Bringing Nanotechnology into Fiber Optics

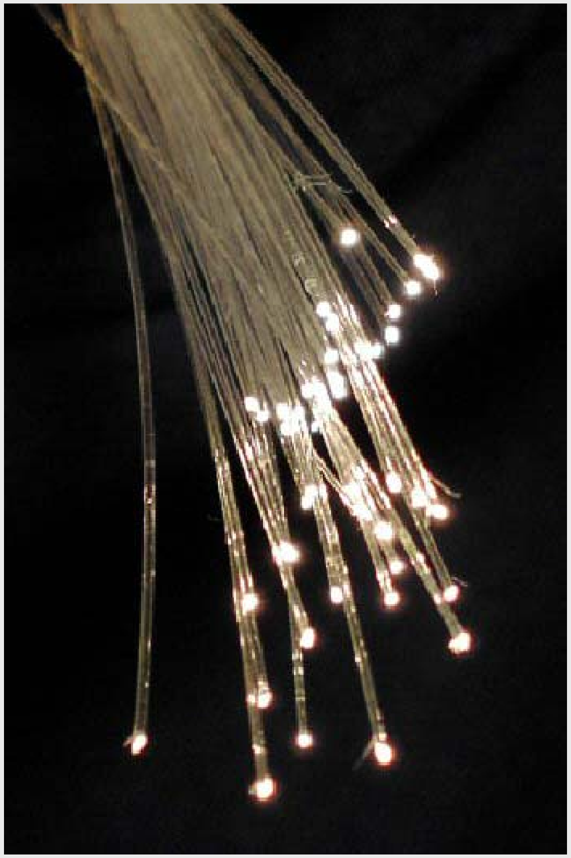
Prof. Maksim Skorobogatiy

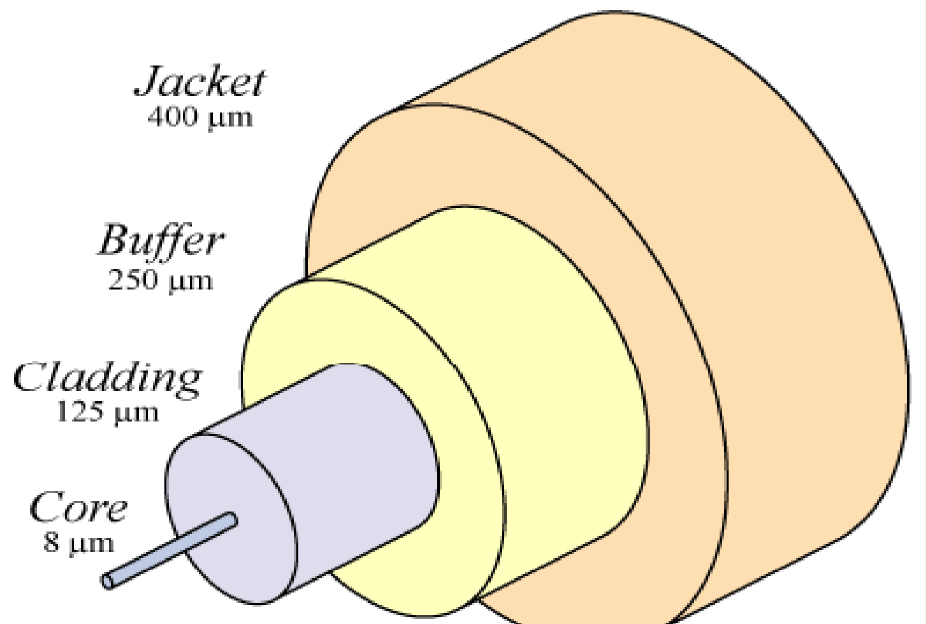
www.photonics.phys.polymtl.ca

Canada Research Chair in Micro and Nano Photonics
École Polytechnique de Montréal
www.photonics.phys.polymtl.ca

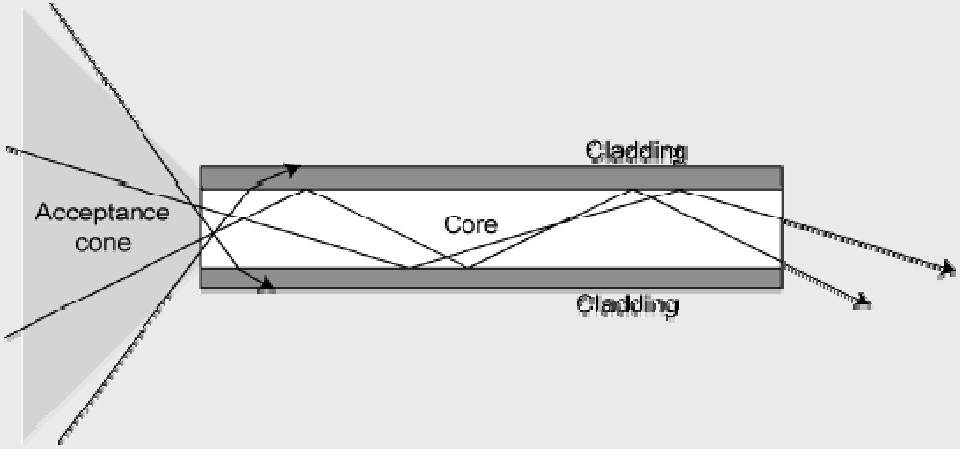
Total Internal Reflection (conventional) optical fibers

Very efficient guiding in the fiber core, almost no light escapes sideways



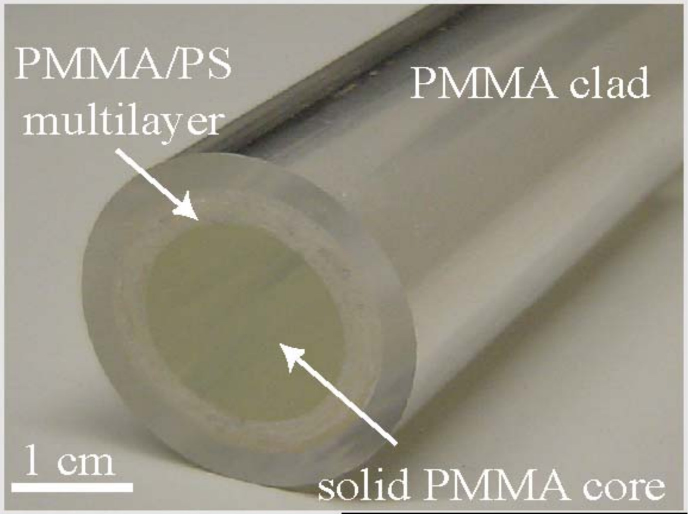


http://en.wikipedia.org/wiki/Optical_Fiber

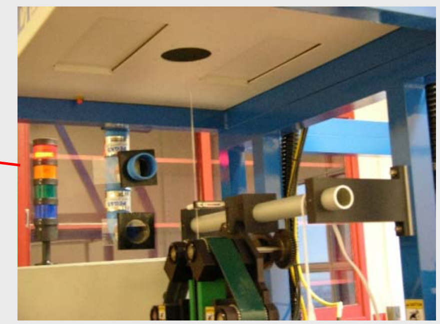


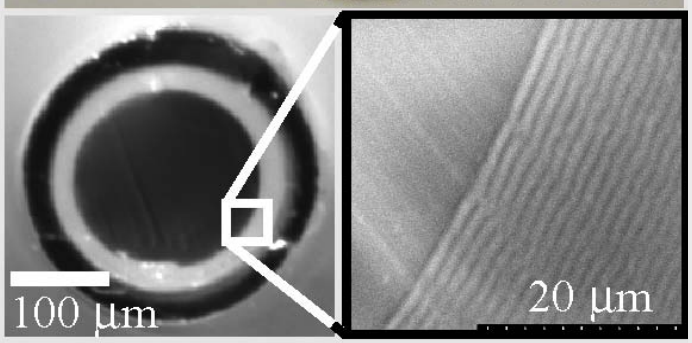
Fiber drawing

Fiber preform fabrication

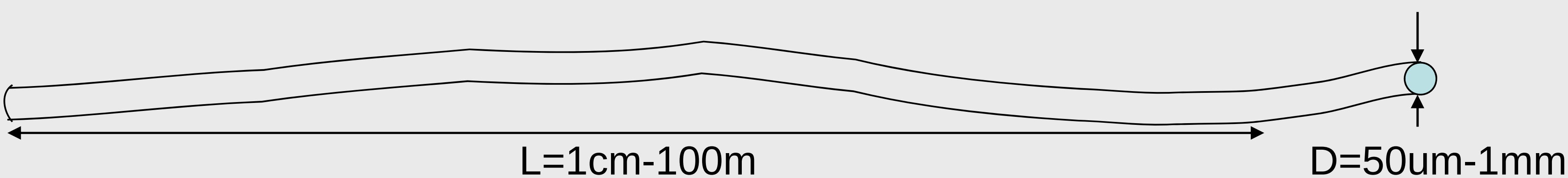


Fiber drawing





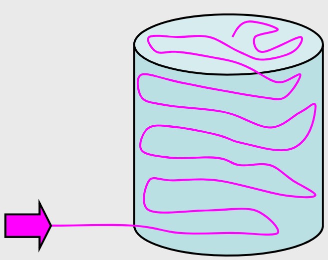
Micro/nanostructured fibers



Applications of fiber optics beyond telecommunications

Mechanically flexible technology for large area illumination, distributed sensing, information transmission, and fashion

Photonic textiles enable

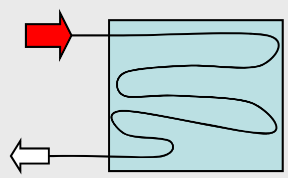


Illumination

1. Practically unlimited coverage area and complex shapes
2. Apparel with unusual or/and dynamically addressable appearance
3. Fiber-based illuminators can be used not only in the visible (~500nm) but also in the IR (invisible) ranges (1-10μm) for security and military applications

Sensing (optical fiber-based)

1. Distributed sensing (T, P, …) over 1m-1km X 1m-1km areas without any point sensors
2. Electrically passive technology, ability to operate in flammable environment
3. Textiles can be easily integrated into large scale structures such as bridges, houses, etc. for long term structural integrity monitoring with minimal servicing requirements.

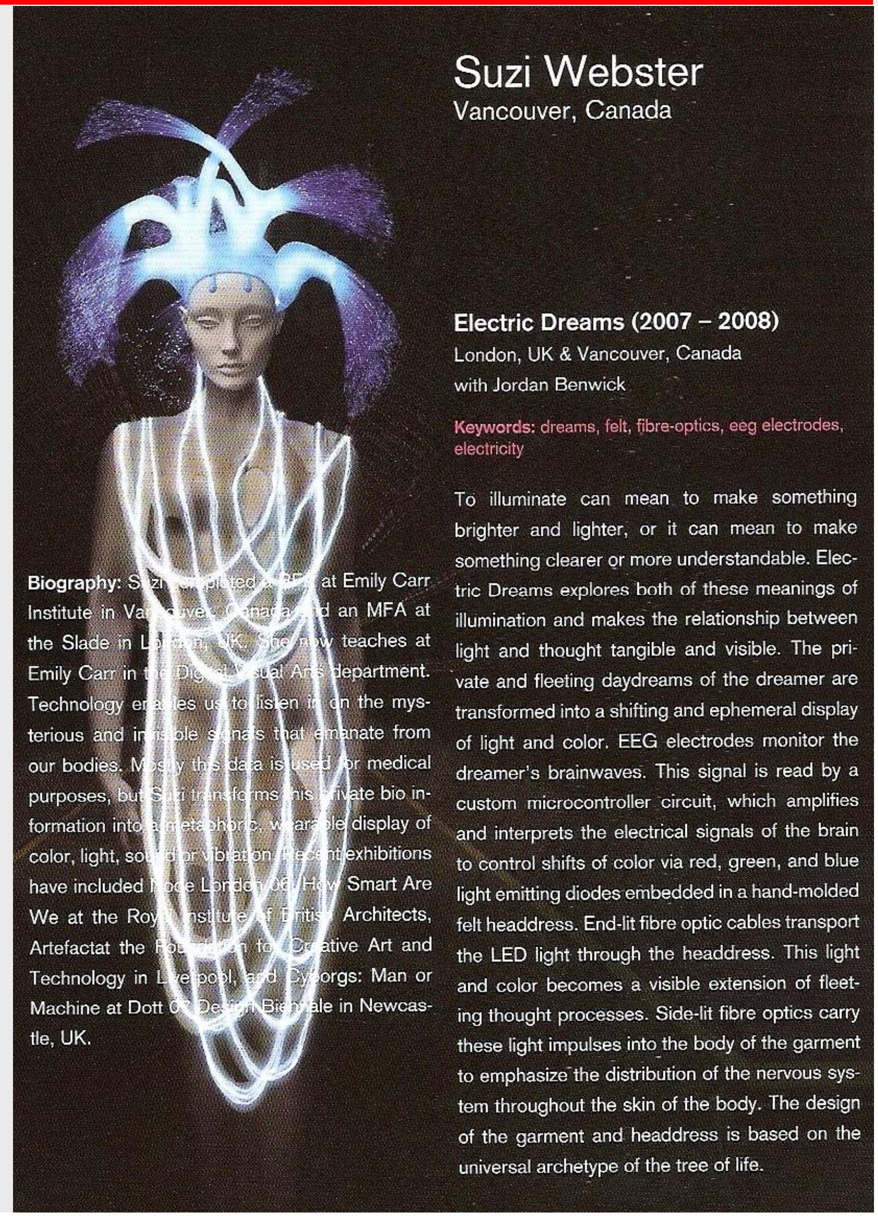


Communication

1. Integration of the fiber optic communication links into uniforms

Simplest application: fiber optic illuminators

Fashionable technology, S. Seymore, Springer



Suzi Webster
Vancouver, Canada

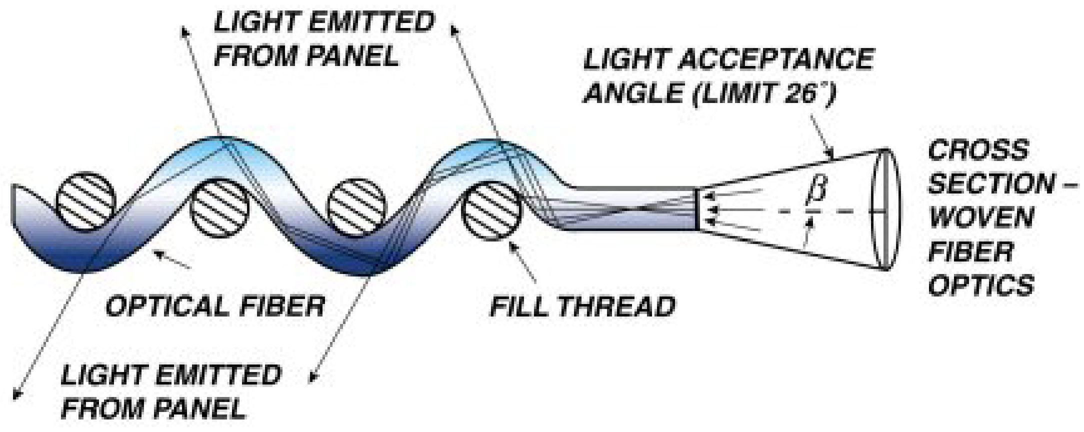
Electric Dreams (2007 – 2008)
London, UK & Vancouver, Canada
with Jordan Benwick

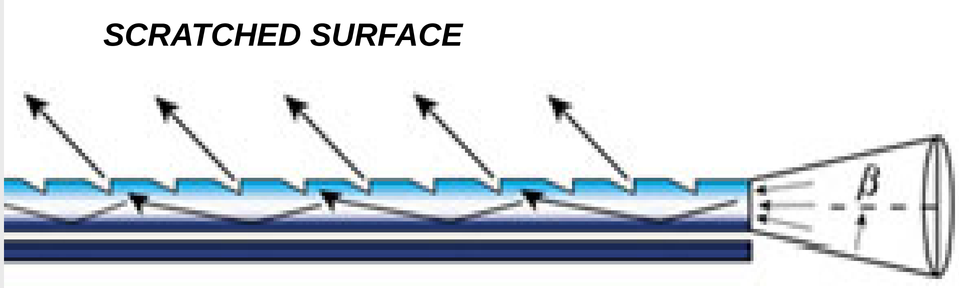
Keywords: dreams, felt, fibre-optics, eeg electrodes, electricity

Biography: Suzi completed a BFA at Emily Carr Institute in Vancouver, Canada and an MFA at the Slade in London, UK. She now teaches at Emily Carr in the Digital Visual Arts department. Technology enables us to listen in on the mysterious and invisible signals that emanate from our bodies. Mostly this data is used for medical purposes, but Suzi transforms this private bio information into a metaphoric, wearable display of color, light, sound or vibration. Recent exhibitions have included Mode London 08, How Smart Are We at the Royal Institute of British Architects, Artefactat the Foundation for Creative Art and Technology in Liverpool, and Cyborgs: Man or Machine at Dott 07 Design Biennale in Newcastle, UK.

To illuminate can mean to make something brighter and lighter, or it can mean to make something clearer or more understandable. Electric Dreams explores both of these meanings of illumination and makes the relationship between light and thought tangible and visible. The private and fleeting daydreams of the dreamer are transformed into a shifting and ephemeral display of light and color. EEG electrodes monitor the dreamer's brainwaves. This signal is read by a custom microcontroller circuit, which amplifies and interprets the electrical signals of the brain to control shifts of color via red, green, and blue light emitting diodes embedded in a hand-molded felt headdress. End-lit fibre optic cables transport the LED light through the headdress. This light and color becomes a visible extension of fleeting thought processes. Side-lit fibre optics carry these light impulses into the body of the garment to emphasize the distribution of the nervous system throughout the skin of the body. The design of the garment and headdress is based on the universal archetype of the tree of life.

Distributed illumination applications with TIR optical fibers





Lumitex Inc.

ÉCOLE POLYTECHNIQUE MONTRÉAL

PolyPhotonique

Applications: Woven fiber optic panels for backlighting by Lumitex Inc.

LCD Backlighting

Membrane switch backlighting

Surgical lighting (any shapes)

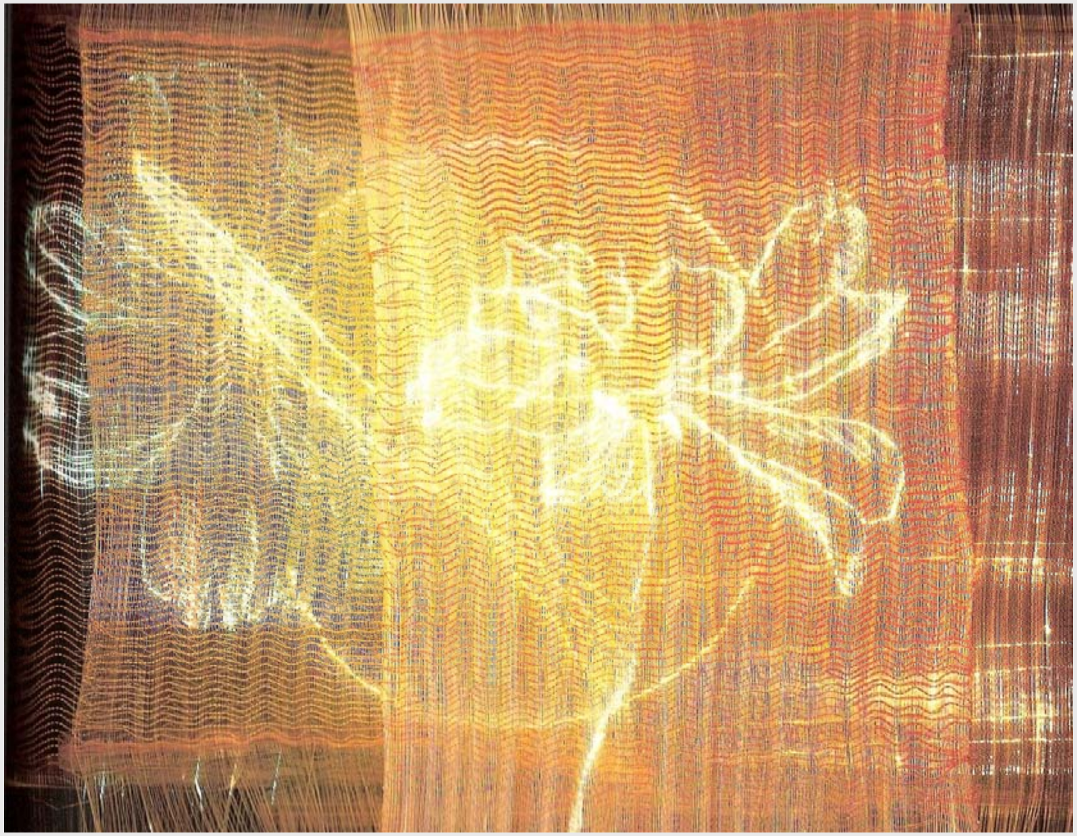
www.lumitex.com/technologies.html

Applications: Fiber optic textiles for décor

Kazu Toki

Wind, moon and flowers

This textile piece as been created by five layers of fabric woven on a handloom.
They used 5 different coloured threads traditionally used in Japan, alongside embedded fiber optics, to produce ambiguous, swimming shapes

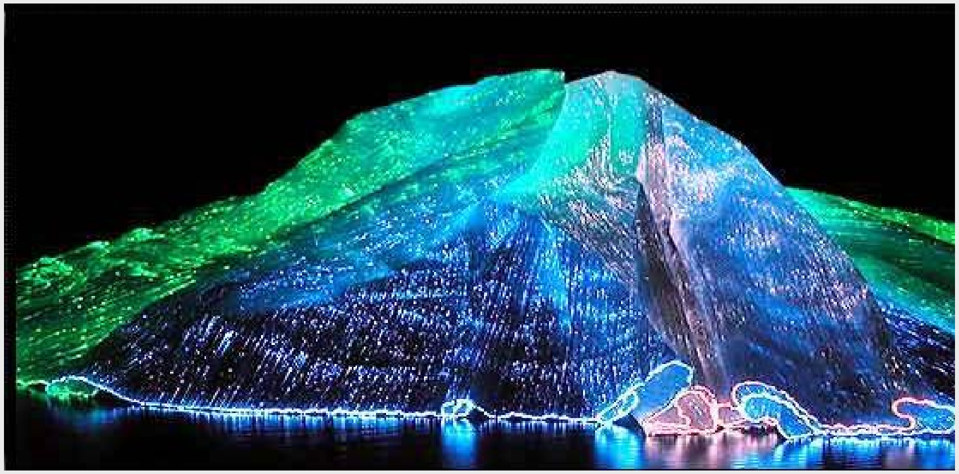


Techno Textiles, S.E. Braddock et al., Thames & Hudson

Applications: Fiber optic textiles for fashion

Luminex

Luminex has created fabrics that incorporate woven optical fibers for decorative effect.
The optic fibers are woven into a synthetic fiber, the ends of which are bundled together to a point from which LED light is transmitted through filaments.
These emit light along the length as well as the filaments ends.

