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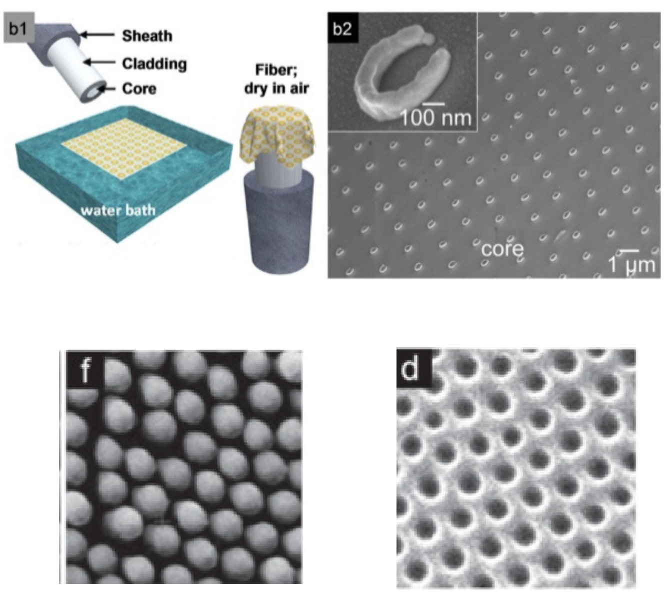
Optoelectronic Division, Engineering Department
University of Sannio, Benevento (Italy)

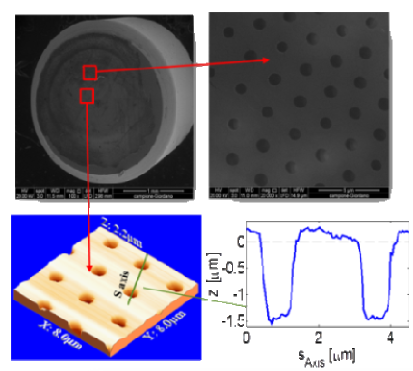
New Functionalities in Optical Fibers using "Lab on Fiber" Technology

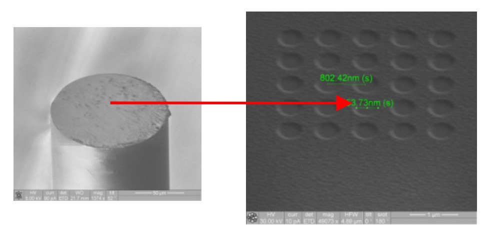
Andrea Cusano

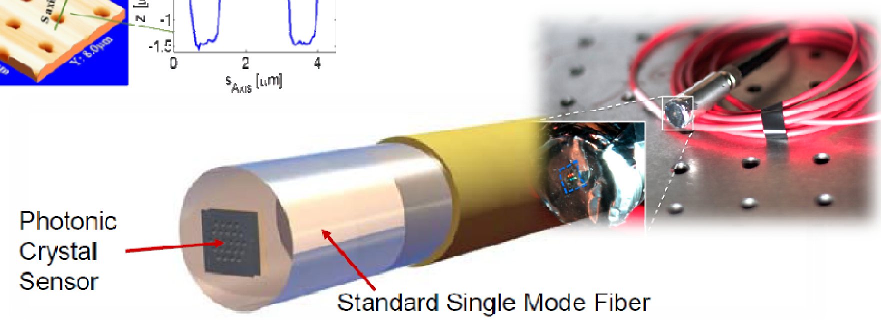
Optoelectronics Division,
Engineering Department,
University of Sannio, Benevento, Italy

2[nd] International Conference and Exhibition on
Lasers, Optics & Photonics
September 08-10, 2014 Hilton Philadelphia Airport, USA









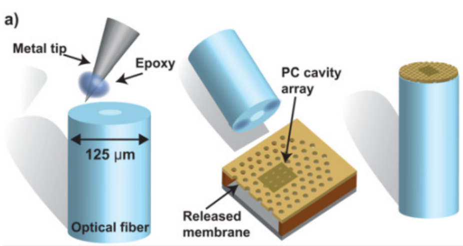
OUTLINE

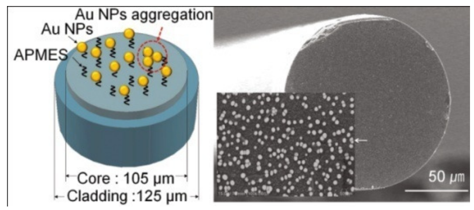
- *LAB-ON-FIBER TECHNOLOGY*
- *LAB ON FIBER AT UNIVERSITY OF SANNIO*
- *FIBER OPTIC NANO-PROBES: PRINCIPLE OF OPERATION AND SENSING FEATURES*
- *CONCLUSIONS*

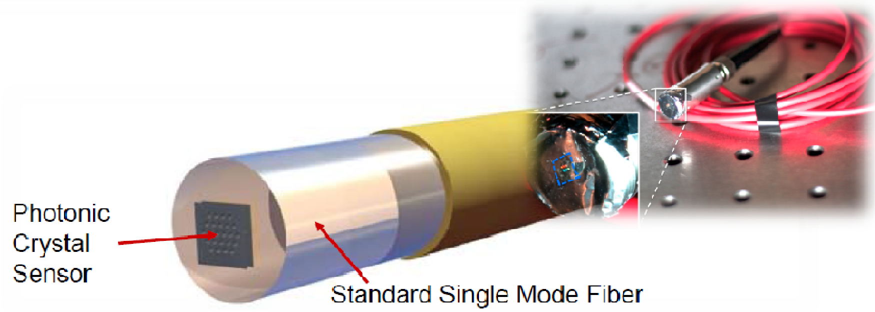
Optoelectronic Division, Engineering Department
University of Sannio, Benevento (Italy)

LAB ON FIBER TECHNOLOGY:
towards integrated and multifunctional nano-probes

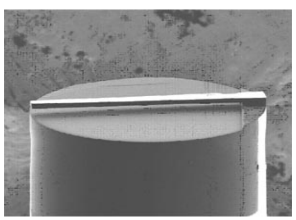
Integration and patterning at micro and nano scale of different functional materials with desired optical, physical and chemical properties

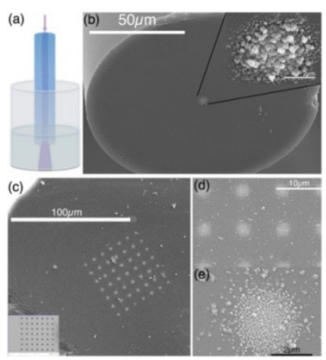


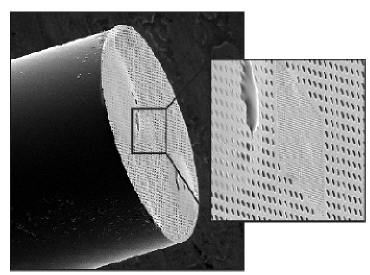


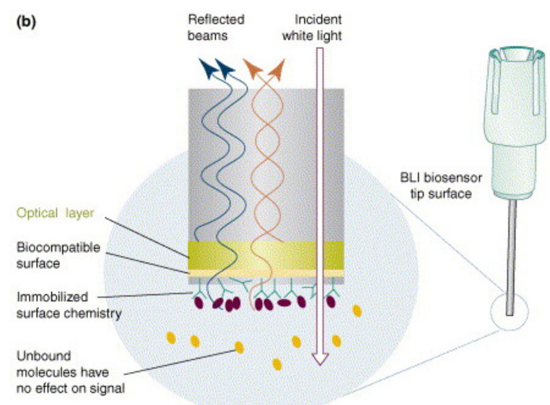


Increased light matter interaction and creation of a technological world completely integrated within optical fibers with significant advantages in terms of functionality, performances, miniaturization, robustness, cost effectiveness and power consumption









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.

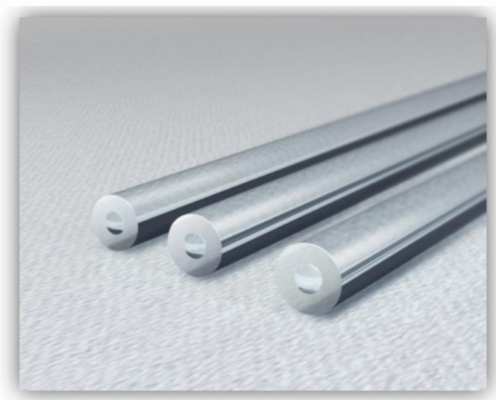
THE FIBER TIP: A UNIQUE LIGHT COUPLED PLATFORM
FOR MICRO AND NANO TECHNOLOGIES

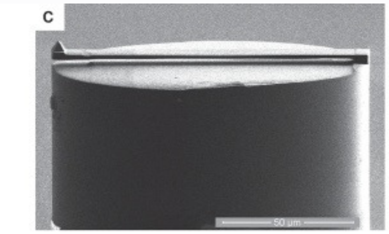
Unique and Uncoventional Platform

Microscopic Cross Section and large aspect ratio

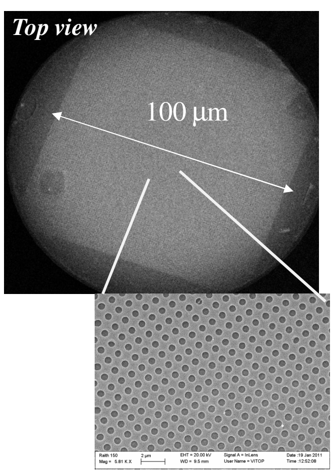
Inherently Light Coupled

Biocompatible

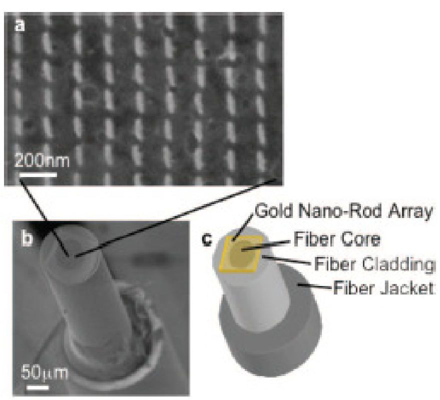




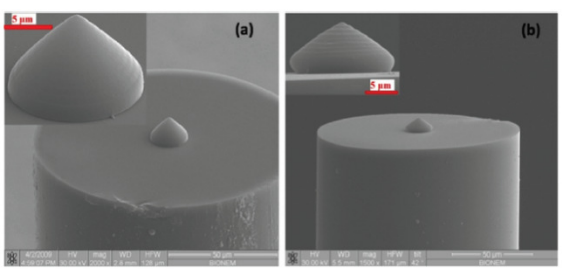
Opto-mechanical Systems
(AFM and near field probes,
Pressure and
Acoustic sensors)



Nanophotonics
(Nanodevices, diffractive filters, light manipulation)

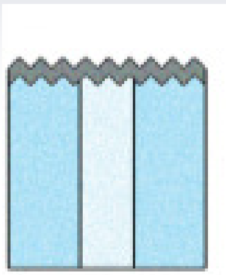


Biophotonics
(SERS, Plasmonics, Optical tweezers, Nanosensors)

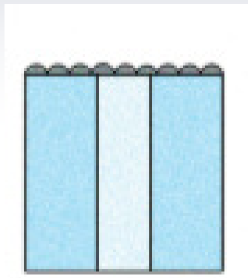


Micro-optics and Beam Shaping

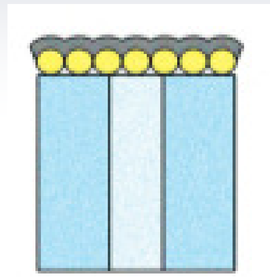
EARLIER DEVELOPMENTS DRIVEN BY SERS



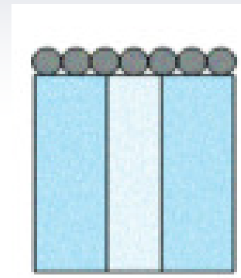
Roughening by mechanical abrasion
Mullen 1991



