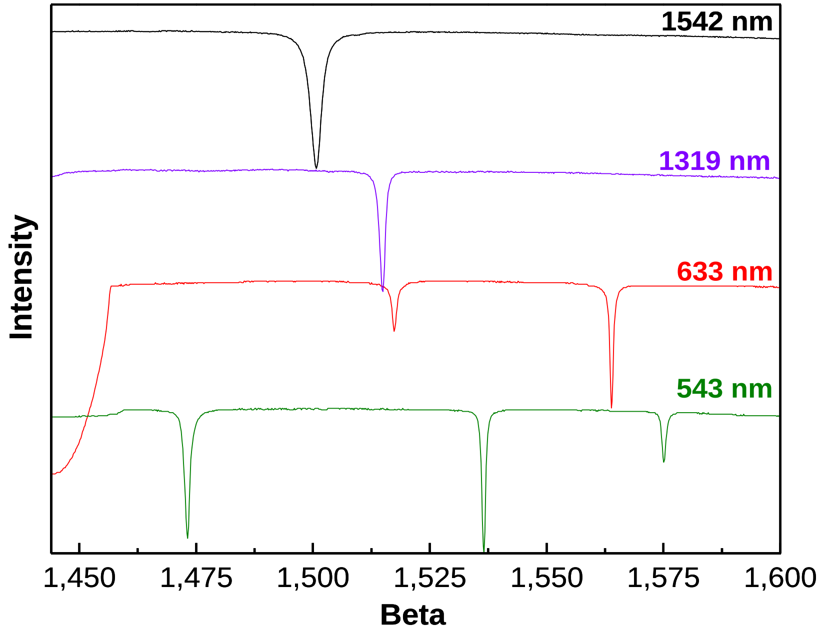


Refractive index of (100-x)SiO_2-xSnO_2-0.5%Er^{3+} waveguides (x= 10, 20 and 30%) HT @1000°C for 1h

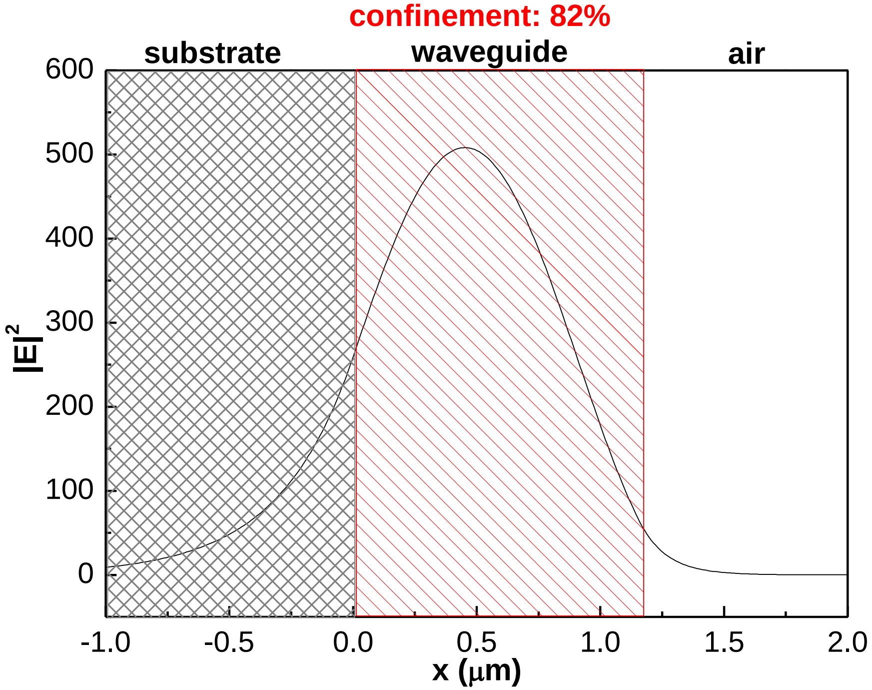
SnO_2-SiO_2:Er^{3+} PLANAR WAVEGUIDES

70%SiO_2-30%SnO_2 -0.5%Er^{3+}, HT@ 1000°C for 1h





M-line measurements of 70%SiO_2-30%SnO_2-0.5%Er^{3+} waveguides

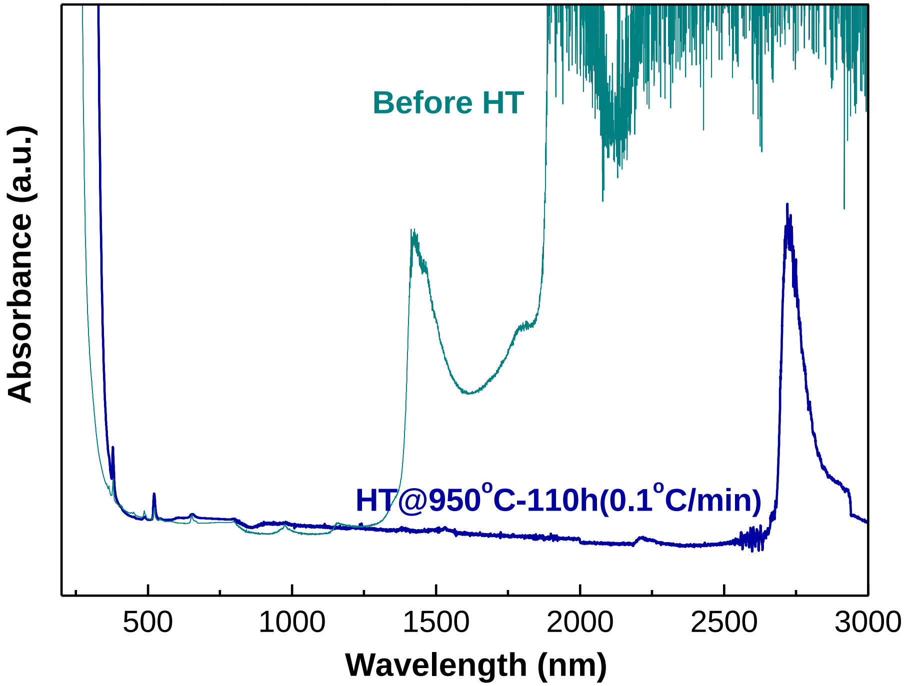


Confinement calculation of 70%SiO_2-30%SnO_2-0.5%Er^{3+} waveguides @1542nm propagation mode

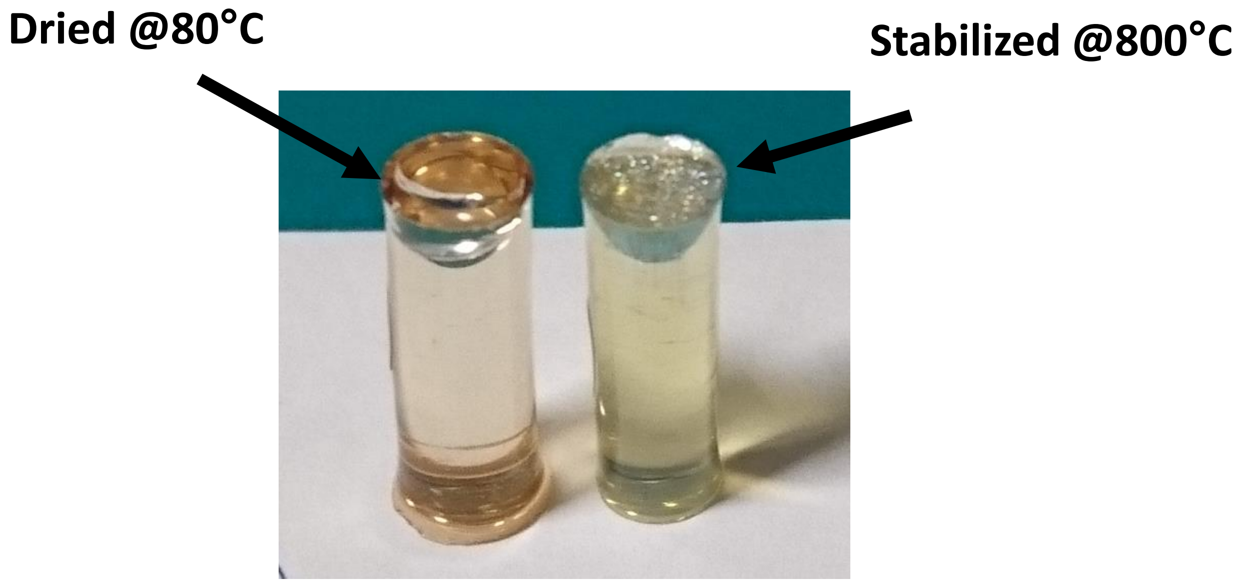
SnO_2-SiO_2:Er^{3+} MONOLITHS

Fabrication process: SOL-GEL	
COMPOSITIONS (mol%)	$xSnO_2$-(100-x)SiO_2-yEr^{3+} x = 5, 10, and 15 mol% y = 0.5 mol%
HEAT-TREATMENT	Stabilized at 800°C for 1h Annealed at 950°C

REMOVAL OF WATER



Absorption spectra of 95%SiO_2-5%SnO_2-0,5%Er^{3+} before and after heat-treatment at 950˚C for 100h



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FONDAZIONE
BRUNO KESSLER

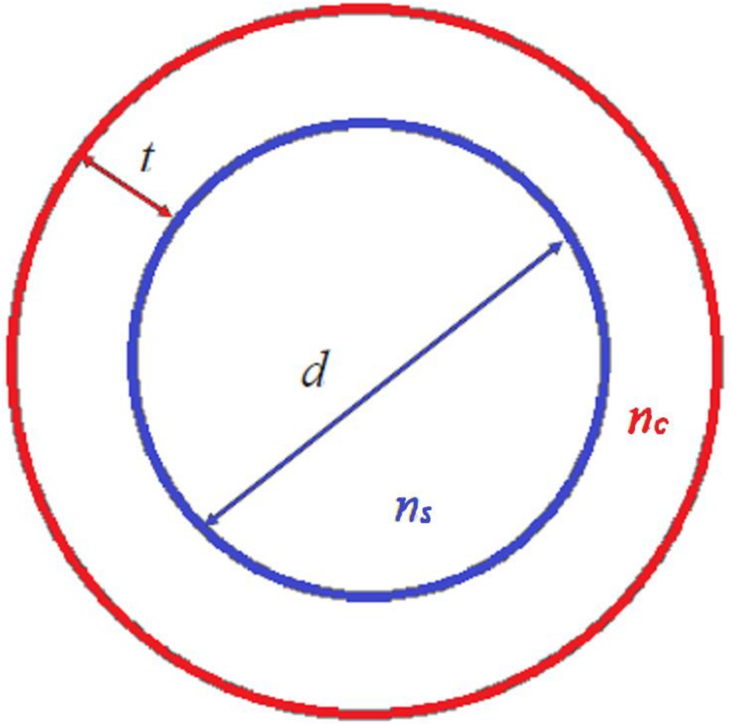
UNIVERSITAS STUDIORUM ATHESINA

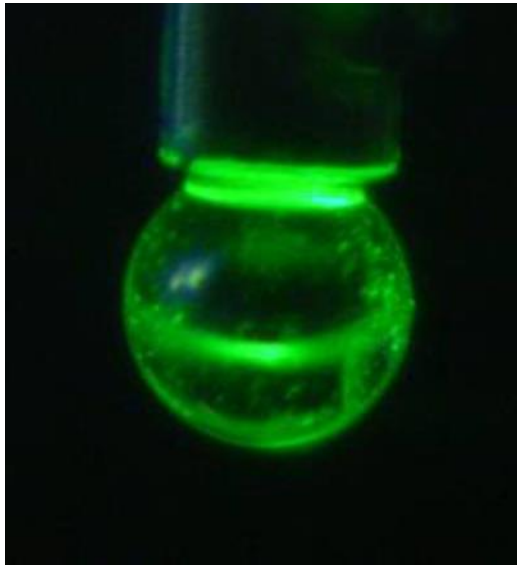
WHISPERING GALLERY MODES

Davor Ristic

Maurizio Mazzola, Maurizio Ferrari, Alessandro Chiasera, Anna Lukowiak, Yann G. Boucher, Stefano Varas, Cristina Armellini, Andrea Chiappini, Alessandro Carpentiero, Mile Ivanda, Giancarlo C. Righini, Gualtiero Nunzi Conti, Silvia Soria

Spherical microresonators WGMs





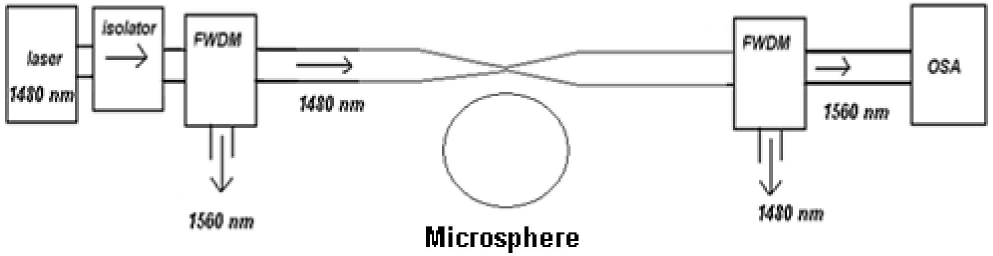
Microsphere of diameter d and refractive index n_s coated by a film of thickness t and refractive index n_c.

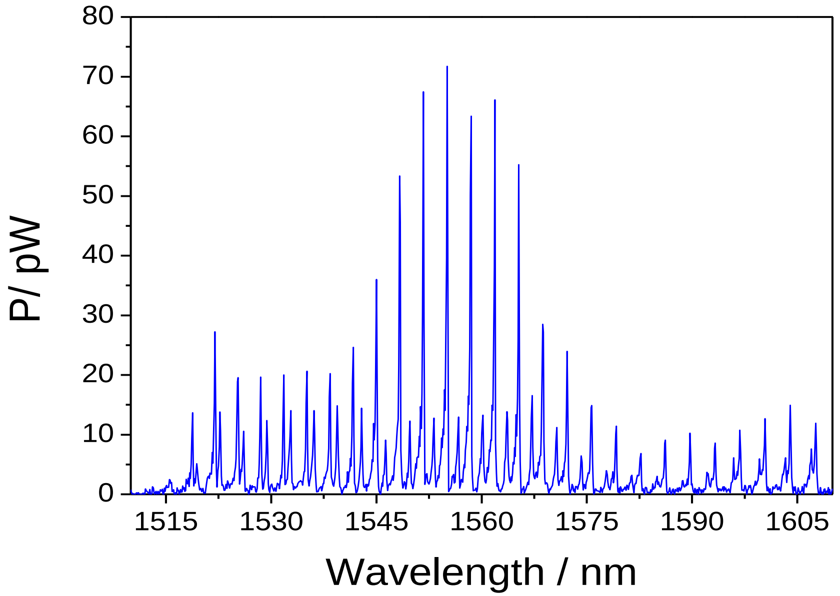
G.C. Righini, Y. Dumeige, P. Féron, M. Ferrari, G. Nunzi Conti, D. Ristic, S. Soria., "Whispering gallery mode microresonators: fundamentals and applications", Rivista del Nuovo Cimento 34 (2011) pp. 435-488.

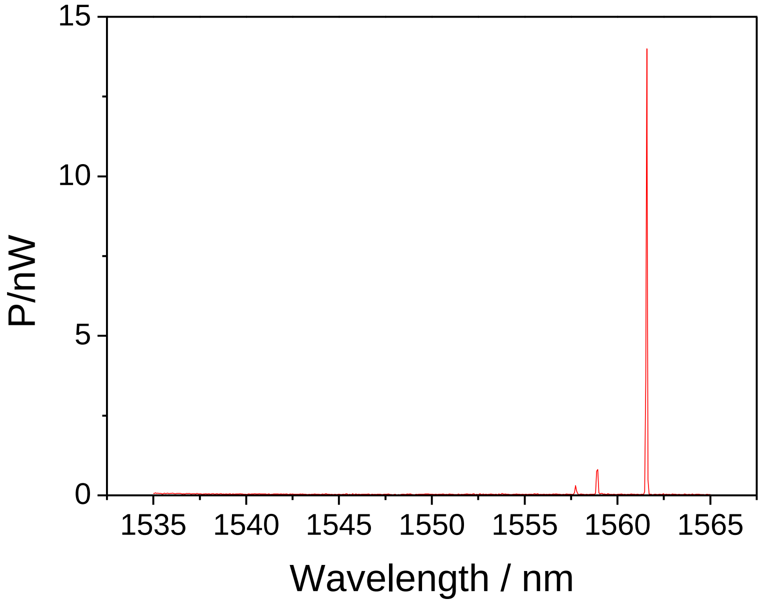
D. Ristić, A. Rasoloniaina, A, Chiappini, P. Féron, S. Pelli, G. Nunzi Conti, M. Ivanda, G.C. Righini, G. Cibiel, and M. Ferrari "About the role of phase matching between a coated microsphere and a tapered fiber: experimental study" Optics Express, 21 (2013) pp 20954-20963

LASER WGMs COATED SPHERICAL RESONATORS

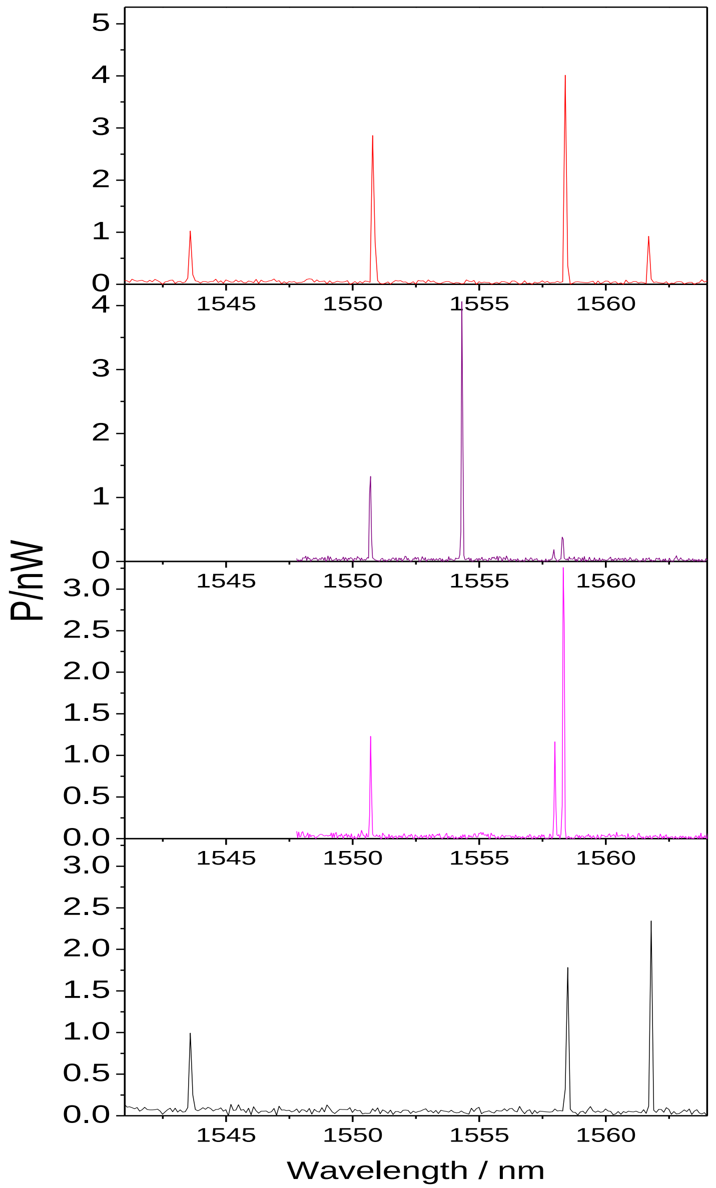
- The effect of the coating on the whispering gallery modes was studied
- The coating used was 70 % SiO_2 – 30% HfO_2 doped with 0.3 mol % Er^{3+}
- The spheres (D=140±10 µm) were characterized using a tapered fiber







Glass coated microspheres – Laser WGMs



Excitation at 1.48 μm

Laser power: ≈ 120 mW.

The peak power of the detected modes was always in the range of nanowatts, the highest power detected being 30 nW.