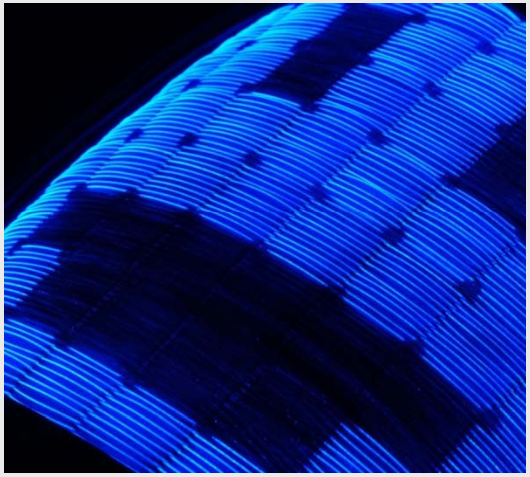


Applications: Flexible screens made of woven optical fibres by France Telecom

France Telecom

France Telecom R&D has designed a prototype for a flexible screen made of woven optical fibres capable of downloading and displaying static or animated graphics, such as logos, texts, patterns and scanned images, directly on clothes.

A special abrasion process for the fibers at the surface of the fabric associated to a specific fabric weave developed by the France Telecom laboratories made it possible to create the first bitmap screen matrix on a flexible textile base.



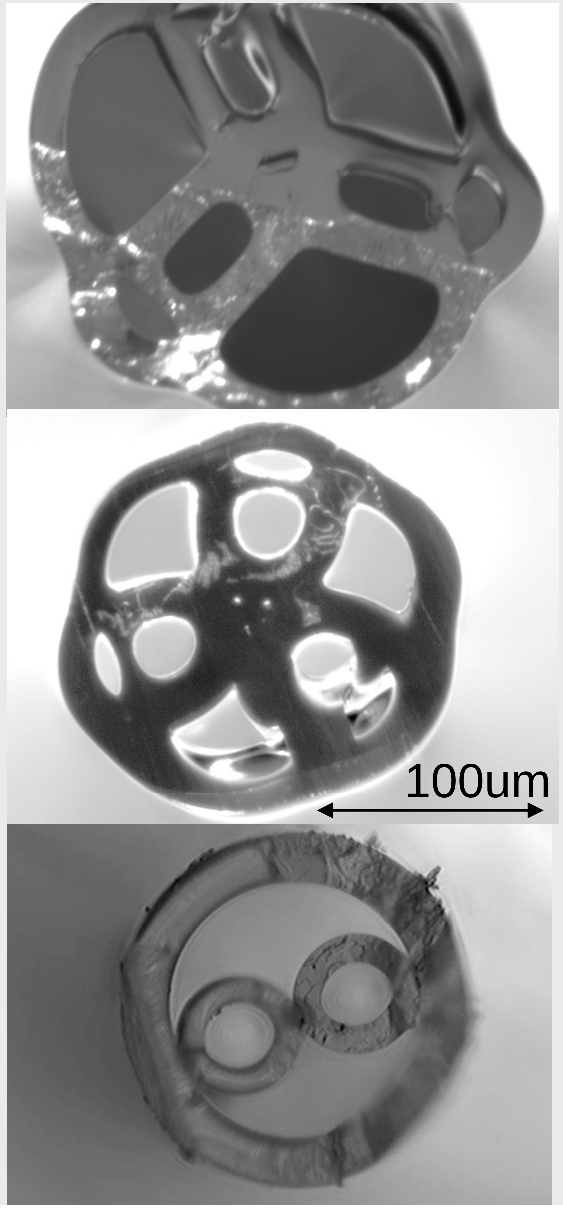
http://www.infotechfrance.com/cgi-local/affichage_signet_secteur.pl?UNI_ID=8&RUB_ID=54&SS_ID=4149&SEC_ID=442

ÉCOLE POLYTECHNIQUE MONTRÉAL

PolyPhotonique

Advantages of fiber drawing, non-optical applications of microstructured fibers

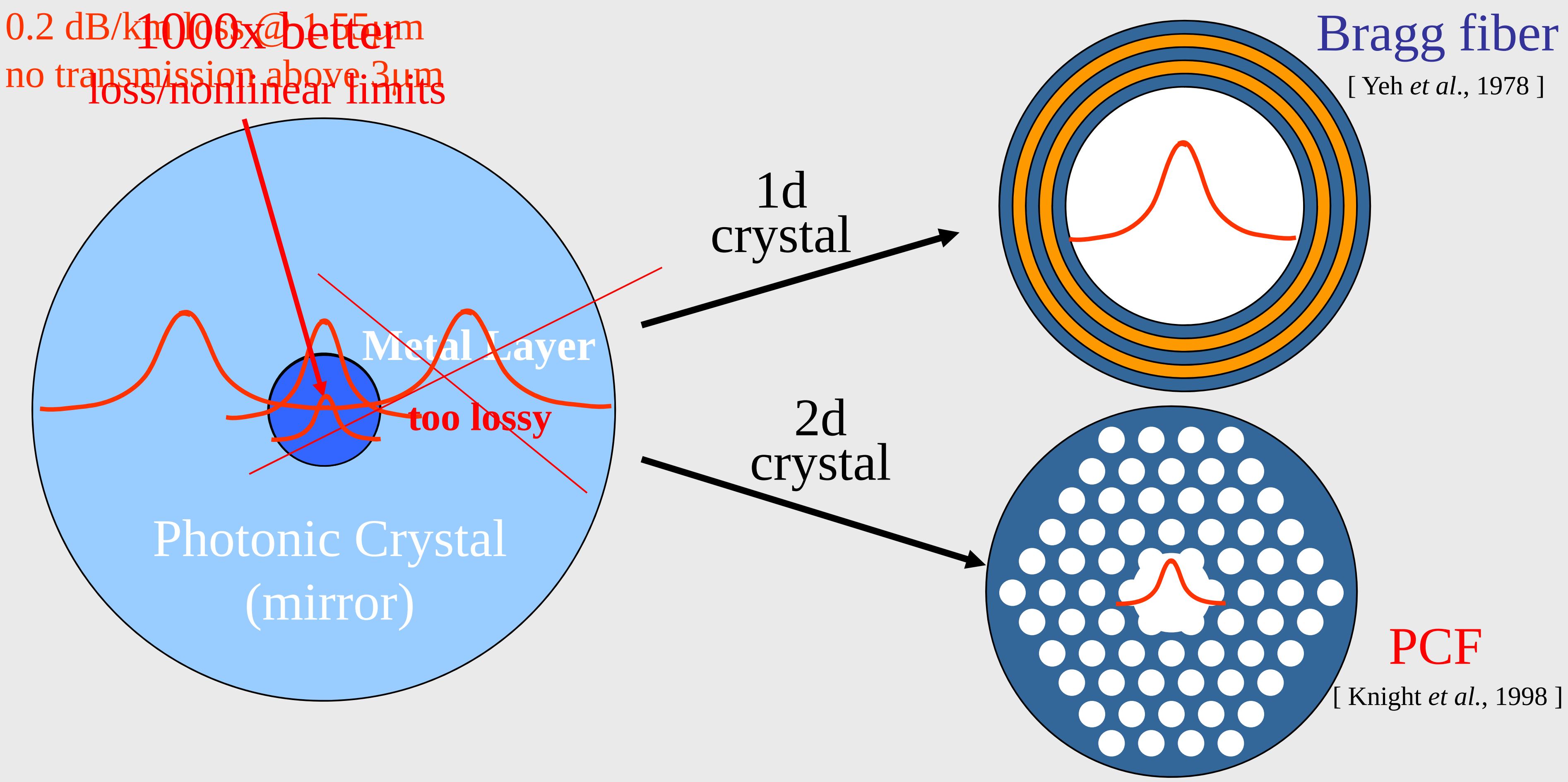
1. Fibers of very complex transverse geometries can be fabricated.
2. Several distinct materials (plastics, glasses, metals, semiconductors) can be integrated into the fiber crossection to integrate complex functionalities.
3. Starting with macroscopic objects, structures with sub-micron and even nano-sized features can be fabricated.
4. Highly cost effective.



Non-optical applications

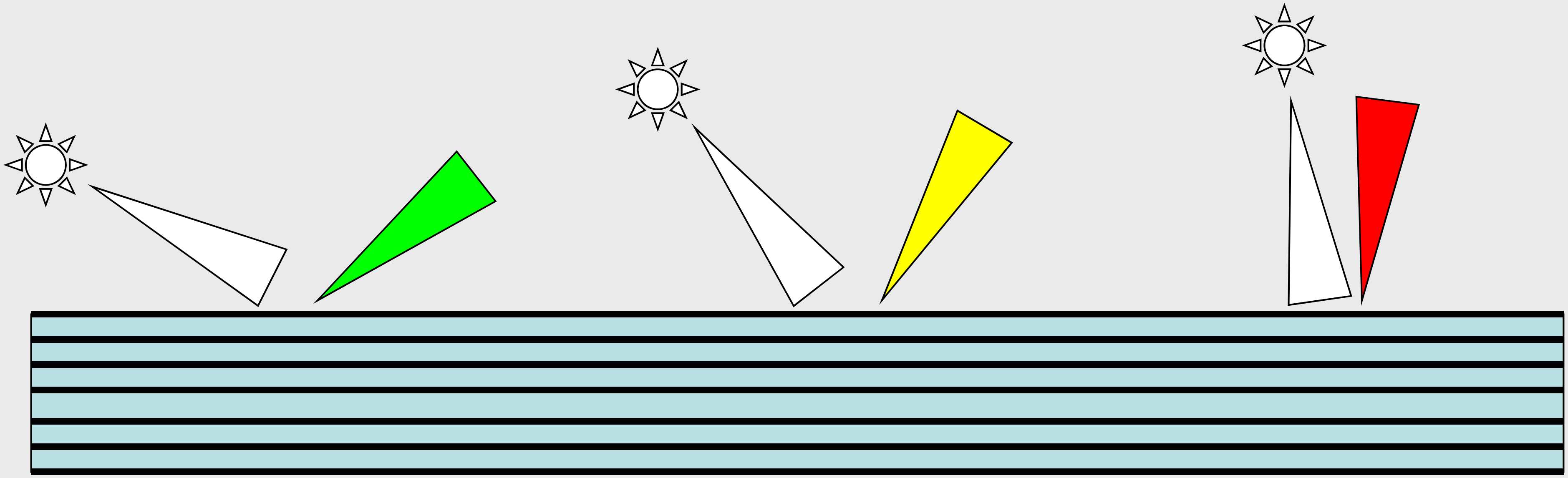
1. Empty holes: heat isolating textile
2. Holes filled with phase changing liquids - heat accumulating/releasing textile
3. Holes filled with anti-biotics + semi-permeable cladding – anti-bacterial textile
4. Fiber made of piesoelectric material + integrated metal electrodes – mechanically active textiles

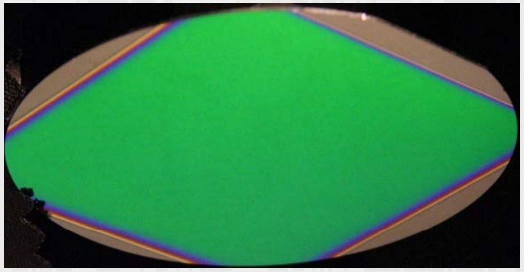
Photonic Bandgap Fibers

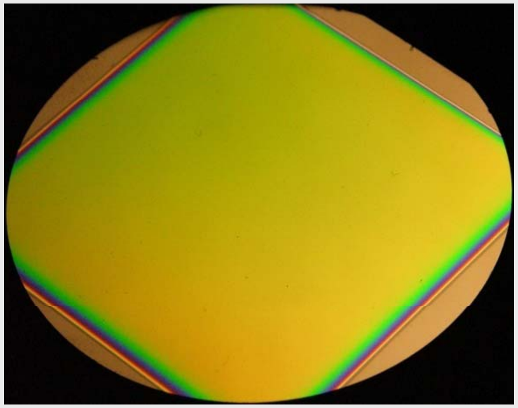


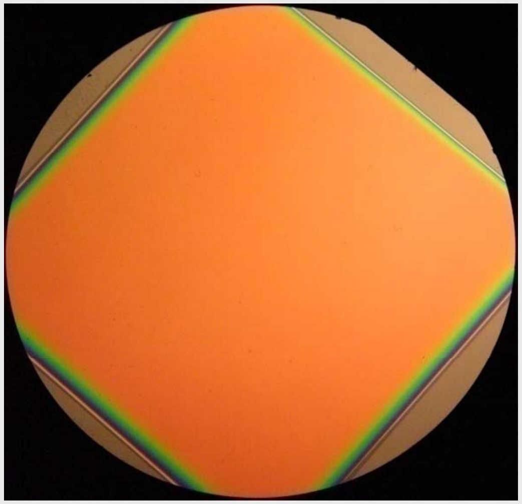
Multilayer films

Dielectric multilayer “mirrors” reflect different colors when looked at different angles





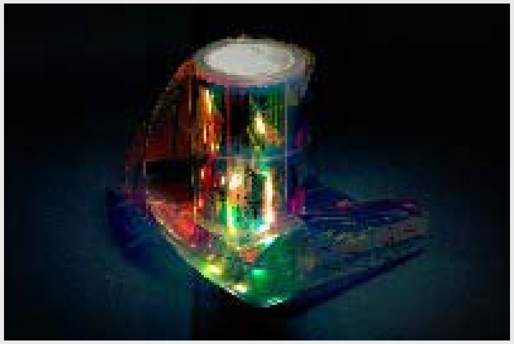




Multilayer films

3M™ Radiant Light Films

These films provide a dazzling array of colour to enhance and bring to life any product packaging. When laminated to a white or coloured background, Radiant Films offer an almost endless array of colour options.

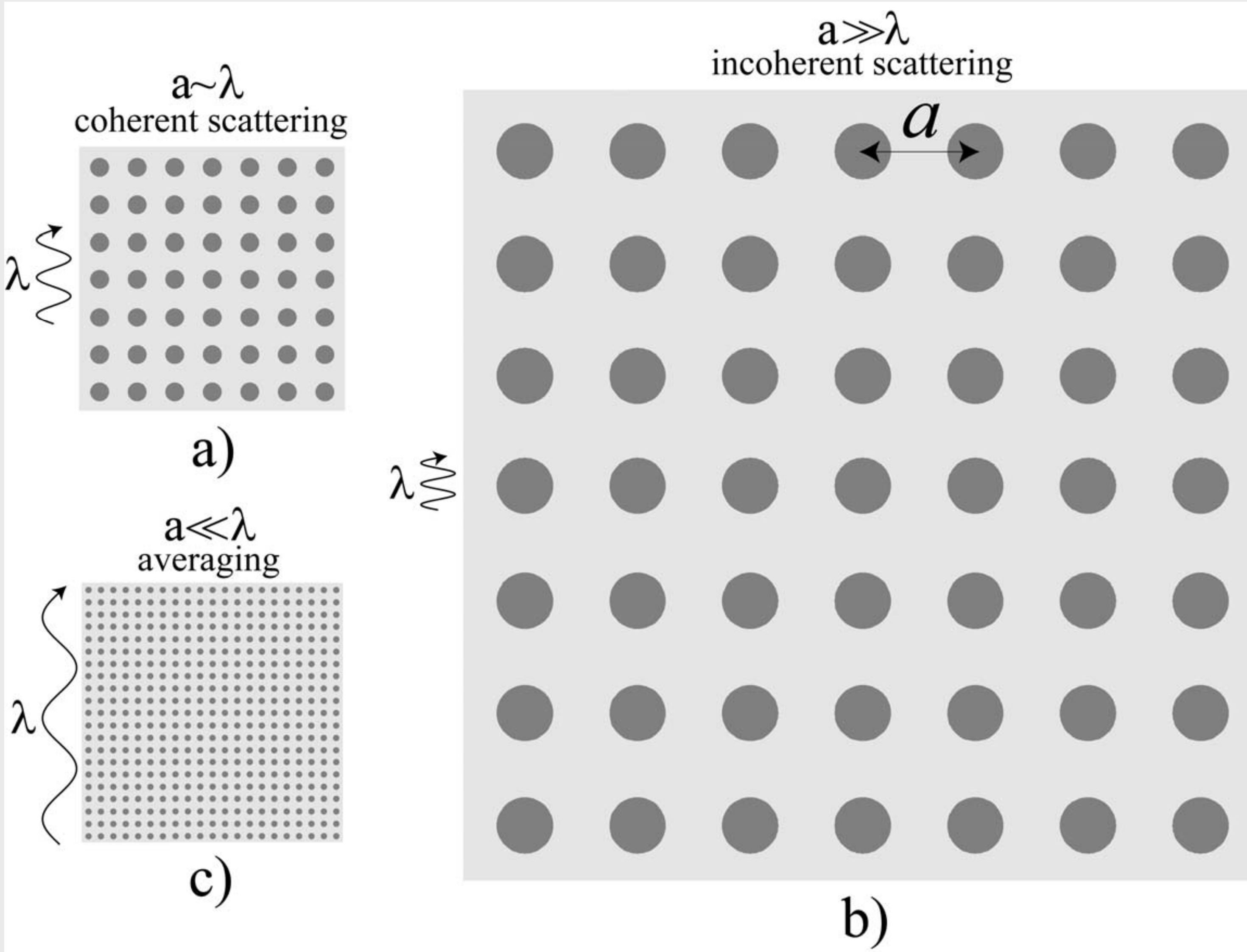


Under normal lighting

Under artificial lighting

What is nano-regime in fiber optics?
(size does determines new physics in optics)

Some PBG structures contain strongly subwavelength features



M. Skorobogatiy, J. Yang, Fundamentals of Photonic Crystal Guiding, Cambridge University Press, 2009.

Three examples of guided nano-photonics

λ

- Subwavelength structure in the fiber crossection (regular dielectrics, features < $\lambda/5$). PBG fibers (**resonant light confinement**).
- Metallic inclusions that support plasmons (**strongly confined modes** with size < $\lambda/5$-$\lambda/20$). Fibers and waveguides with integrated metallic elements.
- Strongly subwavelength structure in the fiber crossection (regular dielectrics, features < $\lambda/20$). Porous subwavelength fibers (**metamaterial**).

$\lambda/10$

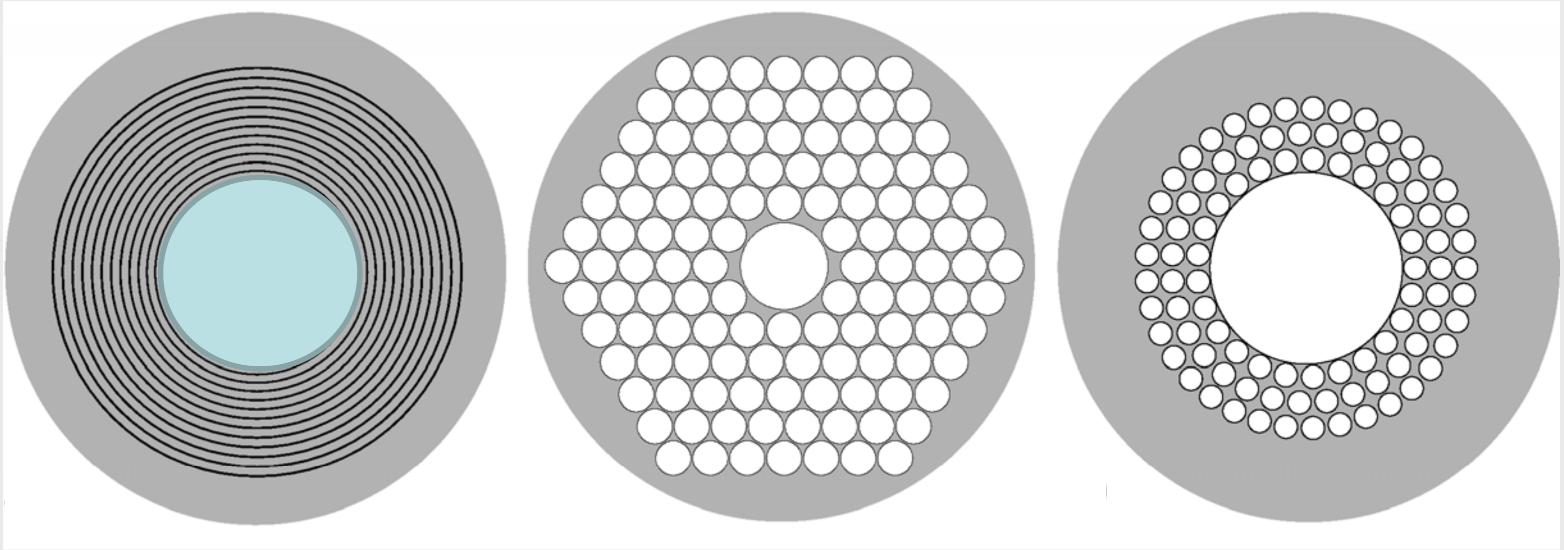
I

- Photonic bandgap fibers feature highly subwavelength features in their crossection, while still operating in the regime of coherent scattering (**resonant confinement**).

Most PBG structures contain strongly subwavelength inclusions

Hollow core PBG fibers have highly subwavelength features

(applications in high-power laser light transmission, liquid-filled core sensing in biotech, gas-filled core sensing, photonic textiles, ultra-low nonlinearity telecom applications, etc.)