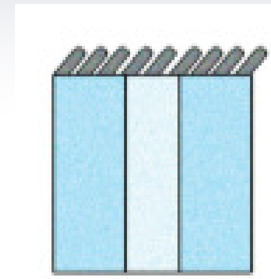
Island growth during thin film deposition
Viets and Hill, 1998



Self-assembly of colloidal templates
Vo Dinh, 1995

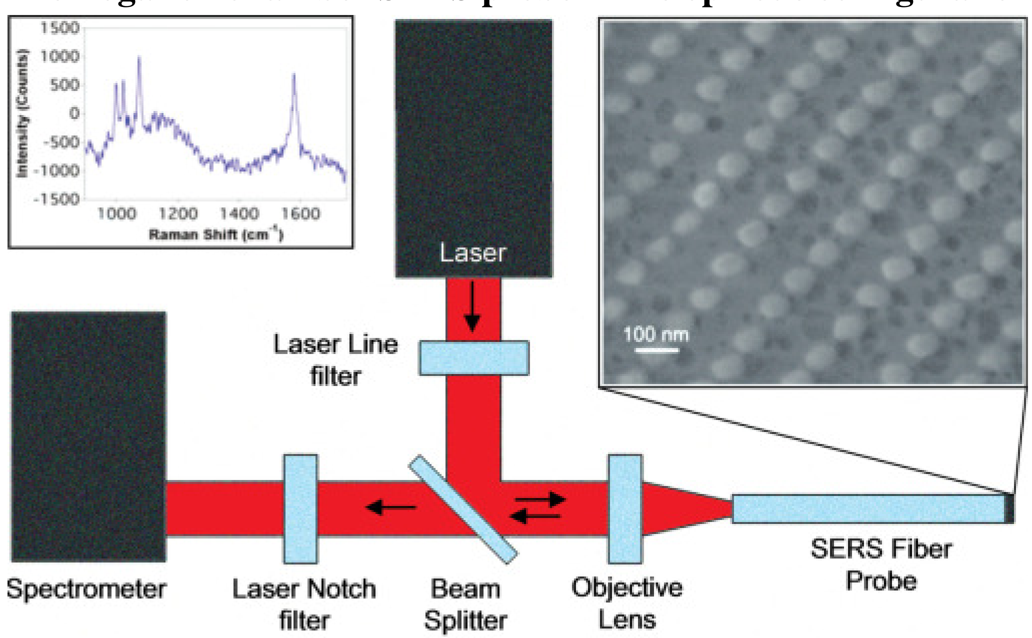


Coating with metal nanoparticles
Sadler, 2000



Nanorods formed by glancing angle deposition
Zhao , 2006

Interrogation of a fiber SERS probe in the optrode configuration



Gorgi Kostovski et al.
Advanced Materials 2014
DOI: 10.1002/adma.201304605

Technologies:
Earlier development mainly rely on the use of decoration and self assembly techniques

Advantages:
Simple and low cost fabrication techniques
Ready access to the nano-regime

Main Issue
Stochastic deposition affects the order and regularity of the final nanostructure

Optoelectronic Division, Engineering Department
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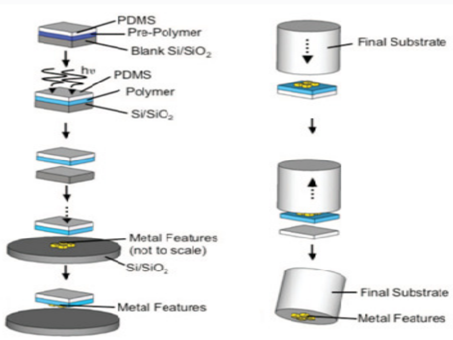
TOWARDS ENGINEERED NANOSTRUCTURES INTEGRATION

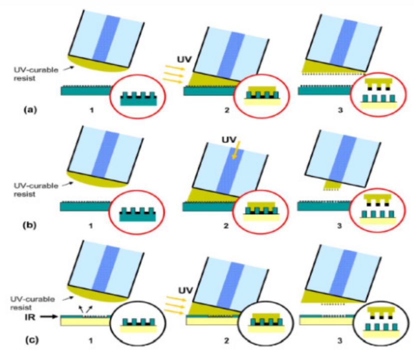
Nano-fabrication on planar substrates and transferring onto optical fibers

EBL and soft lithography



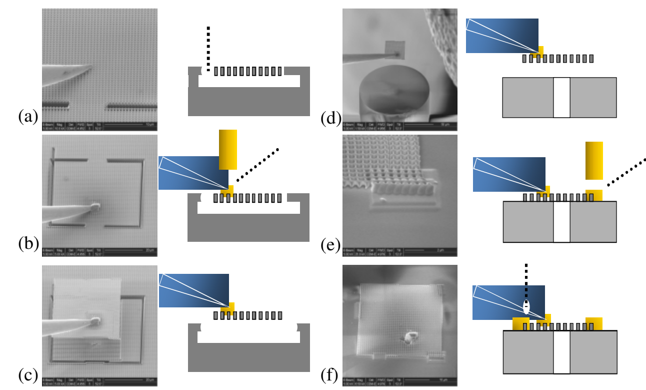
E. J. Smythe, F. Capasso et al., ACS Nano, 2009, 3 (1), 59-65

UV nano imprint and transfer lithography (NITL)



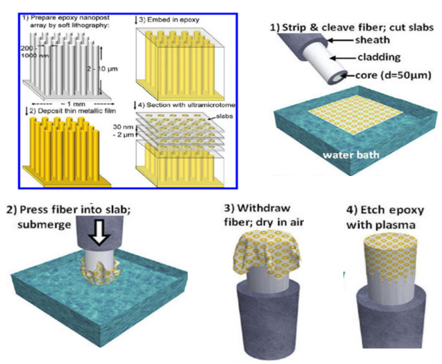
S. Scheerlinck , R. Baets et al., J. Light. Tech., pp.1415-1420, 2009

Monolithic silicon photonic crystal integration



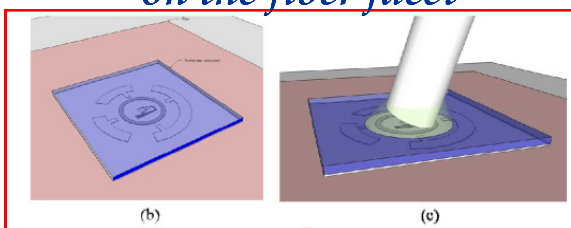
O. Solgaard, I. W. Jung, et al., J. Light. Tech., 2011, 29(9), 1367-1374.

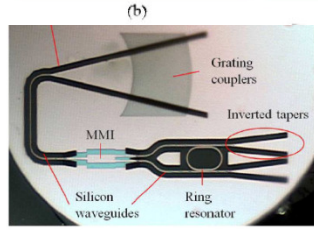
Soft lithography, nano-skiving and dipping



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

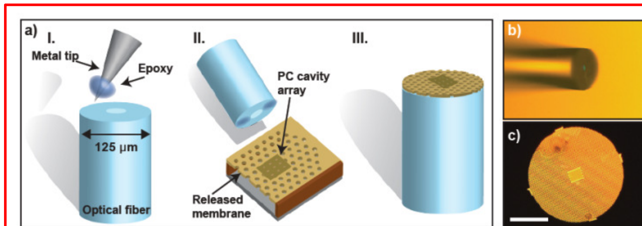
Soi microring resonator integrated on the fiber facet





P. Bienstman, C. L. Arce, et al., IEEE Photon. Techn. Lett., 2011, 23(13), 890-892

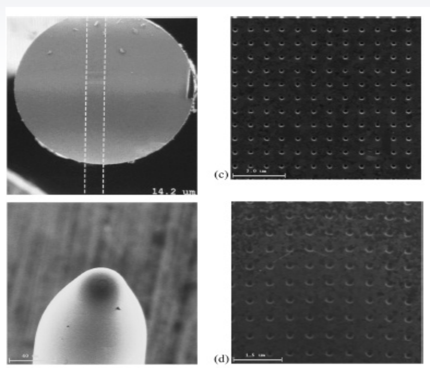
Photonic crystal cavity transfer



G. Shambat et al., Appl. Phys. Lett. 99(19), 191,102 (2011)

OVERCOMING THE TRANSFERRING APPROACH

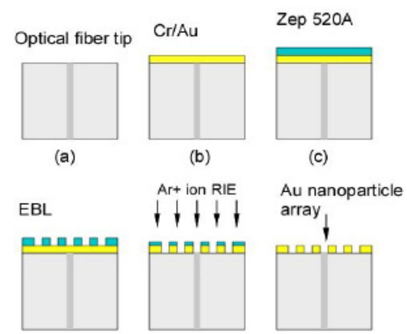
FIB milling



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

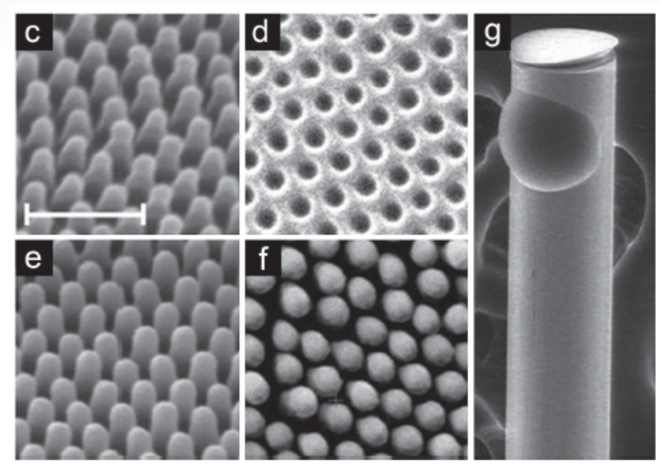
Direct-writing

EBL and Reactive Ion Etching



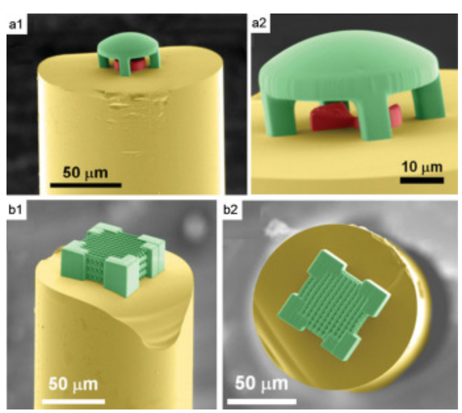
Y. Lin, R. G. Lindquist et al., Biomed Opt Express. 2011; 2(3): 478–484.

