GLASS-BASED PHOTONIC STRUCTURES: ADVANCES AND PERSPECTIVES

Maurizio Ferrari maurizio.ferrari@ifn.cnr.it

Alessandro Chiasera1, Thi Ngoc Lam Tran1,2,3, Lidia Zuur4,1, Anna Lukowiak5, Yann G. Boucher6,7, Alessandro Vaccari8, Damiano Massella9,1, Cesare Meroni9,1, Stefano Varas1, Cristina Armellini1, Andrea Chiappini1, Alessandro Carpentiero1, Davor Ristic10,11, Mile Ivanda10,11, Francesco Scotognella12,13, Silvia Pietralunga13, Stefano Taccheo14, Daniele Zonta1,2,15, Dominik Dorosz16, Roberta Ramponi13,17, Giancarlo C. Righini4,17, Maurizio Ferrari1,4

1IFN-CNR CSMFO Lab. and EBK Photonics Unit via alla Cascata 56/C Povo, 38123 Trento, Italy
2Department of Civil, Environmental and Mechanical Engineering, Trento University Via Mesiano, 77, 38123 Trento, Italy
3Ho Chi Minh City University of Technical Education, 1 Vo Van Ngan Street, Linh Chieu Ward, Thu Duc District, Ho Chi Minh City, Viet Nam
4Centro di Studi e Ricerche “Enrico Fermi”, Piazza del Viminale 1, 00184 Roma, Italy
5Institute of Low Temperature and Structure Research PAS, Okólna St. 2, 50-422 Wroclaw, Poland
6CNRS FOTON (UMR 6082), CS 80518, 22305 Lannion, France
7École Nationale d’Ingénieurs de Brest, CS 73862, 29238 Brest Cedex 3, France
8EBK CMM-ARES Unit, Via Sommarive 18, 38123 Povo-Trento, Italy
9Department of Physics, Università di Trento, Via Sommarive 14, 38123 Povo-Trento, Italy
10Ruder Bošković Institute, Division of Materials Physics, Laboratory for Molecular Physics, Bijenička c. 54, Zagreb, Croatia
11Center of Excellence for Advanced Materials and Sensing Devices, Research unit New Functional Materials, Bijenička c. 54, Zagreb, Croatia
12Center for Nano Science and Technology@PoliMi, Istituto Italiano di Tecnologia, via Giovanni Pascoli, 70/3, 20133, Milano, Italy
13IFN-CNR and Department of Physics, Politecnico di Milano, p.zza Leonardo da Vinci 32, 20133 Milano, Italy
14College of Engineering, Swansea University, Bay Campus, Swansea, UK
15Department of Civil and Environmental Engineering, University of Strathclyde, 75 Montrose Street, Glasgow, G11XJ, UK
16AGH University of Science and Technology, 30 Mickiewicz Av., 30-059 Krakow, Poland
17MDF Lab. IFAC - CNR, Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy
OUTLINE

❖ Welcome to the Glass Age
❖ Glass Ceramics and Energy Transfer
❖ Whispering gallery modes
❖ 1D microcavities
❖ Opals
❖ Conclusions and Perspectives
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

Light control

Micro scale confined structures

Photons management
YOU CAN SAVE ENERGY REDUCING ENERGY CONSUMING

LOW THRESHOLD LASER ACTION

\[ I_{th} = \frac{h \nu}{\sigma_p \tau} \]
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

<table>
<thead>
<tr>
<th>Composition (Yb concentration in mol%)</th>
<th>1%</th>
<th>2%</th>
<th>3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated transfer efficiency (in glass ceramic)</td>
<td>14%</td>
<td>24%</td>
<td>25%</td>
</tr>
<tr>
<td>Estimated effective quantum efficiency (in glass ceramic)</td>
<td>114%</td>
<td>124%</td>
<td>125%</td>
</tr>
<tr>
<td>Estimated transfer efficiency (in glass)</td>
<td>2%</td>
<td>4%</td>
<td>6%</td>
</tr>
<tr>
<td>Estimated effective quantum efficiency (in glass)</td>
<td>102%</td>
<td>104%</td>
<td>106%</td>
</tr>
</tbody>
</table>

### 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”
GLASS - BASED INTEGRATED OPTICS TECHNOLOGIES

GLASS IO FABRICATION TECHNIQUE

THIN FILM DEPOSITION

PHYSICAL
- VACUUM
  - Electron Beam Evaporation; Arc Evaporation; Pulsed laser deposition