Bragg fibers

Layer thickness h ~ λ/4/n

Polymers (n=1.5) h < λ/5

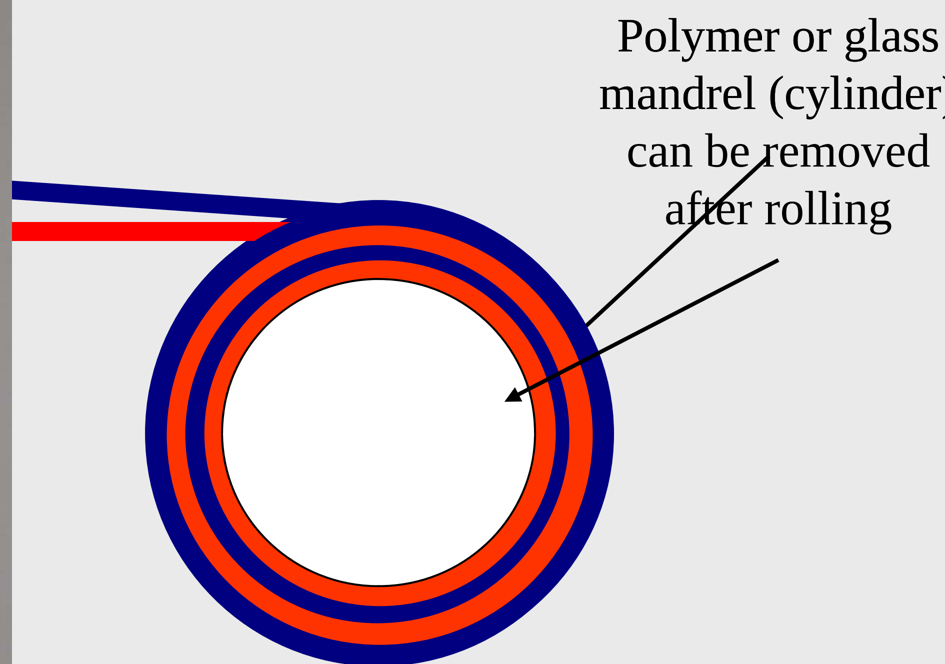
Chalcogenide glass (n=2.8) h < λ/10

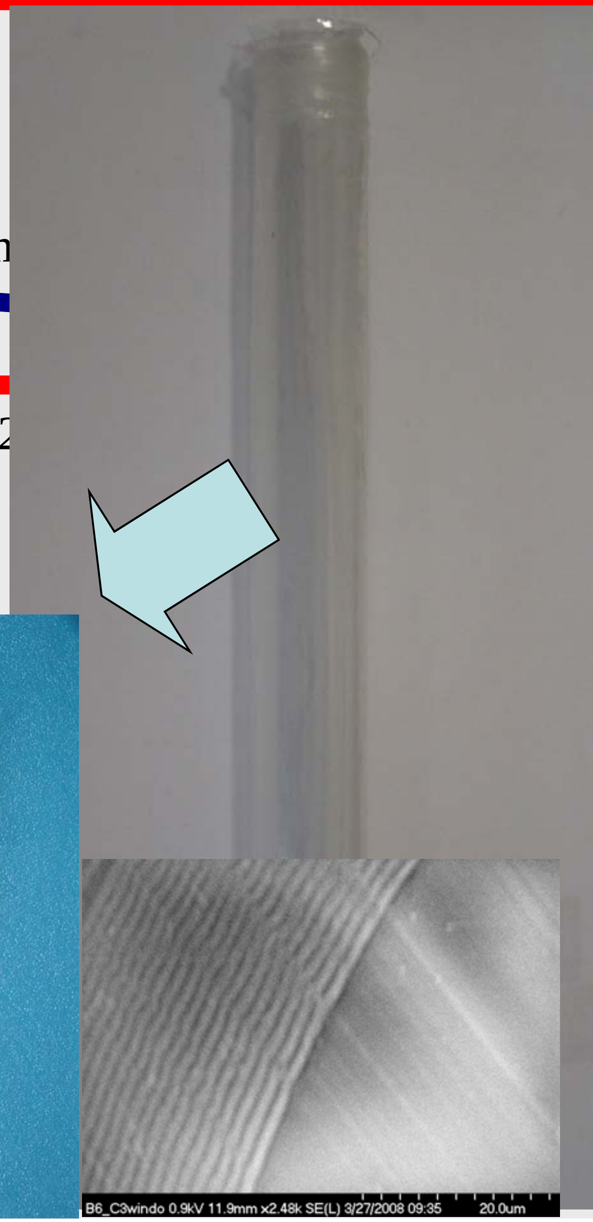
Hollow core Photonic Bandgap Fibers

material vein thickness should be smaller than 2-5% of the period Λ~ λ,

thus h_{vein} < λ/20

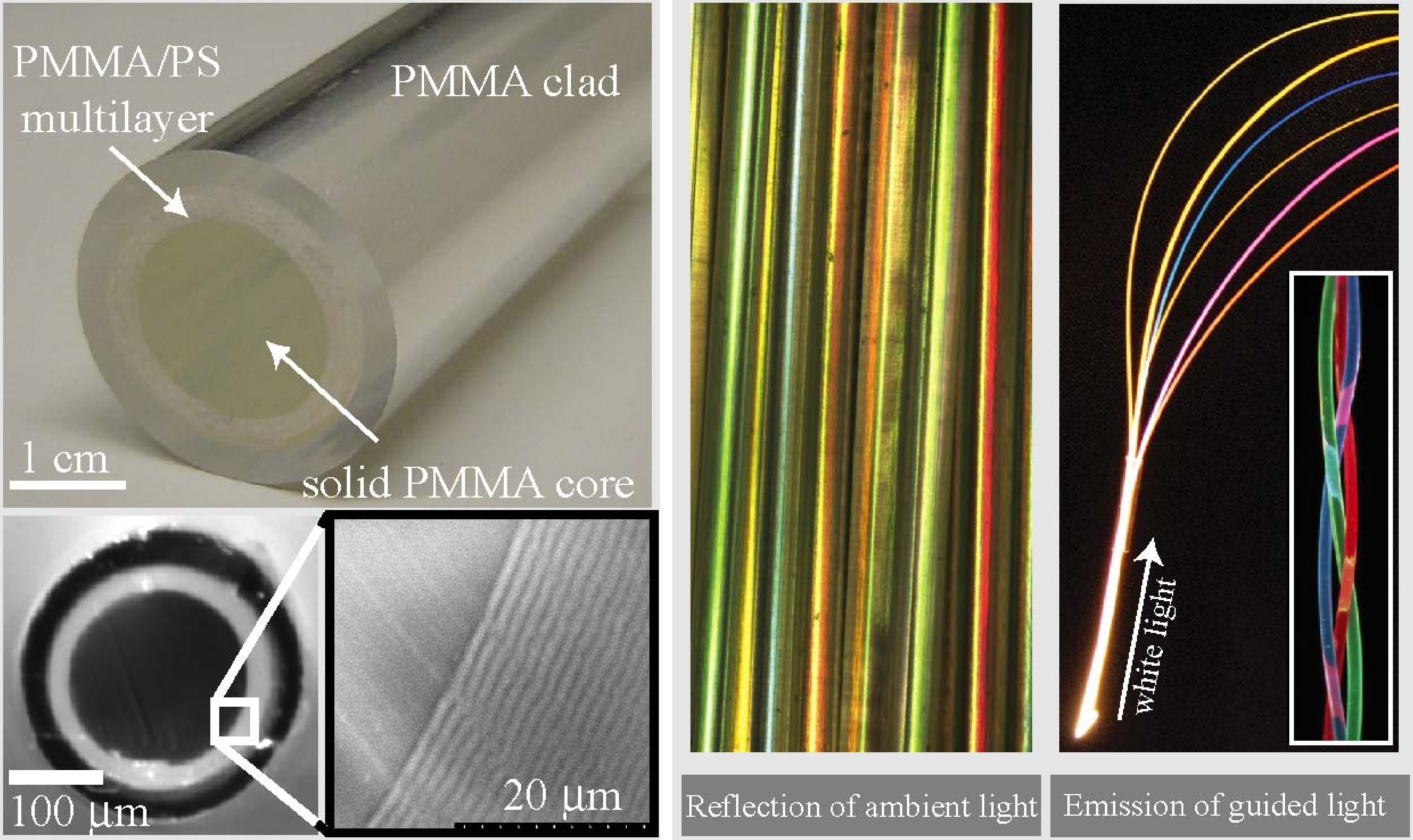
All-Polymer Bragg fiber preforms via Co-Rolling of polymer films





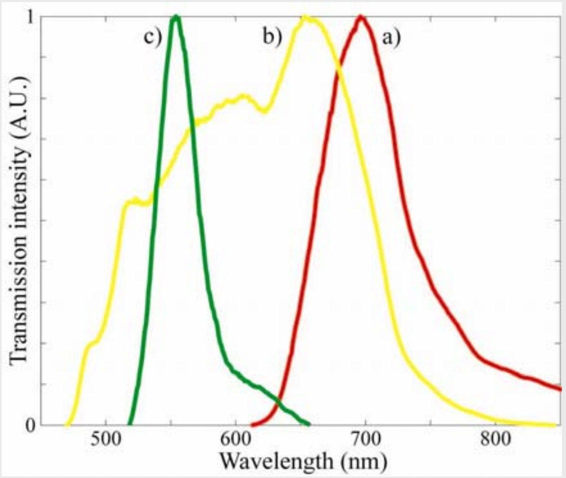
E. Pone, M. Skorobogatiy et al., "Drawing of the hollow all-polymer Bragg fibers," Optics Express **14**, 5838 (2006)

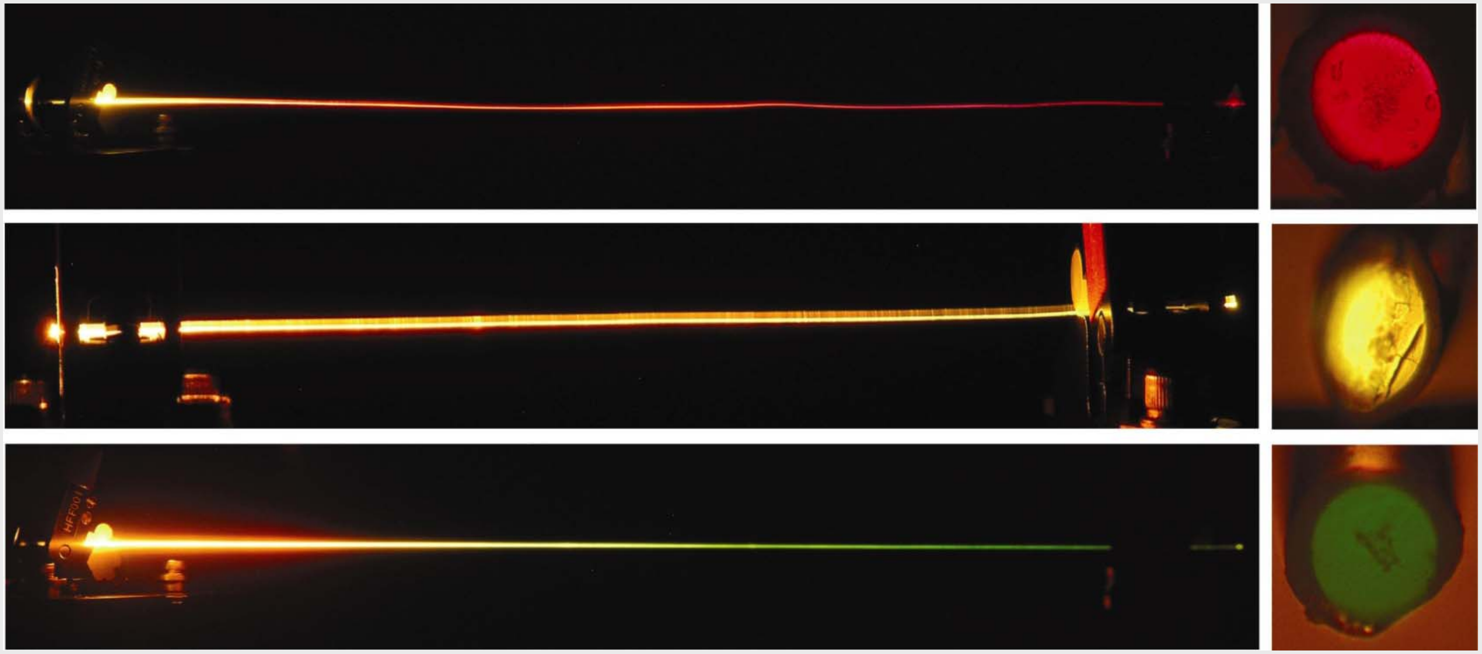
‘ColorFull’ plastic fibers for advanced textiles, short-range communications and sensing



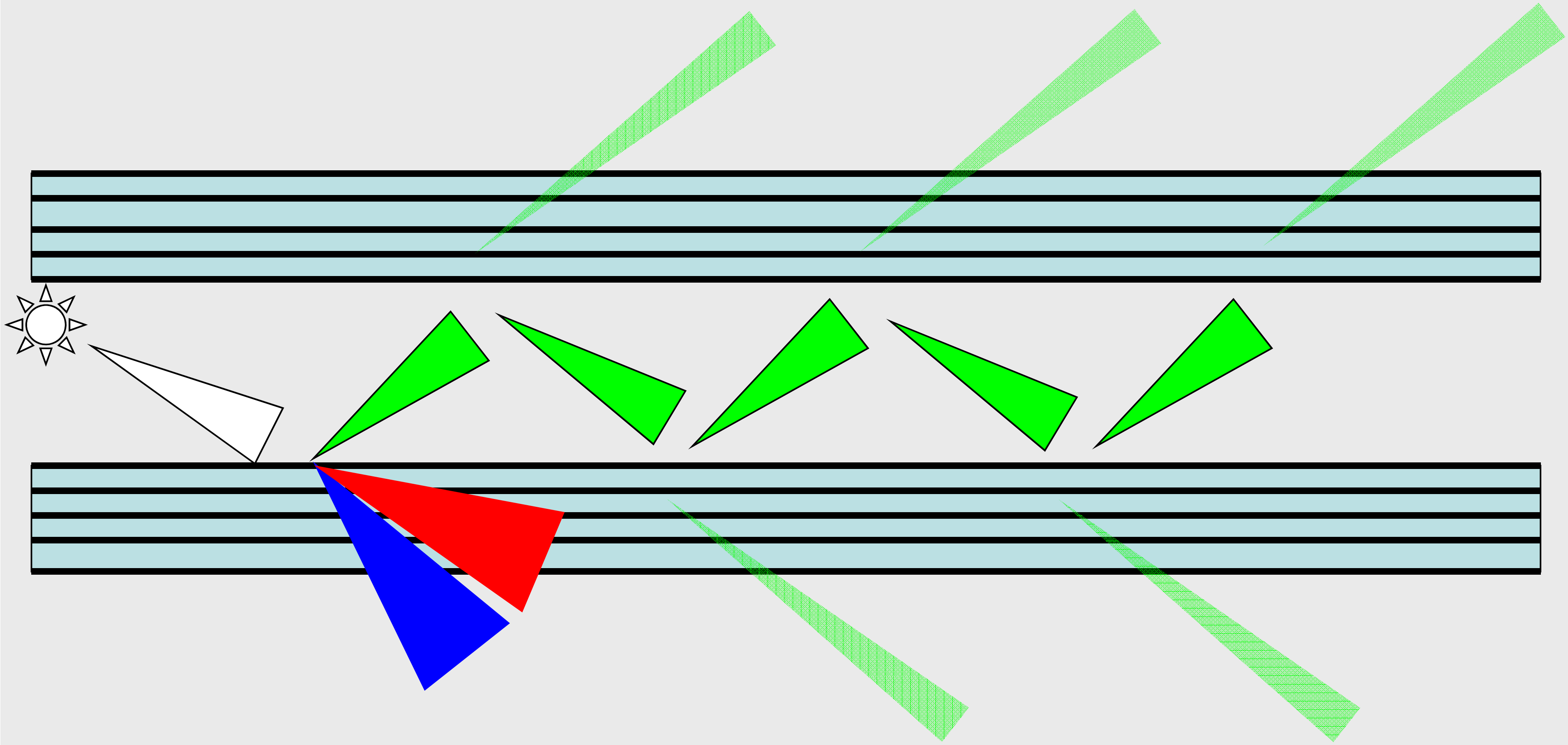
A. Dupuis, N. Guo, B. Gauvreau, A. Hassani, E. Pone, F. Boismenu, and M. Skorobogatiy, "Guiding in the visible with "colorful" solid-core Bragg fibers," Opt. Lett. **32**, 2882-2884 (2007).

Transmitted and emitted colors

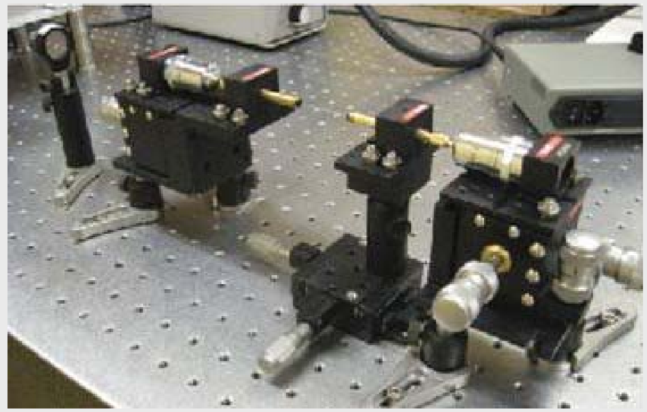


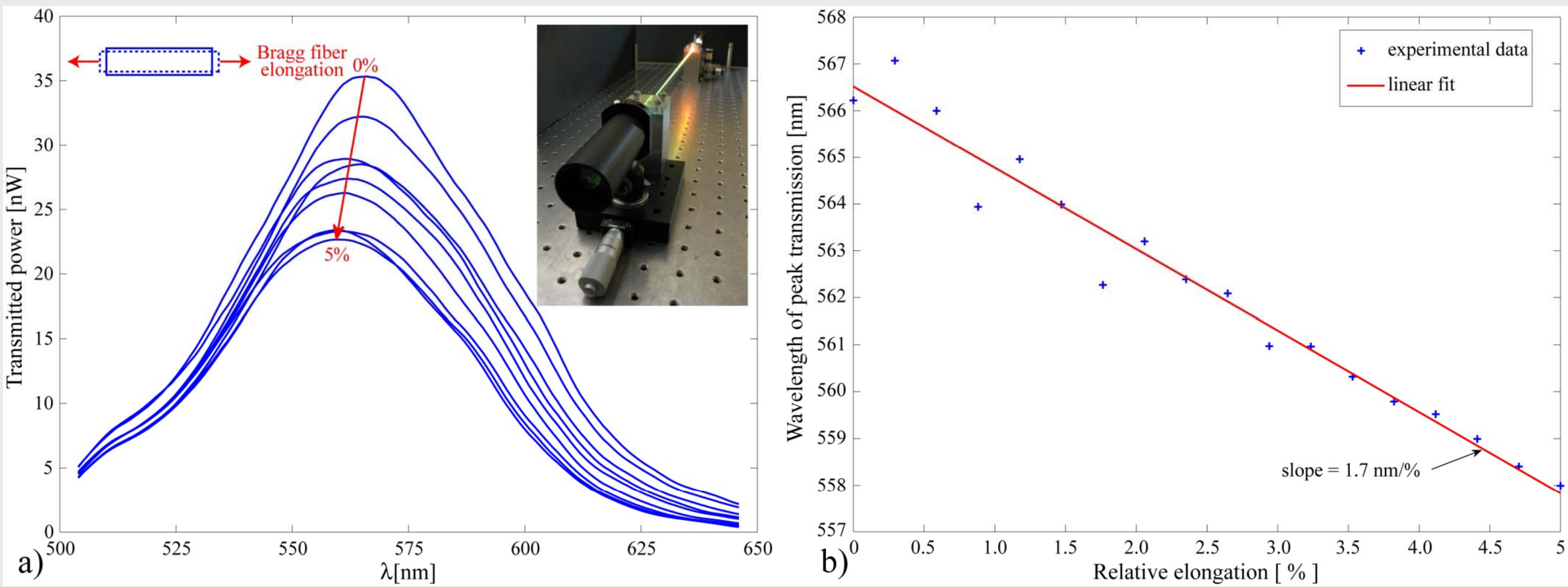


Photonic Bandgap fibers are spectral filters



Bangap shift due to fiber elongation applications in sensing of strain





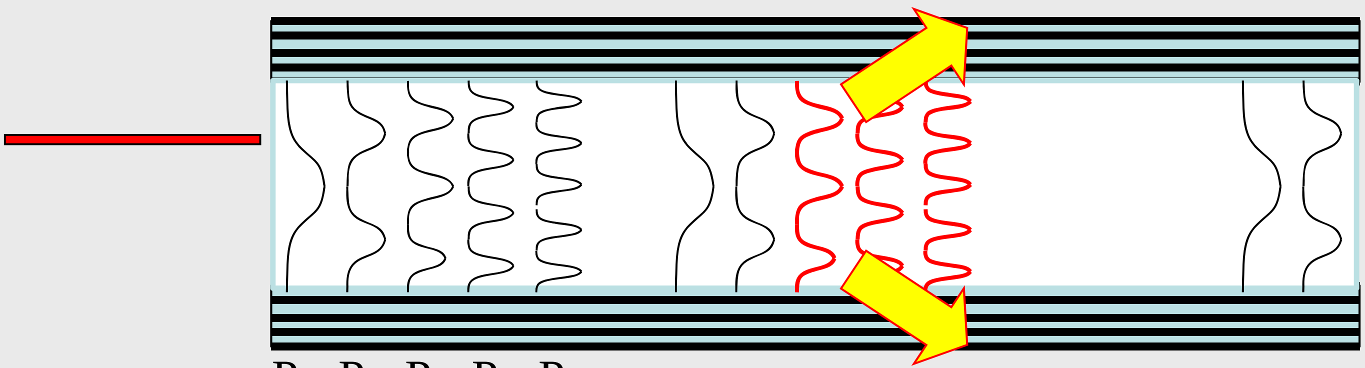
B. Gauvreau, N. Guo, K. Schicker, K. Stoeffler, F. Boismenu, A. Ajji, R. Wingfield, C. Dubois, M. Skorobogatiy, "Color-changing and color-tunable photonic bandgap fiber textiles," Opt. Express, Vol. 16, pp. 15677-15693 (2008).

Photonic Bandgap fibers are effectively single mode regardless of the core diameter.

In SI-TIR fibers almost all the modes lunched into the multimode fiber reach the fiber end with similar relative powers.