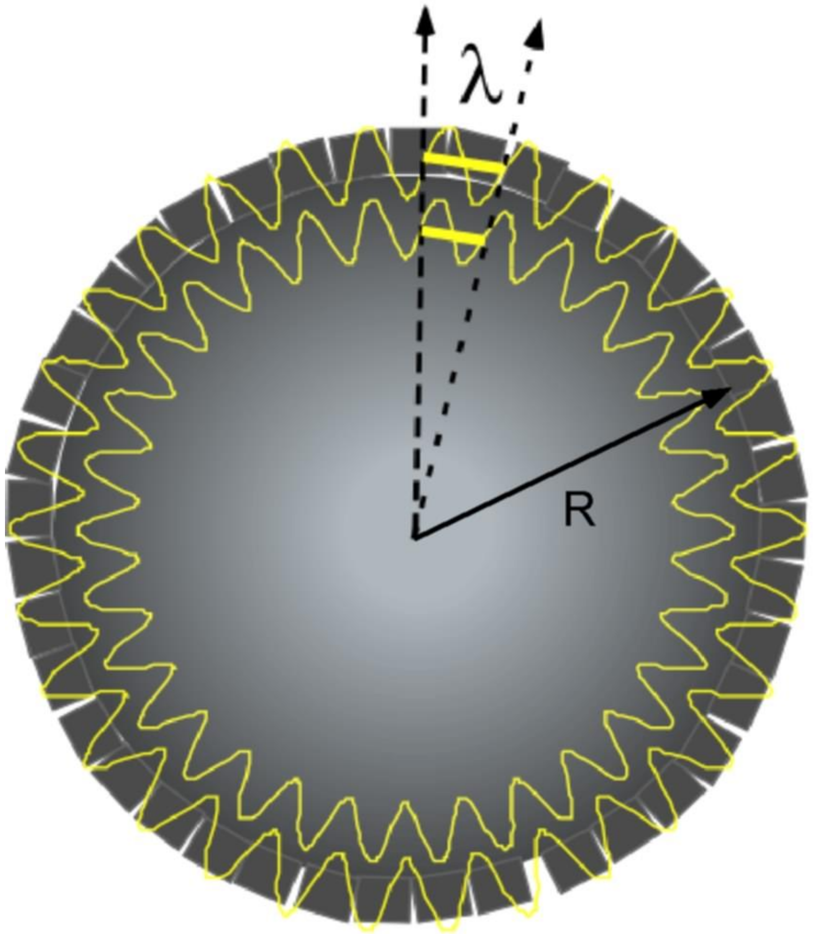
WGM modes are clearly visible
Different modes are excited depending on the position of the taper

$$FSR_{l,l\pm1} = \frac{\lambda^2}{\pi N d}$$

N=1.6
λ = 1550 nm (wavelength of the signal)

FSR is 3.7 nm corresponding to a microsphere of about 130 μm
Q-factor is greater than the resolution of our detector (>3x10^4)

• Biosensor for protein detection



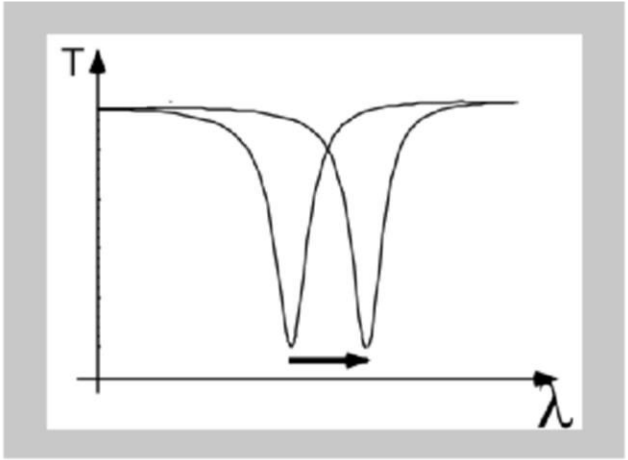


Figure 2: Binding of e.g. Proteins or DNA (represented as squares) on the microsphere surface increases the initial microsphere radius R and leads to a red shift of a given optical resonance wavelength λ

http://www.photonicatomsensors.com

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FONDAZIONE BRUNO KESSLER

UNIVERSITAS STUDIORUM ATHESINA

1D MICROCAVITIES



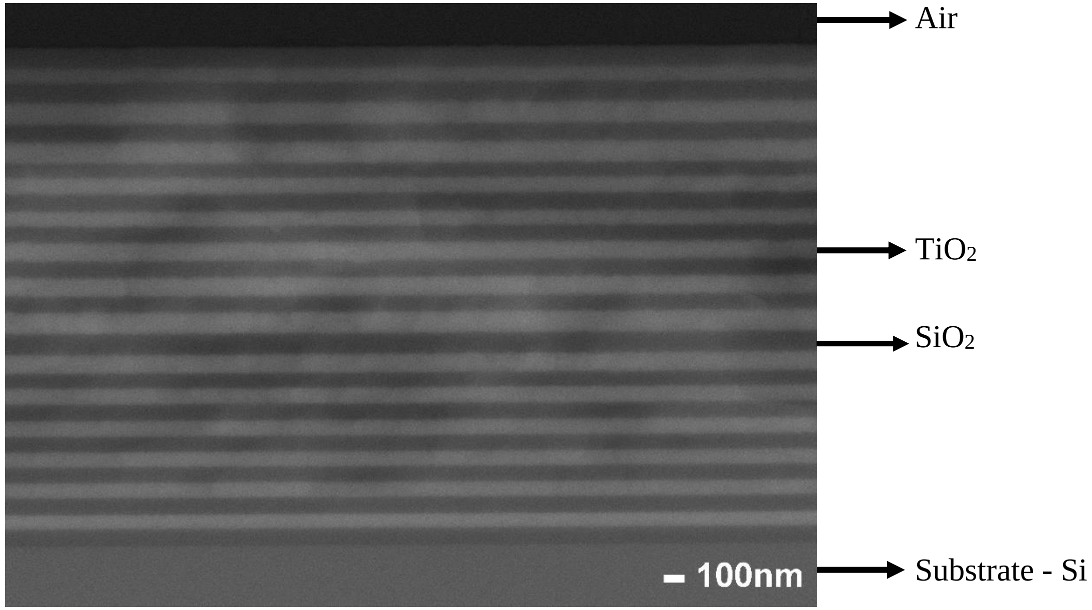

Alessandro Chiasera

Cesare Meroni, Stefano Varas, Osman Sayginer, Oreste Bursi, Anna Lukowiak, Yann G. Boucher, Alessandro Vaccari, Iustyna Vasilchenko, Giorgio Speranza, Davor Ristic, Mile Ivanda, Francesco Scotognella, Stefano Taccheo, Dominik Dorosz, Roberta Ramponi, Giancarlo C. Righini, Maurizio Ferrari

GLASS-DERIVED 1-D PHOTONIC CRYSTALS

One-dimensional photonic crystals

outstanding tool for ***new photonics***, being the ***simplest system*** to exhibit a so-called ***photonic bandgap*** and therefore one of the easiest to handle in order to obtain ***tailored optical devices***



- ICT
- Lighting
- Laser
- Sensing
- Energy
- Environment
- Biological sciences
- Medical sciences
- Quantum optics

Luminescence enhancement Photon Management

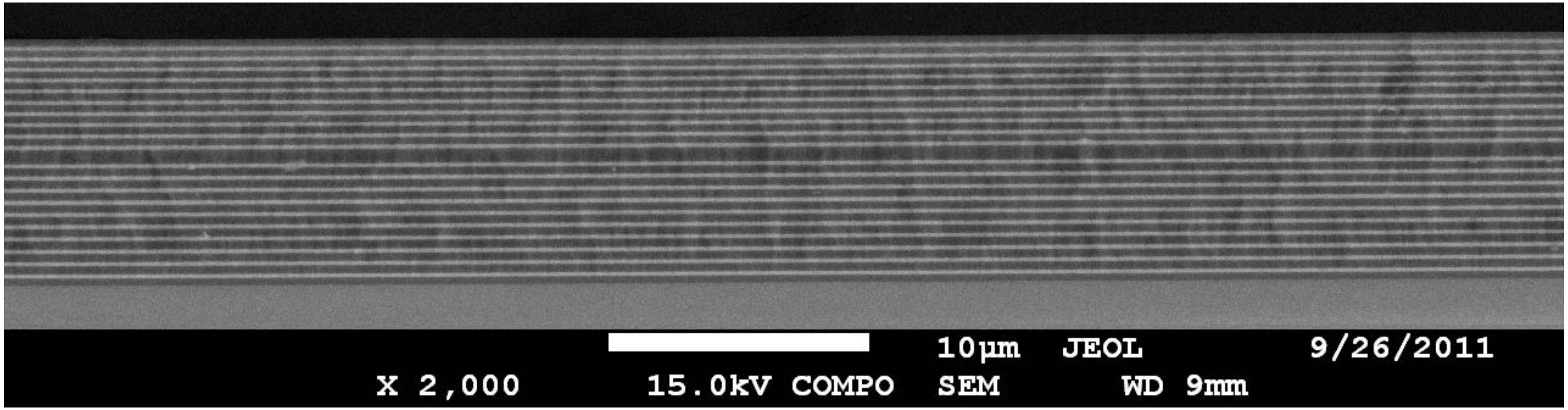
- One of the interesting features of the 1-D microcavities is the possibility to enhance the luminescence, resonant with the cavity, when the defect layer is activated by a luminescent species.

- When the cavity dimensions approach the wavelength of the emission the density of electromagnetic states inside the cavity are strongly perturbed and can lead to significant enhancement of the luminescence quantum yield.

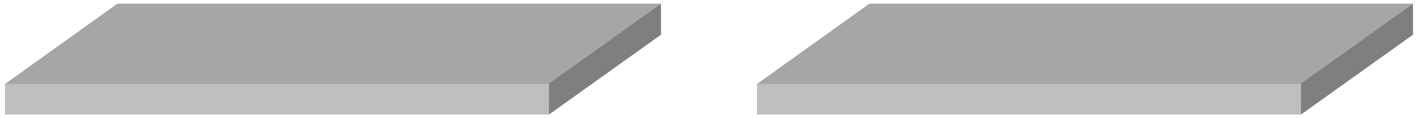
- This enhancement is achieved by increasing the number of the localized modes coupled with the emitter

1-D PHOTONIC CRYSTALS FOR LOW THRESHOLD LASER ACTION

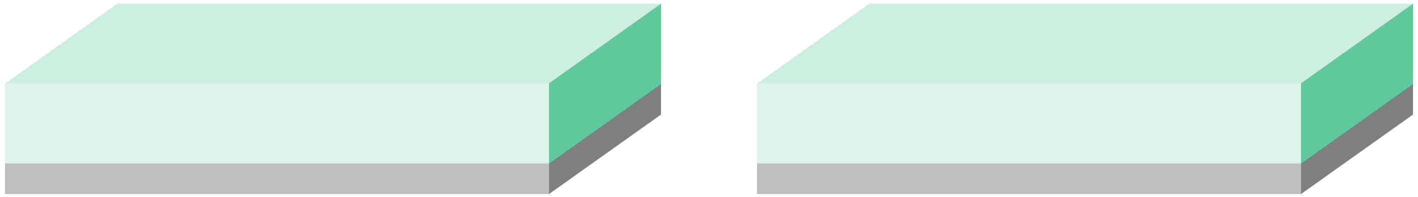
When the spontaneous emission of the emitter, embedded in the defect layer of a 1-D photonic crystal, is strongly enhanced the possibility of low threshold lasing could take place.



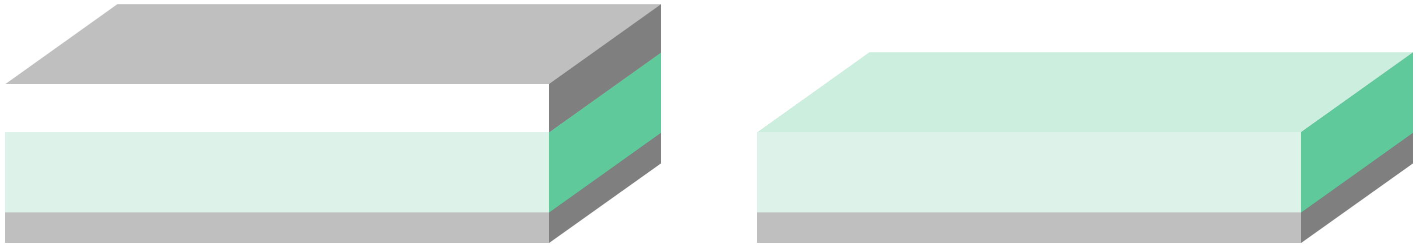
Hybrid 1-D microcavity: fabrication



SiO_2 substrates

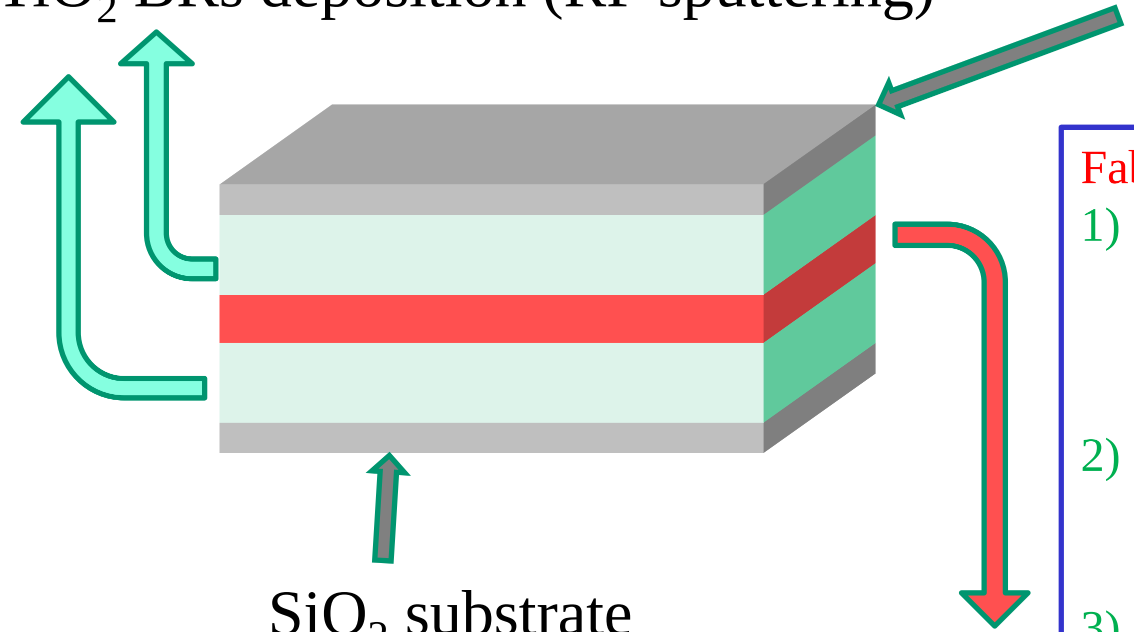


1) SiO_2/TiO_2 BRs deposition (RF sputtering)



2) Active layer deposition (sol-gel)

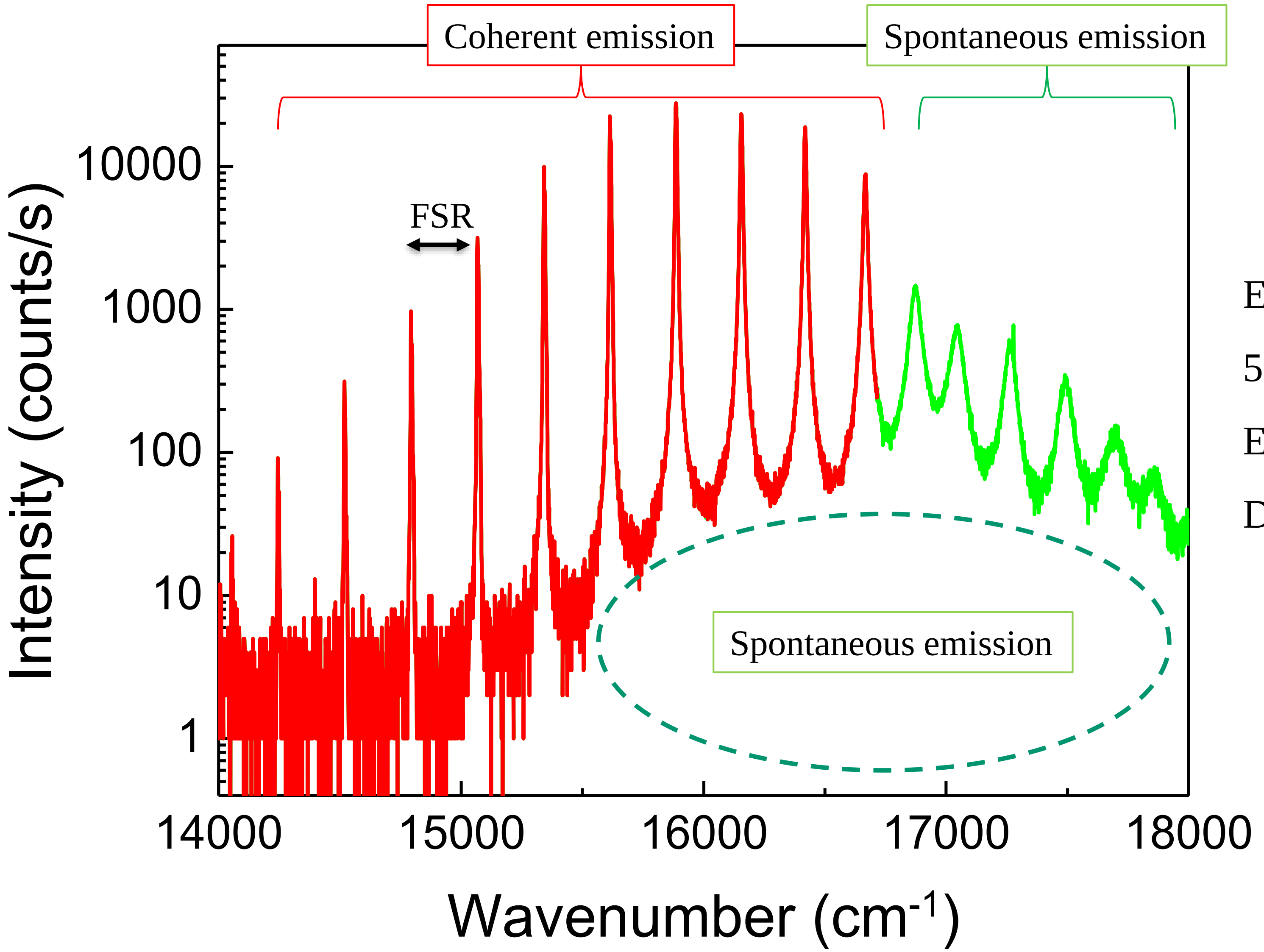
Hybrid 1-D microcavity: fabrication



Fabrication steps:
1) SiO_2/TiO_2 BRs deposition by RF sputtering
2) Active layer deposition by solution process
3) Enclosing

PMMA polymer matrix containing
CdSe-CdS-ZnS

Hybrid 1-D microcavity: Laser action



Excitation:

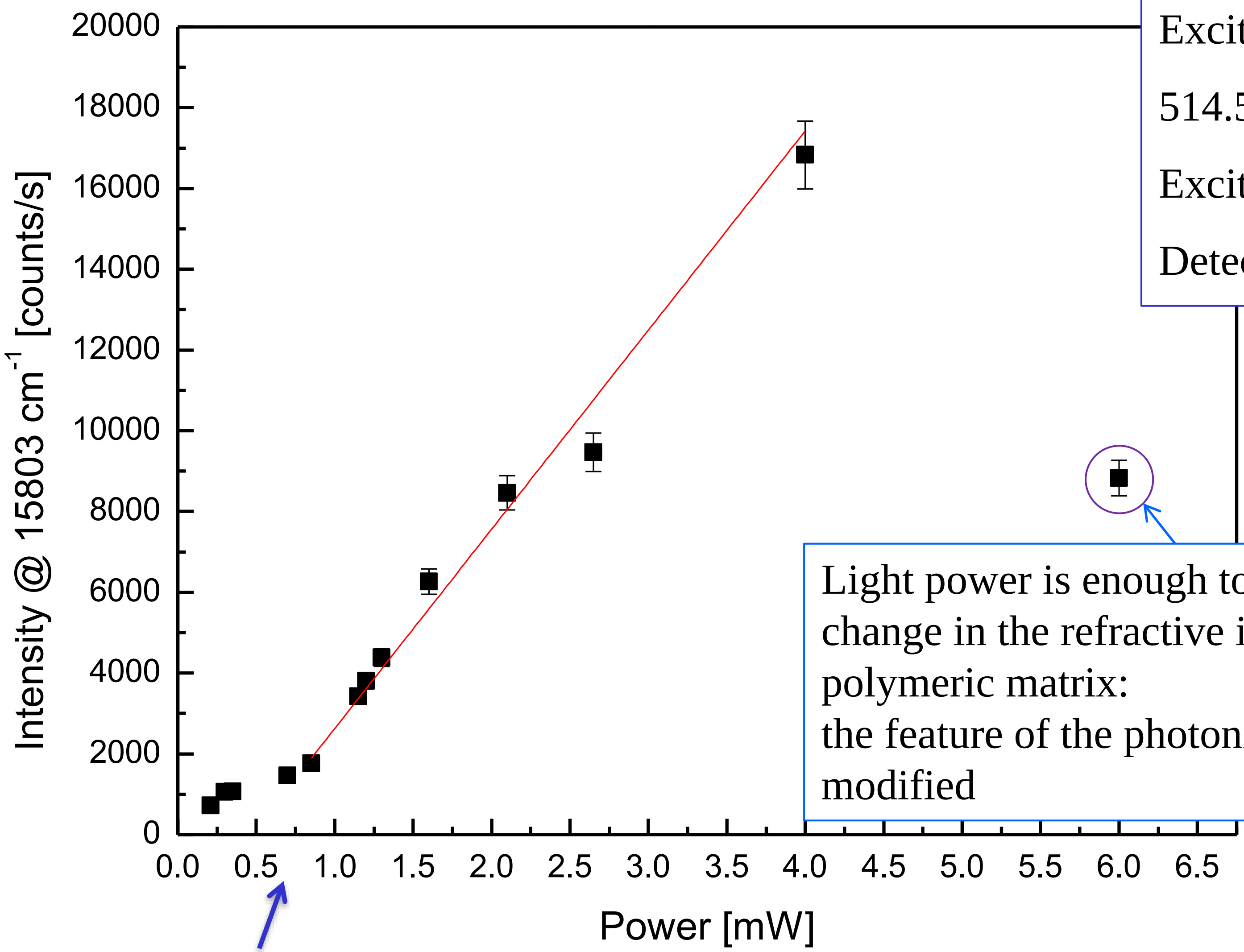
514.5nm 3mW CW

Excitation angle: 7°

Detection angle: 0°

FSR → Thickness ~ 20 µm

Hybrid 1-D microcavity: Laser action



Excitation:

514.5nm CW

Excitation angle: 7°

Detection angle: 0°

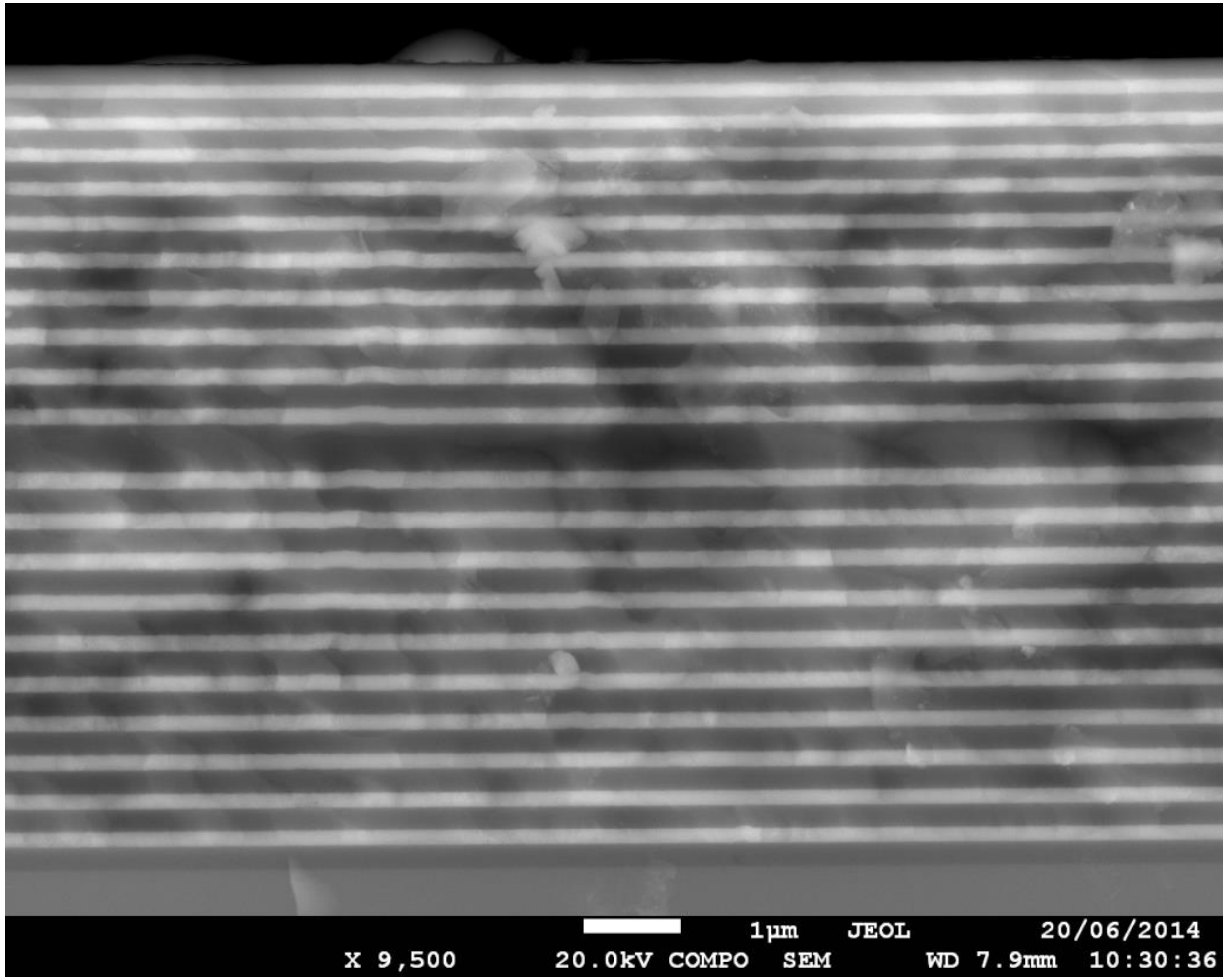
Light power is enough to induce a change in the refractive index of the polymeric matrix:
the feature of the photonic crystals are modified

0.6 mW

A. Chiasera, J. Jasieniak, S. Normani, S. Valligatla, A. Lukowiak, S. Taccheo, D.N. Rao, G.C. Righini, M. Marciniak, A. Martucci, M. Ferrari, "Hybrid 1-D dielectric microcavity: Fabrication and spectroscopic assessment of glass-based sub-wavelength structures", Ceramics International l41 (2015) pp. 7429-7433.

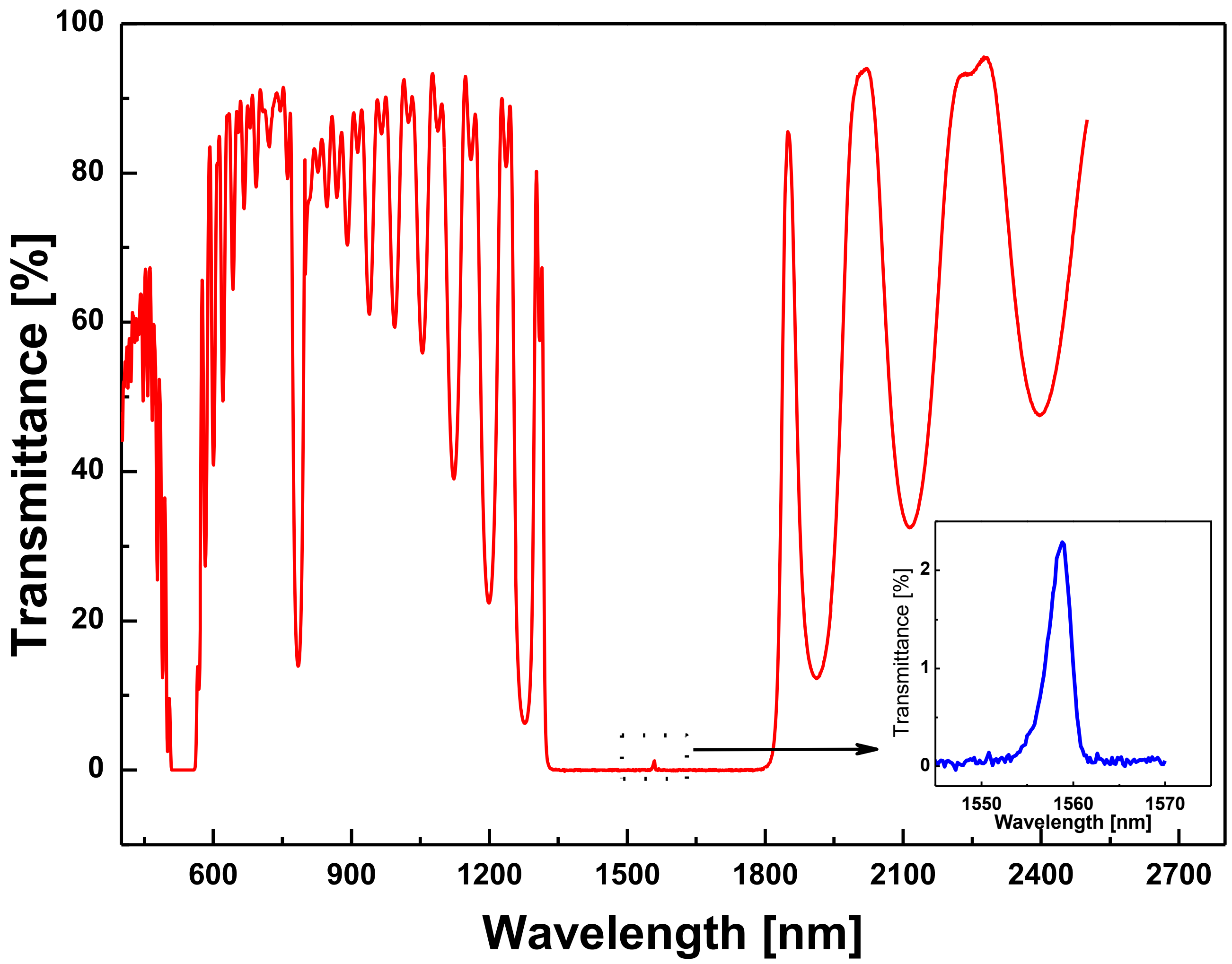
Coherent emission from fully Er^{3+} doped monolithic 1-D dielectric microcavity fabricated by rf-sputtering

Morphology



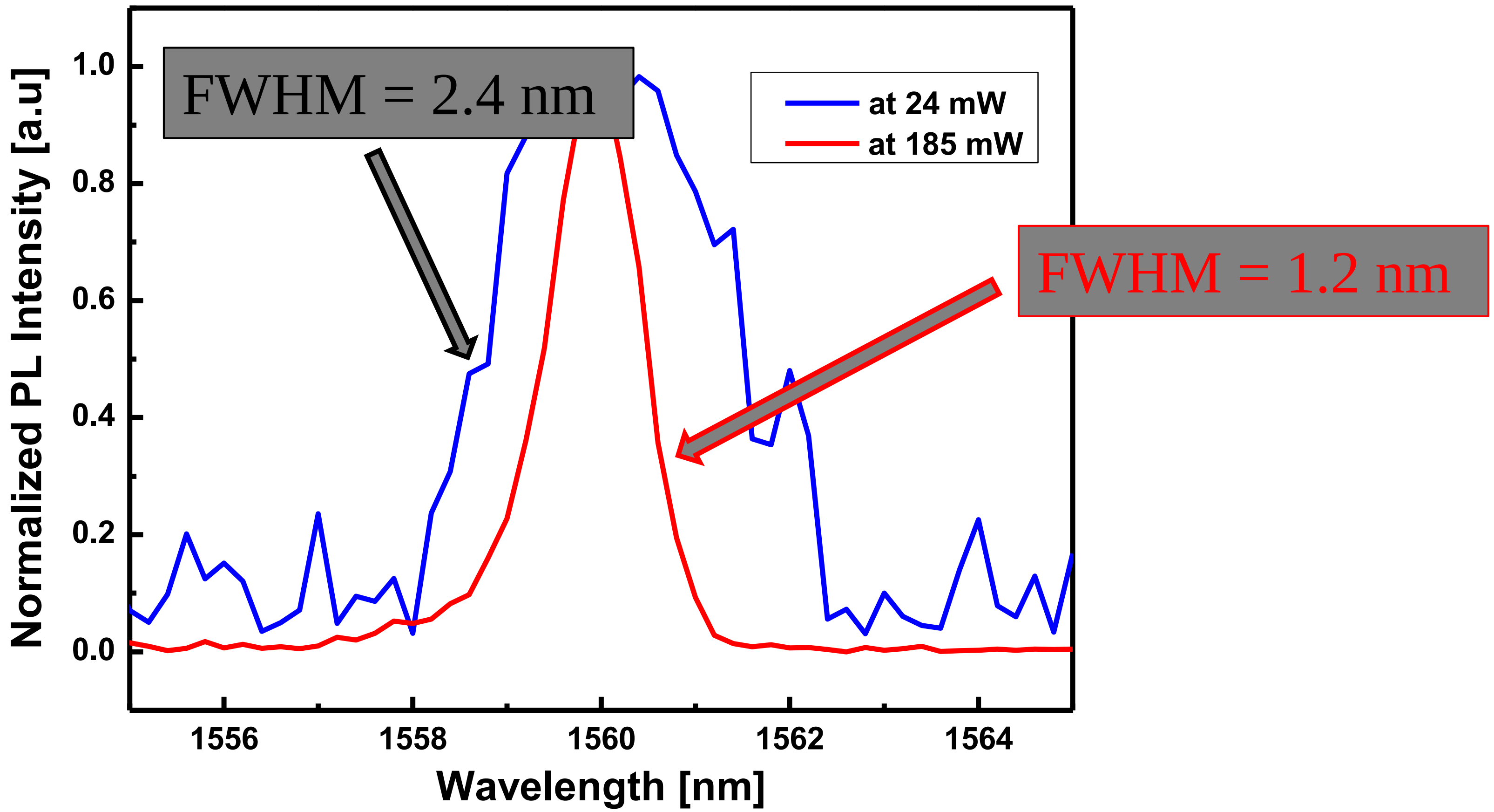
SEM micrograph of the Er^{3+} doped 1D dielectric microcavity cross section. The bright and dark region corresponds to TiO_2 and SiO_2 layers, respectively. The substrate is located on the bottom of the images and air on the top.

Transmission



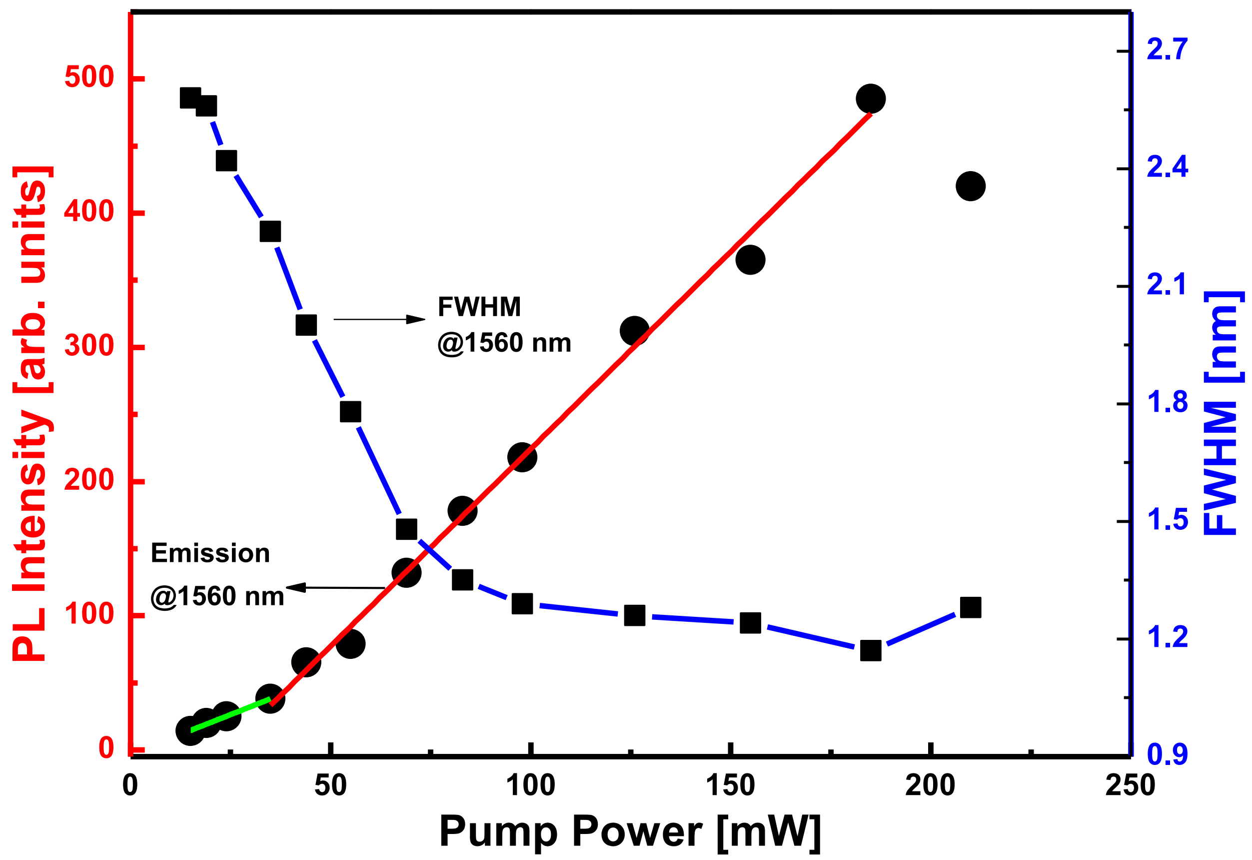
Transmission spectrum of the cavity with two Bragg mirrors, each one consisting of ten pairs of SiO_2/TiO_2 layers in the region between 450 nm and 2500 nm. The first order stop band ranges from 1300 nm to 1850 nm. The first order cavity resonance corresponds to the sharp maximum centered at 1559.2 nm.

${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ photoluminescence spectrum



${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ photoluminescence spectrum of the cavity activated by Er^{3+} ions in 1D dielectric microcavity. The emission is recorded at 0 degree from the normal on the samples upon excitation at 514.5 nm at the input power of 185 mW (red line) and 24 mW (blue line). 30 degree of excitation angle for both the measurements.

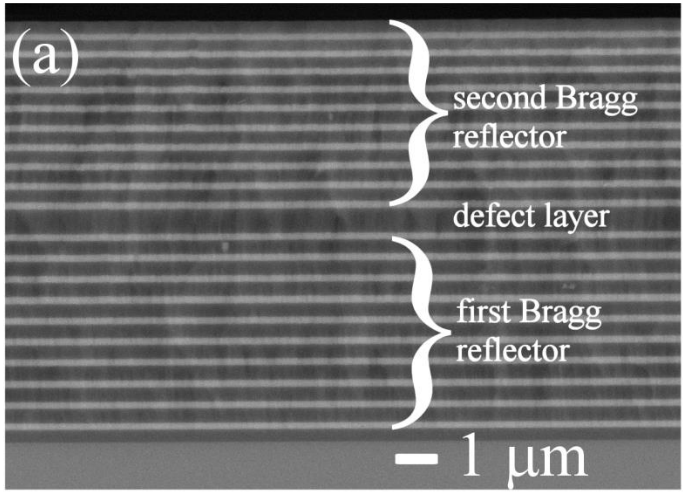
Peak intensity and FWHM vs Pump Power
Exciting at 514.5 nm / 30°



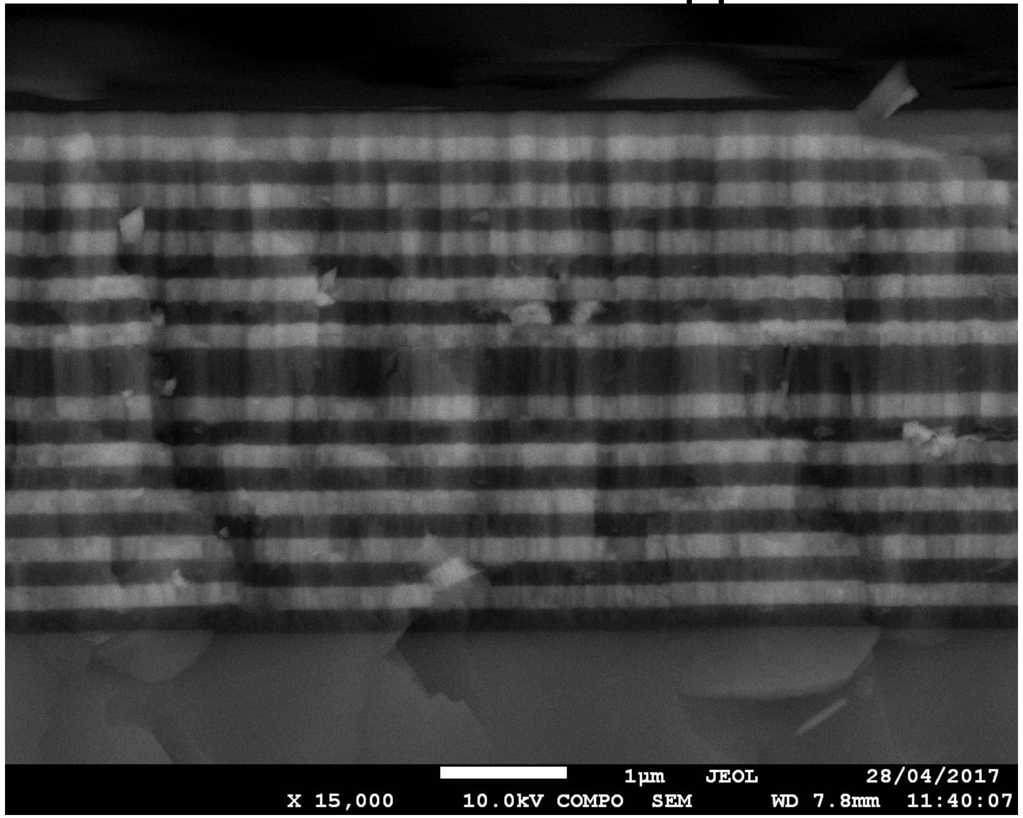
$^4I_{13/2} \rightarrow {}^4I_{15/2}$ photoluminescence peak intensity and FWHM (blue line) at 1560 nm as a function of 514.5 nm pump power with 0 degree of detection angle and 30 degree of excitation angle. Red and green line are the results of linear fit while the blue line is a guide for the eyes.