Nanoimprint lithography



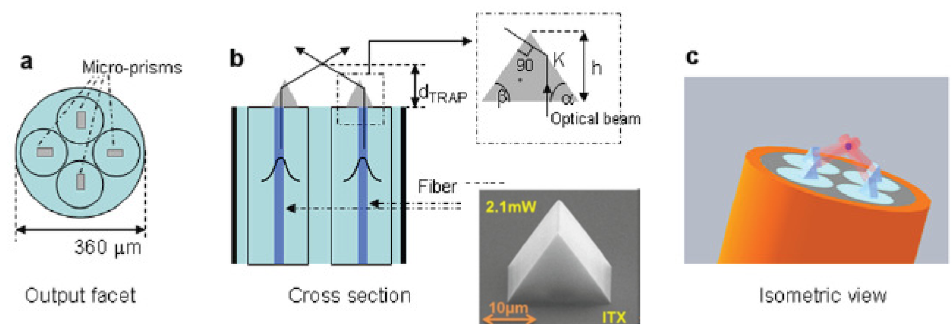
G. Kostovski , et al., Biosensors Bioelectron. 2009, 24 , 1531

Micro-optics using two-photon direct laser writing



H. E. Williams et al., Opt. Express 2011, 19, 22910

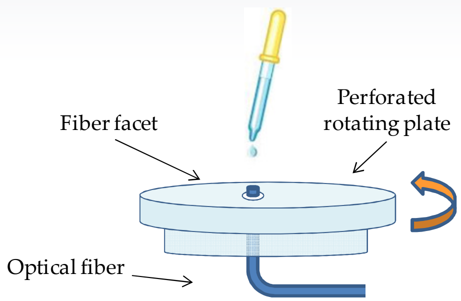
Optical tweezers using two photon litography

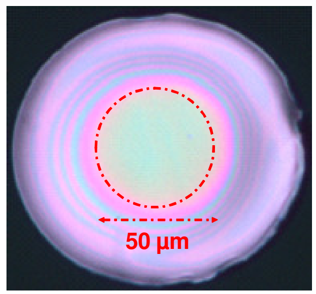


E. Di Fabrizio, Sci. Rep. 3, 1258 (2013)

EBL DIRECT WRITING

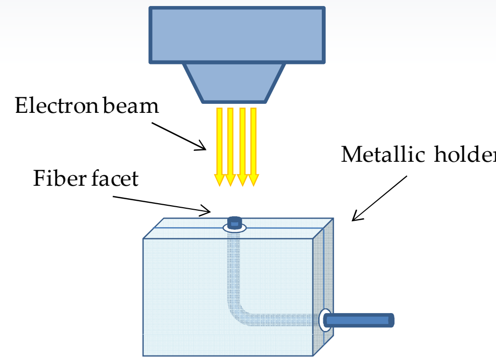
1) Electron-resist spin coating

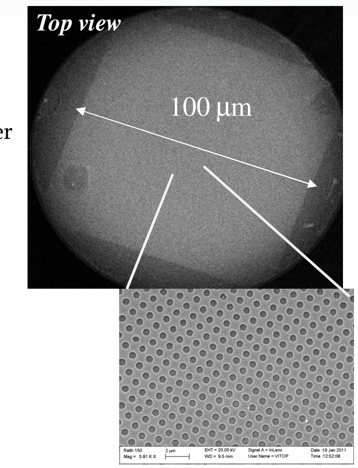




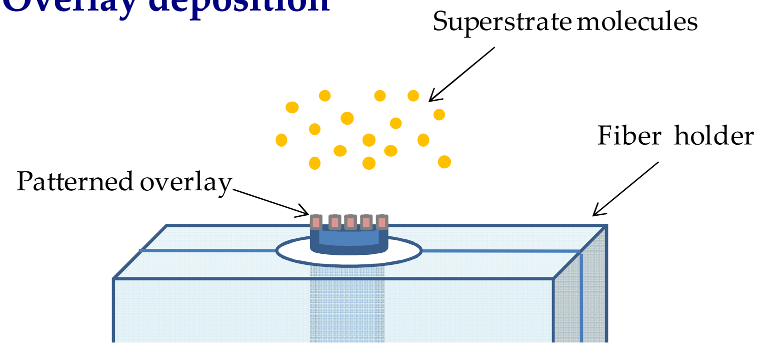
100-400nm thick (ZEP) overlay can be reproducibly obtained

2) EBL patterning

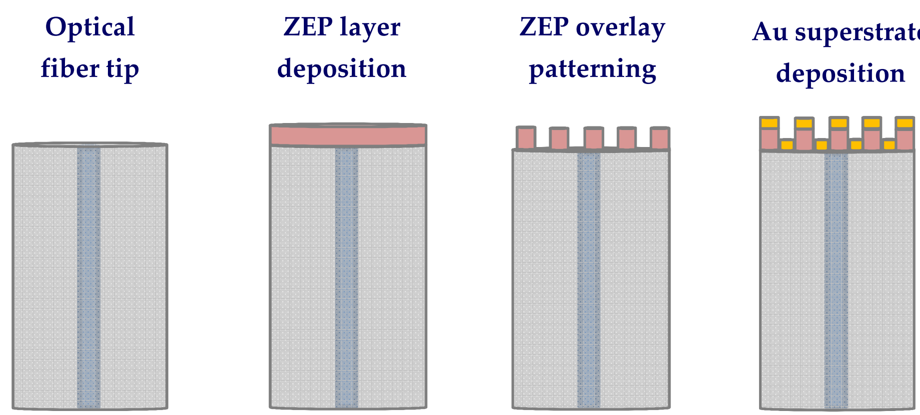




3) Overlay deposition



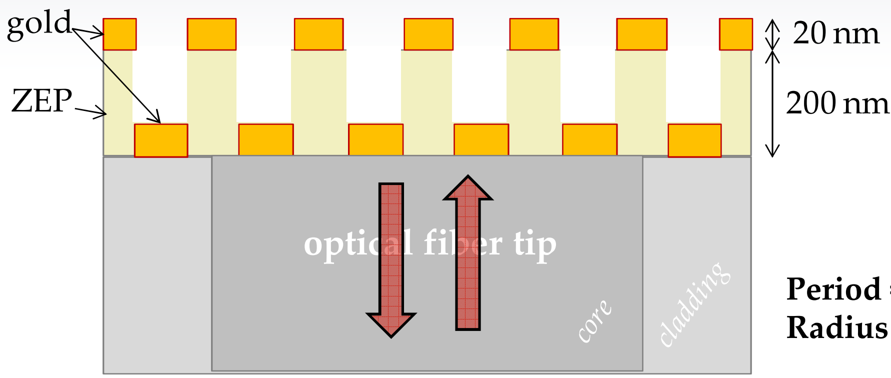
Different materials (metallic or dielectric) can be easily deposited



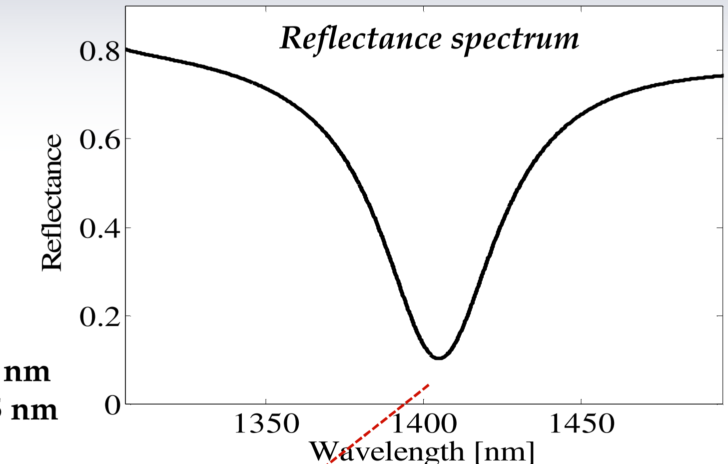
M. Consales, A. Ricciardi, A. Crescitelli, E. Esposito, A. Cutolo, A. Cusano, ACS Nano, 6 (4), pp 3163–3170 (2012).

NANOPLASMONICS WITHIN OPTICAL FIBERS

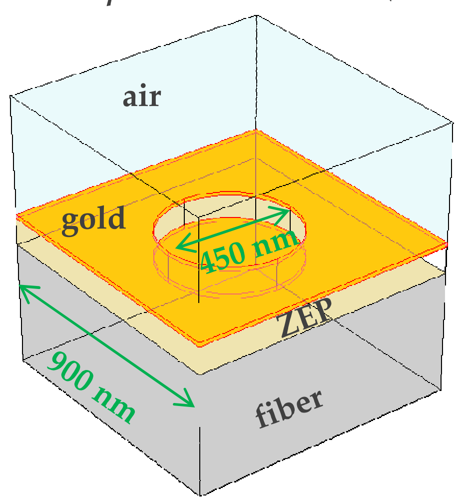
Cross section view



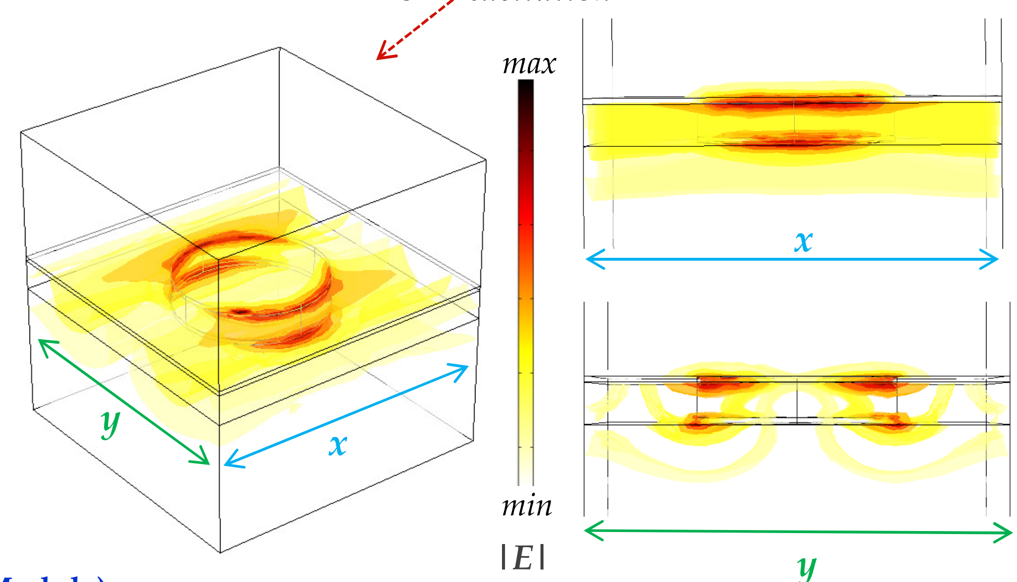
Period = 900 nm
Radius = 225 nm



3D computational domain (unit cell)