CHEMICAL
- SPUTTERING
  - RF Sputtering; Magnetron Sputtering; Ion beam sputtering
- GAS PHASE
  - Chemical vapor Deposition; Plasma enhanced CVD; Atmospheric pressure CVD
- LIQUID PHASE
  - Sol-gel process Spray Pyrolysis

INDEX MODIFICATION

SnO$_2$ nanocrystals
Innovative solution exploiting SnO$_2$ nanocrystals
SnO$_2$ NCs as sensitizers for Rare Earth ions

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 (630 cm$^{-1}$) 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 ($\Delta n \sim -10^4$) 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”
TEM

Homogeneous distribution

About 4 nm NCs


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.
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

$\lambda_{\text{ex}} = 351$ nm


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.

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 SnO$_2$-based photonic systems”
Print ISBN: 978-3-319-19454-7 Online ISBN: 978-3-319-19454-7 doi: 10.1007/978-3-319-19454-7_116-1

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

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

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

70%SiO$_2$-30%SnO$_2$-0.5%Er$^{3+}$, HT@ 1000°C for 1h
**SnO$_2$-SiO$_2$:Er$^3+$ MONOLITHS**

**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

<table>
<thead>
<tr>
<th>Fabrication process: SOL-GEL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COMPOSITIONS</strong> (mol%)</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
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<tr>
<td><strong>HEAT-TREATMENT</strong></td>
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</tbody>
</table>

**Dried @80°C**

**Stabilized @800°C**
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
Microsphere of diameter $d$ and refractive index $n_s$ coated by a film of thickness $t$ and refractive index $n_c$.


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
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

\[ FSR_{l,l±1} = \frac{\lambda^2}{\pi N d} \]

N=1.6
\( \lambda = 1550 \text{ nm (wavelength of the signal)} \)

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**

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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 $\lambda$.

http://www.photonicatomsensors.com
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
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

1) SiO$_2$/TiO$_2$ BRs deposition (RF sputtering)

2) Active layer deposition (sol-gel)
Hybrid 1-D microcavity fabrication

**SiO$_2$/TiO$_2$ BRs deposition (RF sputtering)**

**SiO$_2$ substrate**

**Fabrication steps:**
1) SiO$_2$/TiO$_2$ BRs deposition by RF sputtering
2) Active layer deposition by solution process
3) Enclosing

**Solution deposition process**

PMMA polymer matrix containing CdSe-CdS-ZnS
Hybrid 1-D microcavity: Laser action

Excitation:
514.5 nm 3 mW CW
Excitation angle: 7°
Detection angle: 0°

Wavenumber (cm\(^{-1}\))

Intensity (counts/s)

FSR

Thickness ~ 20 μm
Light power is enough to induce a change in the refractive index of the polymeric matrix: the feature of the photonic crystals are modified.

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 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 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.

FWHM = 2.4 nm

FWHM = 1.2 nm
$^4I_{13/2} \rightarrow ^4I_{15/2}$ 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

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 $\rightarrow$ High Q
- High number $\rightarrow$ Low Transmittance
Emission Features – Bragg reflectors with 10 layers

- Excitation by commercial tungsten lamp 60W + Interference filter at 514.5 nm
- Excitation by 514.5 nm Ar+ Laser not focalized 30 mW on the sample
Emission Features – Bragg reflectors with 10 layers

• Excitation angle: 30°
• Detection angle: 0°

Threshold 0.6 ± 0.1 mW
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 (1mm²)
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

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?

1) SiO₂/TiO₂ BR deposition (RF sputtering)
2) Graphene layer deposition (Graphenea)
3) Second SiO₂/TiO₂ BR deposition (RF sputtering)
Monolithic 1D Photonic crystal with graphene layer in the defect

![Graph showing transmitance vs wavelength with and without graphene](image)
Monolithic 1D Photonic crystal with graphene layer in the defect

![Graph showing transmittance vs wavelength with and without graphene]

Without Graphene $Q = 152 \pm 1$

With Graphene $Q = 115 \pm 1$
Hybrid 1-D microcavity: acoustic sensor
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
fcc structure provides stable system from thermodynamical point of view

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

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

\[ f = 74\% \]

\[ d = \frac{2}{\sqrt{3}} \cdot D \]