Structure of the microcavity

OLD approach

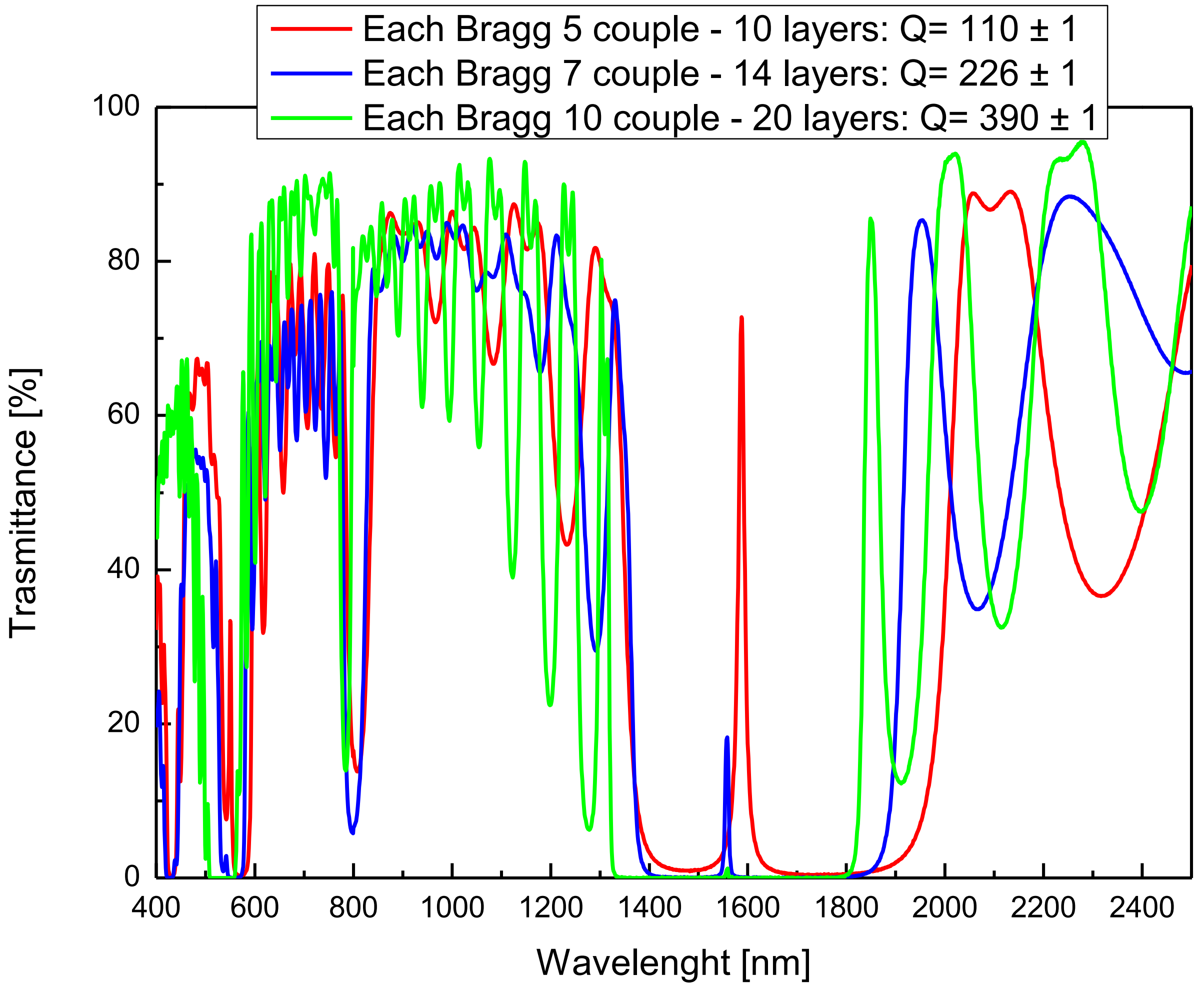


NEW approach



Active Bragg Mirror: 10 alternated quarter wave layers TiO_2 (172 nm) and SiO_2 (262 nm) activated with 0.2 mol % of Er^{3+}.
Active layer: half wave (525 nm) SiO_2 activated with 0.2 mol % of Er^{3+}.
The dark regions corresponds to SiO_2 and the white regions corresponds to TiO_2

Transmission

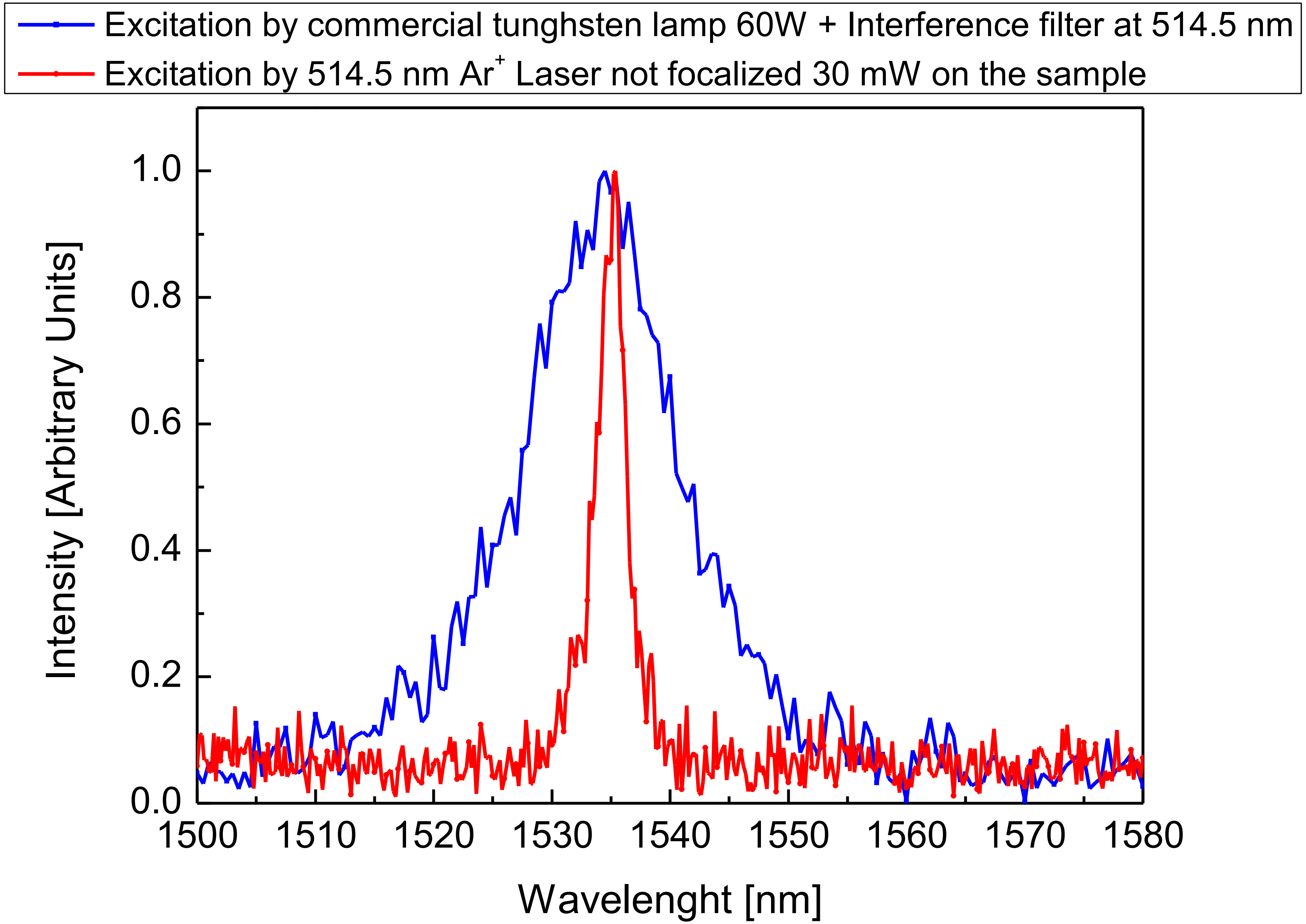


Different number of layers

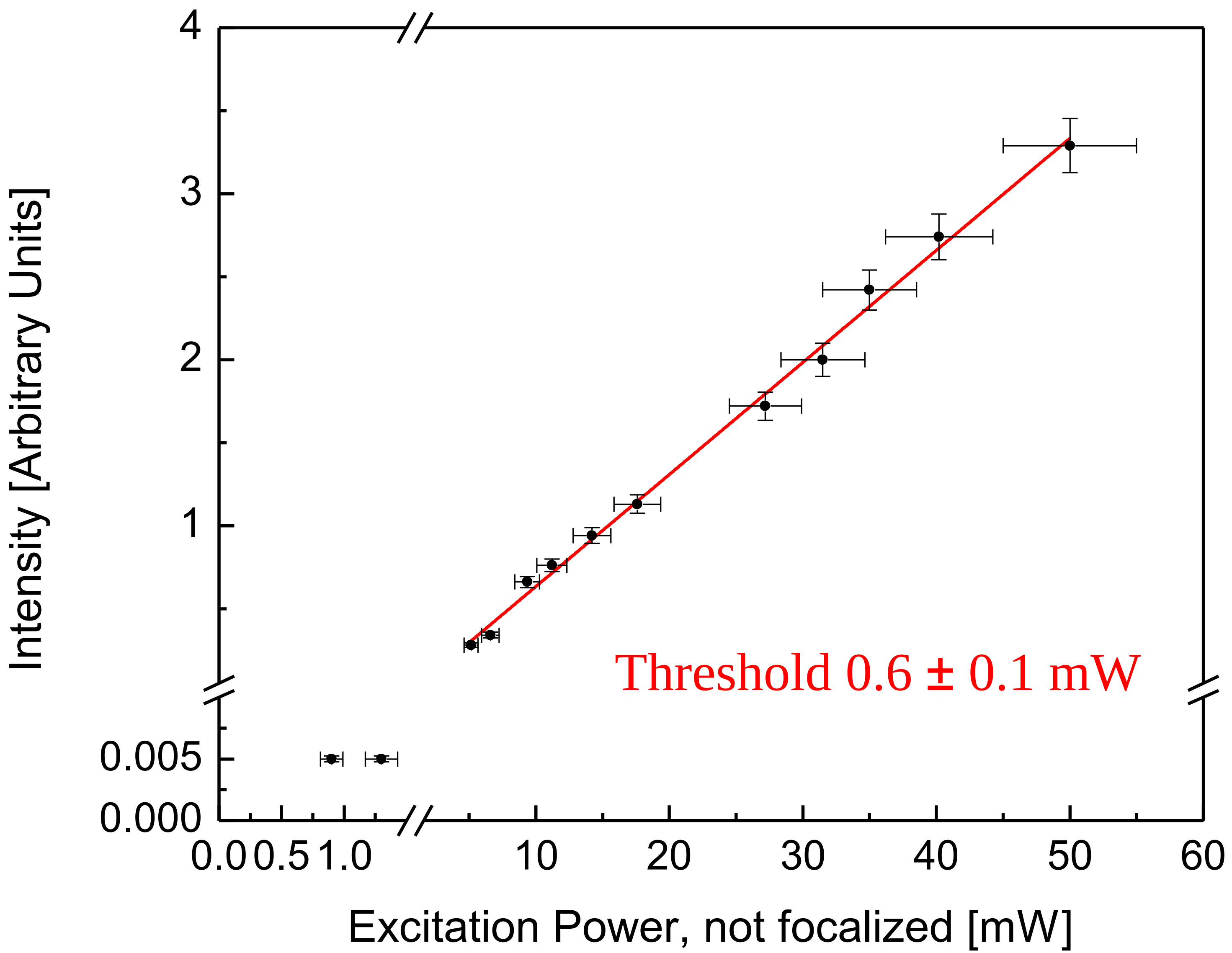
High number → High Q

High number → Low Transmittance

Emission Features – Bragg reflectors with 10 layers

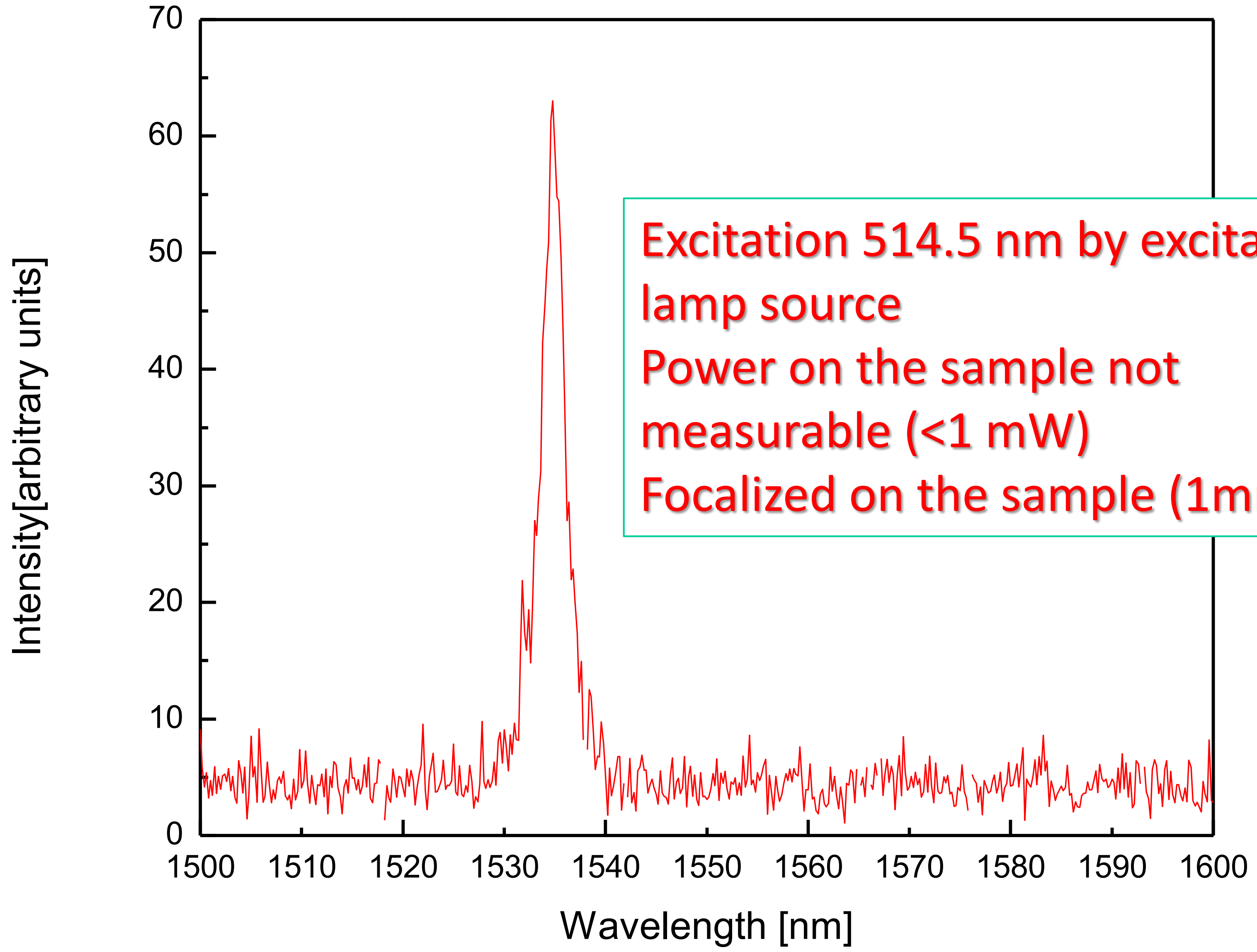


Emission Features – Bragg reflectors with 10 layers



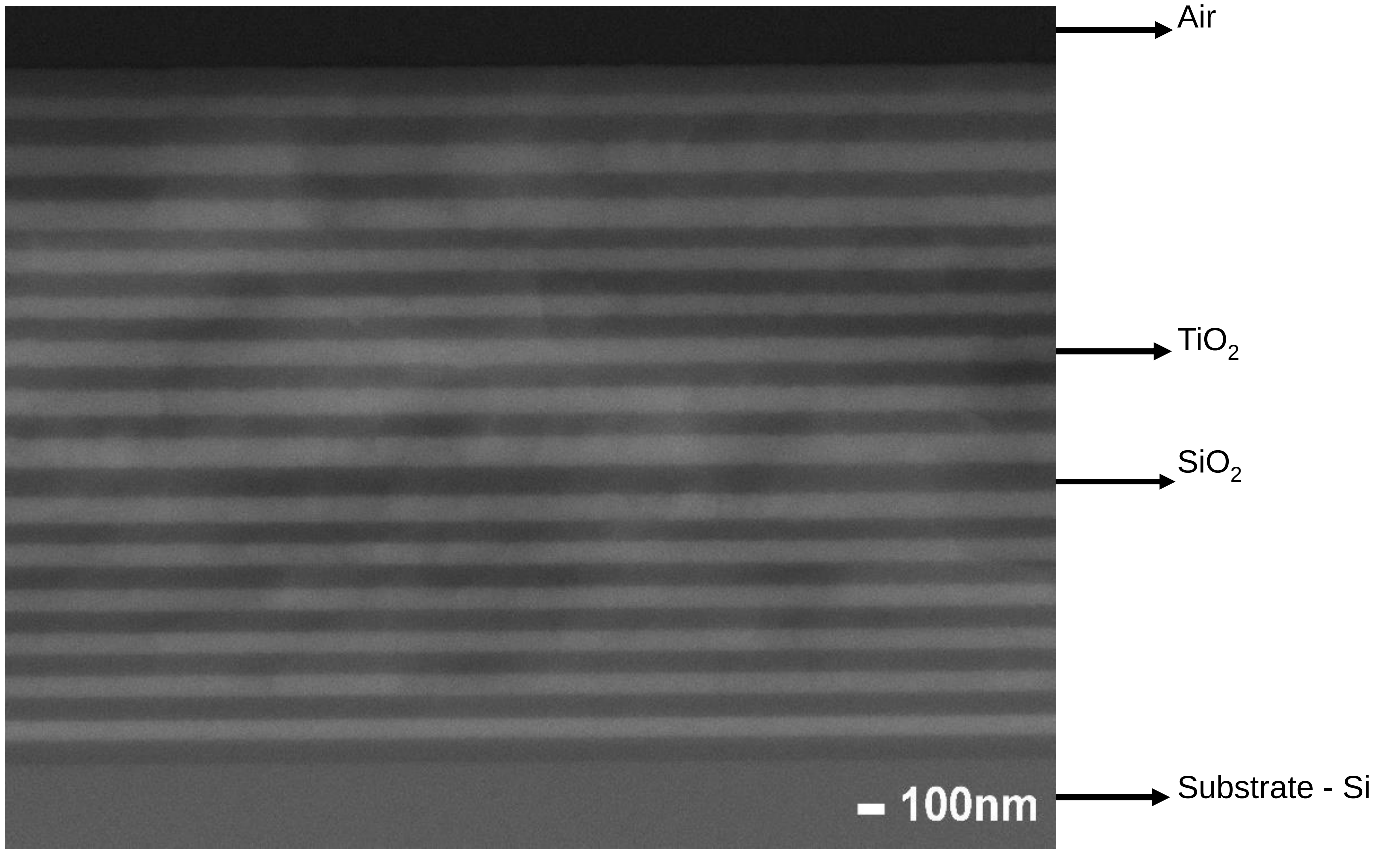
- Excitation angle: 30°
- Detecton angle: 0°

Emission Features – Bragg reflectors with 14 layers



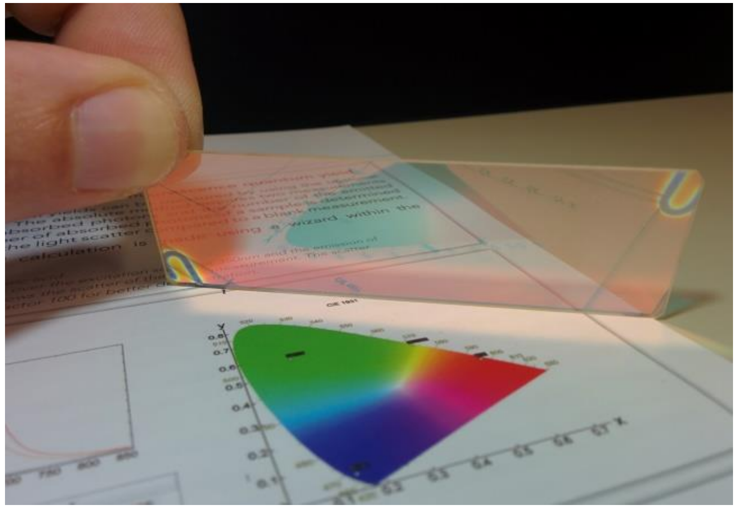
Excitation 514.5 nm by excitation lamp source
Power on the sample not measurable (<1 mW)
Focalized on the sample (1mm^2)

Disordered 1-D photonic structures

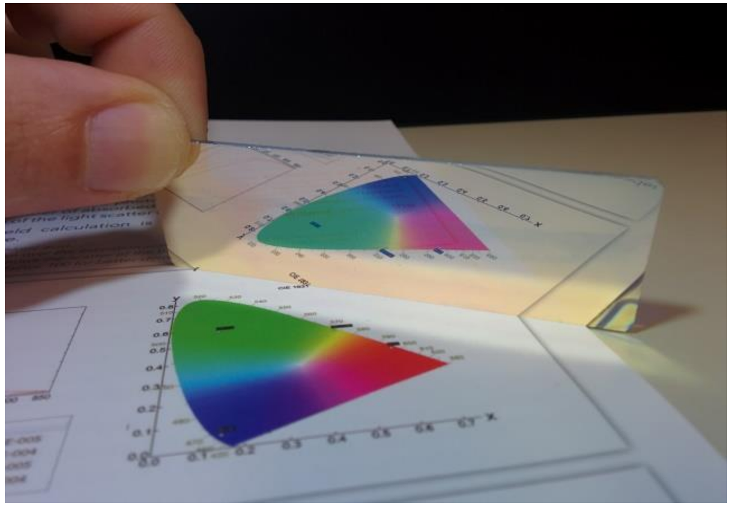


SEM micrograph of the microcavity composed by 14 couple of TiO_2/SiO_2 layers. To realize the disordered photonic structure we have alternated layers of SiO_2 and TiO_2, with a thickness of $(80 + n)$ nm, where n is a random integer $0 \leq n \leq 40$. In this way we obtain a random sequence of thicknesses, between 80 and 120 nm.