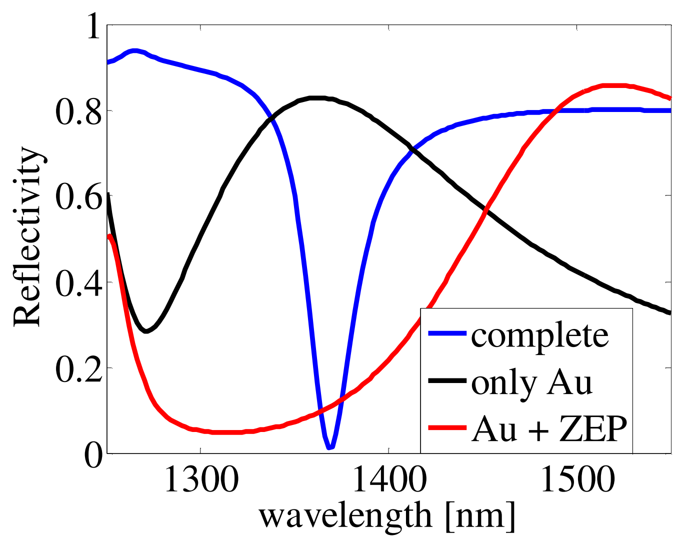


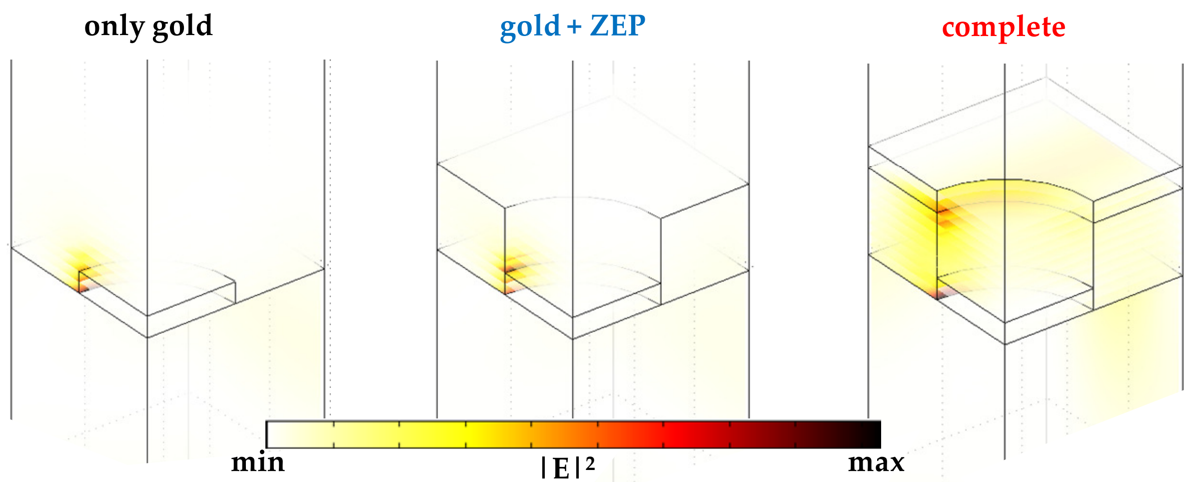
LSPR excitation

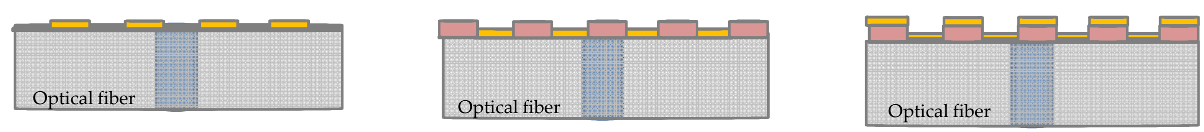


Full-wave simulations , COMSOL Multiphysics (RF Module)

THE WHOLE IS BETTER THAN THE SINGLE PARTS

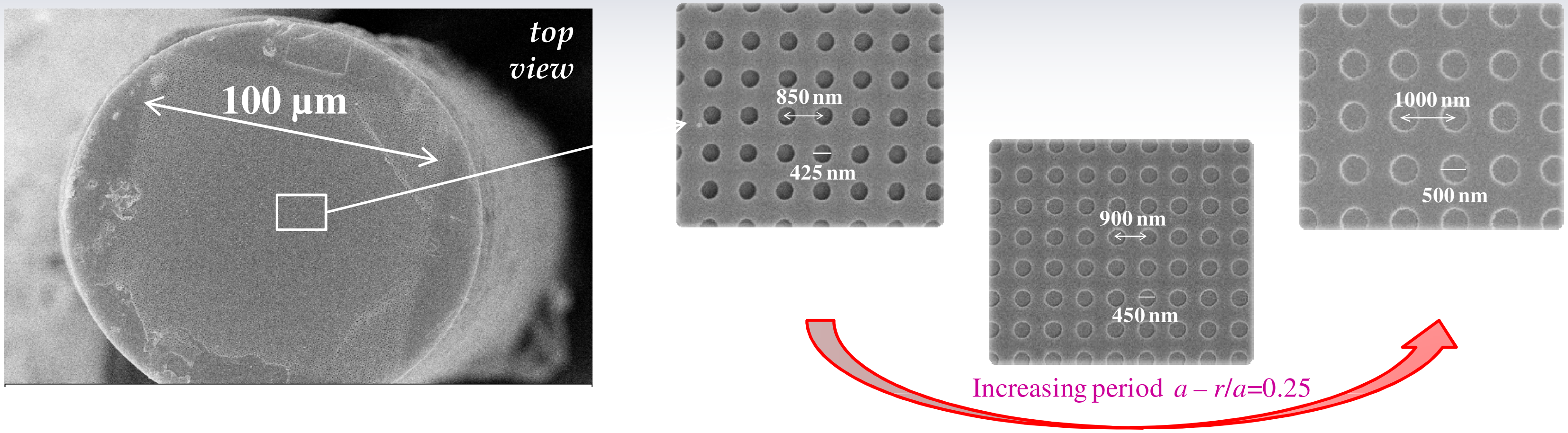


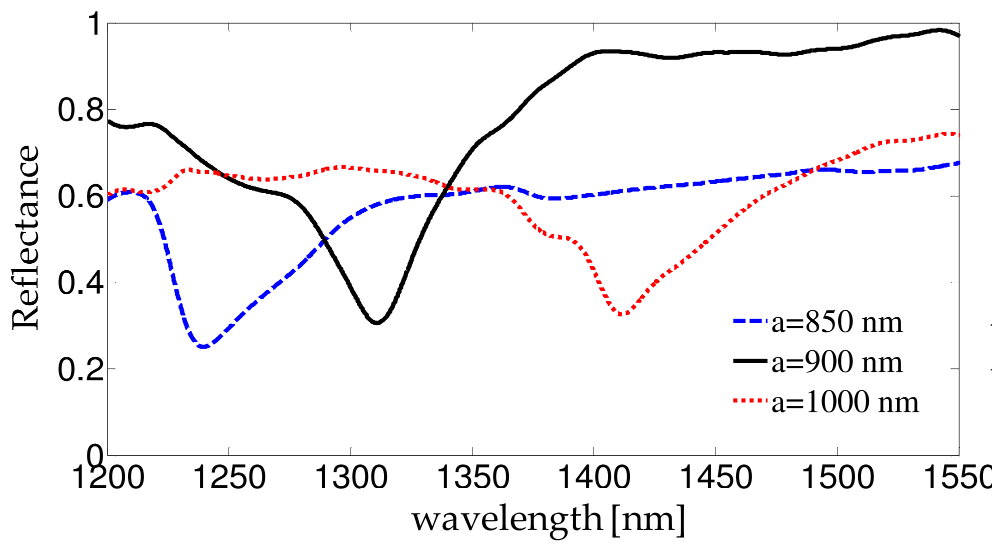




Enhancement of Field Intensity up to 7 times

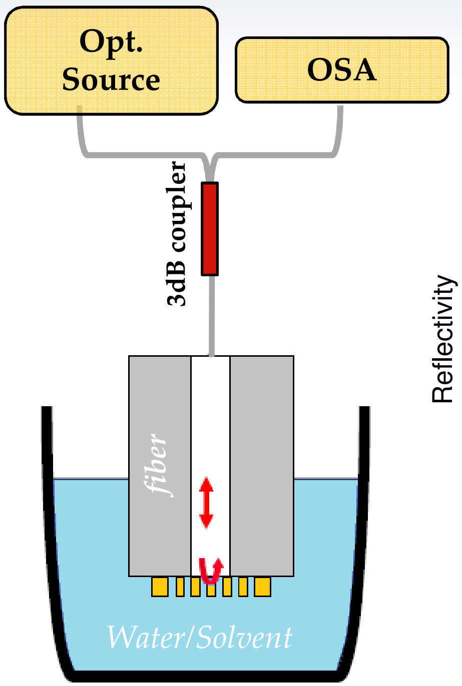
EXPERIMENTAL REALIZATION

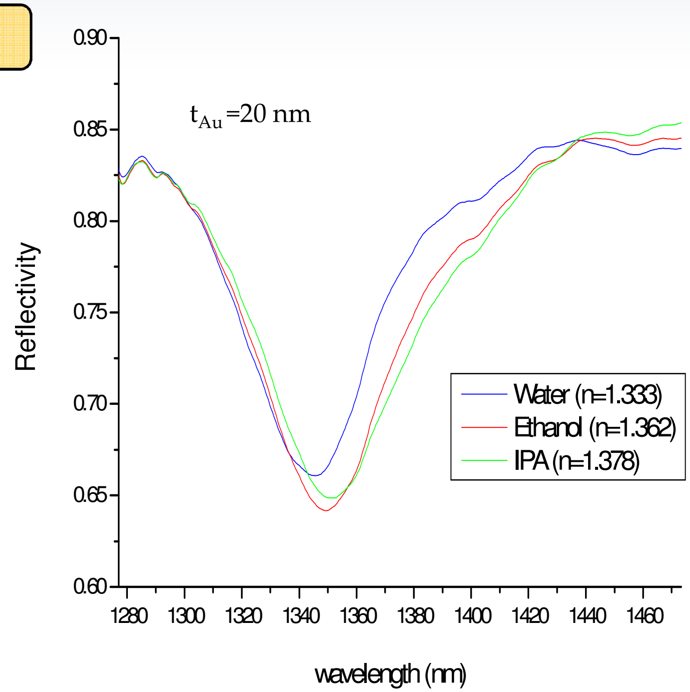


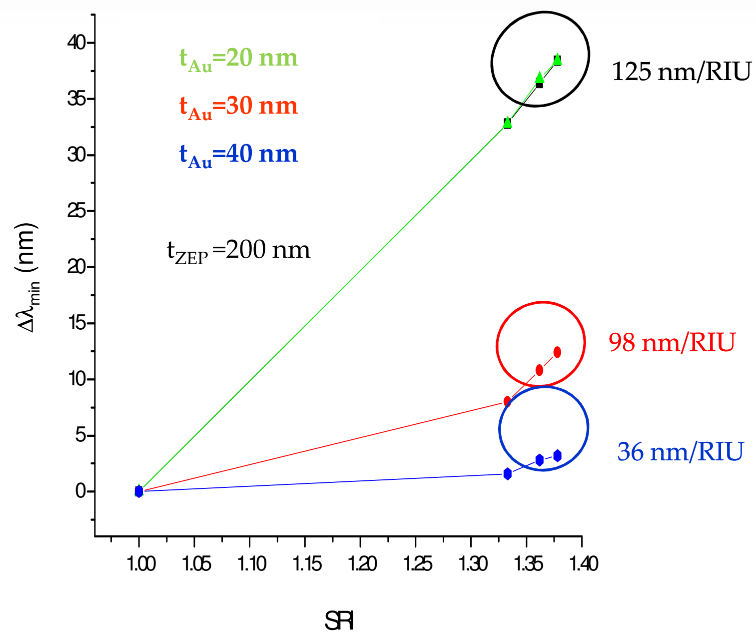


t_{ZEP}=200 nm
t_{Au}=40 nm

REFRACTIVE INDEX (BULK) SENSITIVITY





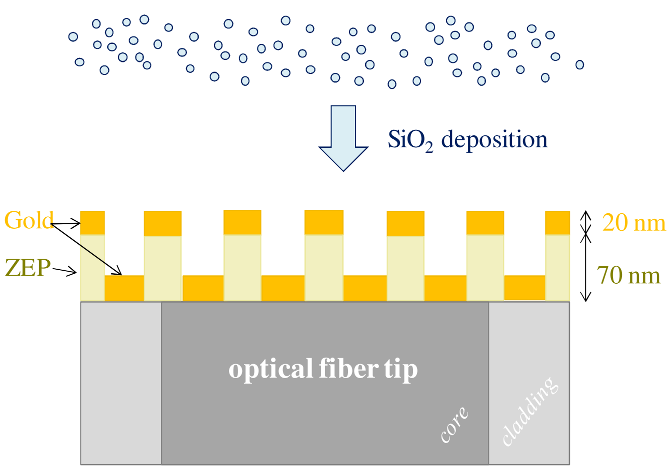


Further optimization margins exist acting on the large degree of freedom exhibited by the platform