If \( \theta = 0 \), then \( \lambda = 2 \cdot n_{\text{eff}} \cdot d \)

\( \theta \) – incident angle, \( d \) – interplanar distance, \( l_0 \) – initial length, \( D \) – spheres diameter
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 $T = 50^\circ$

3. Infiltration with PDMS
   • base : curing agent (3:1)
   • 4h for curing at $T = 65^\circ$. 
SENSITIVITY TO STRAIN

\[ \lambda = 2 \cdot n_{eff} \cdot d \]

\[ \varepsilon_Z = -\nu \varepsilon_X \]

\[ \Delta \lambda = 2 \cdot n \cdot \varepsilon_Z \cdot d_0 \]

\[ \Delta \lambda = \frac{-2 \cdot n \cdot d_0 \nu \varepsilon_X}{\lambda_0} \]

\[ \Delta l \] – elongation
\[ \Delta d \] - change of interplanar distance

\[ \frac{\lambda}{d} \] values after deformation

\[ \nu \] - Poisson coefficient;
\[ \varepsilon_X, \varepsilon_Z \] - strain value along X,Z axis
TESTING 3D STRUCTURE

Unloaded Sample (\(\lambda = 583\text{nm}\))

Elongated Sample (\(\lambda = 550\text{nm}\))

Blue - shift
Experimental performances

- sensitivity to strain: $-288 \text{ pm/\mu\varepsilon}$
- inverse sensitivity: $3.47 \, \mu\varepsilon/\text{pm}$
- resolution of the reflected peak: $\sim 100 \, \text{pm}$
- instrumental resolution: $\sim 350 \, \mu\varepsilon$
- max measurable elongation: $>150 \, \mu\varepsilon \ [= 15\%]$  
- to appreciate a change in colour: $\Delta\lambda > 10 \, \text{nm}$  
  $>35 \, \mu\varepsilon \ [= 3.5\%]$
## PCs vs. FBGs

<table>
<thead>
<tr>
<th>Photonic crystals</th>
<th>FBGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>• resolution of the reflected peak in the order of ~100 pm</td>
<td>• width of the reflected peak in the order of ~20pm</td>
</tr>
<tr>
<td>• reflected band depends on the transversal strain</td>
<td>• the grating is deformed directly by the strain of the support</td>
</tr>
<tr>
<td>[ \Delta \lambda \approx 2n_{\text{eff}} d_0 \nu \varepsilon_x ]</td>
<td>[ \Delta \lambda \approx 2n_{\text{eff}} d_0 \varepsilon_x ]</td>
</tr>
<tr>
<td>• work in the visible (( \lambda_0 \sim 400-600 ) nm)</td>
<td>• work in the infrared (( \lambda_0 \sim 1550 ) nm)</td>
</tr>
</tbody>
</table>
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
Silica inverse opals
Latex opals as templates

PS Colloidal particles

Spin deposition technique
Monodisperse particles in DW solution.

Silica solution

D = 236nm

Thermal heat-treatment

f HT: 450 °C
R: 0.1 °C/min

0.3 mol % Er³⁺
Luminescence at 1.5\(\mu\)m

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

Peak at 1540 nm

1490 nm
1567 nm
1617 nm

Intensity (a.u.)
Wavelength (nm)

16.8 \(\pm\) 0.1 ms

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

\(n = 80\%\)
Assessment of the chromatic behavior of colloidal sensors

We assume an isotropic displacement of the spheres assembled in the periodic lattice fcc of the colloidal crystal after solvent application. Clockwise: 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.
The assumption and the analytical model have been verified by the response of specific polar solvents. Agreement between the values of swelling calculated and tabulated demonstrates the accuracy of the model. The optical shift of the reflected peak is a key indicator of chromatic changes caused by the displacement of the spheres, which at first approximation may be considered a homothetic expansion.

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

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Swelling Tabulated*</th>
<th>Swelling Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methanol</td>
<td>1.02</td>
<td>1.03</td>
</tr>
<tr>
<td>Tert-butyl</td>
<td>1.21</td>
<td>1.19</td>
</tr>
</tbody>
</table>

Isomers and alcohol concentration

\[ I \propto \frac{\Delta n}{n_{\text{eff}}} \]

\[ \Delta \lambda = 30 \text{nm} \]

\[ \Delta \lambda = 22 \text{nm} \]

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
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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