BROAD BAND MIRRORS BASED ON DISORDERED 1-D PHOTONIC STRUCTURES



(a)



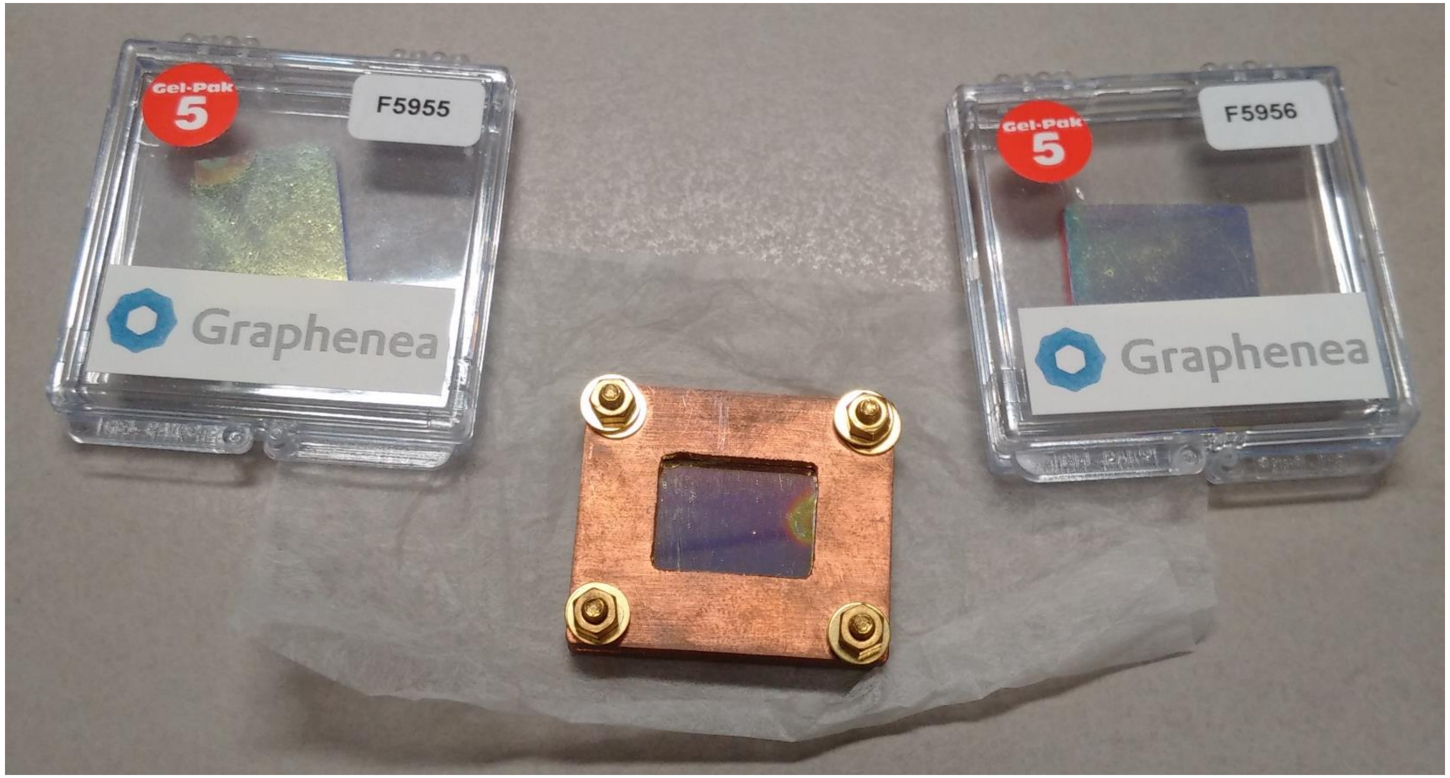
(b)

Reflection of the CIE 1931 diagram by a 1-D photonic crystal (a) and a disordered 1-D photonic structure (b)

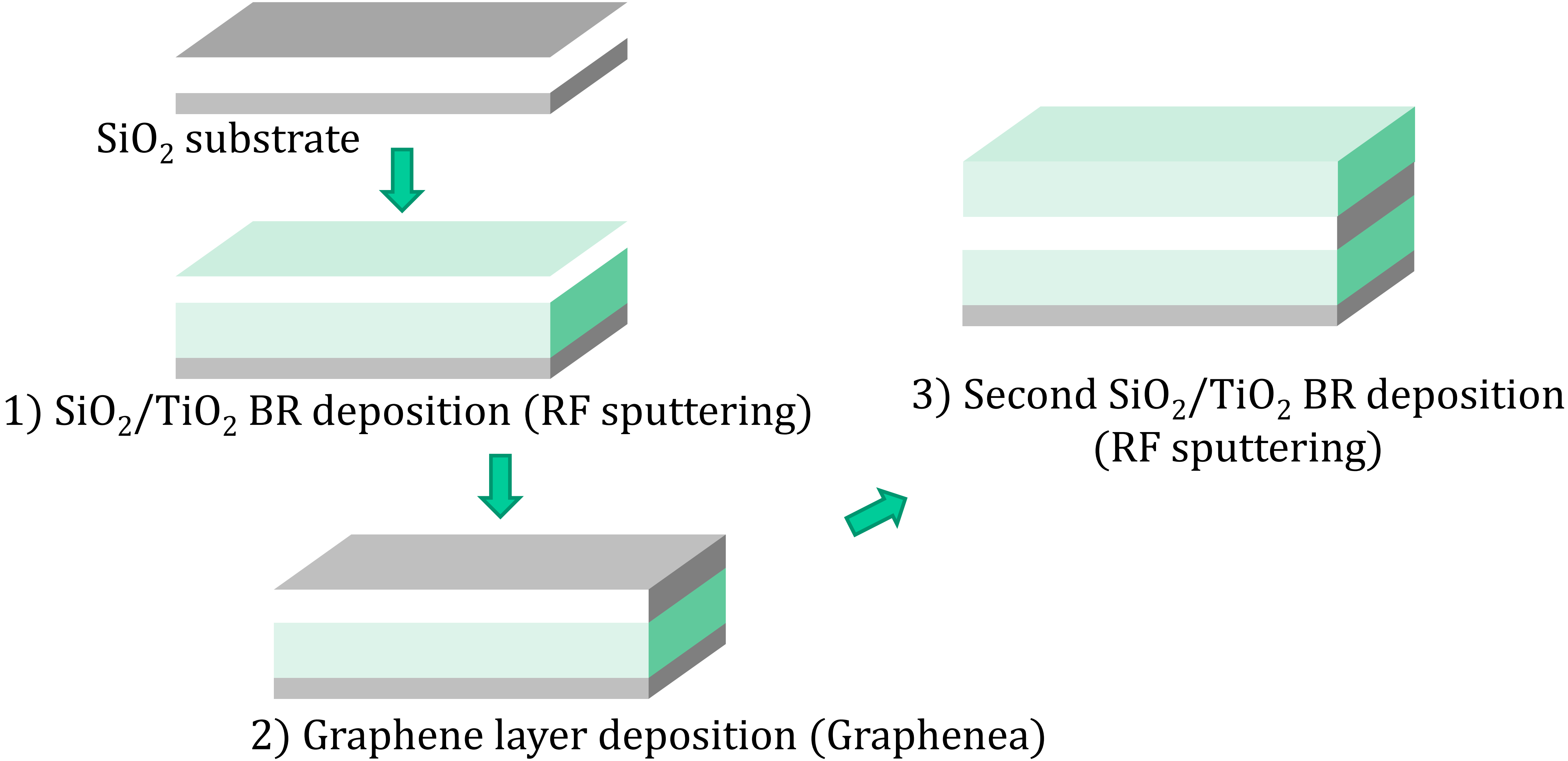
average transmittance value of 0.7 was obtained for the 300 - 1200 nm transmission spectrum

This appealing behavior is due to interference between waves traveling in regions with different optical paths, determined by the disordered distribution of stacked layer thicknesses.

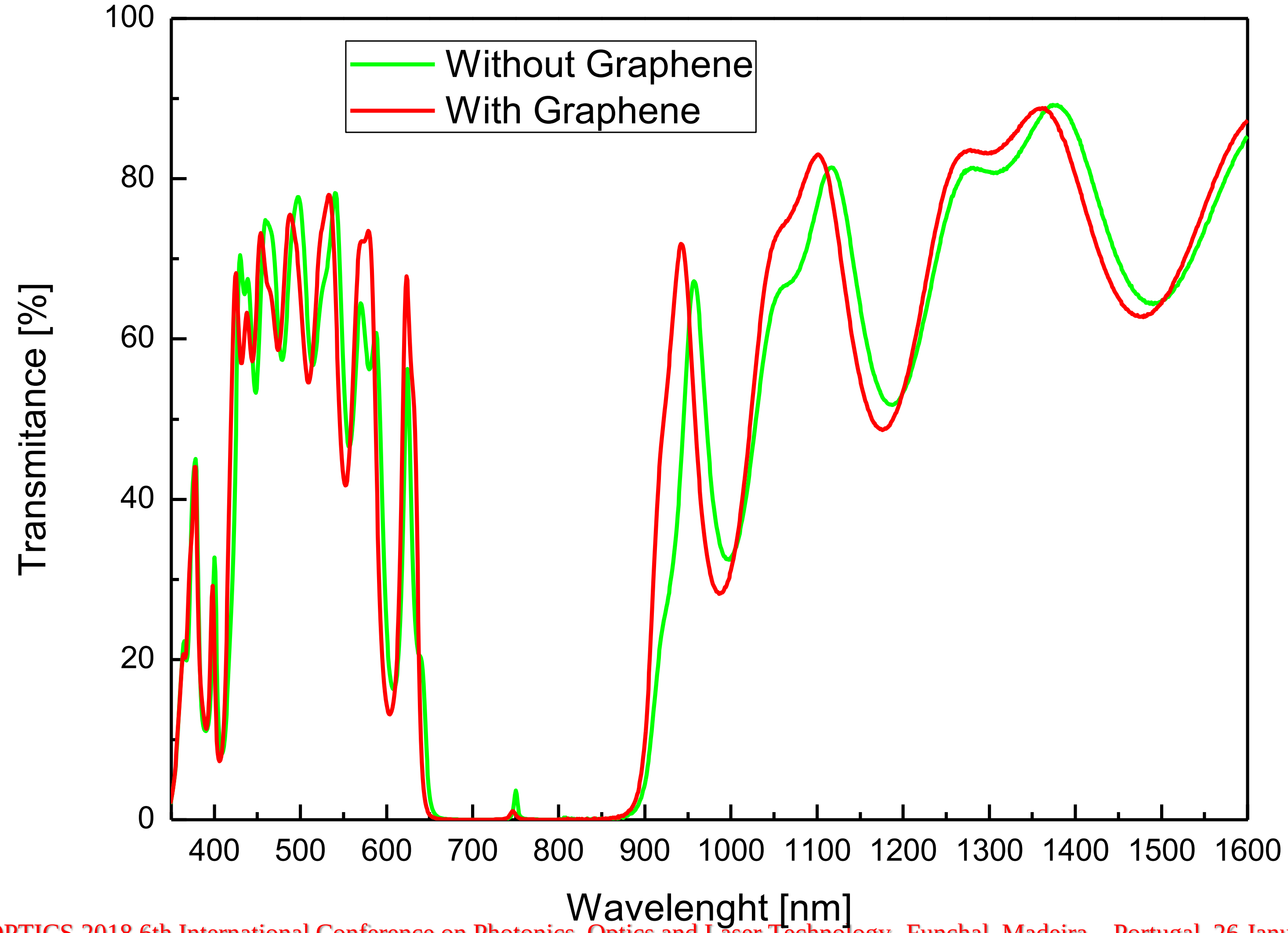
Optical cavity with graphene



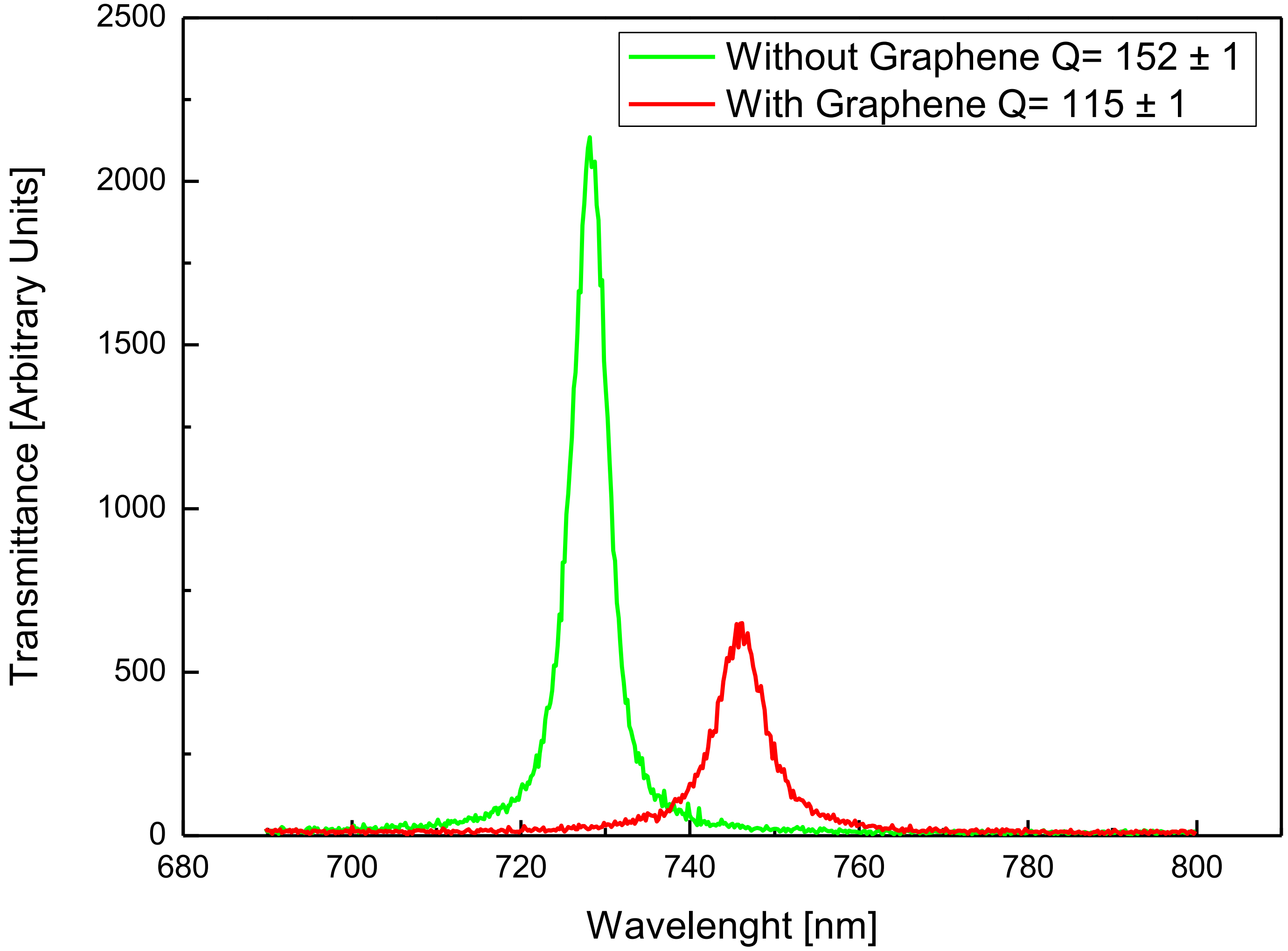
Optical cavity with graphene: It is possible to fabricate a monolithic systems?



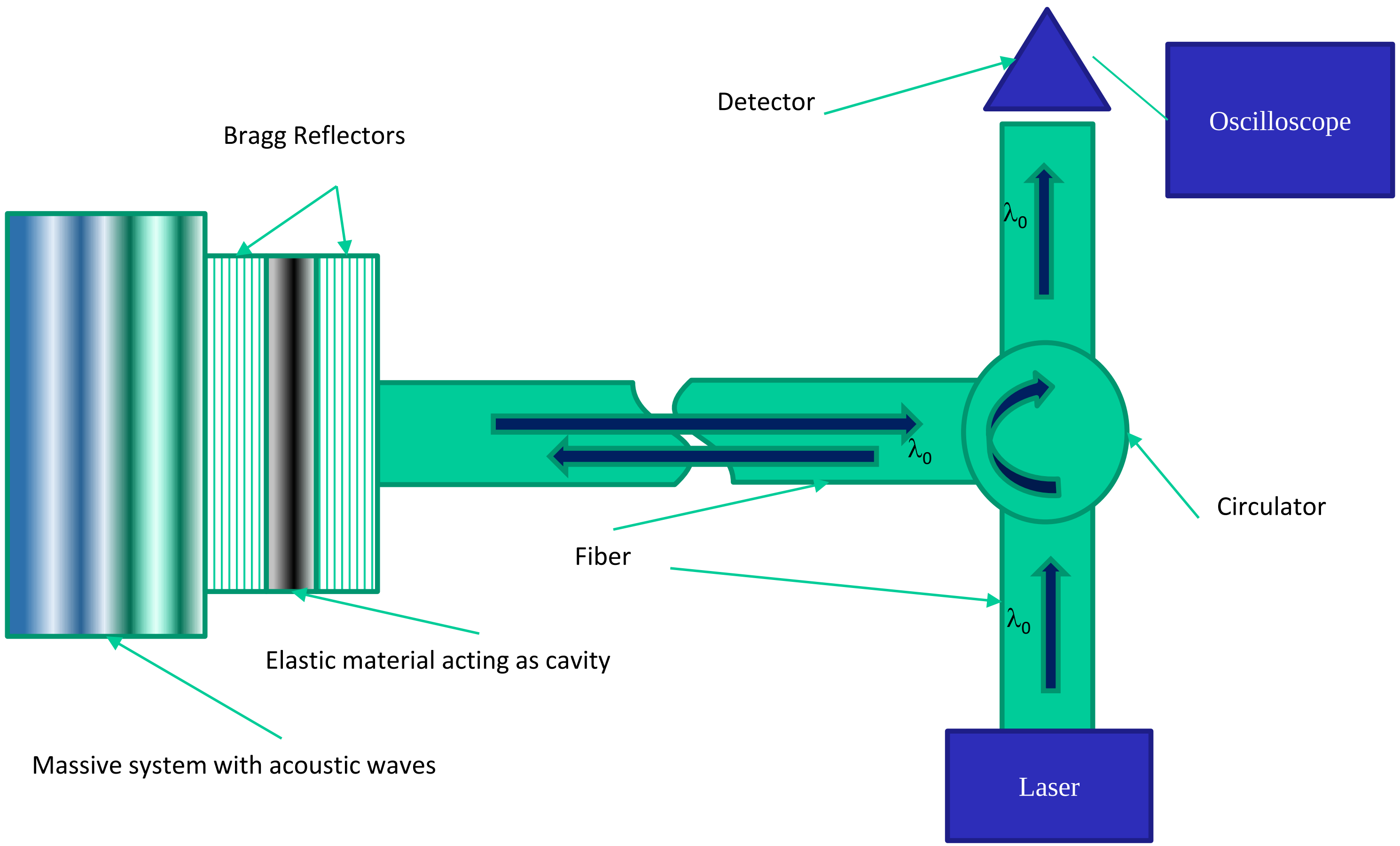
Monolithic 1D Photonic crystal with graphene layer in the defect



Monolithic 1D Photonic crystal with graphene layer in the defect



Hybrid 1-D microcavity: acoustic sensor



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FONDAZIONE BRUNO KESSLER

UNIVERSITAS STUDIORUM ATHESINA

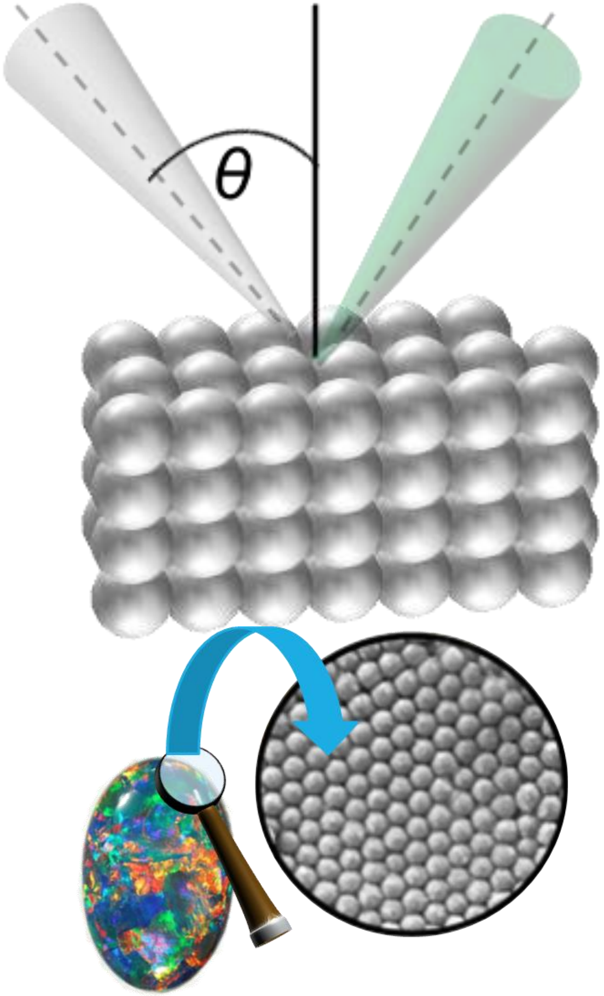
OPALS AS STRAIN SENSORS

Andrea Chiappini

Valentina Piccolo, Anna Lukowiak, Alessandro Vaccari, Cristina Armellini, Alessandro Carpentiero, Davor Ristic, Mile Ivanda, Silvia Pietralunga, Stefano Taccheo, Giancarlo C. Righini, Daniele Zonta, Maurizio Ferrari

PHOTOPTICS 2018 6th International Conference on Photonics, Optics and Laser Technology- Funchal, Madeira – Portugal 26 January 2018