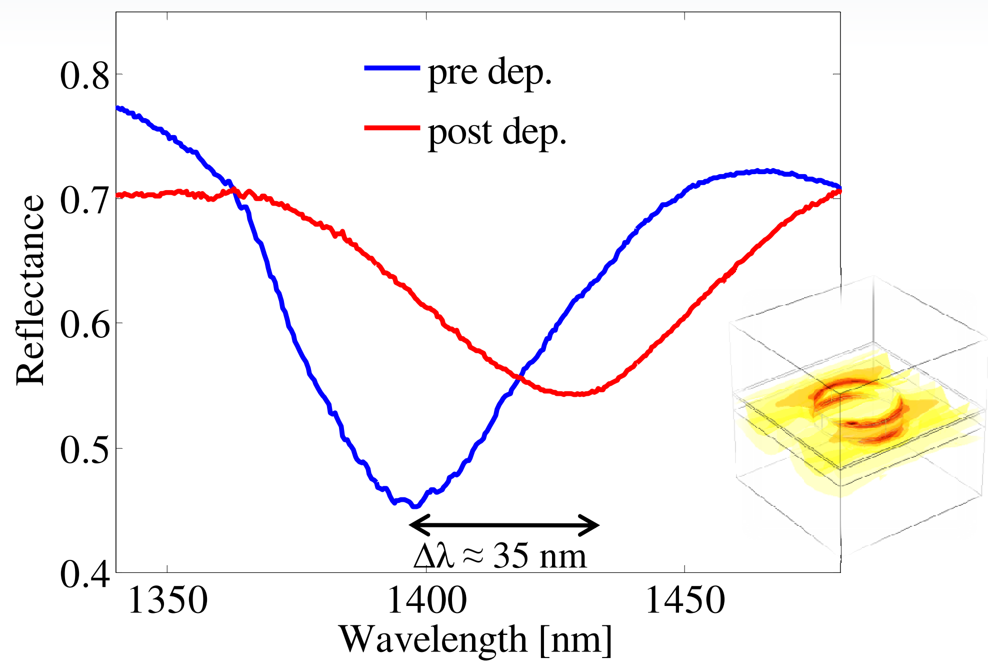
By adjusting the gold and resist thickness, the lattice tiling, SRI sensitivities of the order of ~ 500nm/RIU are expected

SURFACE SENSITIVITY

Deposited silica layer thickness
$d_{SiO2} = 100nm$



experimental

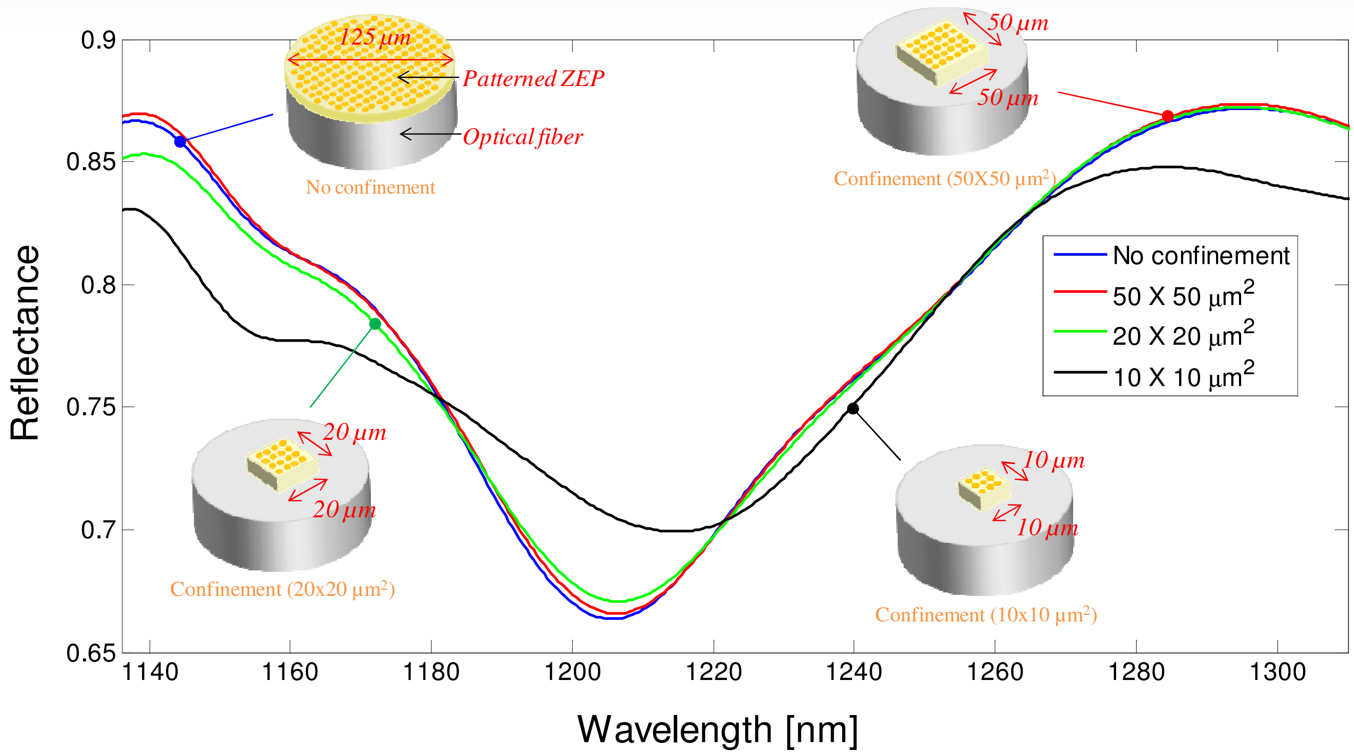


The surface sensitivities (in terms of resonance shift per nanometer of SiO_2 overlay) is 0.35

Considering the typical sizes of biological molecules (3.8-5.2 nm), the binding of a single biological monolayer generates a resonance shift of ~ 1.3-1.8 nm, which may be easily detected.

THE SENSING AREA

Structural confinement has been done on the same sample by using a laser micromachining ablation process



The sensing area can be reduced down to 20 × 20 µm² without affecting the spectral features (and thus the sensitivity)

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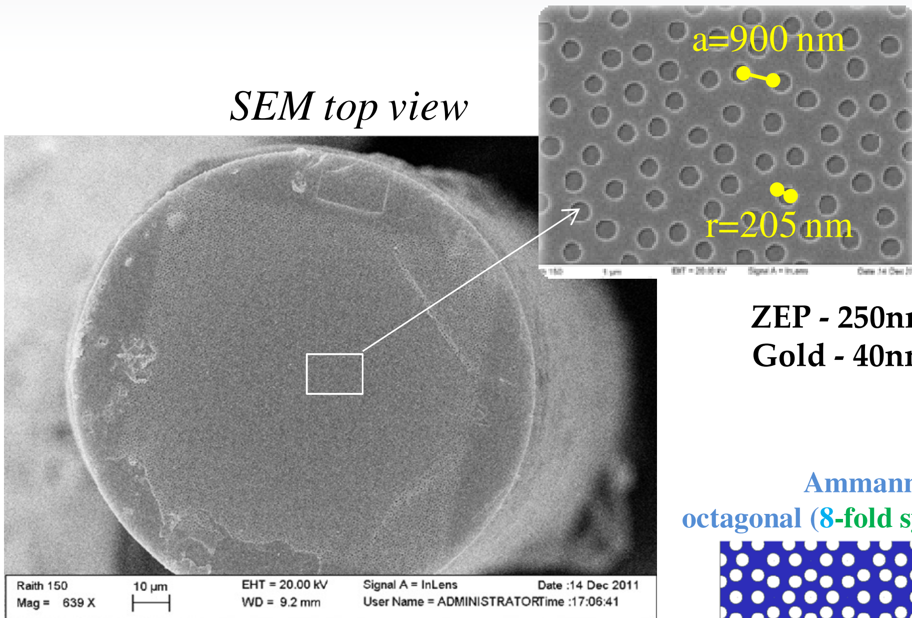
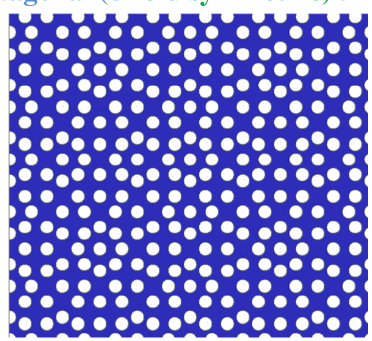
RI SENSITIVITY ENHANCEMENTS WITH QUASICRYSTALS

SEM top view

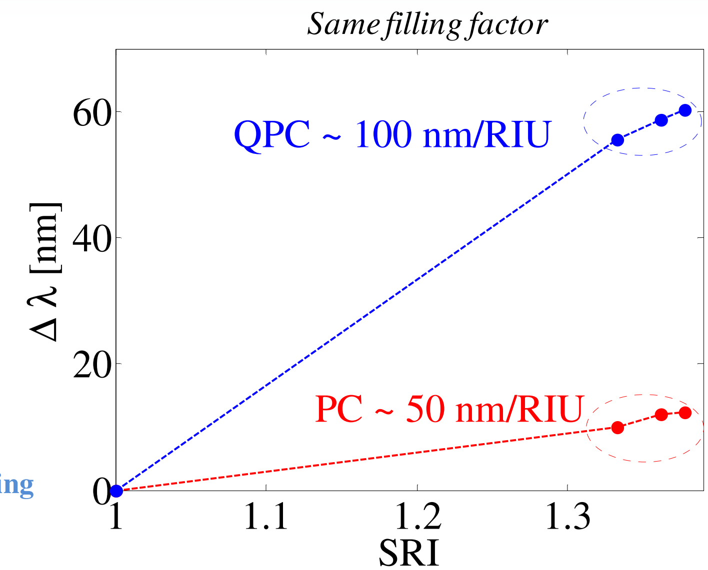


ZEP - 250nm
Gold - 40nm

Ammann-Beenker octagonal (8-fold symmetric) tiling



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



For a given filing factor and equivalent period, QC can outperform the periodic counterpart

A. Crescitelli, A. Ricciardi, M. Consales, E. Esposito, C. Granata, V. Galdi, A. Cutolo, and A. Cusano, Adv. Funct. Mater. 22, 4389-4398 (2012).