P_0 P_1 P_2 P_3 P_4 … $\sim P_0 \sim P_1 \sim P_2 \sim P_3 \sim P_4$ …

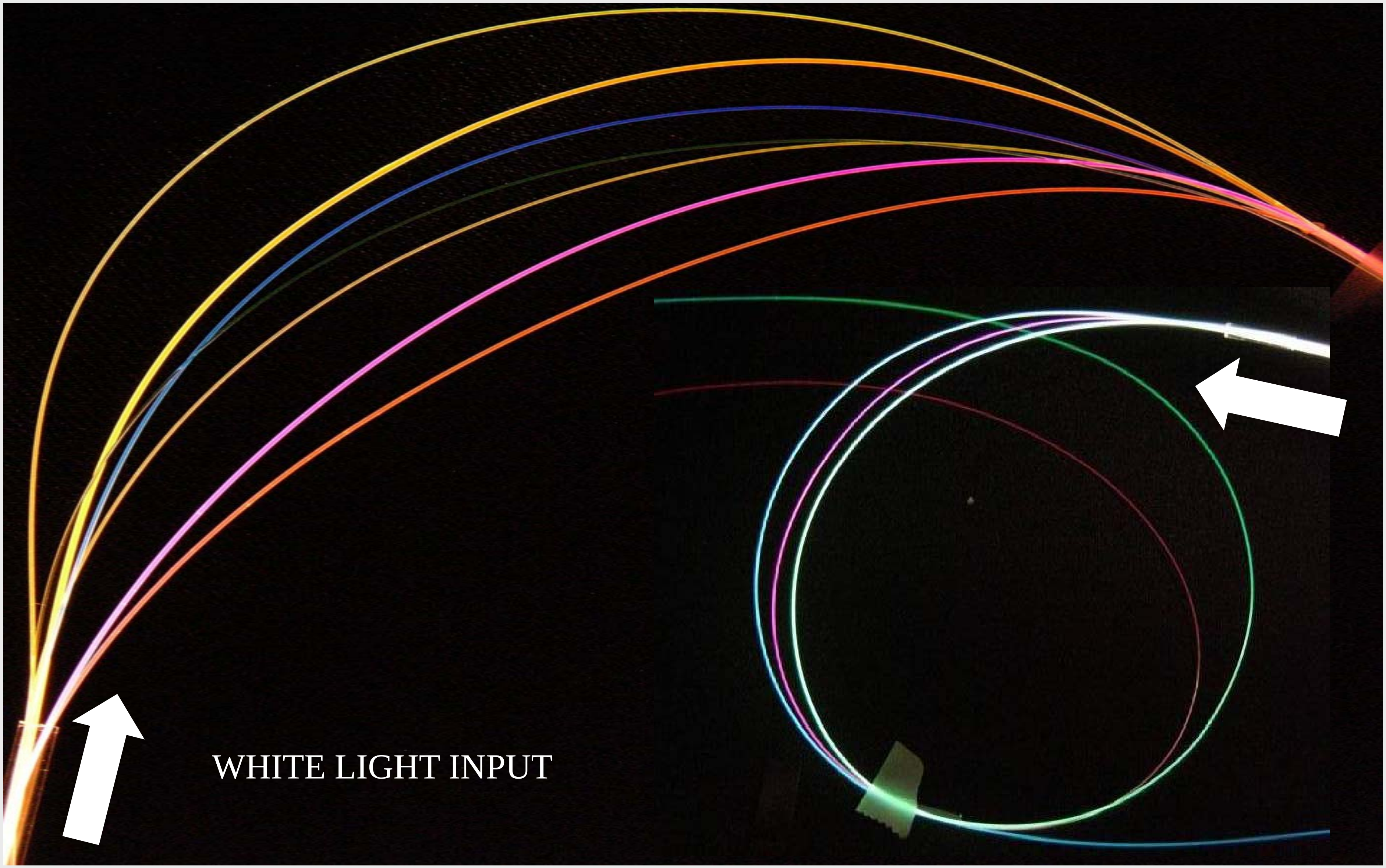
In Photonic Band Gap fibers only the lowest loss modes reach the fiber end.



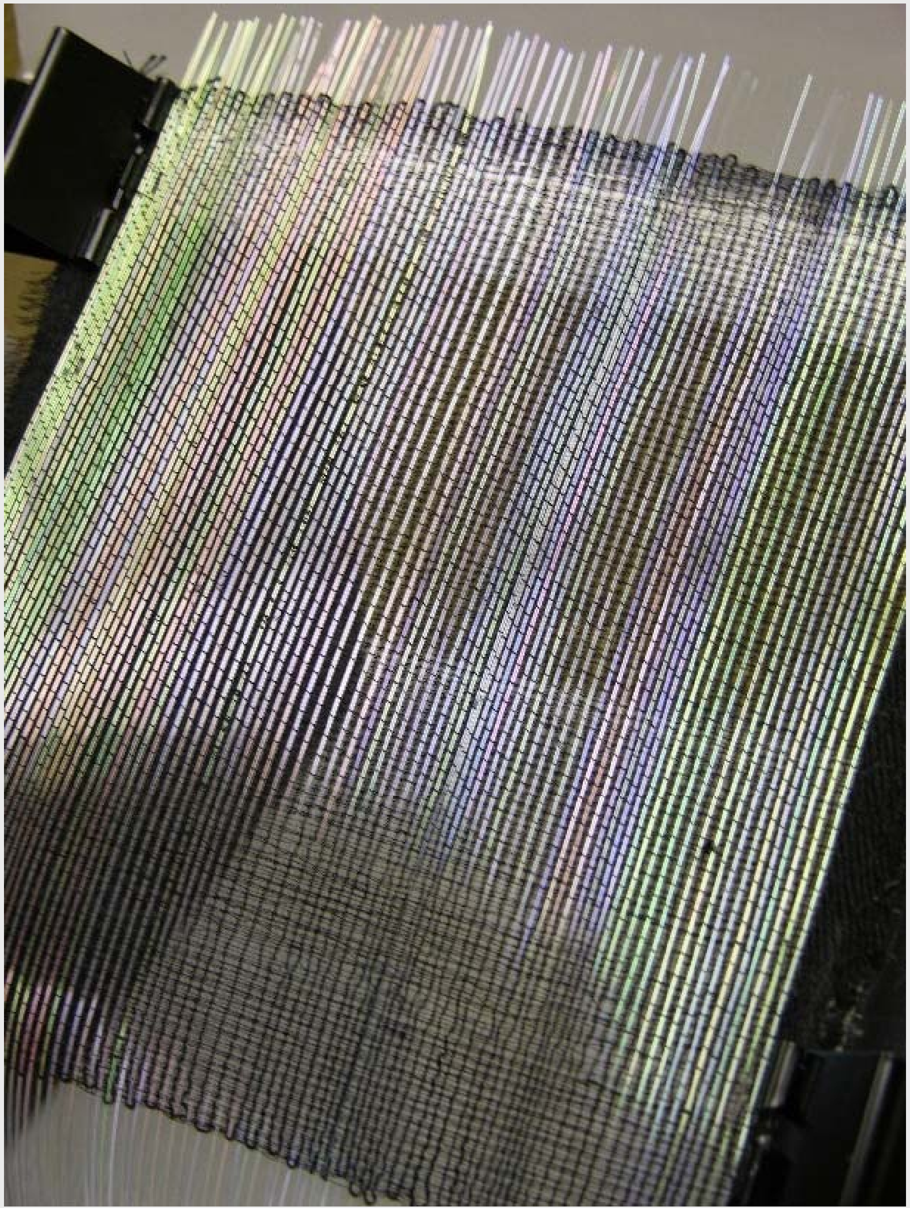
P_0 P_1 P_2 P_3 P_4 …

M. Skorobogatiy and N. Guo, "Bandwidth enhancement by differential mode attenuation in multimode photonic crystal Bragg fibers," Opt. Lett., Vol. 32, p. 900 (2007).

PBG fiber bundles, application in colorful illumination and all-fiber spectral filtering



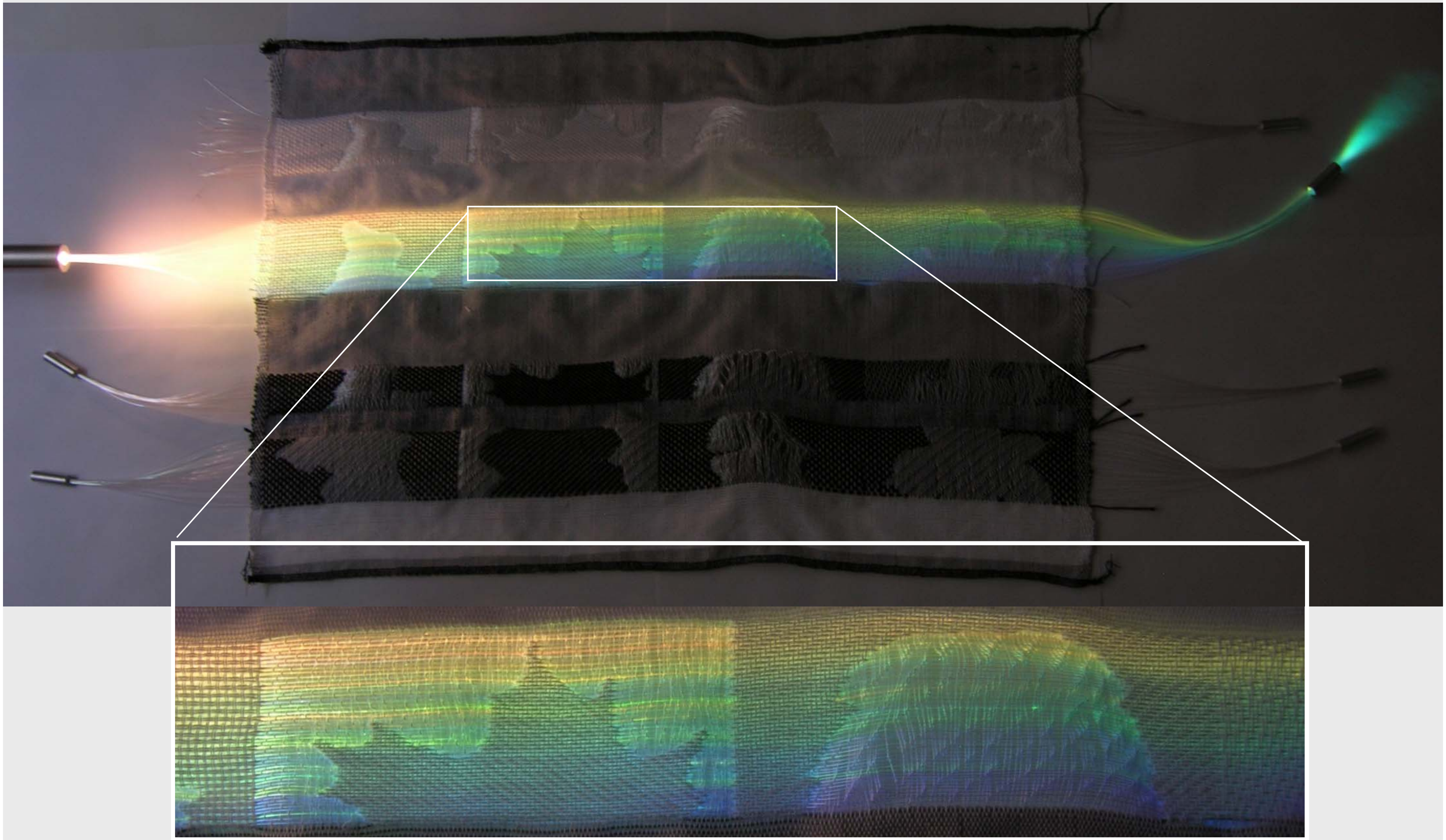
Colored Reflection of ambient light
(no guided light)



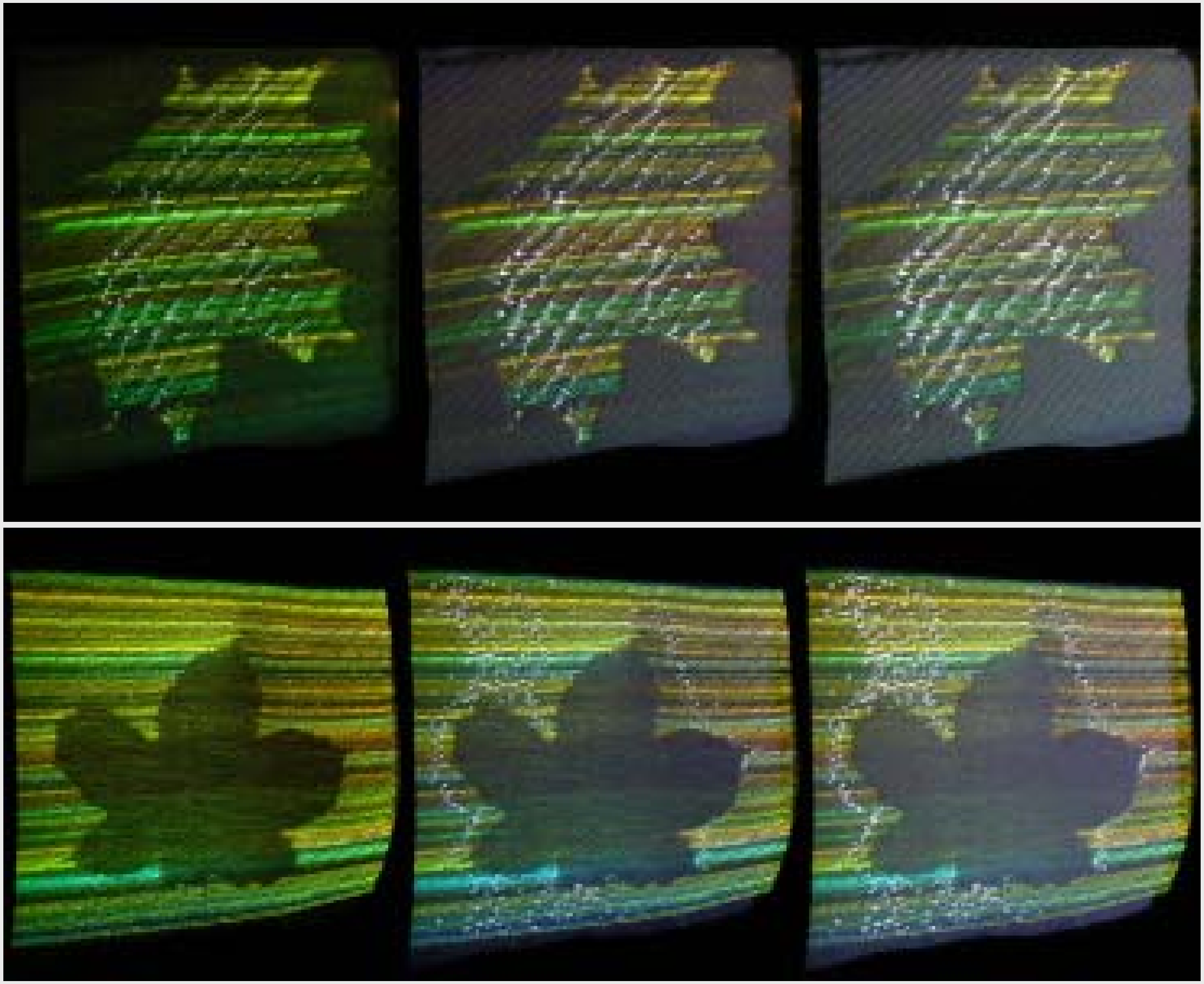
Photonic textiles using photonic bandgap fibers

B. Gauvreau, M. Skorobogatiy et al. "Color-changing and color-tunable photonic bandgap fiber textiles," Opt. Express, Vol. 16, pp. 15677-15693 (2008).

Nature Photonics – News and Views, Color-tunable textiles, Nov. 2008

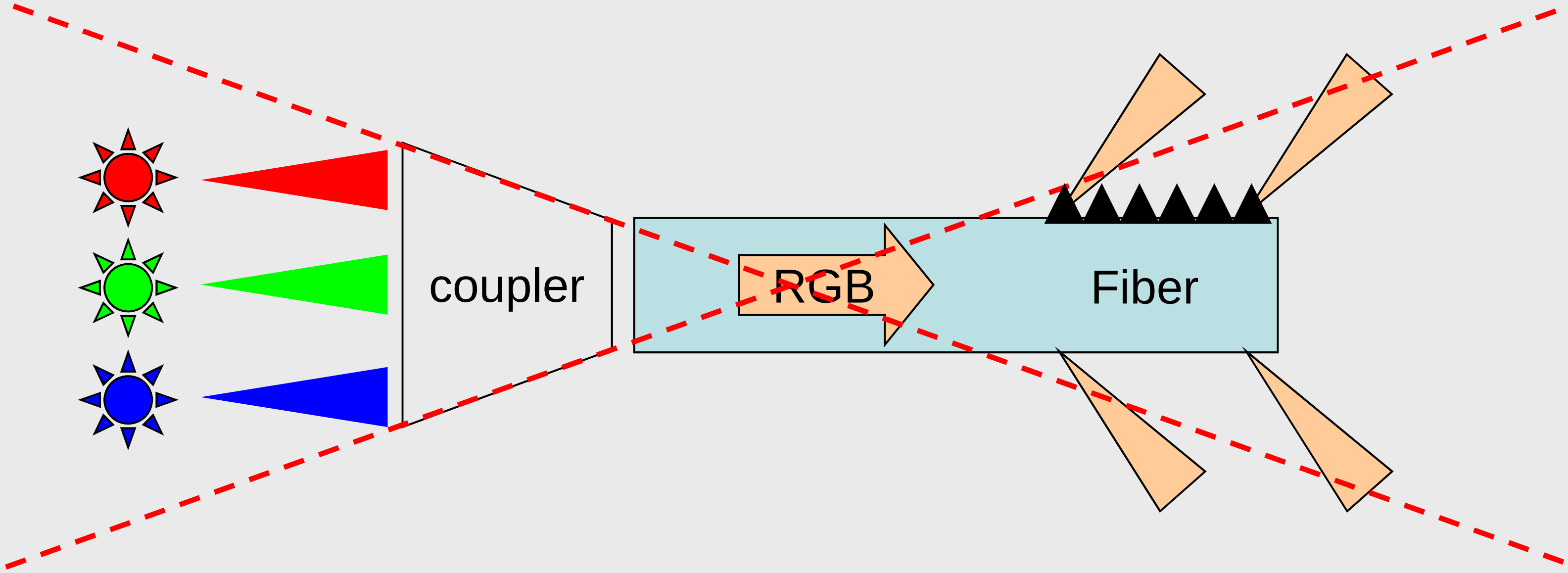


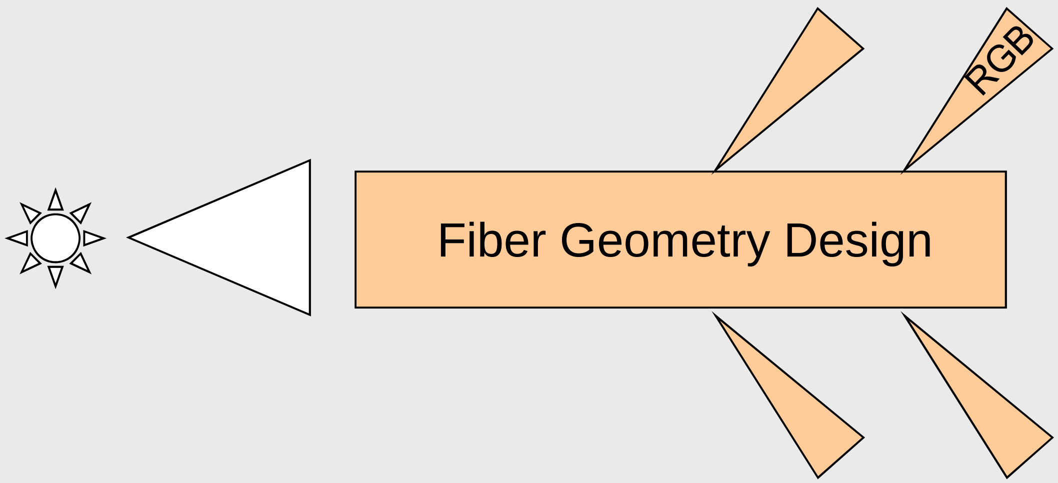
Changing textile appearance by mixing the ambient and emitted light

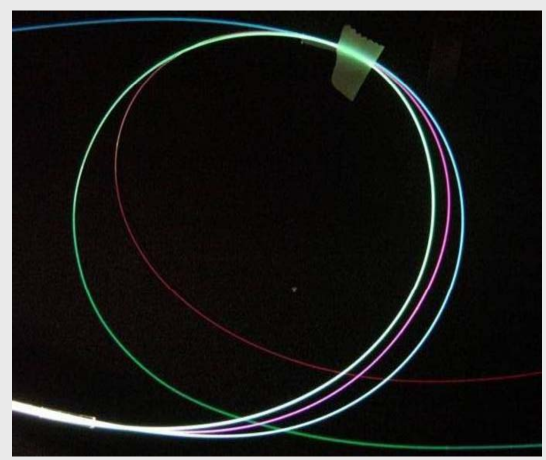


Color on demand by fiber geometry design

No mechanical perturbations for light extraction







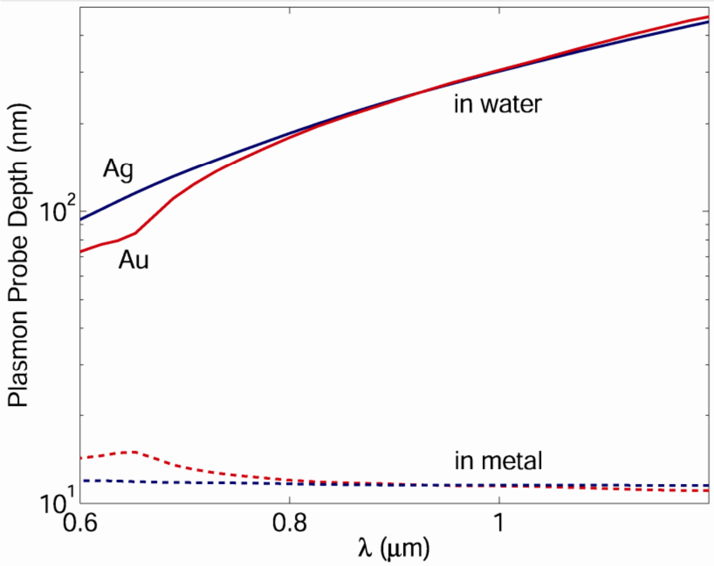
Photonic Bandgap Textiles

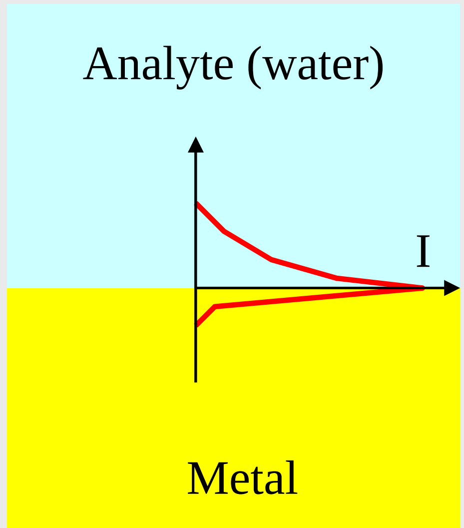
VIDEO

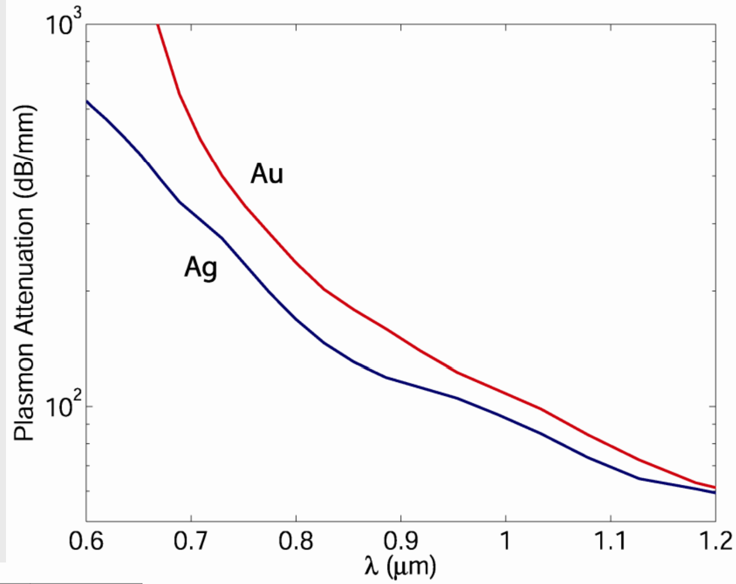
II

- Fibers and waveguides with integrated metallic elements can support highly localized **plasmonic modes** with size < λ/5-λ/20.