OPALS



$$\lambda = 2 \cdot \sqrt{(n_{eff})^2 - (sin\theta)^2} \cdot d$$

$$n_{eff}{}^2 = n_{spheres}{}^2 \cdot f + n_{medium}{}^2 (1 - f)$$

$$f = 74\%$$

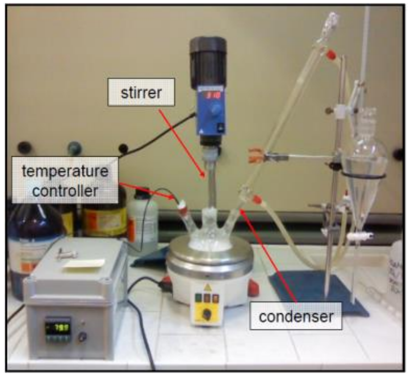
$$d = \sqrt{\frac{2}{3}}\ D$$

If $\theta = 0$, then $\boxed{\lambda = 2 \cdot n_{eff} \cdot d}$

fcc structure provides stable system
from thermodynamical point of view

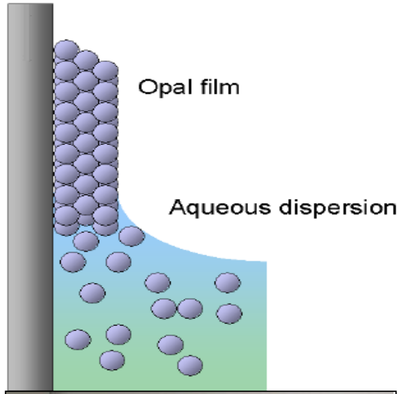
θ – incident angle, d – interplanar distance, l_0 – initial length, D – spheres diameter

FABRICATION: 3D PC



1. Producing polystyrene spheres (PSs):

- mixture of water, surfactant (SDS), styrene, polymerization initiator ($K_2S_2O_6$)
- desired dimension ($D_{PS} = 230nm$) with low polydispersivity



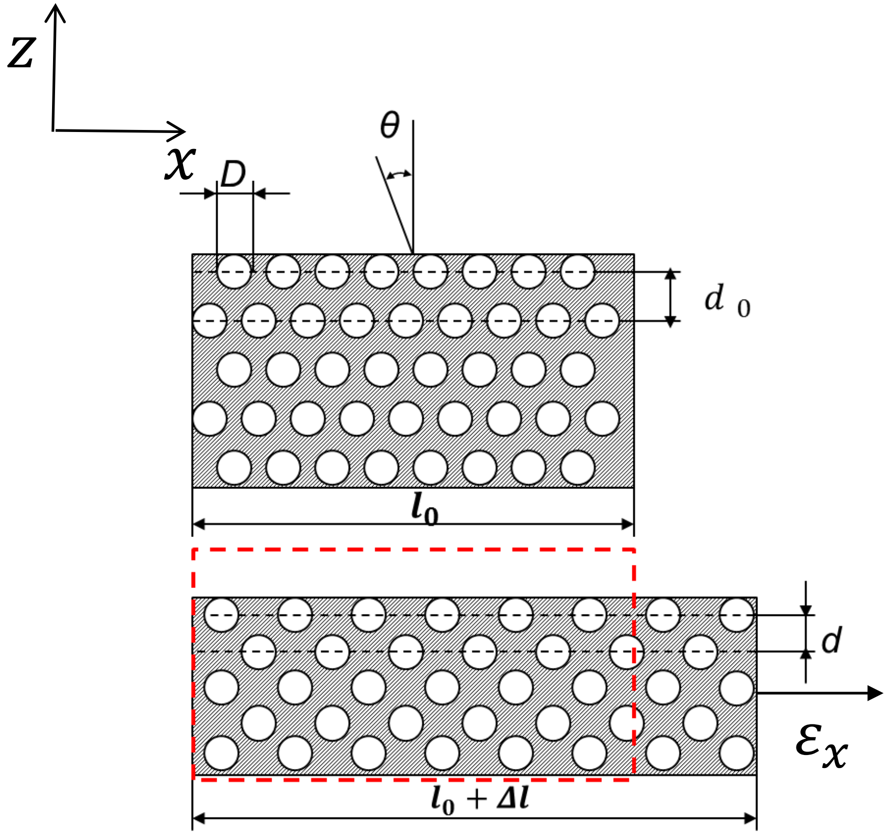
2. Arranging the PS spheres into ordered structure

- vertical deposition of PSs onto Viton substrate (50mm×15mm×1mm)
- constant temperature T = 50°

3. Infiltration with PDMS

- base : curing agent (3:1)
- 4h for curing at T = 65°.

SENSITIVITY TO STRAIN



$$\boxed{\lambda = 2 \cdot n_{eff} \cdot d}$$

$$\varepsilon_z = -\upsilon \varepsilon_x$$

$$\Delta\lambda = 2 \cdot n \cdot \varepsilon_z \cdot d_0$$

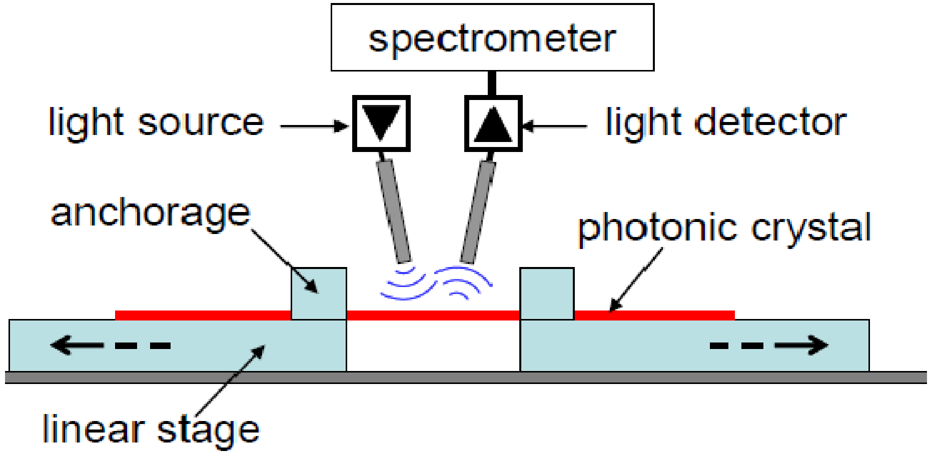
$$\Delta\lambda = \underbrace{-2 \cdot n \cdot d_0}_{\lambda_0} \upsilon \varepsilon_x$$

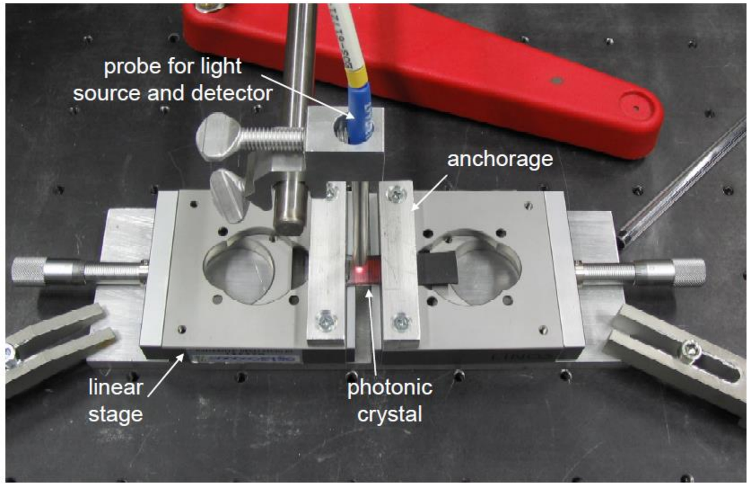
Δl – elongation
Δd - change of interplanar distance

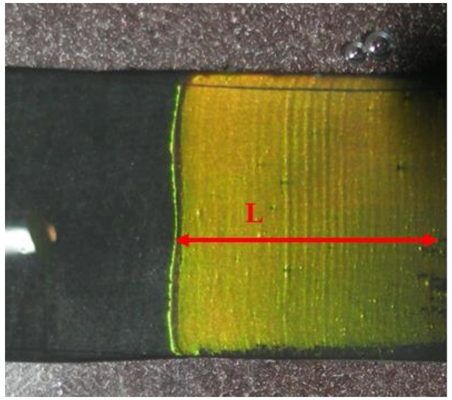
$\left.\begin{array}{l}\boldsymbol{\lambda}\\ \boldsymbol{d}\end{array}\right\}$ values after deformation

υ - Poisson coefficient;
ε_x, ε_z- strain value along *X,Z* axis

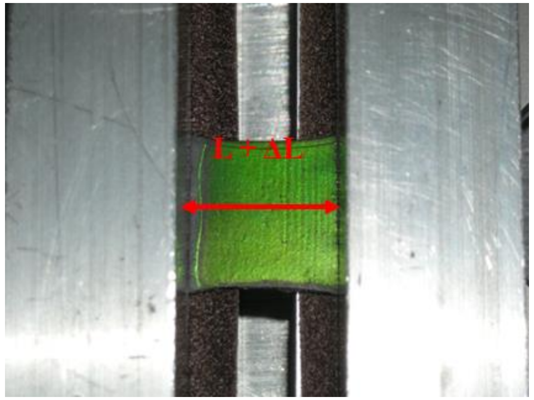
Testing 3D structure





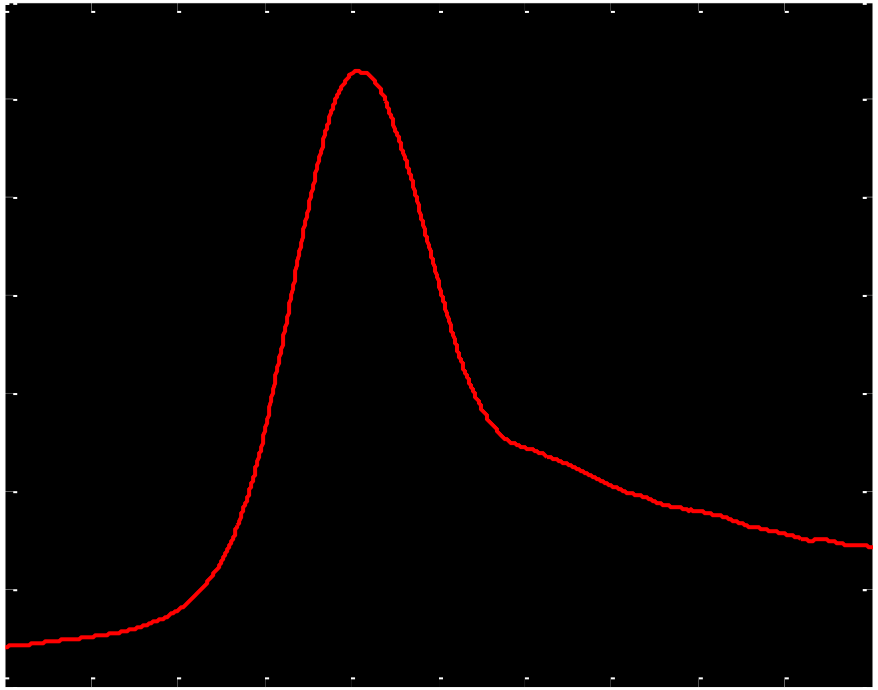


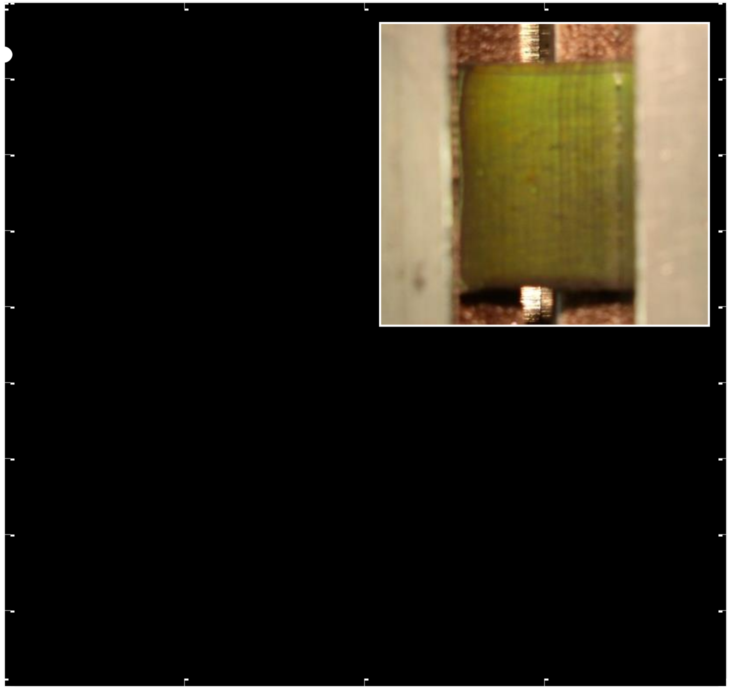
Blue - shift



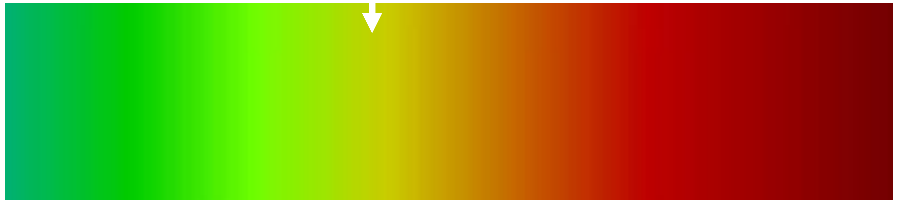
Unloaded Sample (λ =583nm)

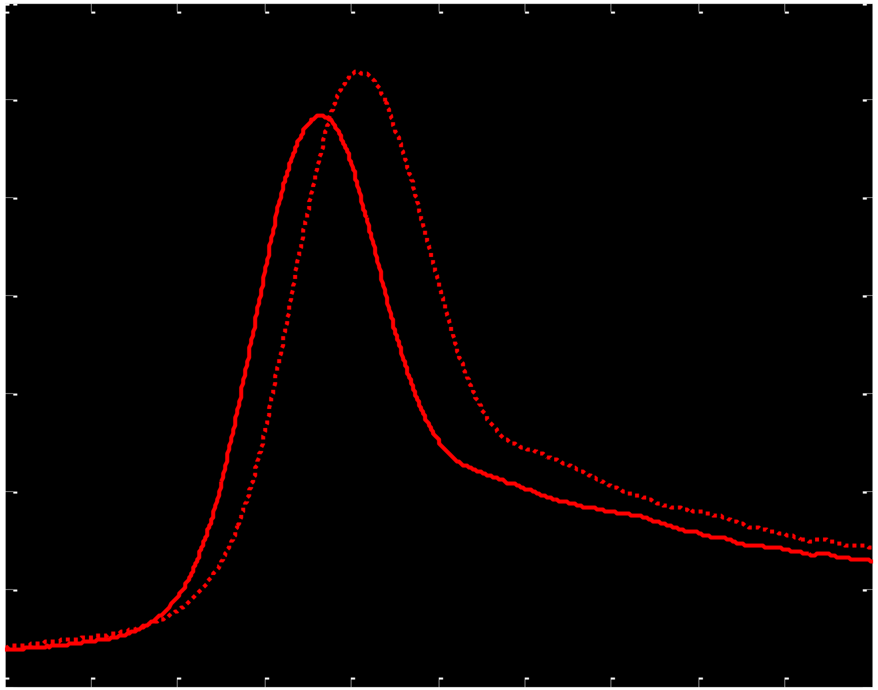
Elongated Sample (λ =550nm)

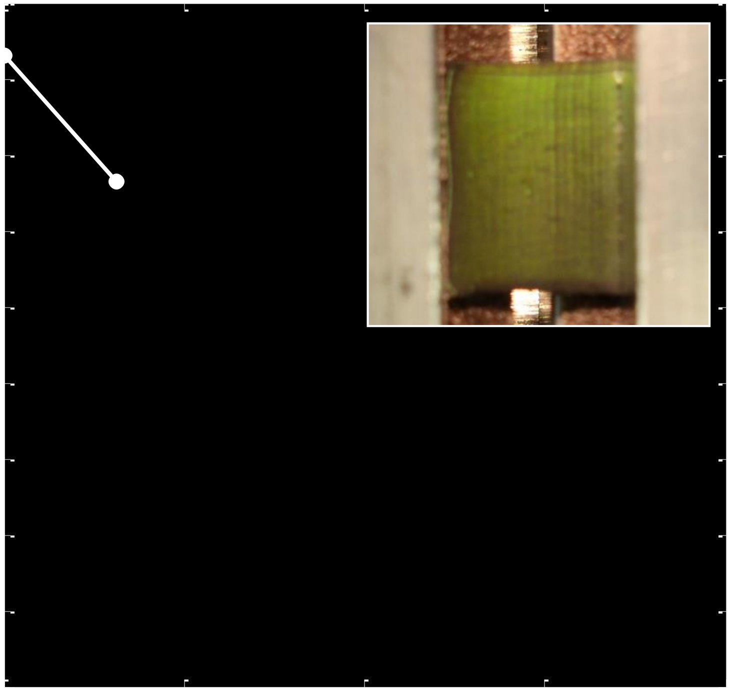




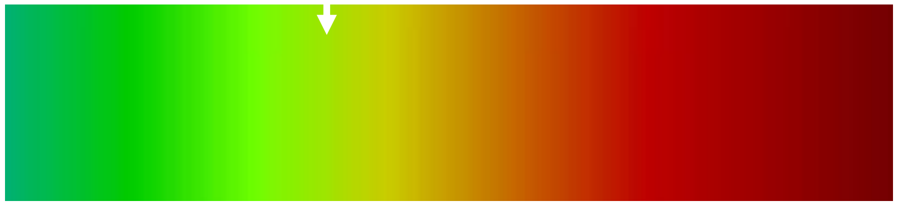
[mε]

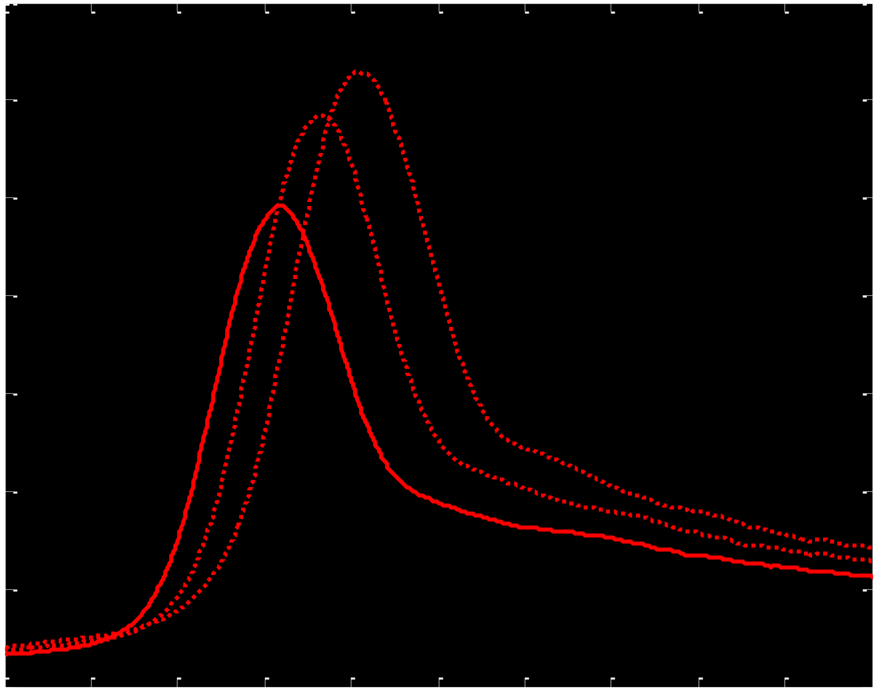


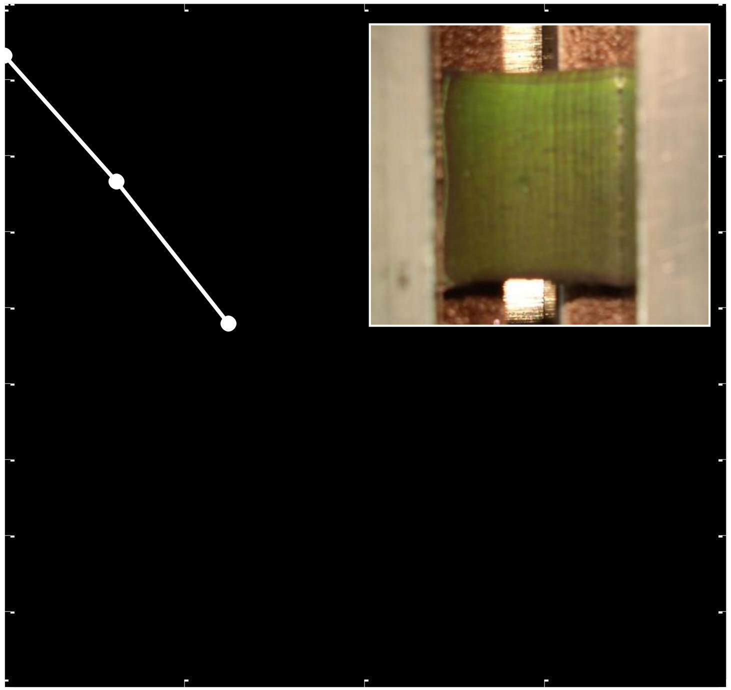




[mε]







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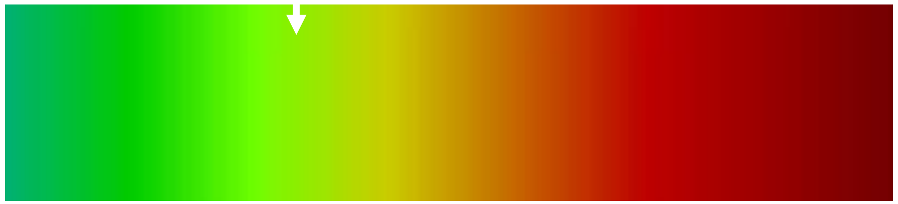