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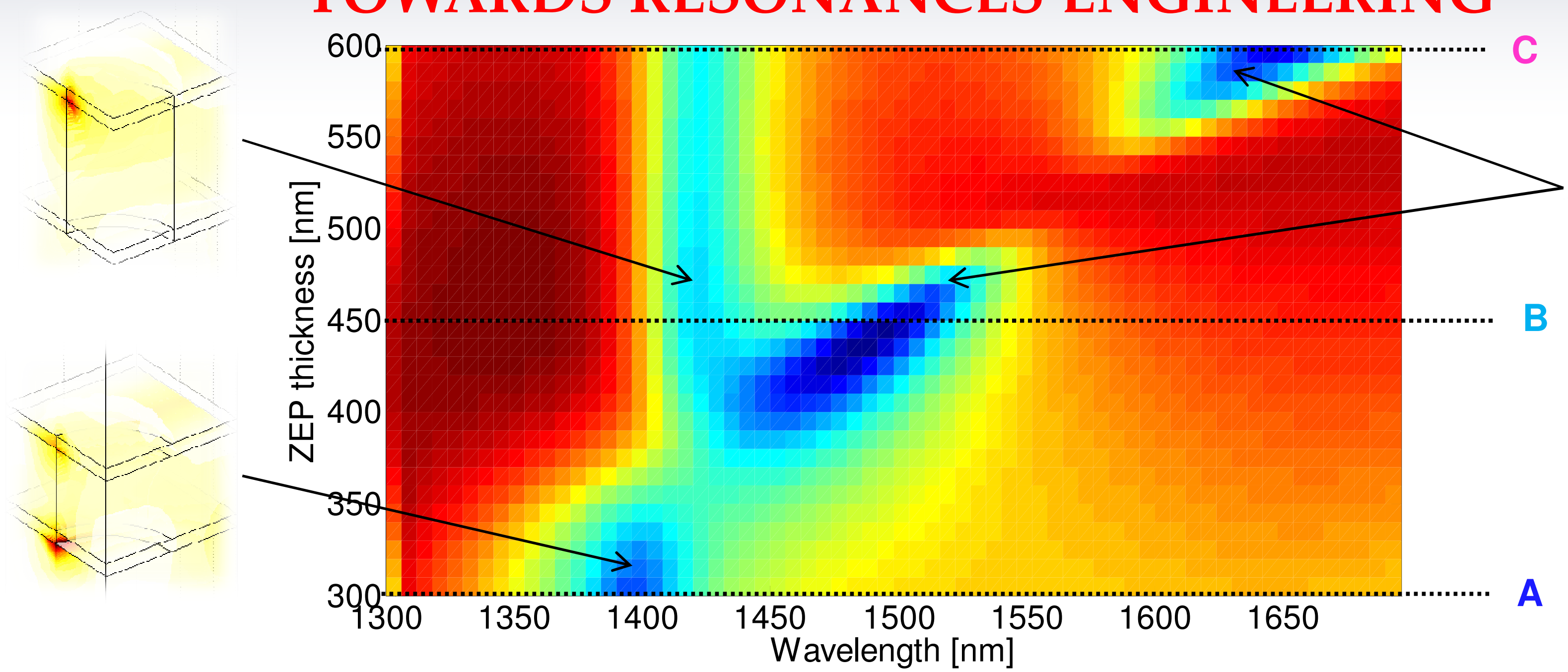
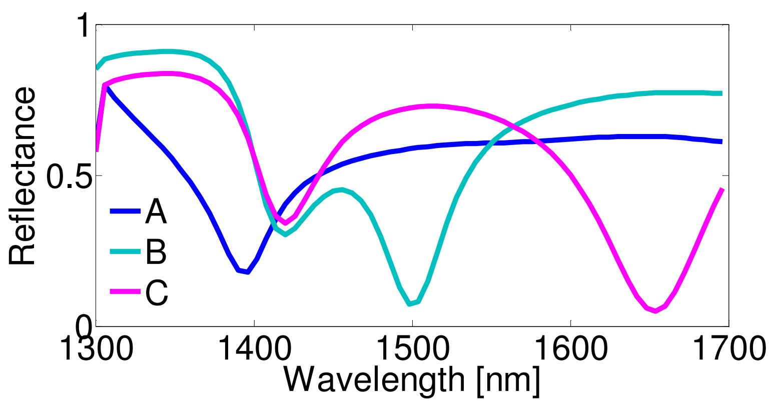
University of Sannio, Benevento (Italy)

DIELECTRIC THICKNESS TUNING : TOWARDS RESONANCES ENGINEERING

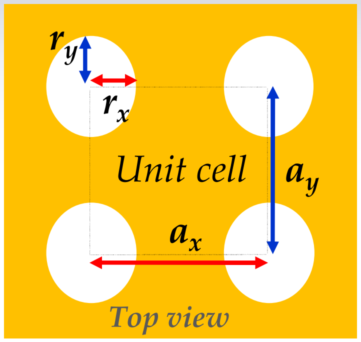




A. Cusano et al. Optical Fiber Technology 2013; 19 (6), Part B, pp. 772-784 (Invited Paper)

Optoelectronic Division, Engineering Department
University of Sannio, Benevento (Italy)

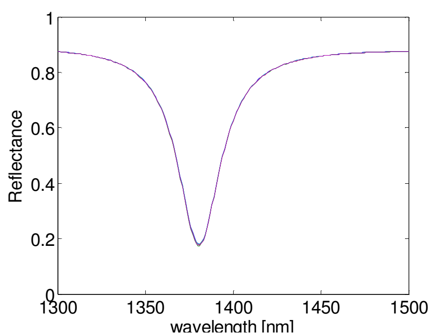
TOWARDS POLARIZATION SENSITIVE DEVICES



Symmetric

$r_y = \eta\, r_x$, $\eta = 1$, $r_y = 225\ nm$

$a_x = a_y = 900\ nm$

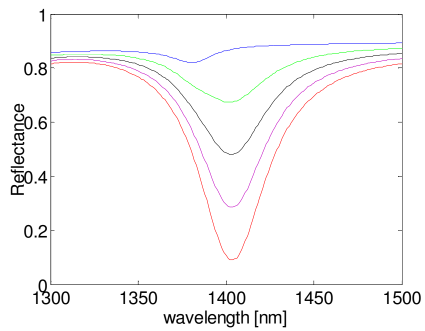


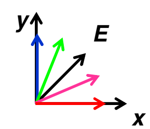
$t_{ZEP} = 100\ nm$ $t_{Au} = 17\ nm$

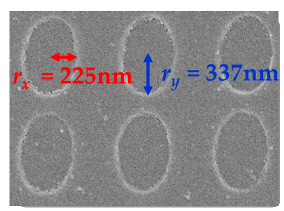
Hole ellipticity

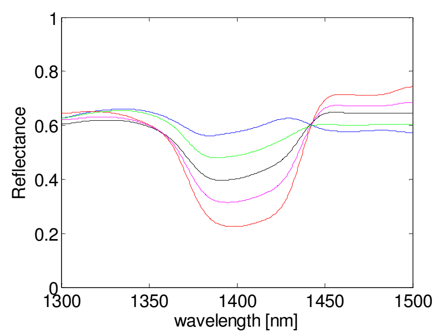
$r_y = \eta r_x$, $\eta = 1.5$

$a_x = a_y = 900\ nm$





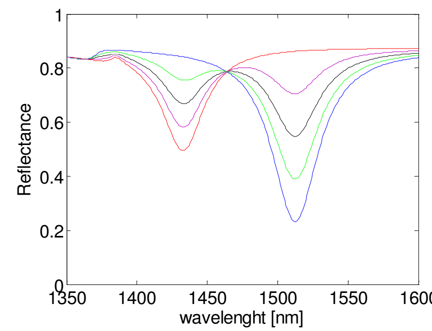


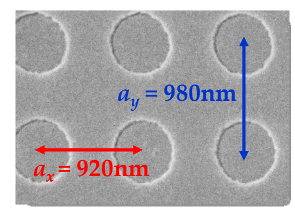


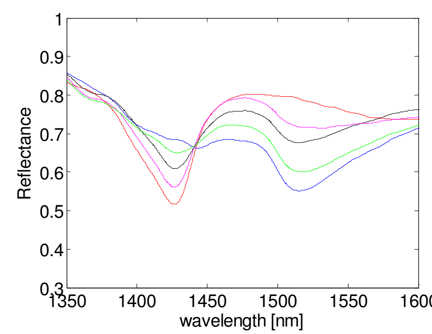
Period Asymmetry

$r_y = \eta r_x$, $\eta = 1$, $r_y = 250\ nm$

$a_x = 920\ nm$, $a_y = 980\ nm$



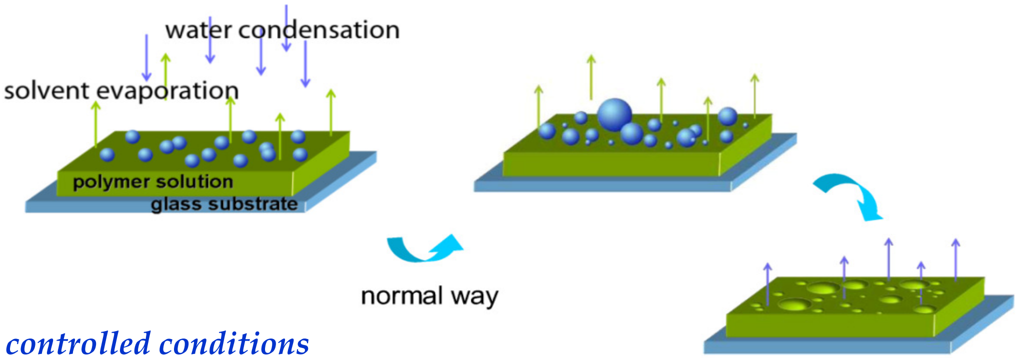




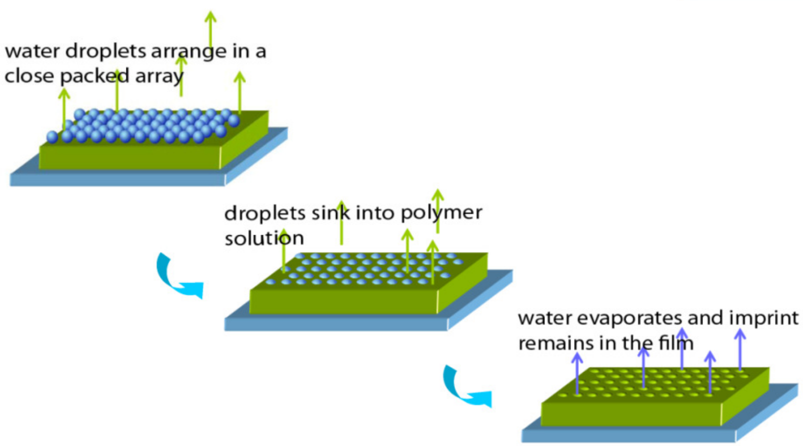
A. Cusano et al. , ACS Photonics 2014 1 (1), 69-78

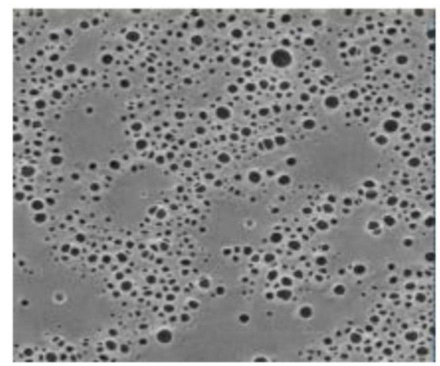
BREATH FIGURE TECHNIQUE FOR RAPID AND COST EFFECTIVE PROTOTYPING

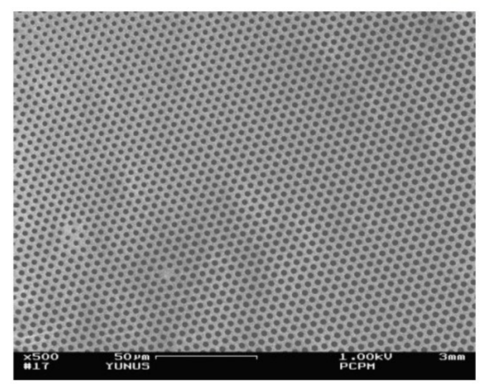
The Breath Figure Technique (Francois, Nature 1994, 369-387-9) relies on the precipitation of a polymer around condensed water droplets triggered by the fast evaporation of polymer solvent in a humid environment