What is a plasmon?

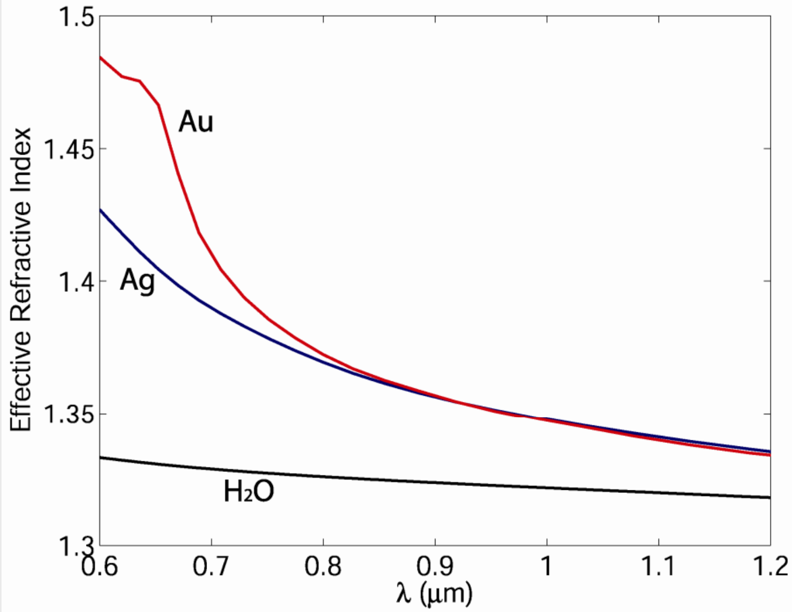






$$n_{plasmon} = \left(\frac{\varepsilon_{metal}\varepsilon_{analyte}}{\varepsilon_{metal} + \varepsilon_{analyte}} \right)^{1/2}$$

$$\mathrm{Re}(\varepsilon_{metal}) < 0$$

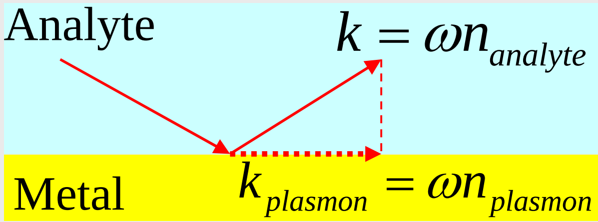


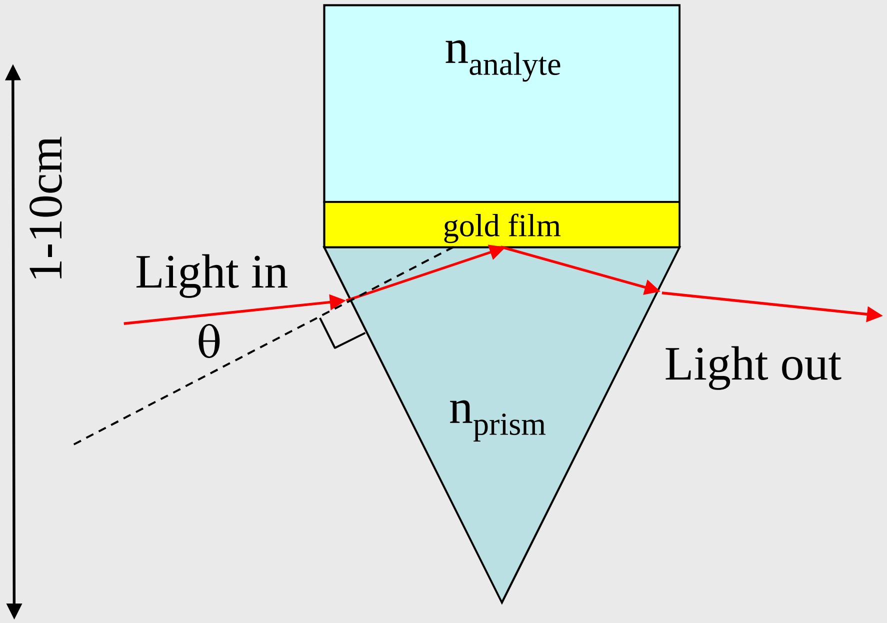
Sensing applications:

$$\delta n_{plasmon} \sim \delta n_{analyte}$$

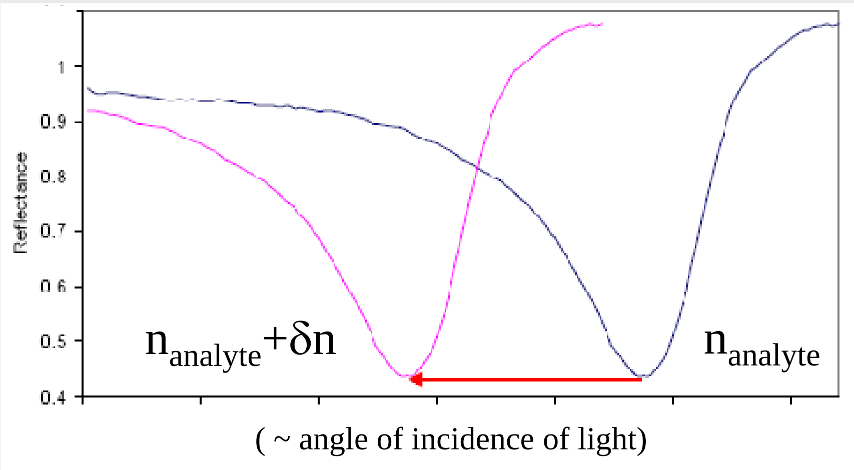
How to excite a plasmon?

As $n_{plasmon} > n_{analyte}$ direct excitation of a plasmon from the analyte side is not possible



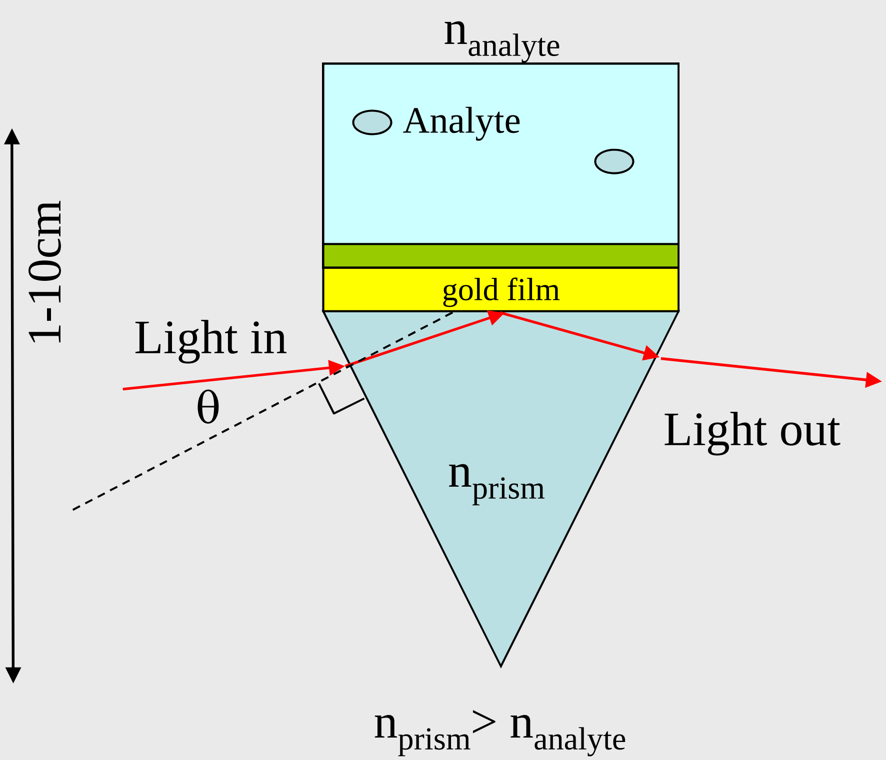


$n_{prism} > n_{analyte}$



Resolution limit min(δn)=10^{-7}-10^{-6}

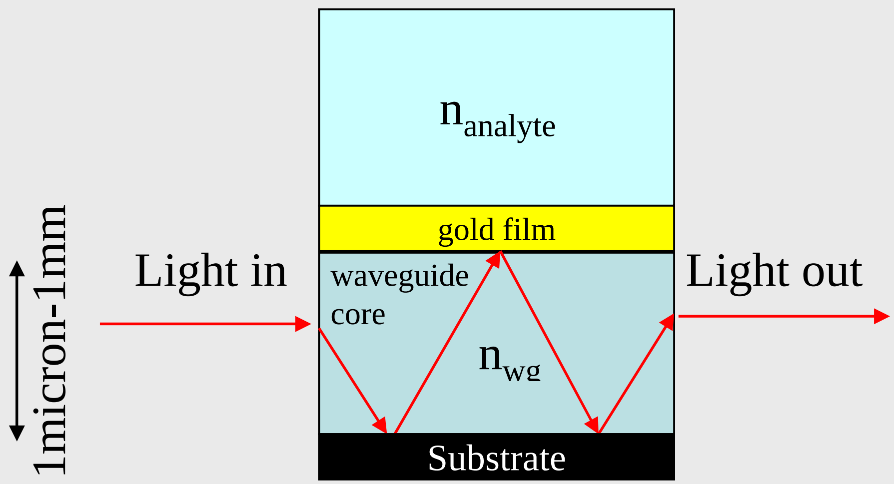
Applications



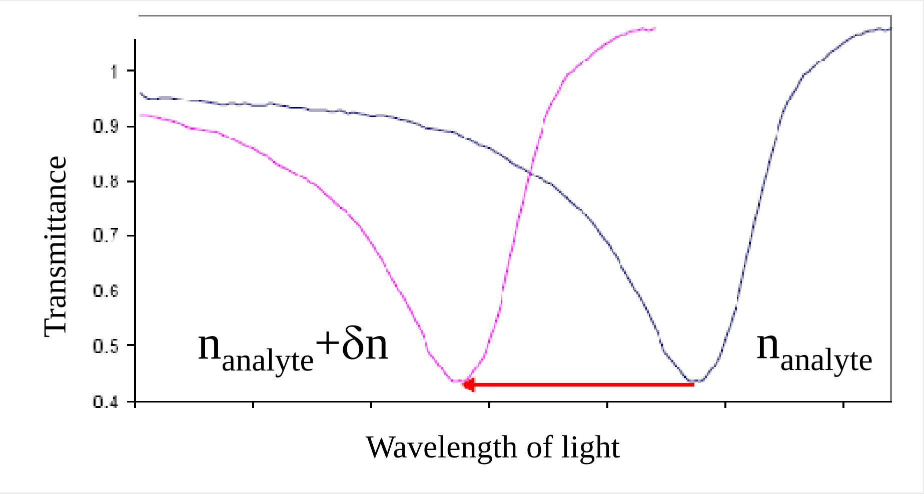
1. Measurement of the refractive indices of liquids
2. Sensing by using changes in the refractive index of an analyte:
   A. Analyte is a missible gas or liquid
   B. Analyte is immisible and condenses onto the gold film
3. Detection of the chemical reactions in the sensing layer on the gold layer (integration of sensor specificity)

Notes:
1. All the measurements are within 200nm of a gold surface
2. Usable wavelength of light is limited by the absorption of a prism material
3. RIU detection range is limited by the RI of a prism
4. Sensitivity 10^{-7}-10^{-5} RIU

How does it work in a compact waveguide (or fiber) configuration?



$n_{wg} > n_{analyte}$

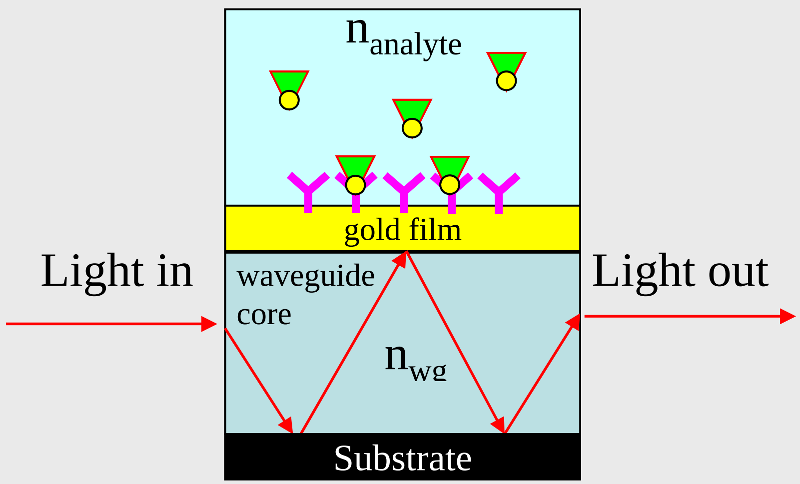


Resolution limit $\min(\delta n)=10^{-4}$-10^{-3}
Integrated optics - expensive

Key advantages:

1. Compactness and lack of bulk components
2. If waveguide is singlemoded, convenient launching

Applications in bio-sensing



$n_{wg} > n_{analyte}$

1. Metal layer is first bio-functionalized with a nanometer thick analyte 'recognition' bio-molecules.

2. When analyte molecules are present in a suspension, some of them are captured by the 'recognition' molecules and held on a gold surface. By detecting refractive index change in the nanometer thick bio-layer due to binding of bio-molecules (n~1.42) one can detect presence of such molecules.

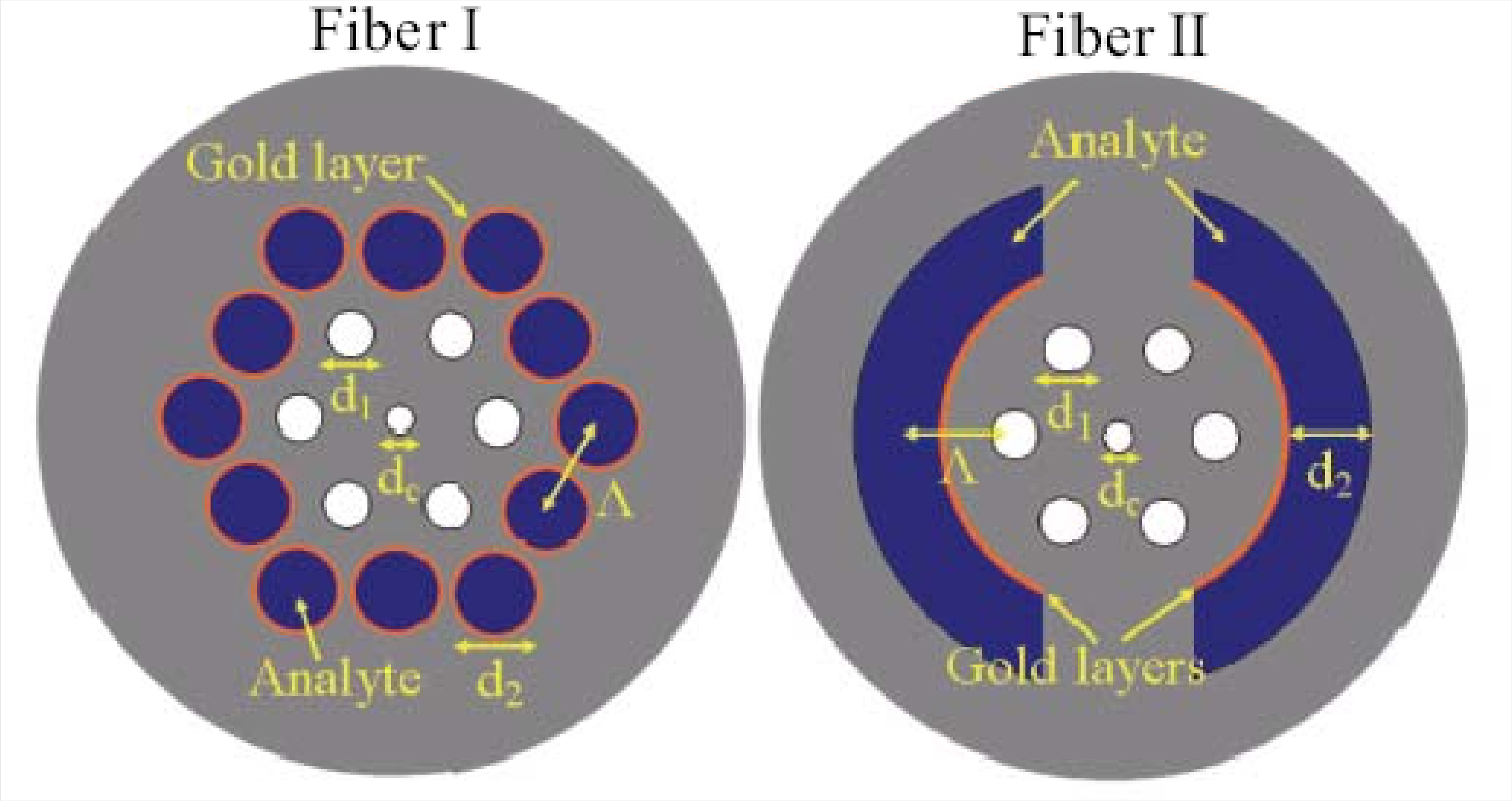
3. Sensitivity can be further enhanced if metal nanoparticles are bound to the analyte molecules. In this mode one detects effective changes in thickness of a sensing metal layer.