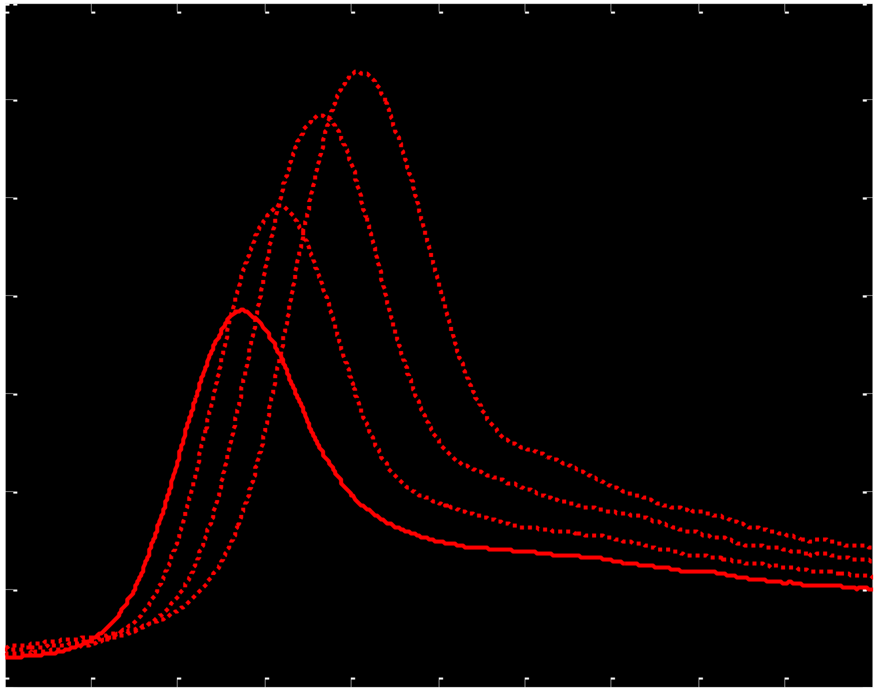

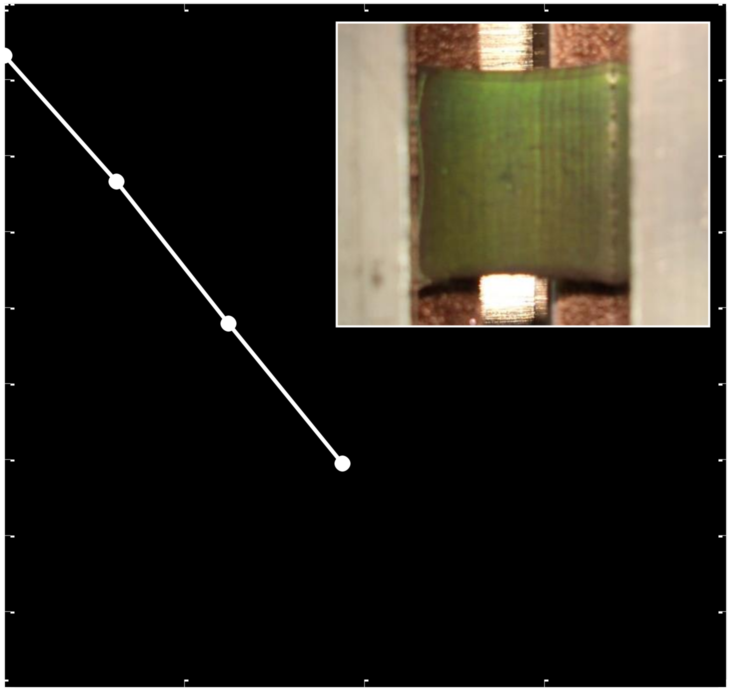

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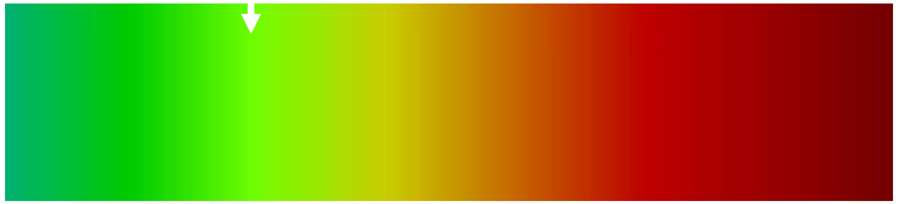

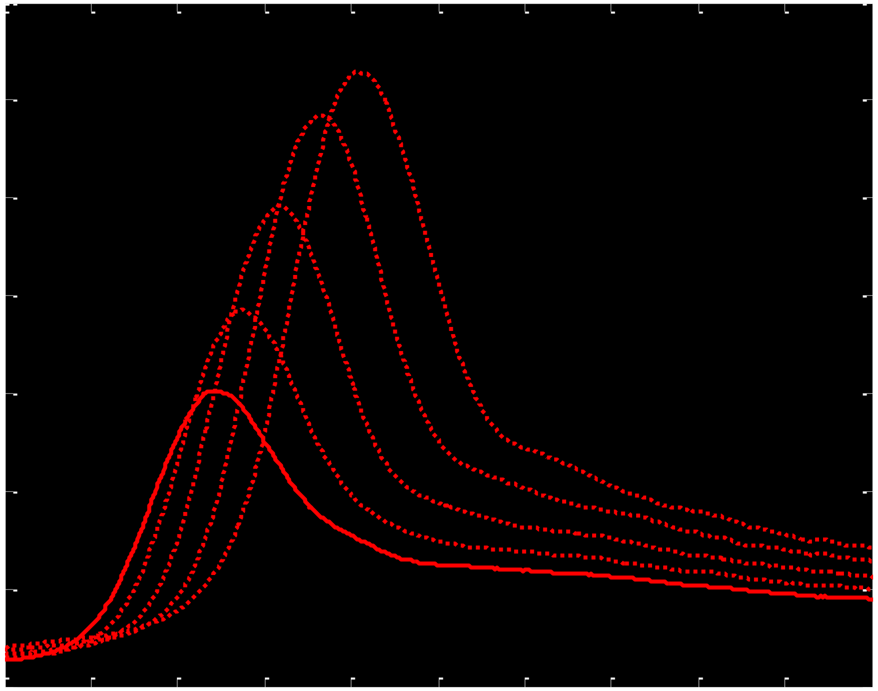

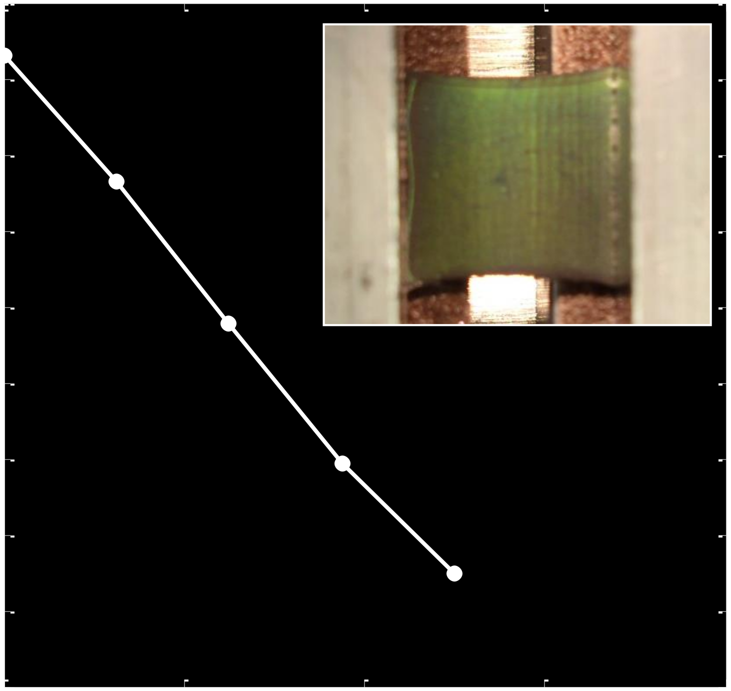

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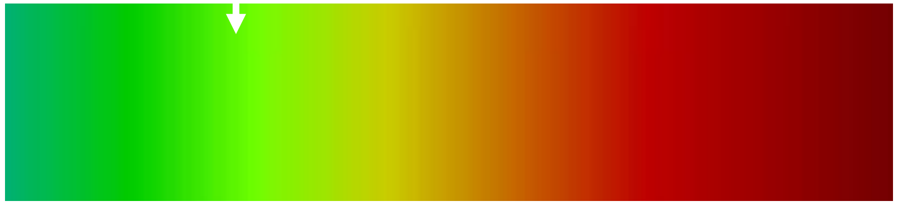

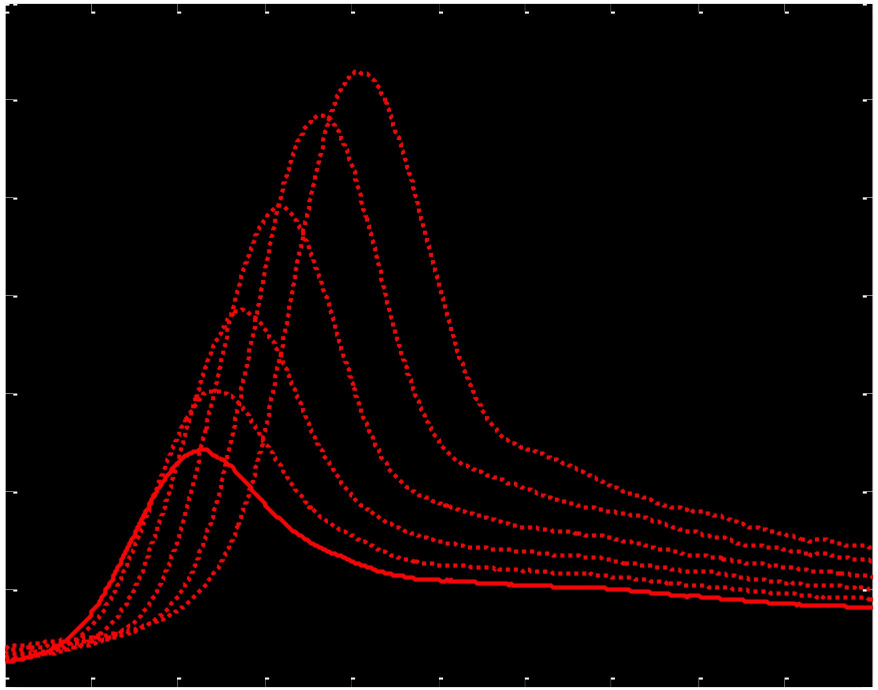

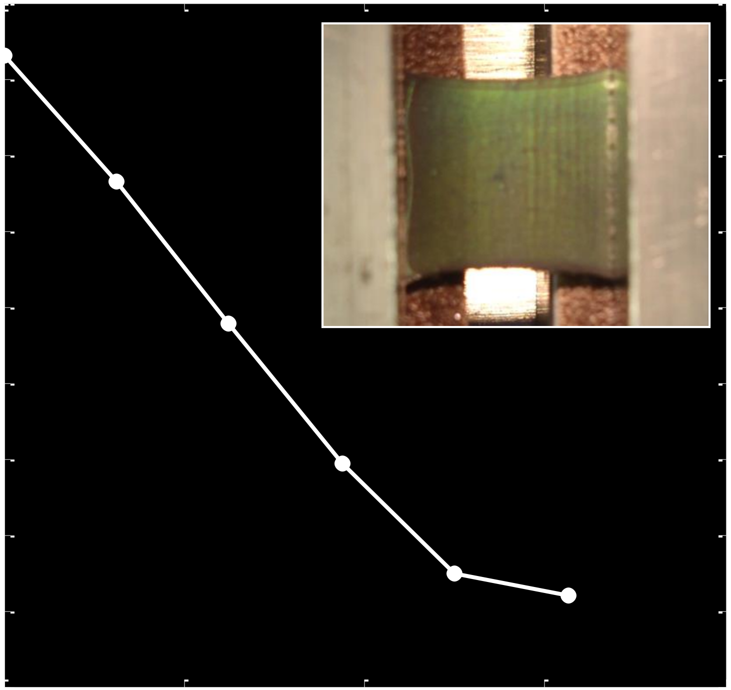

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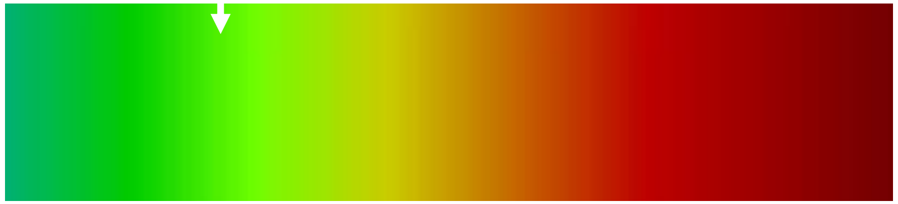

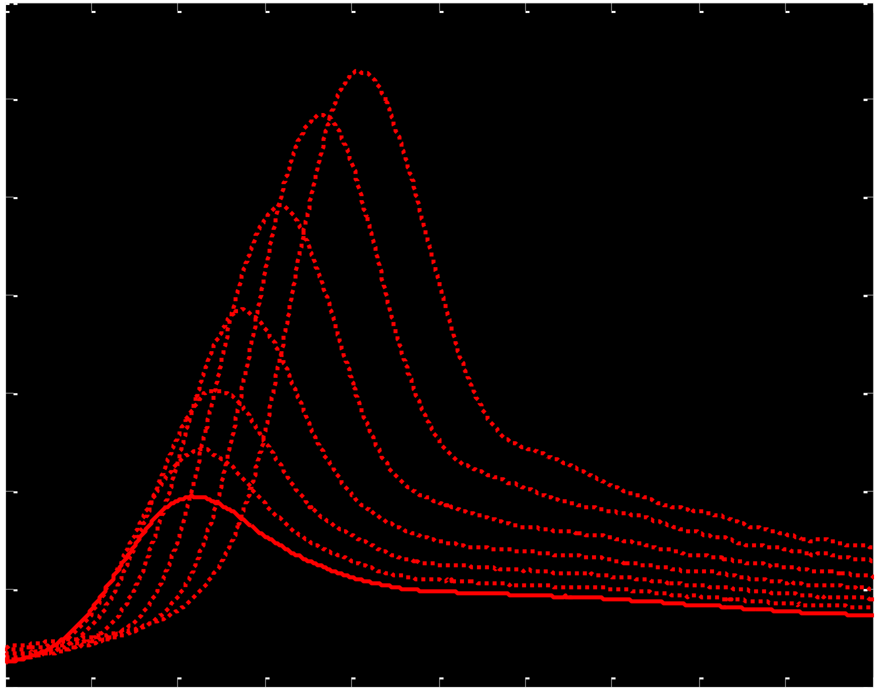

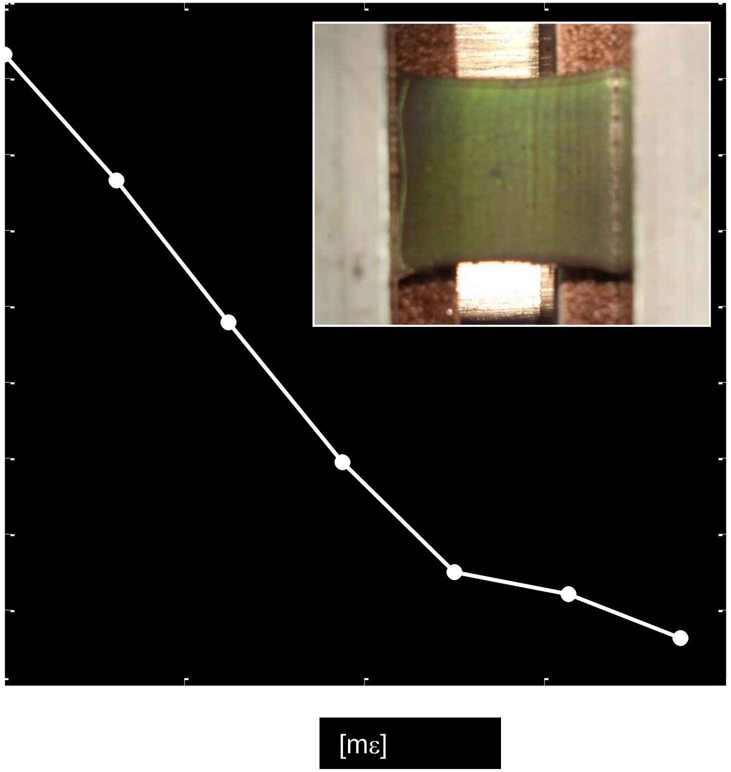
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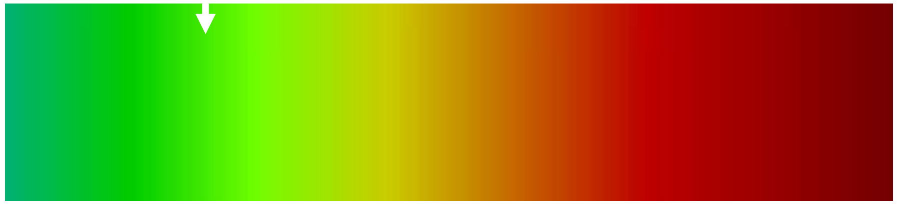

Experimental performances

• sensitivity to strain	-288 pm/με
• inverse sensitivity	3.47 με/pm
• resolution of the reflected peak	~100 pm
• instrumental resolution	~350 με
• max measurable elongation	>150 με [= 15%]
• to appreciate a change in colour:	$\Delta\lambda$ > 10 nm >35 με [= 3.5%]

PCs vs. FBGs

Photonic crystals	FBGs
• resolution of the reflected peak in the order of ~100 pm	• width of the reflected peak in the order of ~20pm
• reflected band depends on the transversal strain	• the grating is deformed directly by the strain of the support
$\boxed{\Delta\lambda \approx 2n_{eff} d_0 \nu \varepsilon_x}$	$\boxed{\Delta\lambda \approx 2n_{eff} d_0 \varepsilon_x}$
• work in the visible (λ_0~400-600 nm)	• work in the infrared (λ_0~1550 nm)

CSMFO LAB. CHARACTERIZATION and DEVELOPMENT of MATERIALS for PHOTONICS and OPTOELECTRONICS Laboratory

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FONDAZIONE BRUNO KESSLER

UNIVERSITAS STUDIORUM ATHESINA

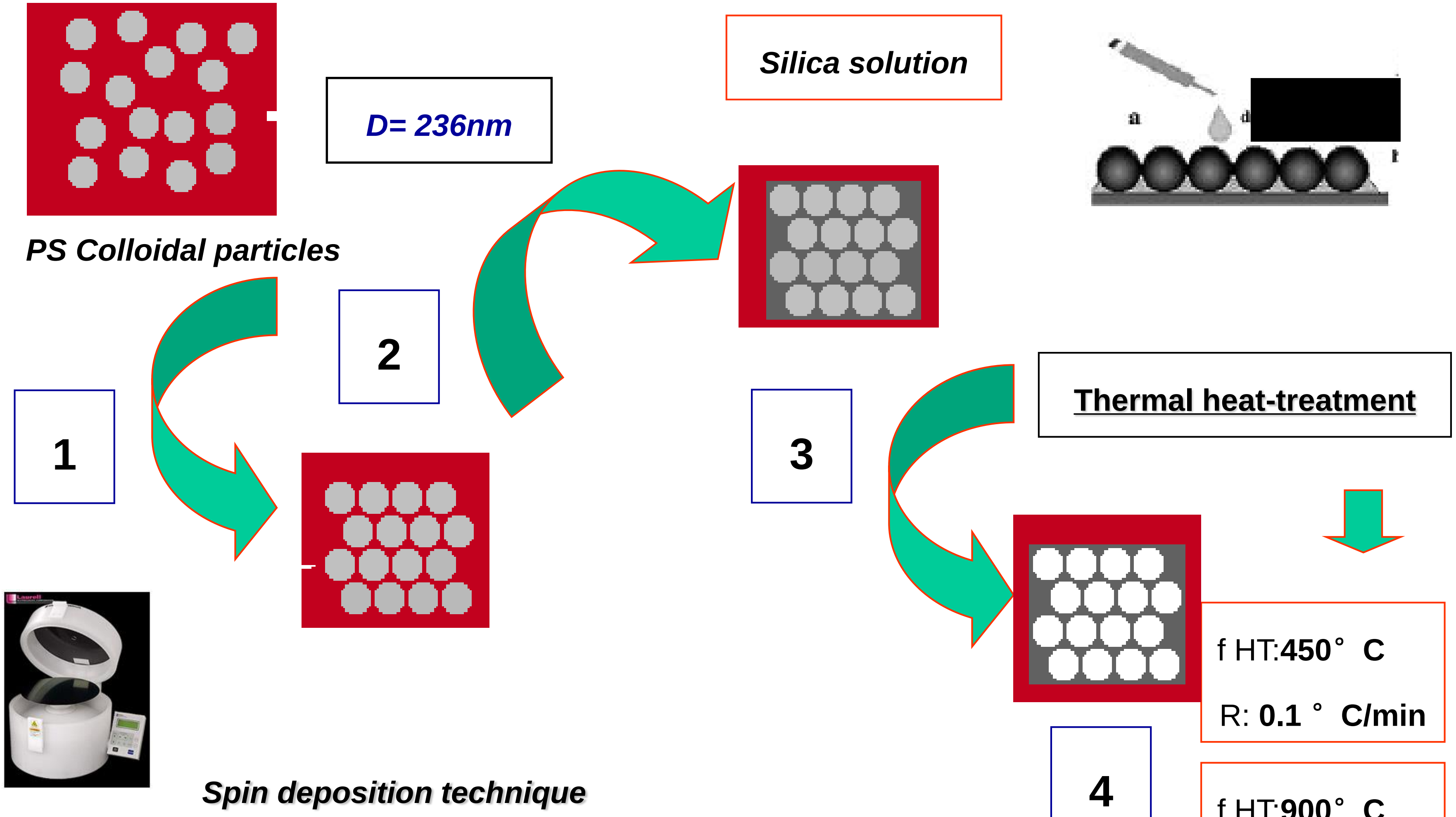
OPALS FOR PHOTONS MANAGEMENT

Andrea Chiappini

Valentina Piccolo, Anna Lukowiak, Alessandro Vaccari, Cristina Armellini, Alessandro Carpentiero, Davor Ristic, Mile Ivanda, Silvia Pietralunga, Stefano Taccheo, Giancarlo C. Righini, Daniele Zonta, Maurizio Ferrari