…in controlled conditions



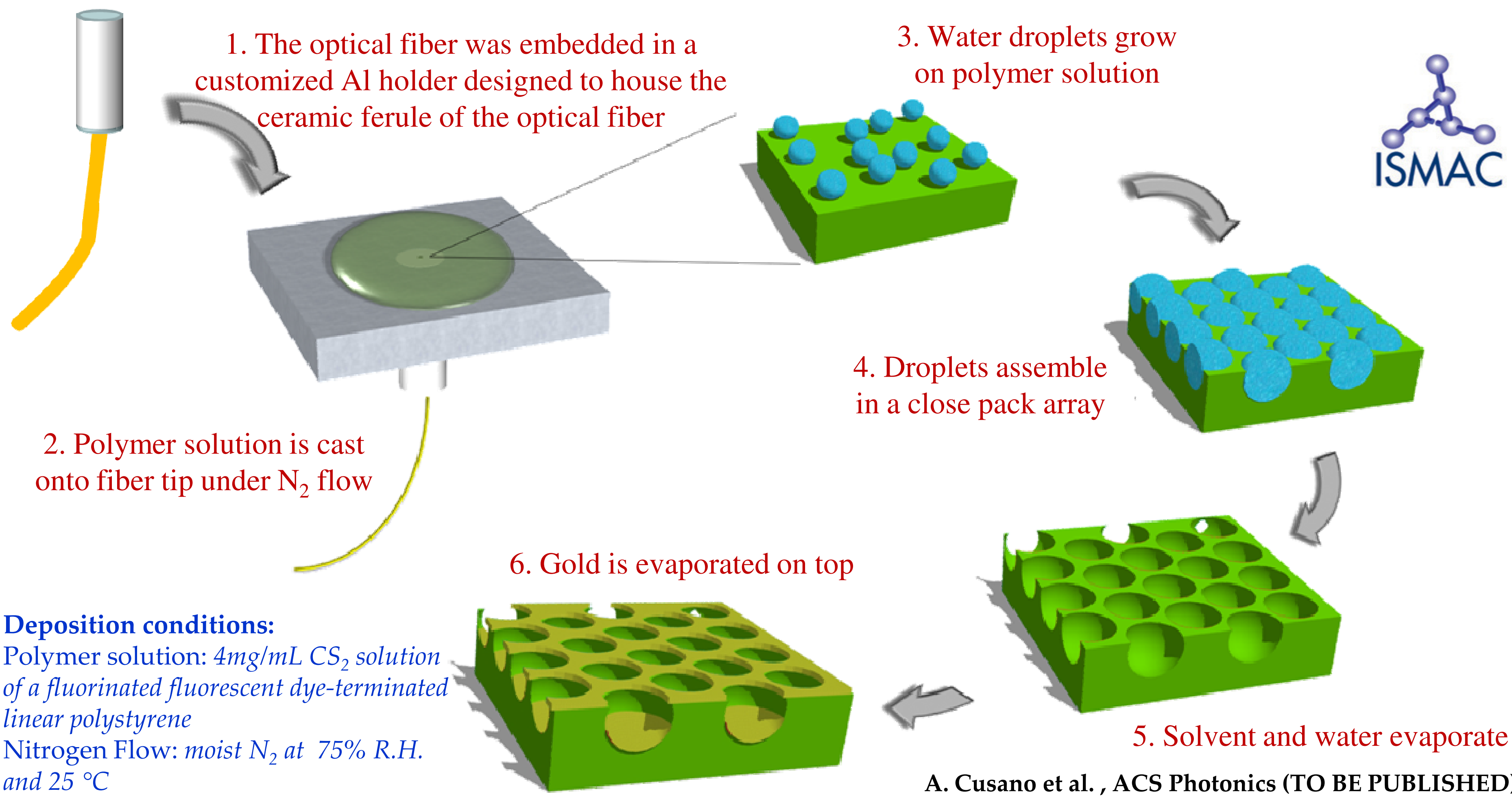




Process control (i.e. by adjusting polymer concentration, kind of solvent, evaporation rate, relative humidity) enables the manipulation of some morphology features in the final film (i.e. degree of order, distribution and size of the cavities)

LAB ON FIBER BY THE BREATH FIGURES TECHNIQUE

We adapted the Breath Figures technique to operate on optical fiber substrates so as to realize self assembled metallo-dielectric photonic crystals onto the optical fiber end facet

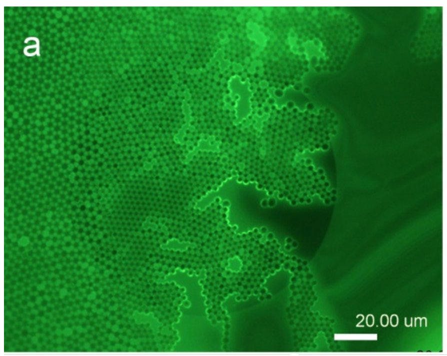


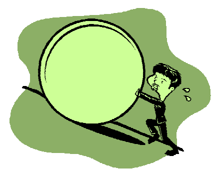
Deposition conditions:
Polymer solution: *4mg/mL CS_2 solution of a fluorinated fluorescent dye-terminated linear polystyrene*
Nitrogen Flow: *moist N_2 at 75% R.H. and 25 °C*

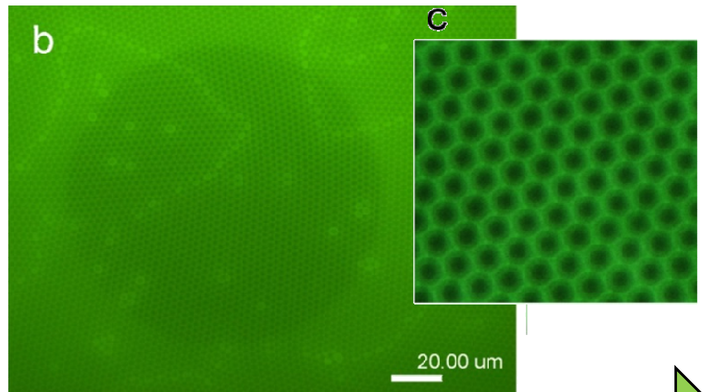
A. Cusano et al. , ACS Photonics (TO BE PUBLISHED)

EXPERIMENTAL RESULTS: PROCESS ASSESSMENT

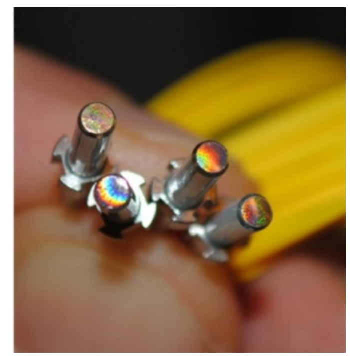
By the assessment of the fabrication process, we are now able to easily obtain well ordered and defect free patterns on the optical fiber tip

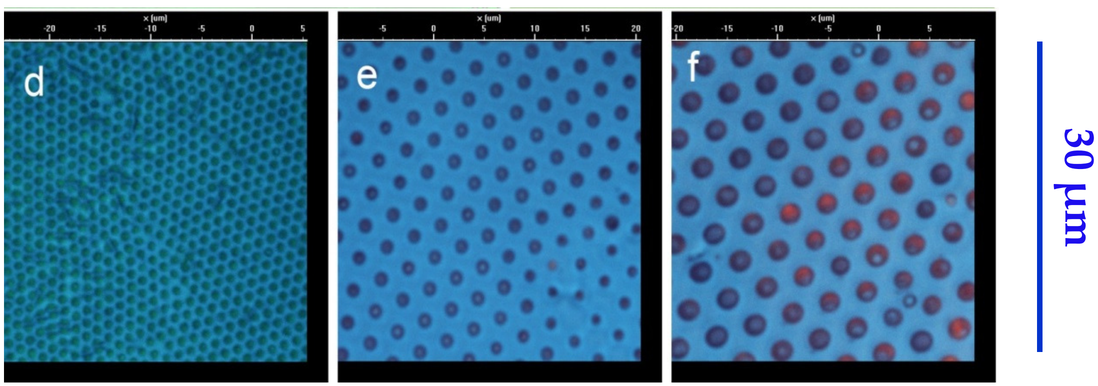






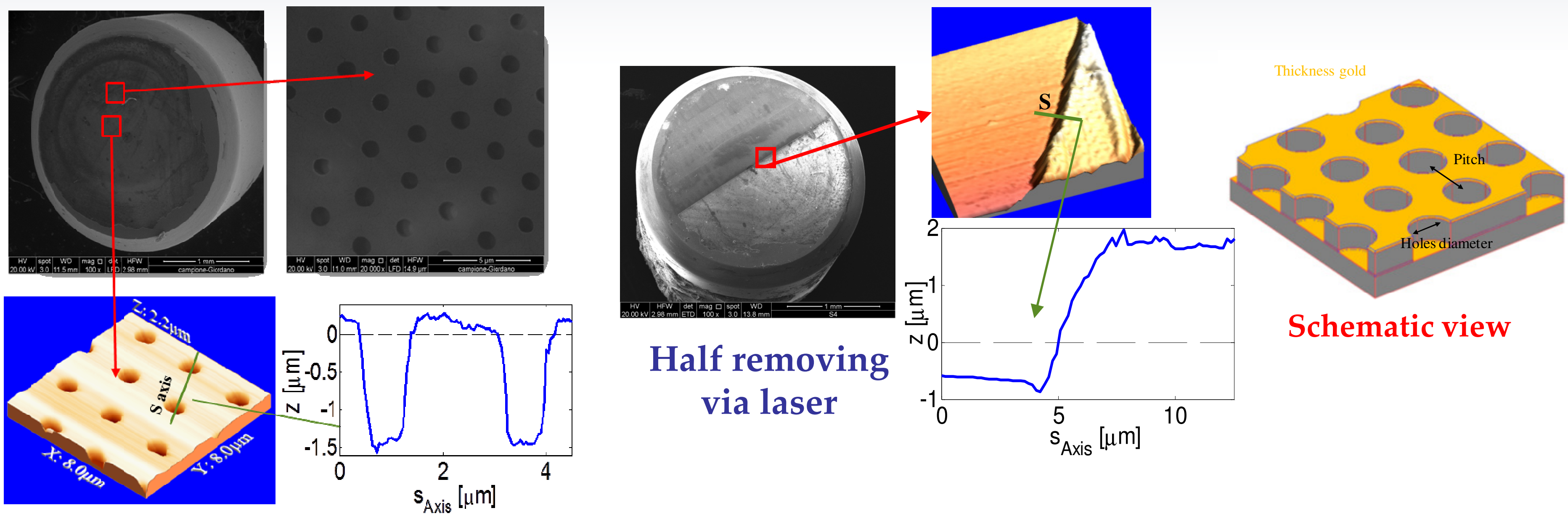
First repeatable and functional prototypes





By changing the flow of humid nitrogen between 100 and 300 L/h, we obtained honeycomb arrays with cavities ranging from 2.5 to 1.0 µm

MORPHOLOGICAL CHARACTERIZATION



Flow rate 300L/h – gold thickness 33nm)

Average values (Relative standard deviation)

Holes Diameter = 0.95 μm (3.2%)

Pitch = 2.67 μm (1.3%)

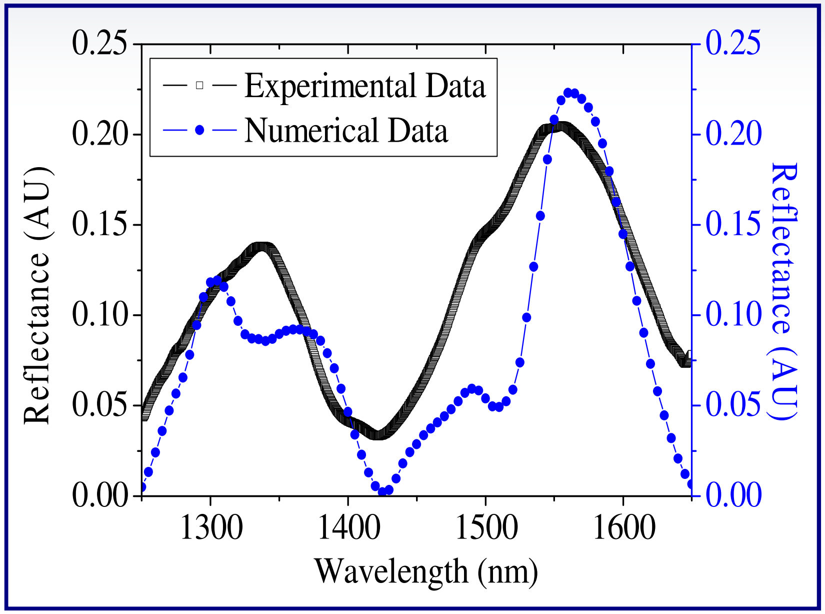
Hole depth = 1.78 μm (3.5%)