Notes:

1. All the measurements are within 200nm of a gold surface
2. Usable wavelength of light is limited by the absorption of a waveguide core material
3. RIU detection range is limited by the waveguide core and cladding indexes
4. Sensitivity 10^{-7}-10^{-5} RIU

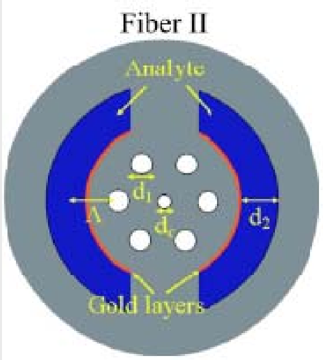
Microstructured fiber-based Surface Plasmon Resonance sensor (no bandgaps)

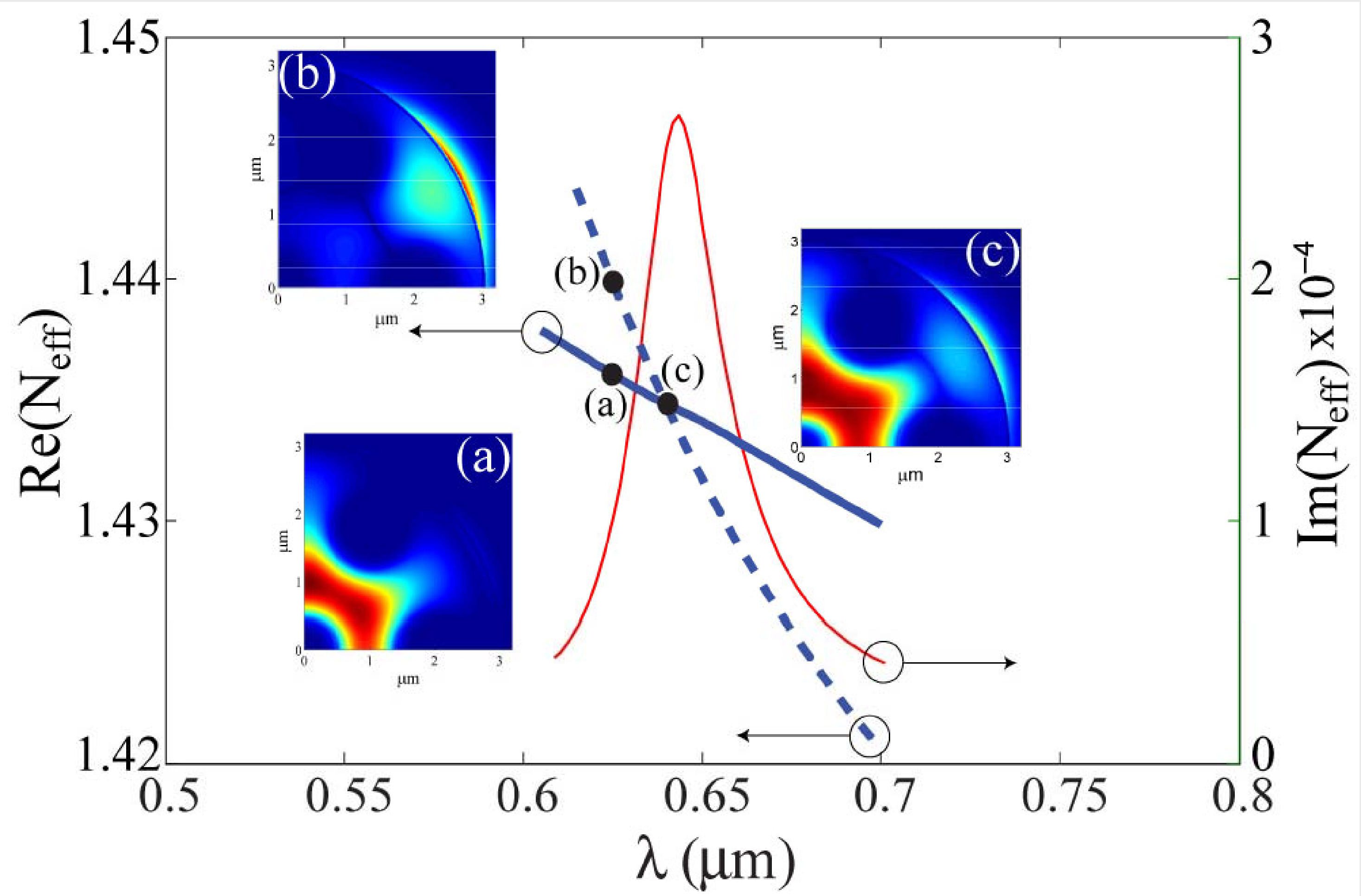
Power fraction of a plasmon field in analyte is close to 1
Amplitude sensing uses resonant coupling of the core-guided mode with plasmon



A. Hassani, M. Skorobogatiy "Design of the microstructured optical fiber-based surface plasmon resonance sensors with enhanced microfluidics," Opt. Express, vol. 14, pp. 11616-11621 (2006) ; JOSA B (2007)

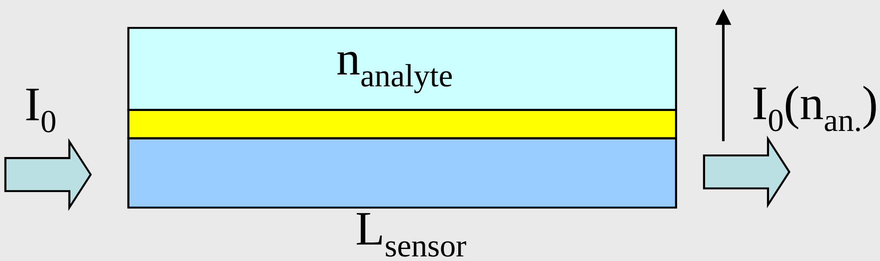
Dispersion relations of a core-guided mode and a surface plasmon in the vicinity of phase-matching point.

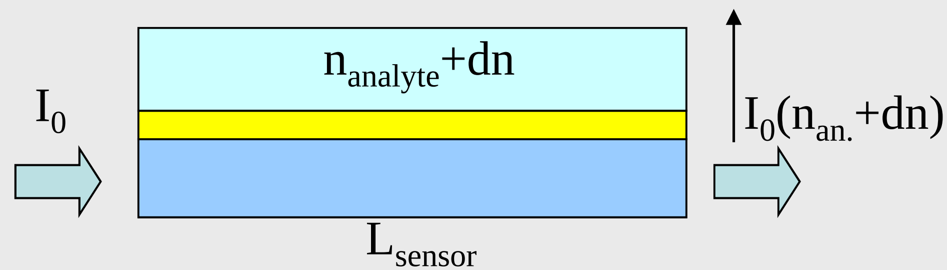




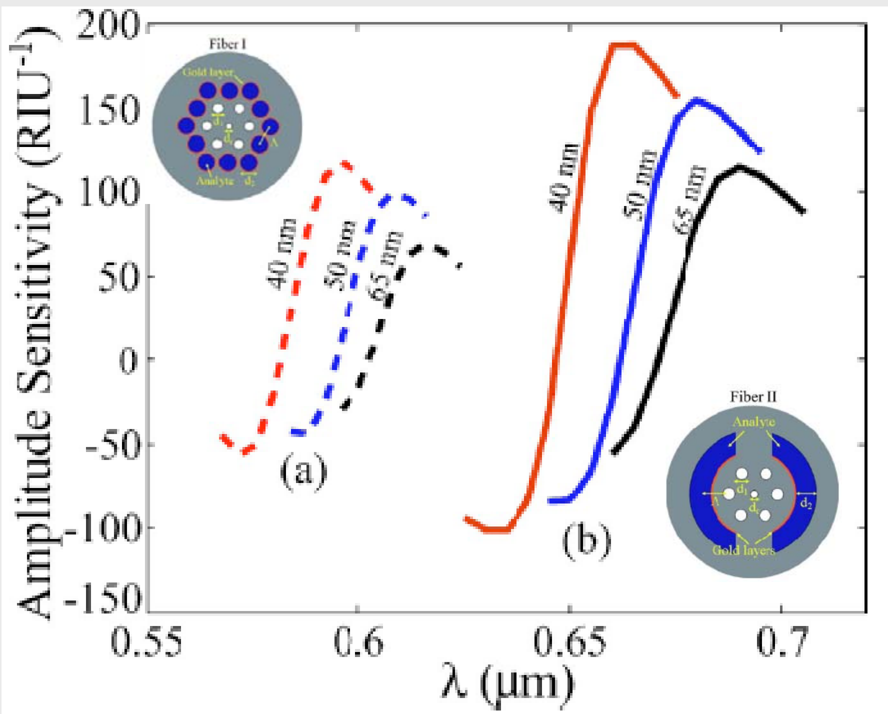
Sensitivity of the MOF-based sensors

$$I_0 \exp\left(-\alpha(\lambda, n_{analyte}) L_{sensor}\right) \qquad I_0 \exp\left(-\alpha(\lambda, n_{analyte} + dn) L_{sensor}\right)$$





$$L_{sensor} = 1/\alpha(\lambda, n_{analyte})$$



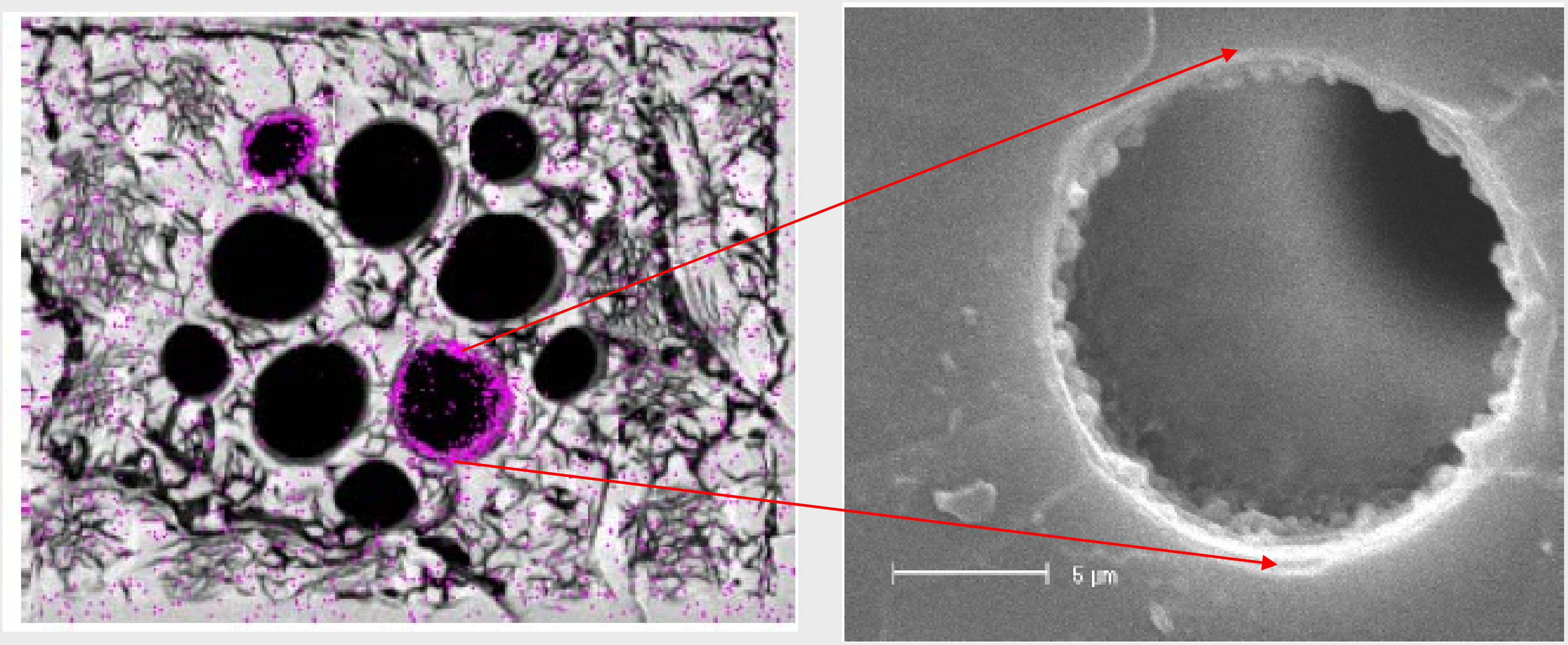
$S(\lambda)=| I_0(n_{an.}+dn)-I_0(\lambda,n_{an.})|/ I_0(n_{an})/dn$

Detectable changes 1%

Detection limit $5 \cdot 10^{-5}$ RIU

Sensor length 250µm

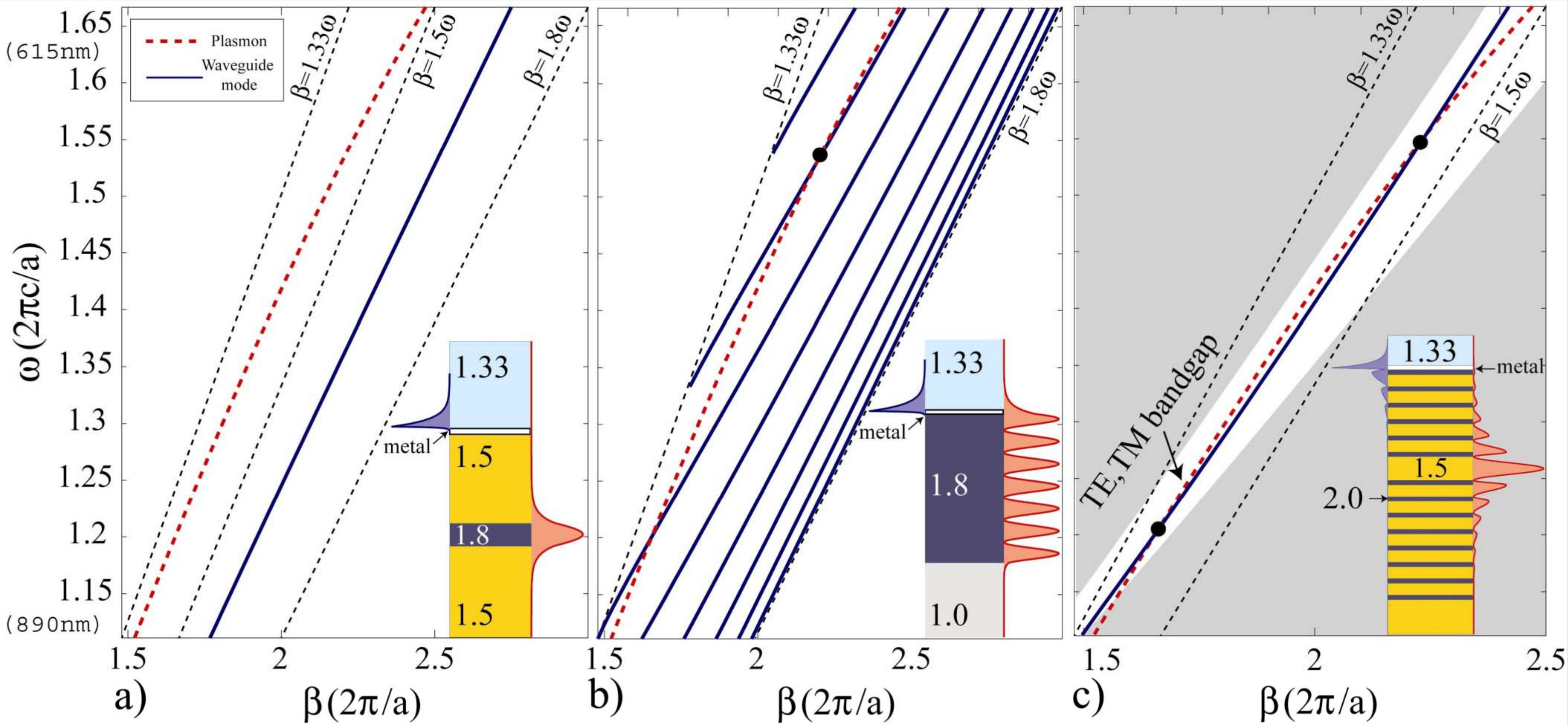
YES, IT IS POSSIBLE to Metalized the Holes inside Microstructured Fibers



A micrograph of the structure, indicating the two coated holes (top). Elemental analysis shows the presence of silver (dots in the image). An SEM of the silver surface of a coated hole is shown on the right.

X. Zhang, R. Wang, F. M. Cox, B.T. Kuhlmey, and M. C. J. Large, “Selective coating of holes in microstructured optical fiber and its application to in-fiber absorptive polarizers,” opt. express, 16270-16278, 2007

Single Mode vs. Multimode vs. Photonic Crystal waveguides



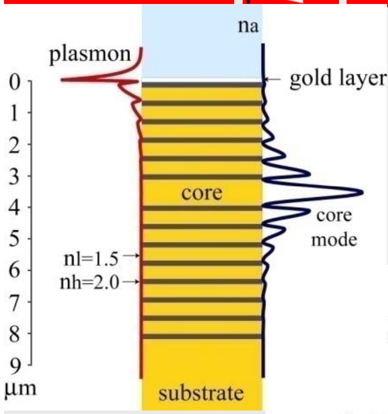
1. Sensitiv. 10^{-4}-10^{-3} RIU 2. Hard to choose proper wg materials, especially for air and water based sensing 3. Convenient and stable coupling	1. Sensitiv. 10^{-5}-10^{-3} RIU 2. Almost any choice of wg materials is fine. 3. Inconvenient and unstable coupling	1. Sensitiv. 10^{-5}-10^{-3} RIU 2. Almost any choice of wg materials is fine 3. Convenient and stable coupling

Nature Photonics - Plasmonics: Sensors tune in, Oct. 2006

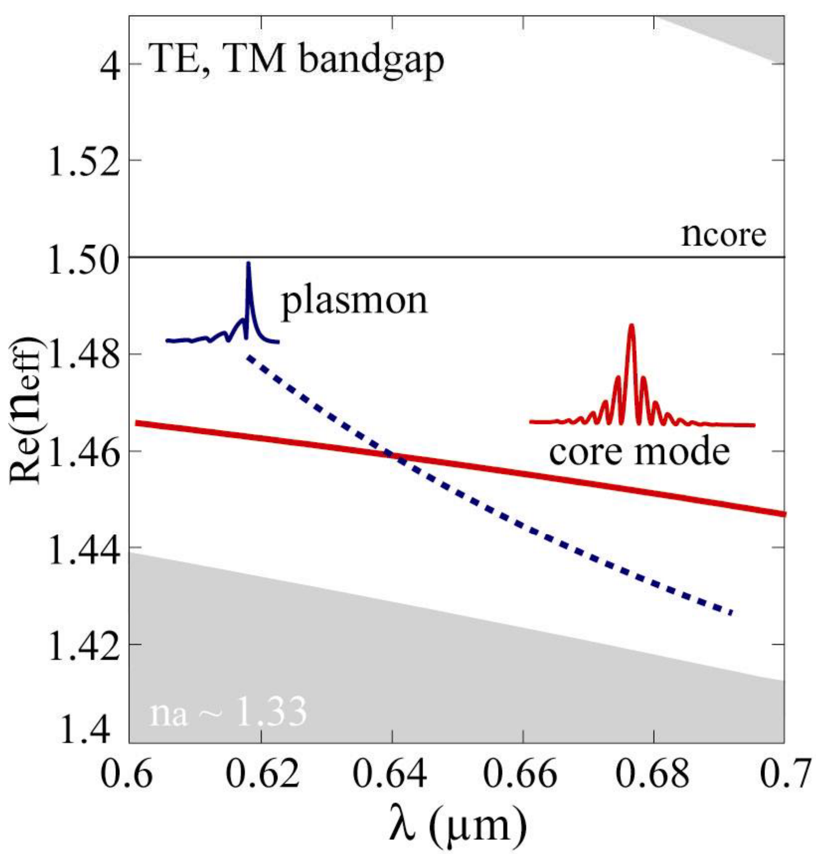
M. Skorobogatiy, Kabashin, “Photon Crystal waveguide-based surface plasmon resonance bio-sensor,” Appl. Phys. Lett. **89**, 143518 (2006)

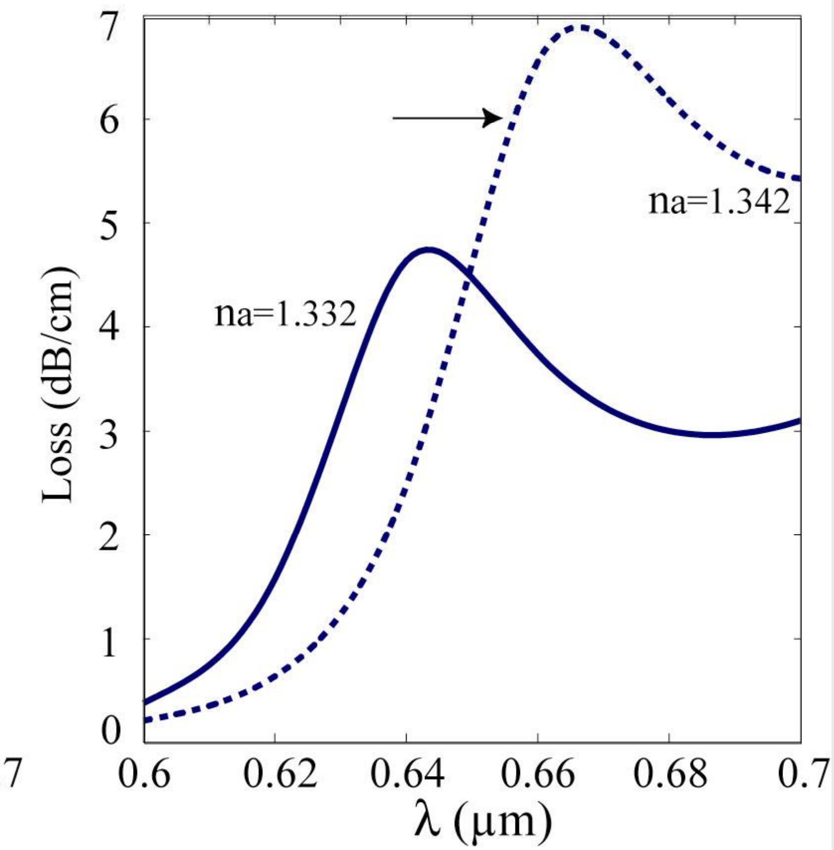
M. Skorobogatiy, Kabashin, “Plasmon excitation by the Gaussian-like core mode of a photonic crystal waveguide,” Opt. Express **14**, 8419 (2006)

Dispersion relations of the core guided and plasmon modes, planar waveguides



B. Gauvreau, A. Hassani, M. Fassi Fehri, A. Kabashin, and M. A. Skorobogatiy, "Photonic bandgap fiber-based Surface Plasmon Resonance sensors," Opt. Express, vol. 15, 11413-11426 (2007).