PHOTOPTICS 2018 6th International Conference on Photonics, Optics and Laser Technology- Funchal, Madeira – Portugal 26 January 2018

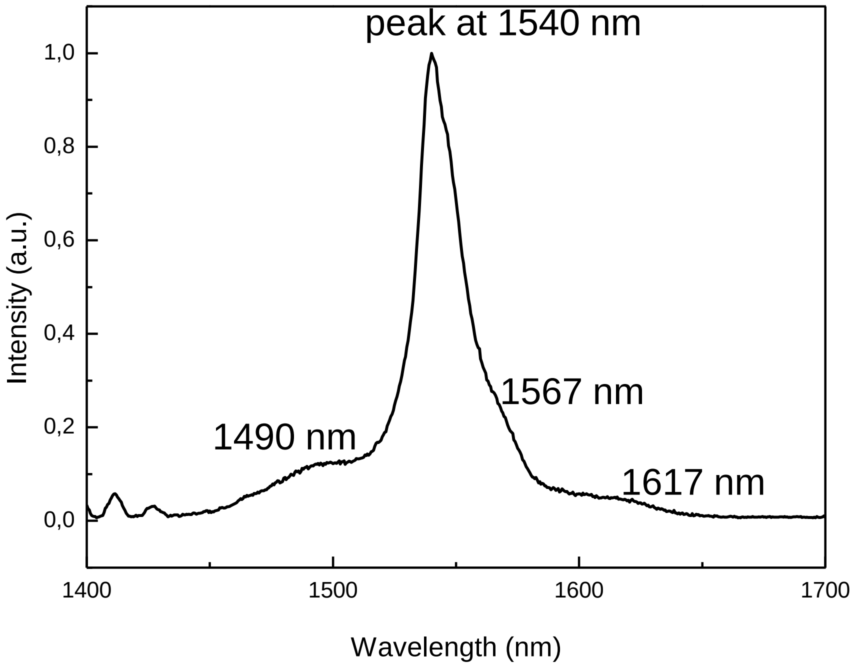
Silica inverse opals
Latex opals as templates



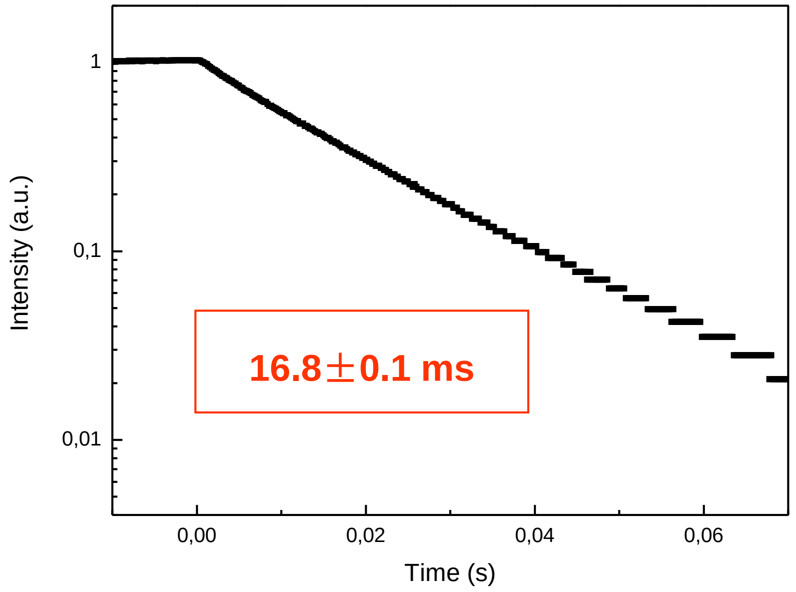
Monodisperse particles in DW solution.

0.3 mol % Er^{3+}

Luminescence at 1.5μm



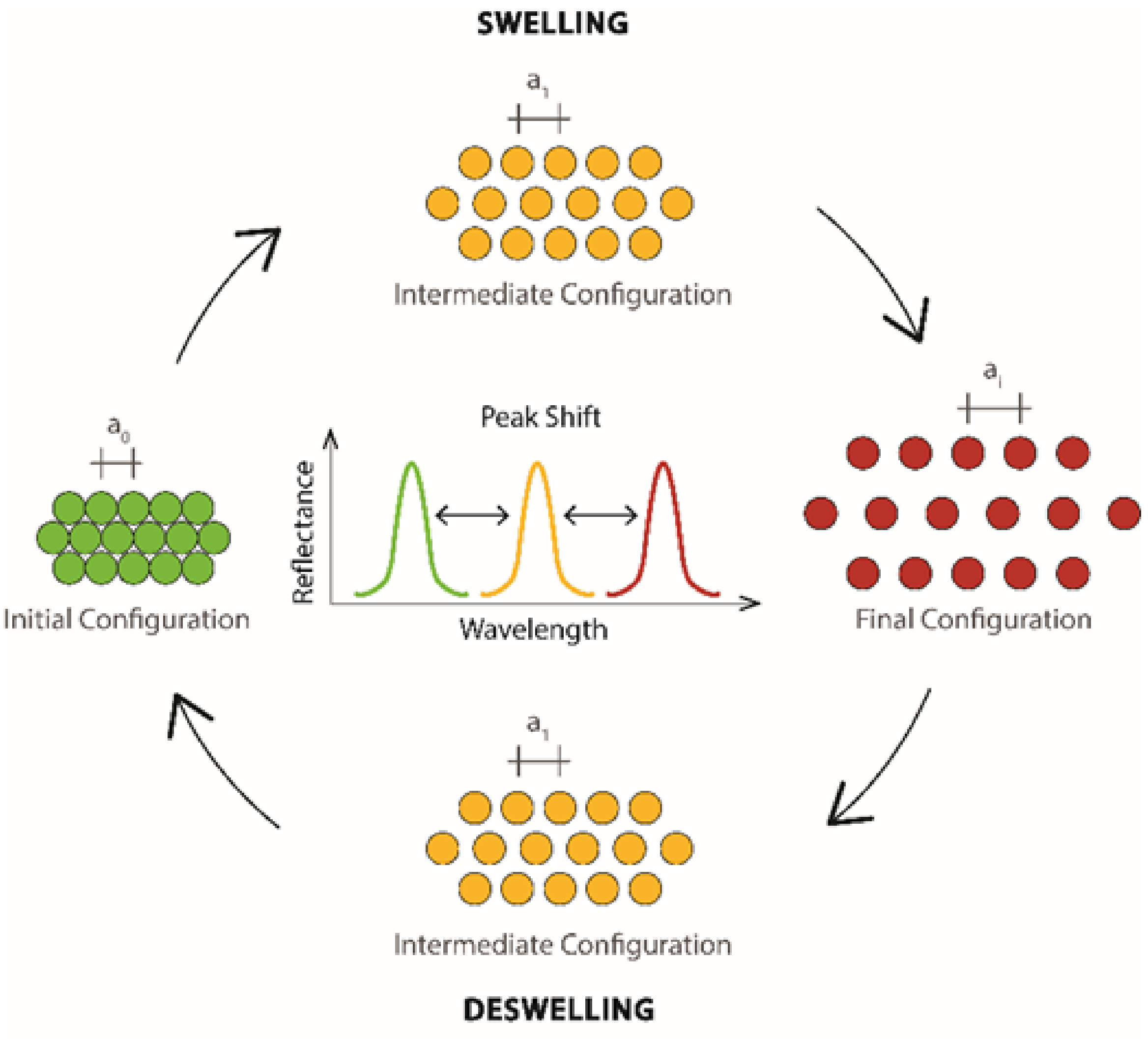
Room temperature photoluminescence spectrum of the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition of Er^{3+} ions



$$W_{SR} = \frac{f(\mathrm{ED})[(n_{\mathrm{eff}}{}^2+2)/3]^2 n_{\mathrm{eff}}}{\lambda_0}$$

$\eta = 80\%$

Assessment of the chromatic behavior of colloidal sensors



Sketch of the isotropic displacement of the spheres assembled in the periodic lattice fcc of the colloidal crystal after solvent application. Clock wise: initial state (green colour), intermediate state (orange colour), and final state (red colour) with their respective reflectance peak shift.

The process is fully reversible

We assume an **isotropic displacement** of the spheres assembled in the periodic lattice fcc

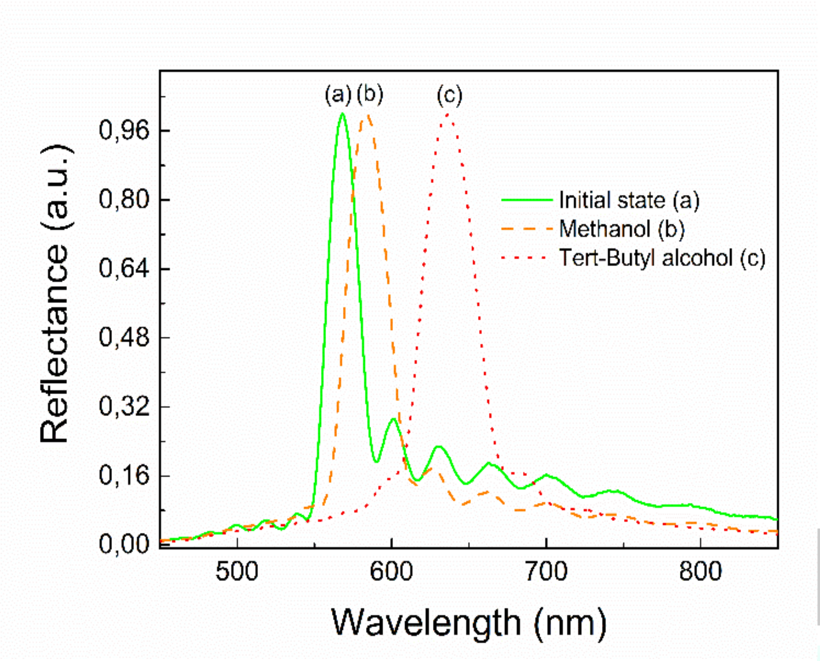
Validation

The assumption and the analytical model have been verified by the response of specific polar solvents

$$S = \frac{(d_{111})_s}{(d_{111})_0}$$

Analyte	Swelling Tabulated*	Swelling Calculated
Methanol	1.02	1.03
Tert-butyl	1.21	1.19

J. Lee et al. Analytical Chemistry 75 (2003) 6544-6554.

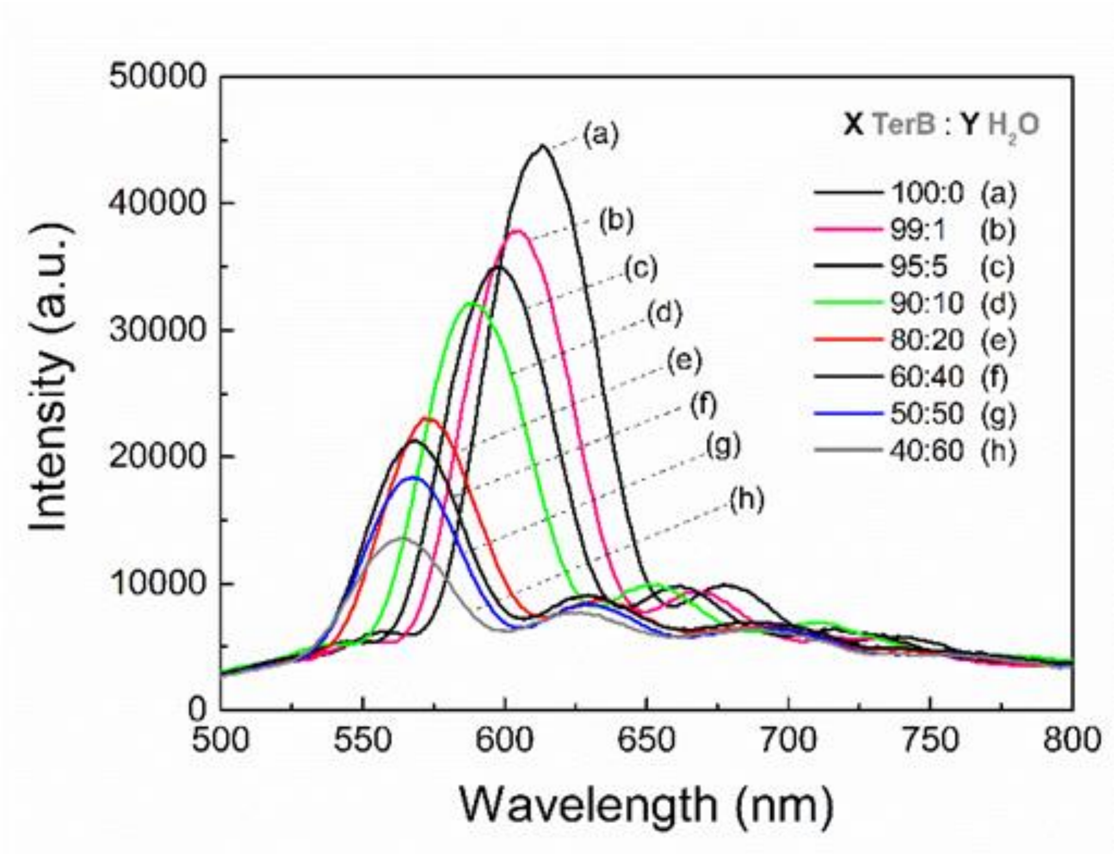


Agreement between the values

- Optical shift of the reflected peak

chromatic changes are caused by the displacement of the spheres which at first approximation may be considered a **homothetic expansion**

Isomers and alcohol concentration

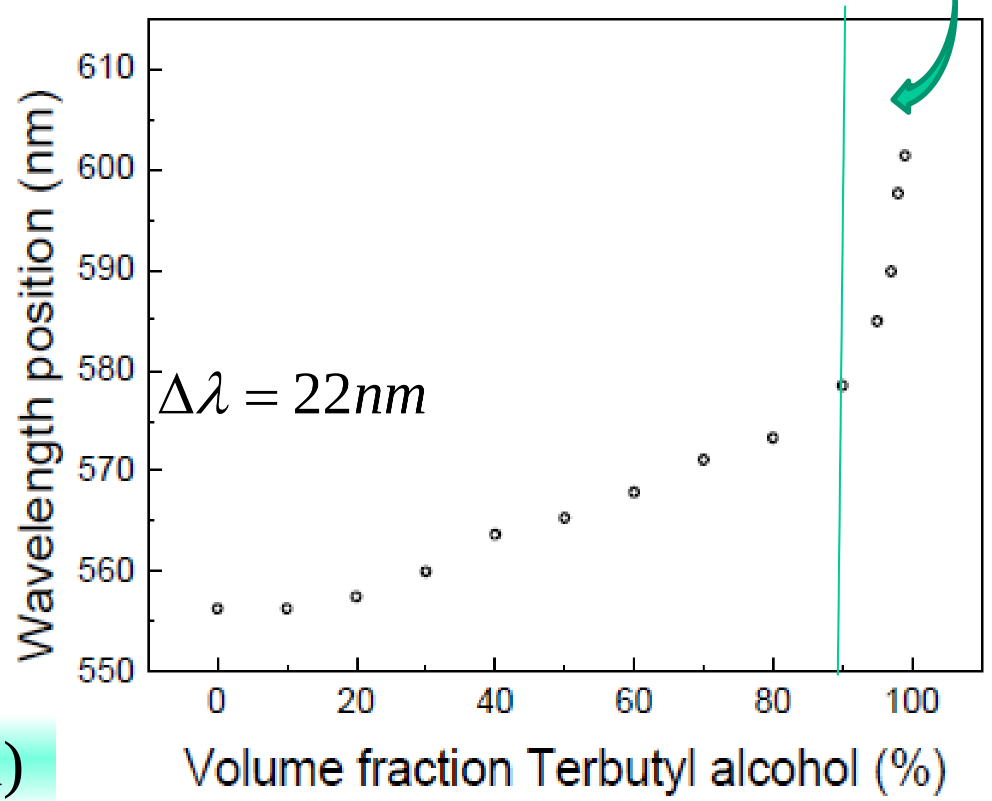


$$I \propto \frac{\Delta n}{n_{eff}}$$

Nanoscale 7 (5), 1857-1863

$\Delta\lambda = 30nm$

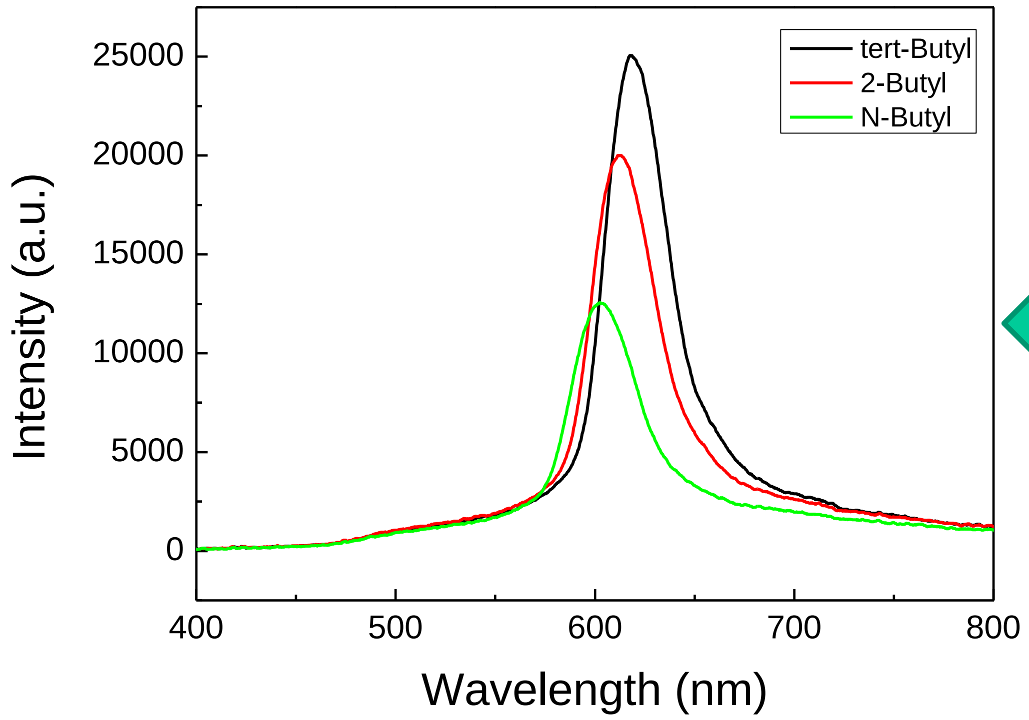
$\Delta\lambda = 22nm$



$$S = \frac{\Delta\lambda}{\Delta n}\left(\frac{nm}{RIU}\right)$$

small water content in organic solvents (1% vol)

Isomers recognition



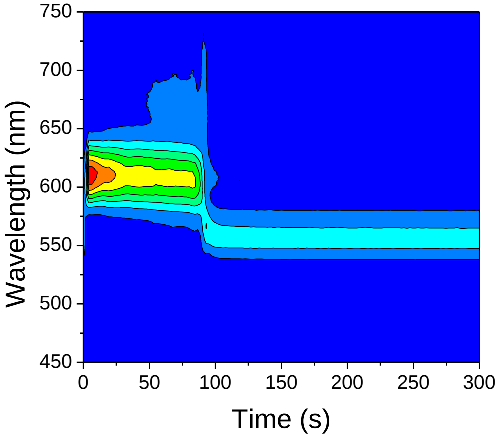
Static reflectance measurements

Isomers of Butanol

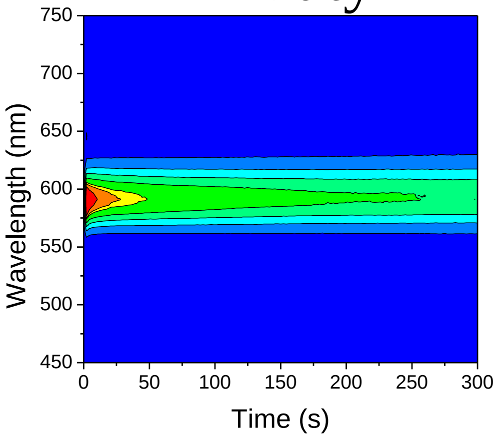
- **refractive index**
- **similar viscosity**
- **comparable polarizability**

Dynamic reflectance measurements

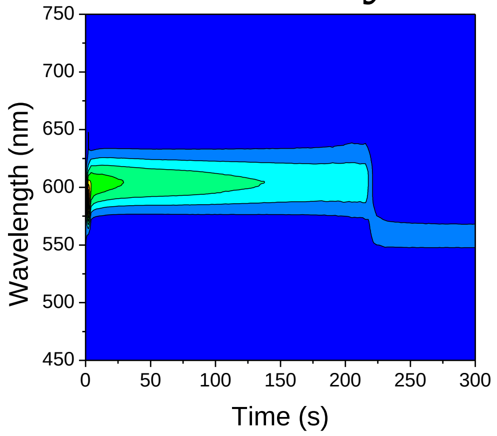
Tert-Butyl



N-Butyl



2-Butyl



Conclusions and Perspectives

Cutting-edge glass based research is present in a huge amount of areas crucial for the improvement of the quality of life:

- ICT
- Lighting
- Laser
- Sensing
- Energy
- Environment
- Biological sciences
- Medical sciences
- Quantum optics

Acknowledgements

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