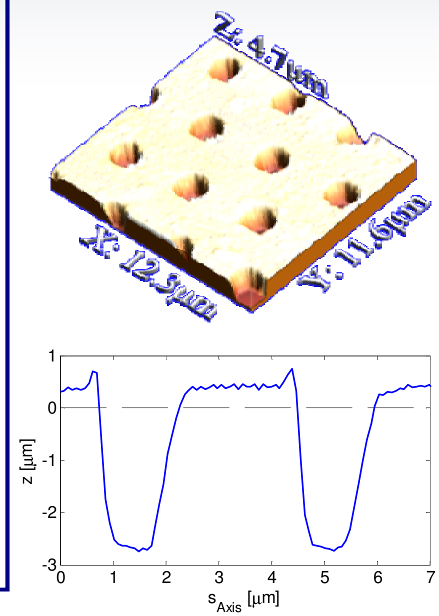
Structure height = 2.5 μm (2.3%)

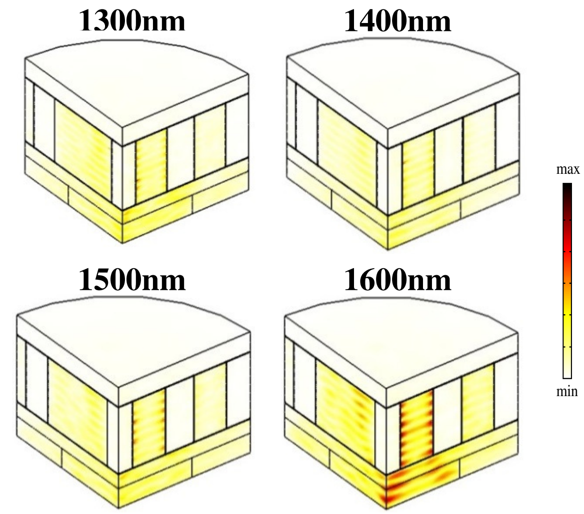
Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) analysis have been carried out to accurately study the morphology of the created patterns

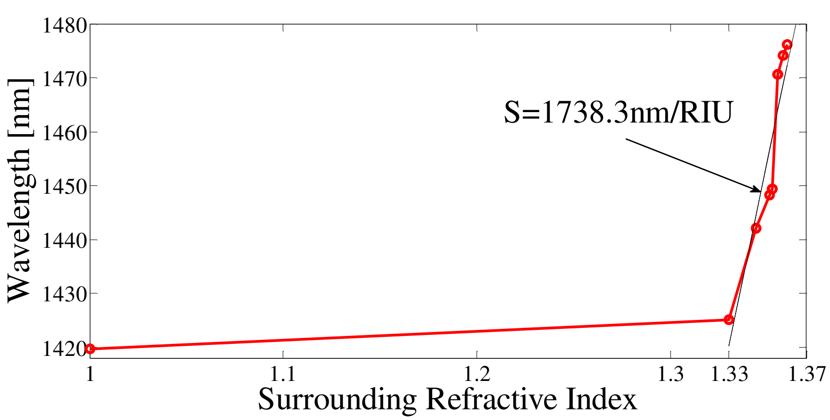
The optimized process ensures Order and Regularity of the polymeric template

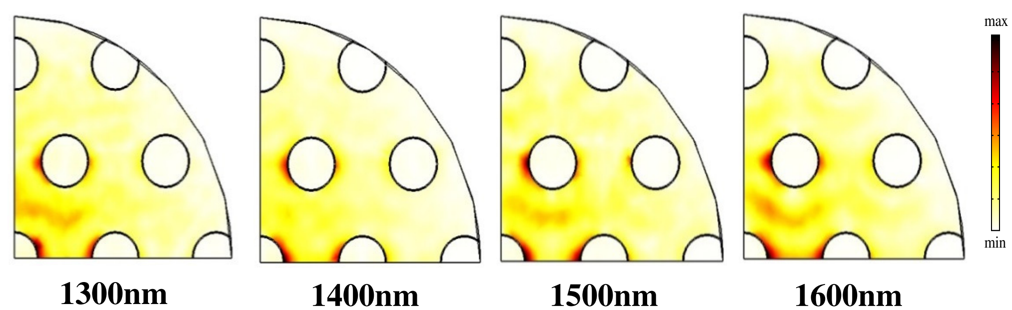
SENSING PERFORMANCES



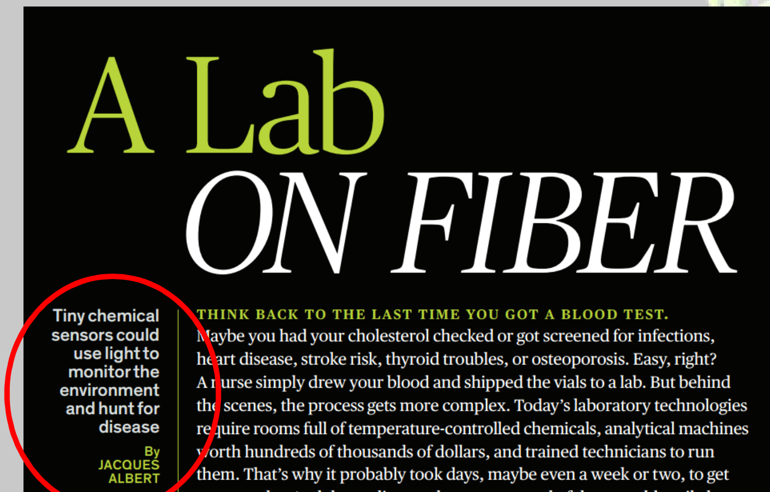








LAB ON FIBER TECHNOLOGY: MORE THAN A VISION



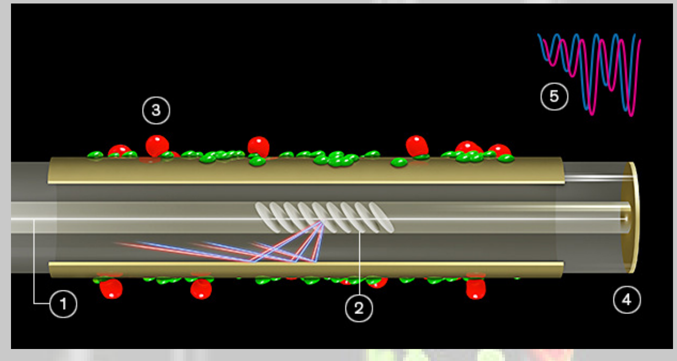
A Lab ON FIBER

Tiny chemical sensors could use light to monitor the environment and hunt for disease

By JACQUES ALBERT

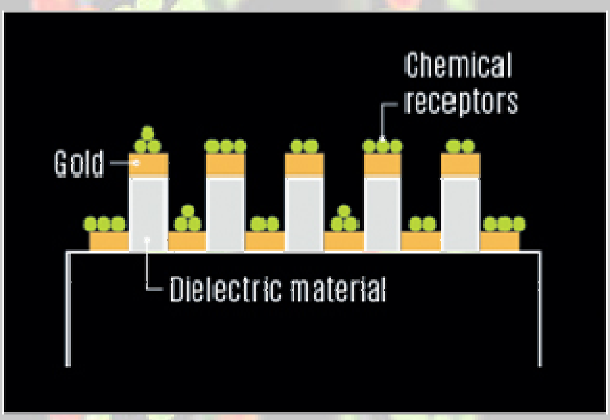
THINK BACK TO THE LAST TIME YOU GOT A BLOOD TEST. Maybe you had your cholesterol checked or got screened for infections, heart disease, stroke risk, thyroid troubles, or osteoporosis. Easy, right? A nurse simply drew your blood and shipped the vials to a lab. But behind the scenes, the process gets more complex. Today's laboratory technologies require rooms full of temperature-controlled chemicals, analytical machines worth hundreds of thousands of dollars, and trained technicians to run them. That's why it probably took days, maybe even a week or two, to get

Tilted Fiber Bragg gratings



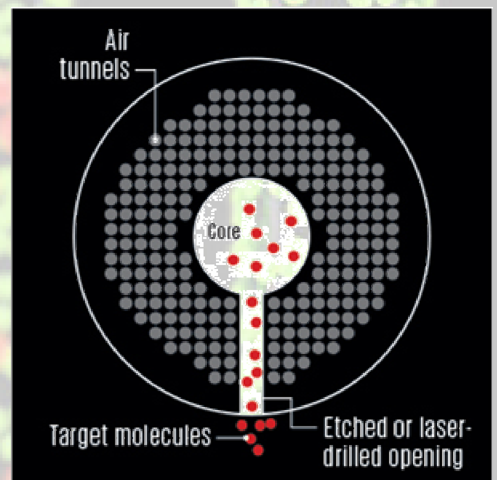
Jacques ALBERT et al., Carleton University, Canada

On the Tip



Andrea CUSANO et al., University of Sannio, Italy

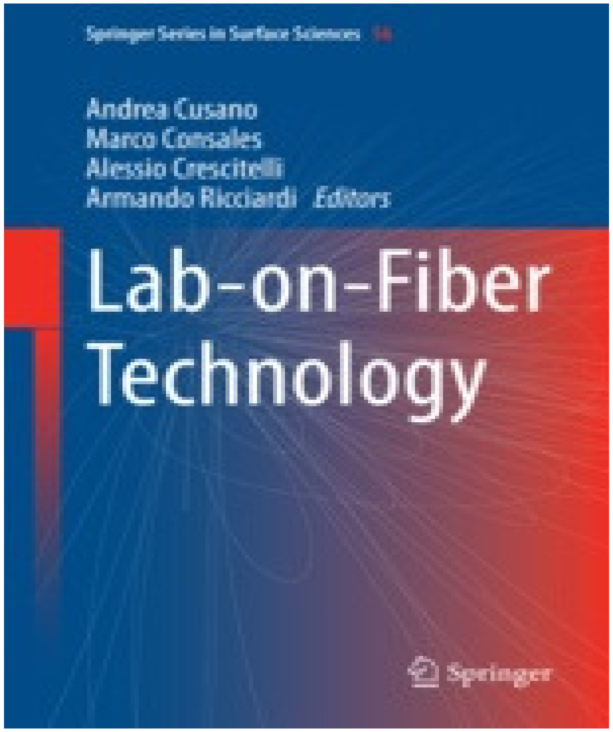
Microstructured optical fiber



Philip St. J. RUSSELL, Max Planck Institute for the Science of Light, Germany, Ole BANG, Technical University of Denmark et al.

Jacques Albert, IEEE Spectrum, April 2014

THE FIRST BOOK



- **Written by the world's leading experts in this field**
- **First book on the lab-on-fiber technology**
- **Explains concepts, methods and applications of the lab-on-fiber technology**

This book focuses on a research field that is rapidly emerging as one of the most promising ones for the global optics and photonics community: the "lab-on-fiber" technology.

Inspired by the well-established "lab on-a-chip" concept, this new technology essentially envisages novel and highly functionalized devices completely integrated into a single optical fiber for both communication and sensing applications.

Based on the R&D experience of some of the world's leading authorities in the fields of optics, photonics, nanotechnology, and material science, this book provides a broad and accurate description of the main developments and achievements in the lab-on-fiber technology roadmap, also highlighting the new perspectives and challenges to be faced.

This book is essential for scientists interested in the cutting-edge fiber optic technology, but also for graduate students.

Optoelectronic Division, Engineering Department
University of Sannio, Benevento (Italy)

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