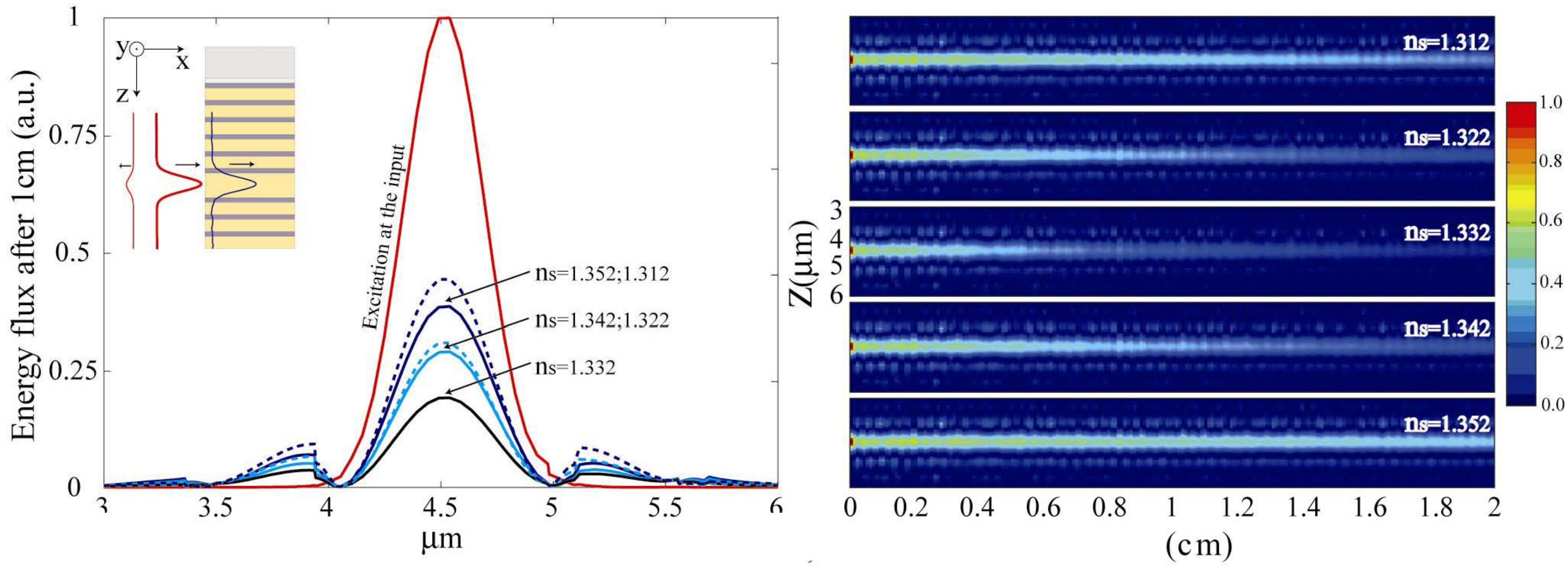




Nature Photonics - Plasmonics: Sensors tune in, Oct. 2006

Energy flux in a multilayer waveguide for various values of the ambient refractive index

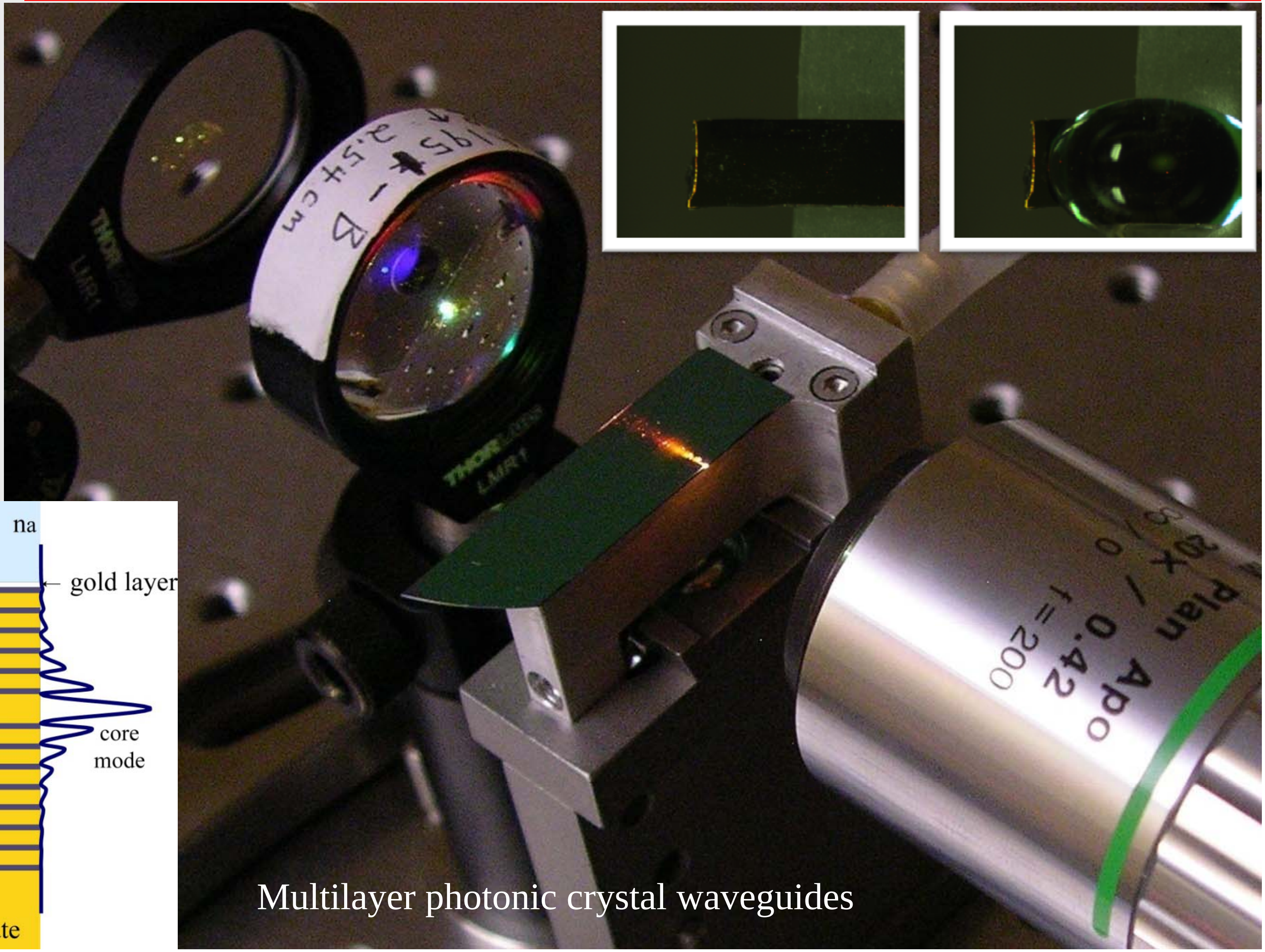
Amplitude Based Sensing



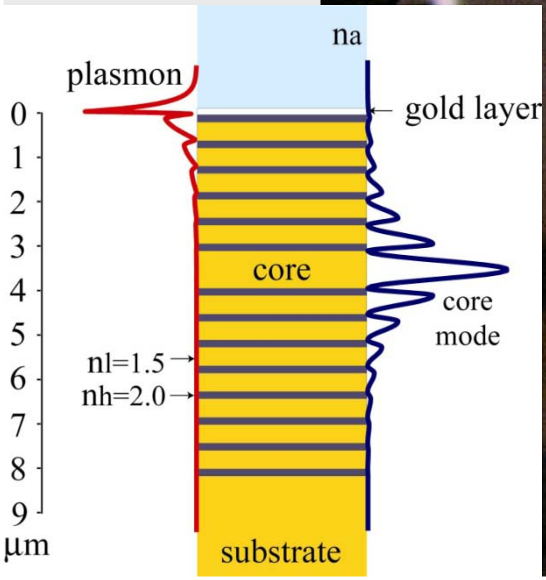
Sensitivity: change in the bulk refractive index resulting in 1% change of the signal amplitude

Optimal designs have theoretical sensitivity as low as $7 \cdot 10^{-6}$ RIU

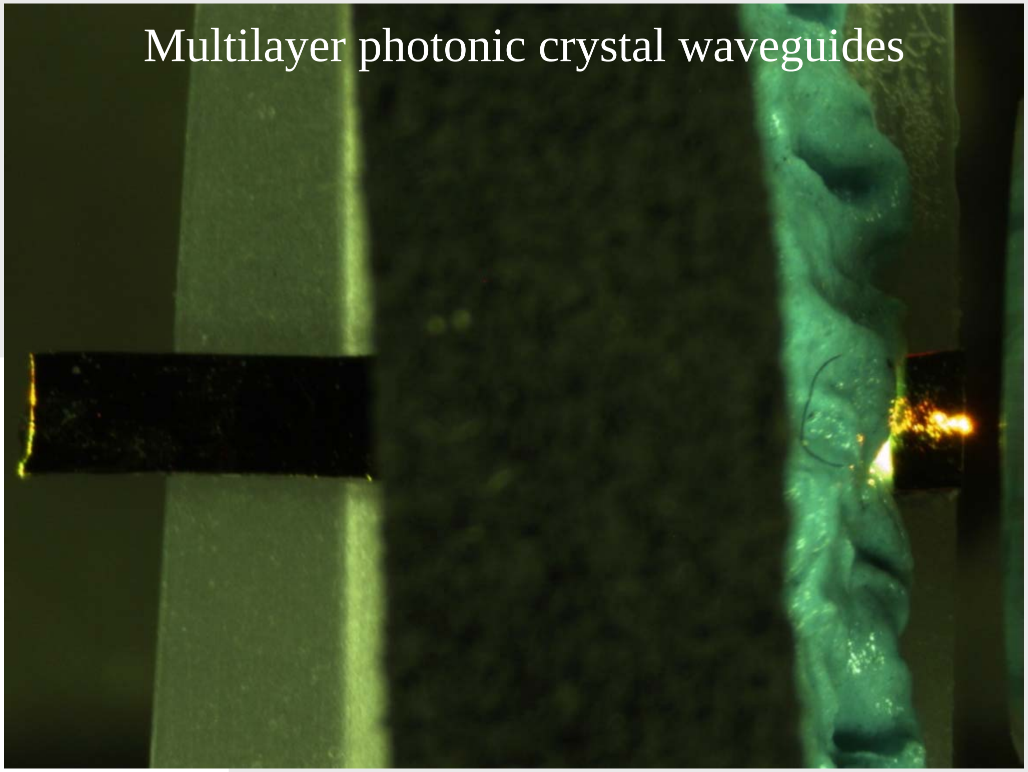
Practical Implementation: thin film deposition

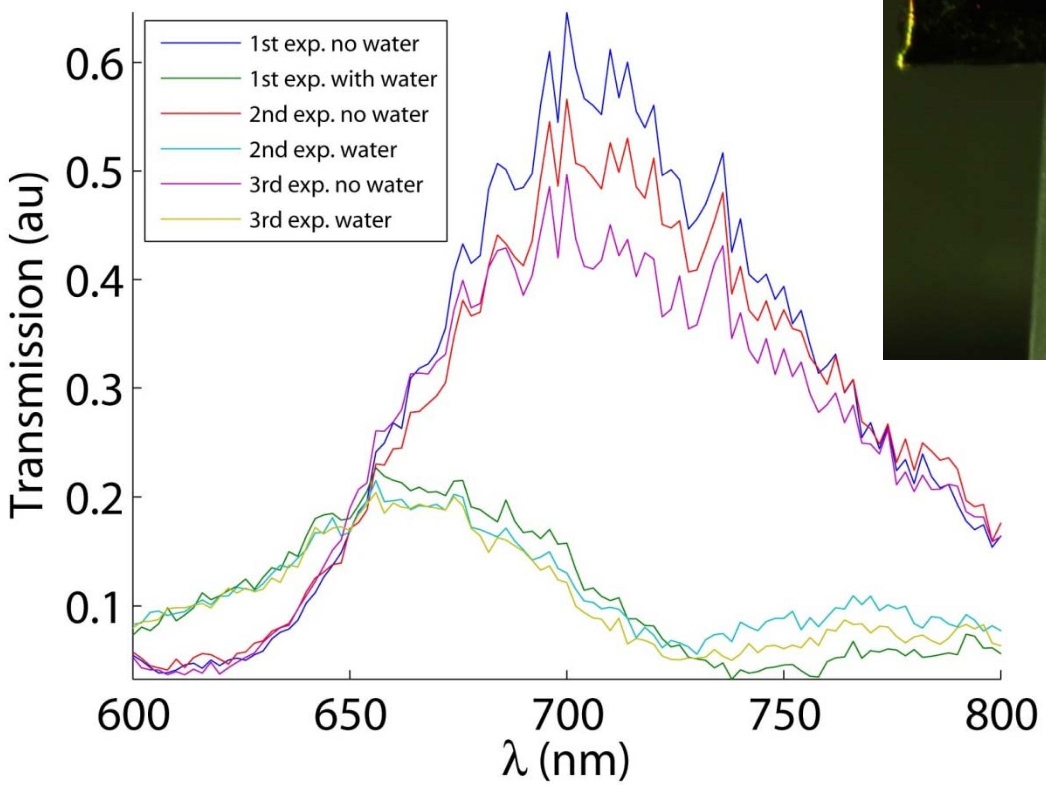


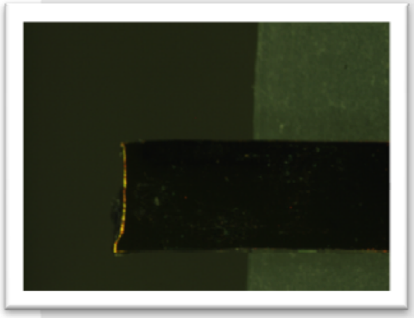
Multilayer photonic crystal waveguides

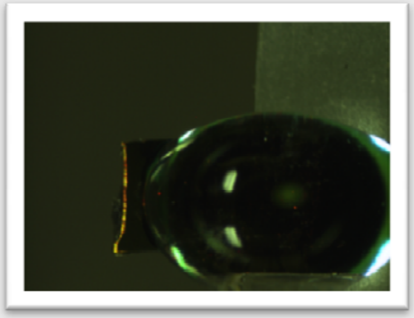


Practical Implementation: planar



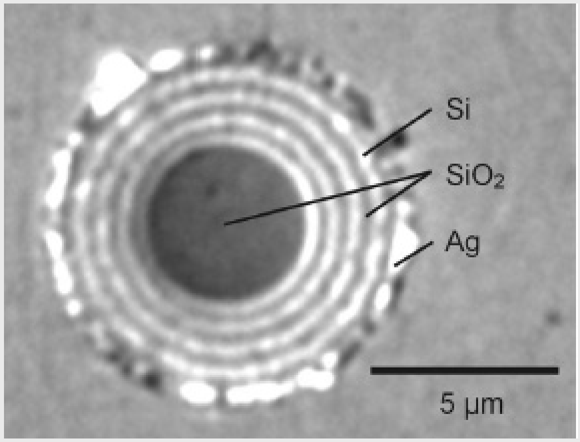




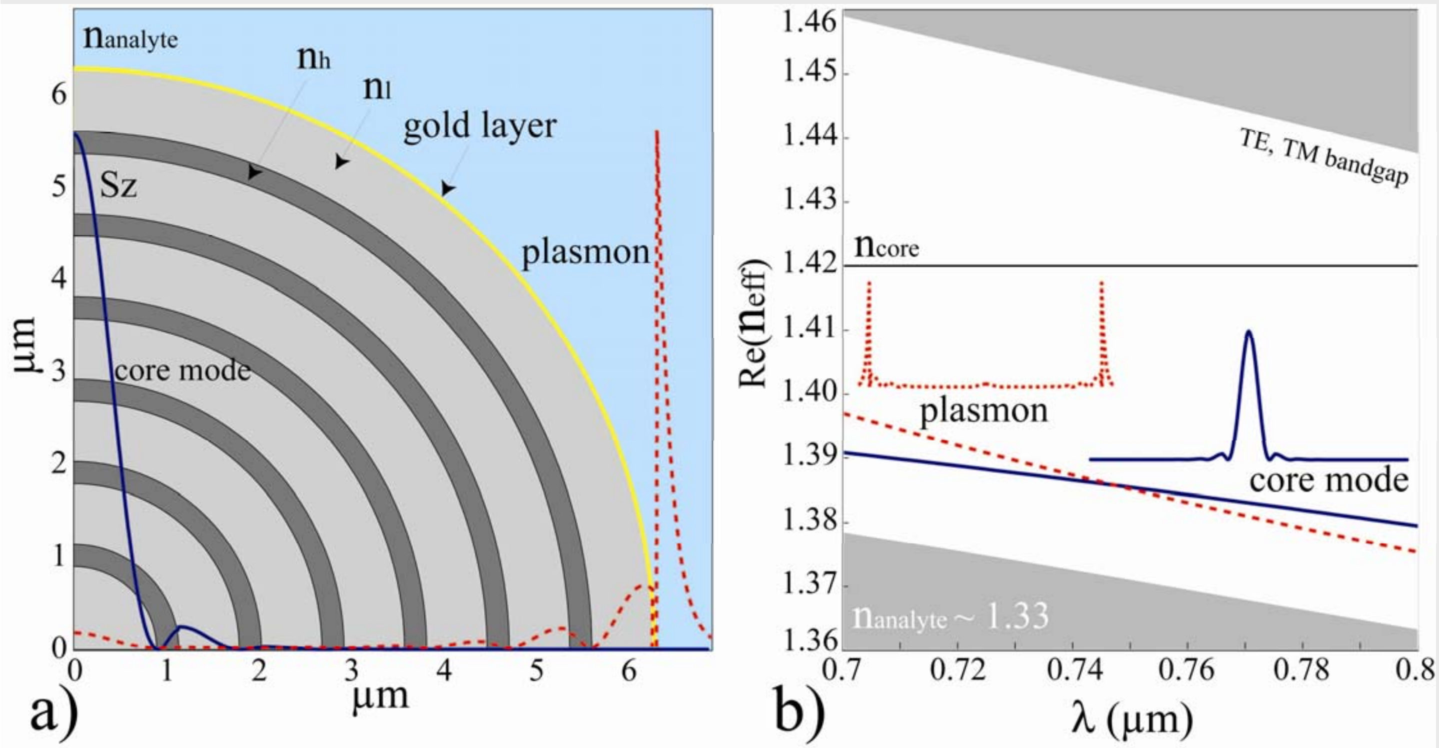


Practical Implementation: tapered Bragg fibers

Lin Ma, Takashi Katagiri, and Yuji Matsuura,” Surface-plasmon resonance sensor using silica-core Bragg fiber,” Optics Letters 34, 1069 (2009)



Bragg fiber-based SPR sensors



III

- Fibers with outer diameters comparable to the wavelength of light, while having highly subwavelength features in their crossection typically operate in the **metamaterial** regime

Applications of THz

•**Inspecting electrical faults in integrated circuits**

Kiwa, Opt. Lett.,

28, 21 (2003)

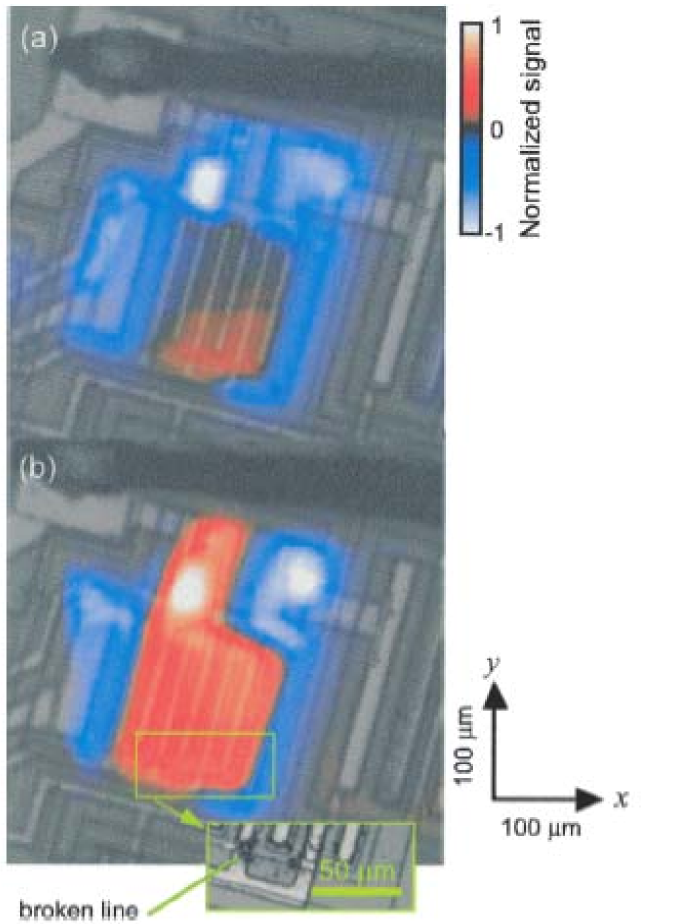
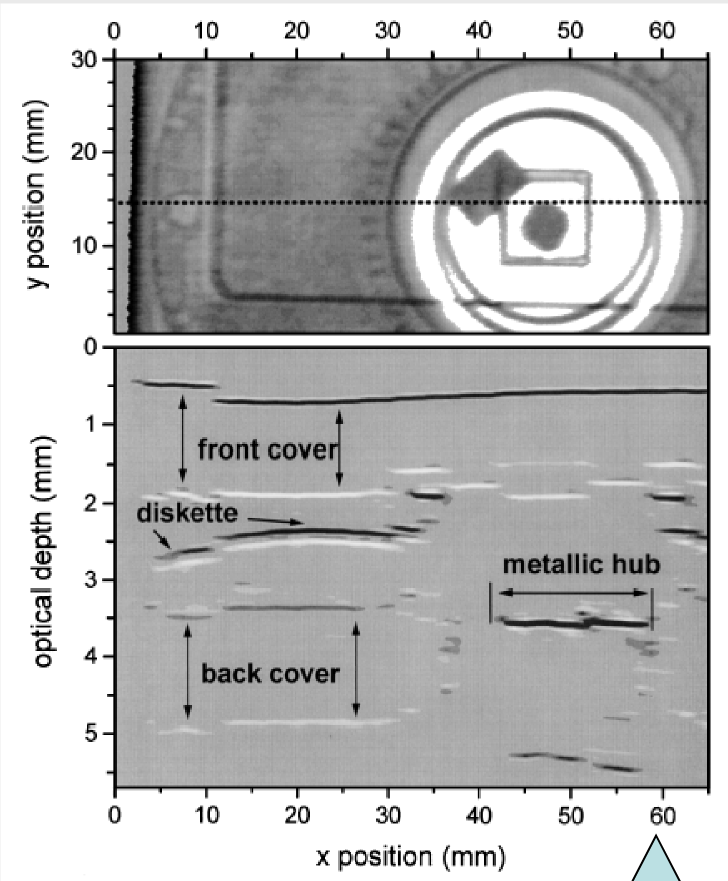


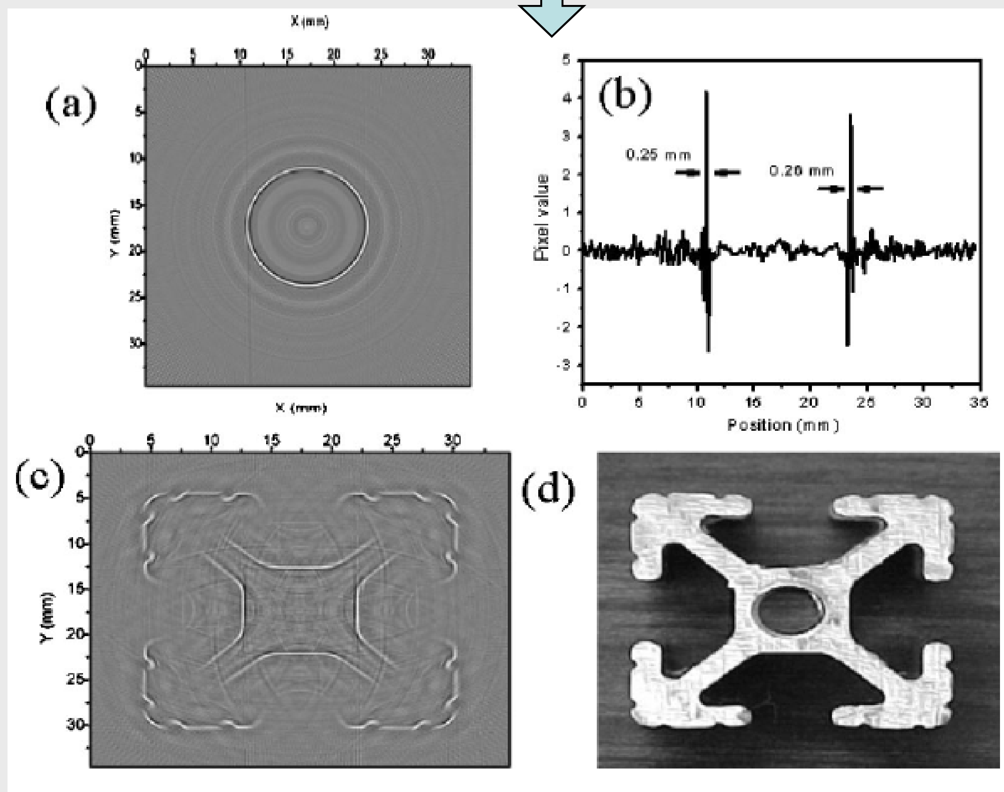
Fig. 4. LTEM images of a (a) normal and (b) broken IC chip. The color scales are normalized with the maximum

Applications of THz

- **Tomography**



Pearce, Opt. Lett., **30**, 13 (2005)

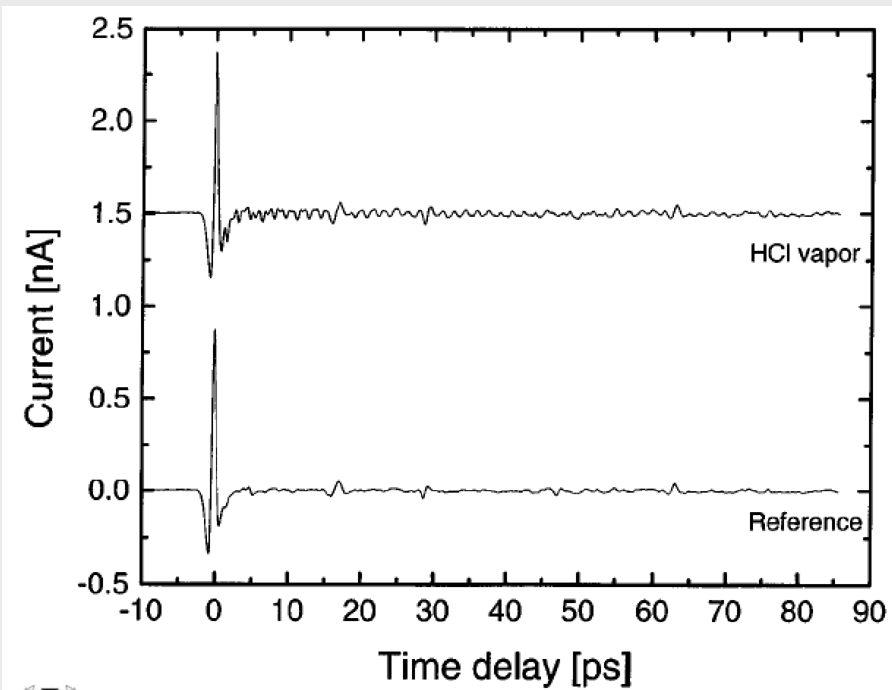


Mittleman, Opt. Lett., **22**, 12 (1997)

Applications of THz

• **Chemical recognition of gases and biomolecules**

Time domain spectroscopy



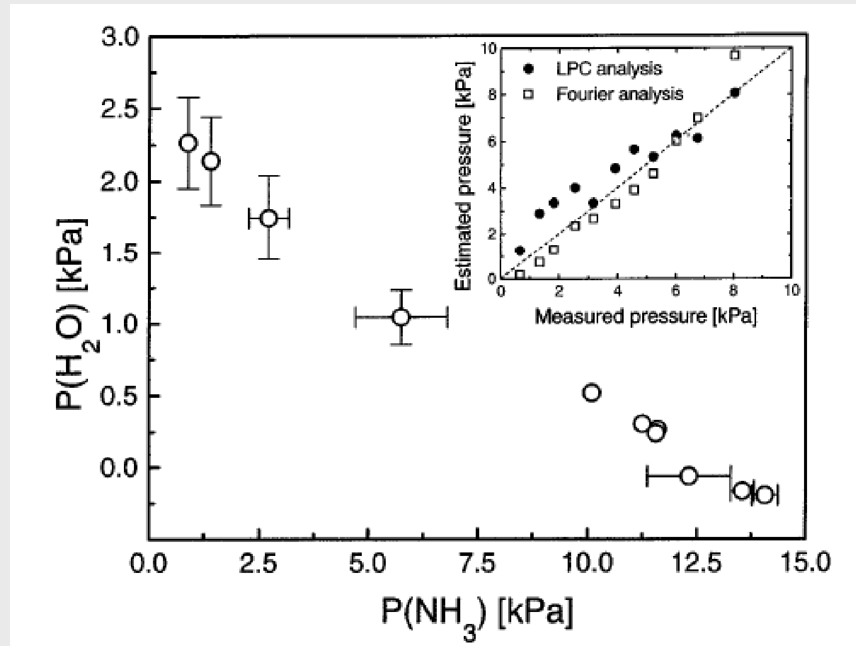
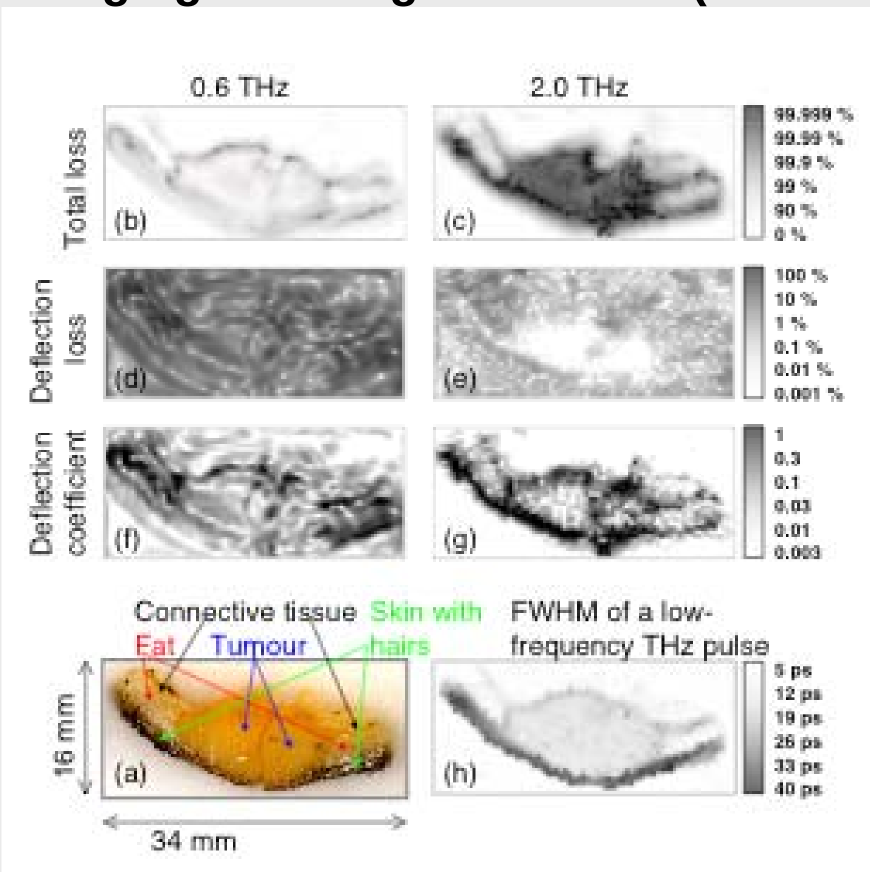


Fig. 4. Result of chemical recognition of mixtures of NH_3 and H_2O. For each mixture we plot a single point representing the estimated partial pressure of the two gas species. The inset shows the estimated versus the measured pressure from a single-species recognition of HCl.

Jacobsen, Opt. Lett., **21**, 24 (1996)

Applications of THz

• **Imaging of biological tissues (tissue recognition)**



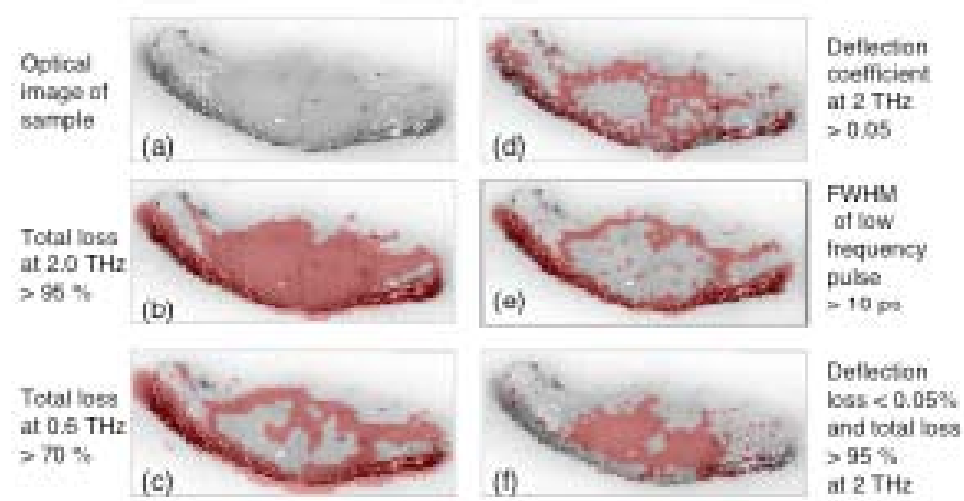


Fig. 4. Optical image of the sample (a) overlapped in (b) ñ (f) with a red mask generated by applying a threshold on various parameters derived from the THz data.

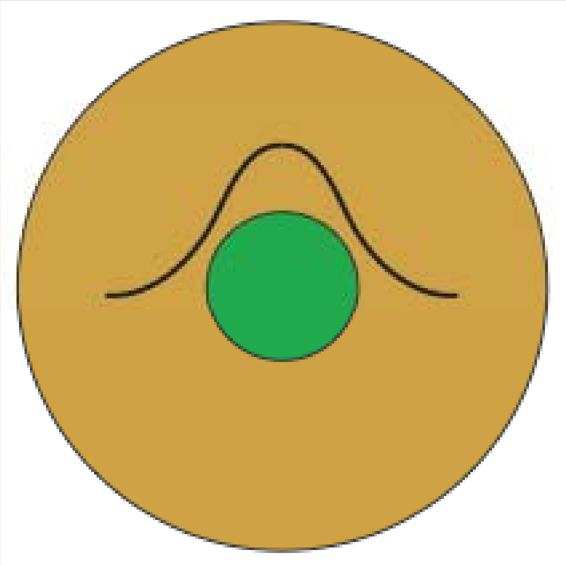
Löffler, Opt. Exp., **9**, 12 (2001)

Introduction to THz guiding

Terahertz: ν = 0.1-10 THz <=> λ = 3000-30 μm

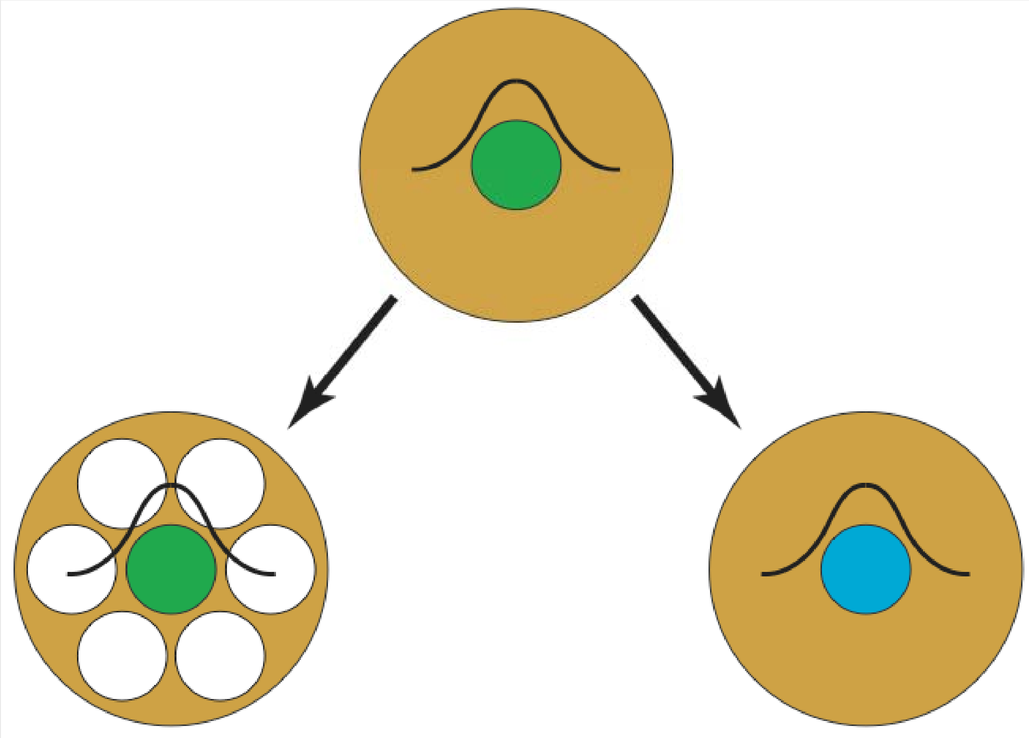
Total Internal Reflection in solid-core waveguide:

- Insensitive to environment (humidity)
- High loss



Introduction

Lowering loss (solid core):

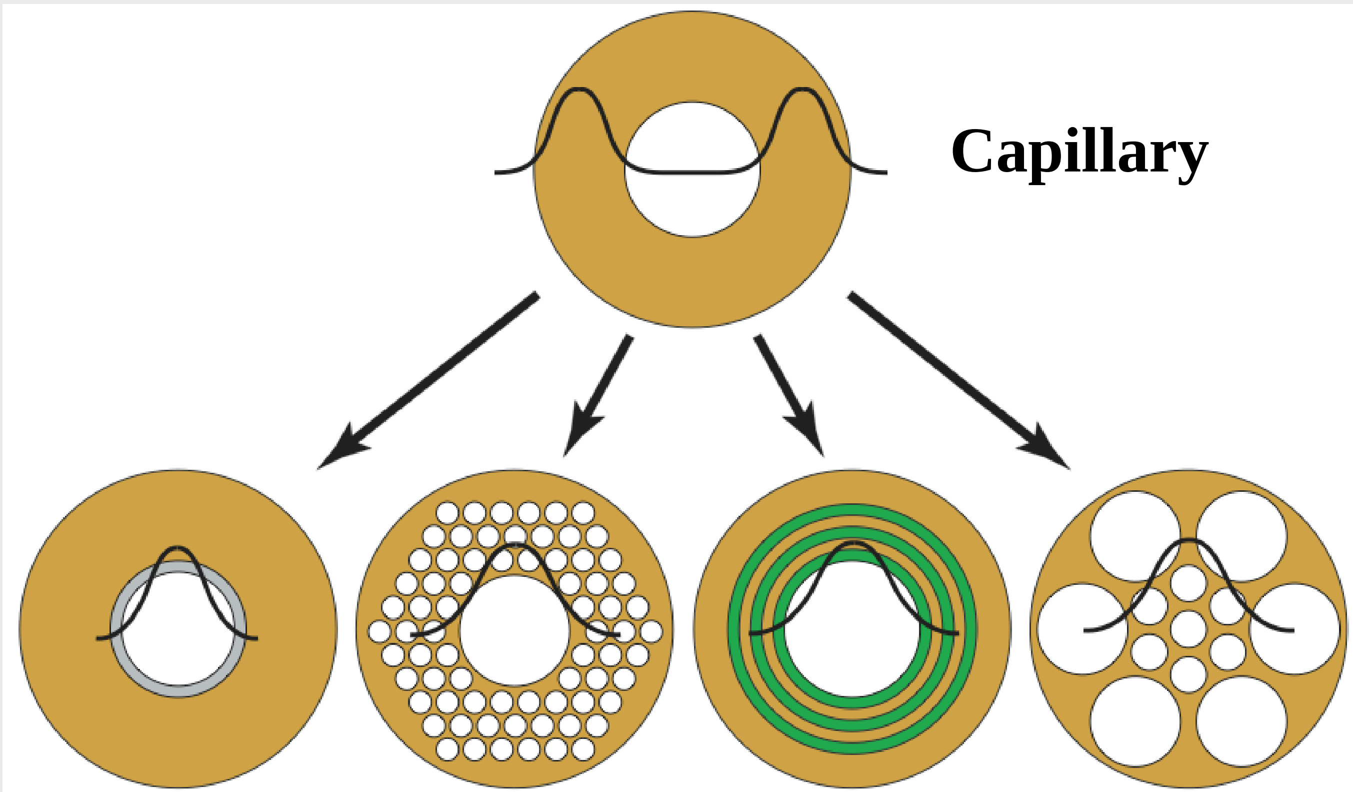


Lower loss dielectric

Holes filled with dry gas

Lowering loss (hollow core):

Metallic



Porous TIR

PCF

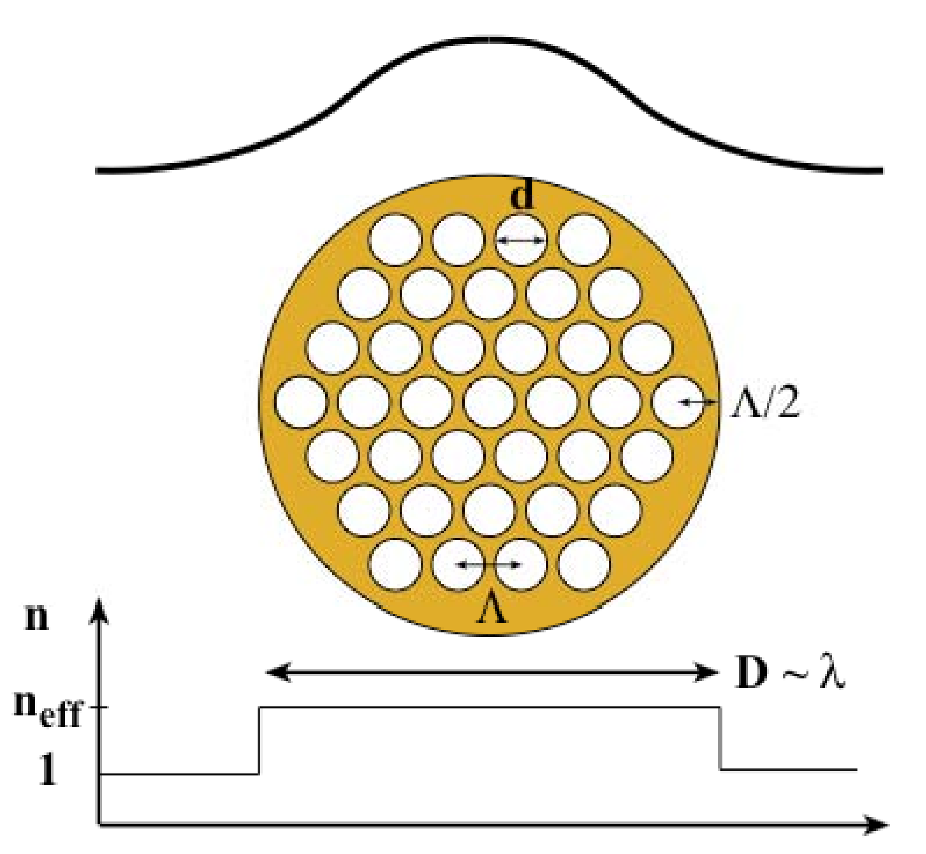
ÉCOLE POLYTECHNIQUE MONTRÉAL

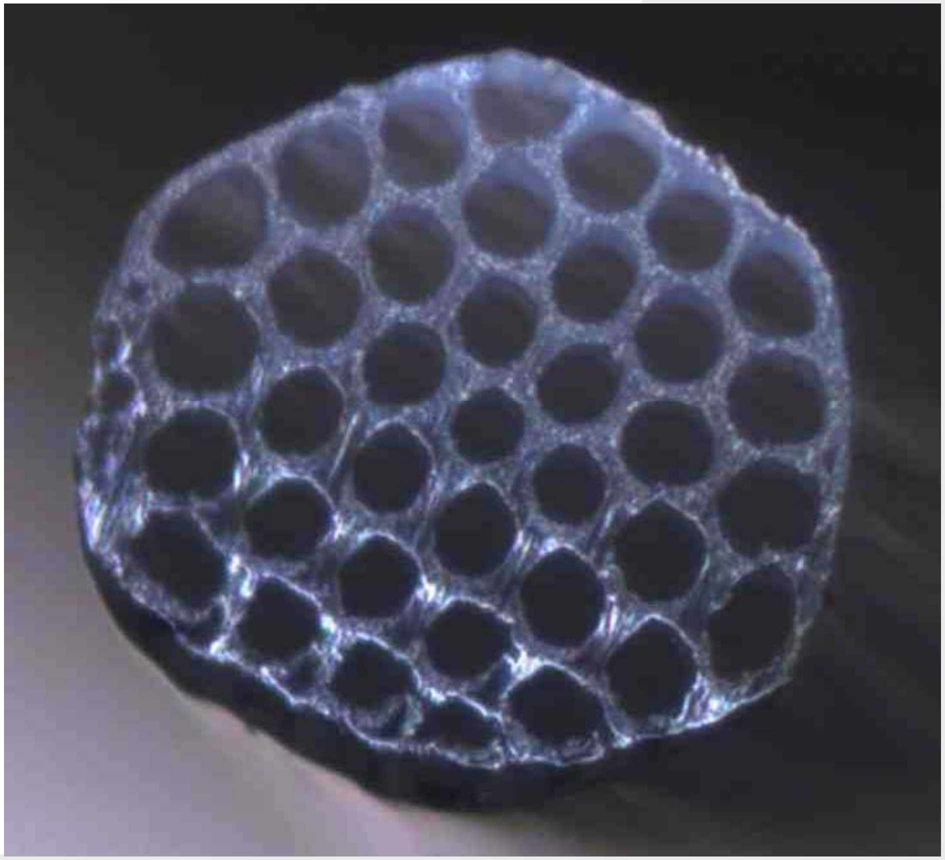
PolyPhotonique

Subwavelength porous fibers for low-loss guidance using strongly absorbing materials (mid-IR, THz)

Subwavelength fibers with highly subwavelength features

Guidance by total internal reflection

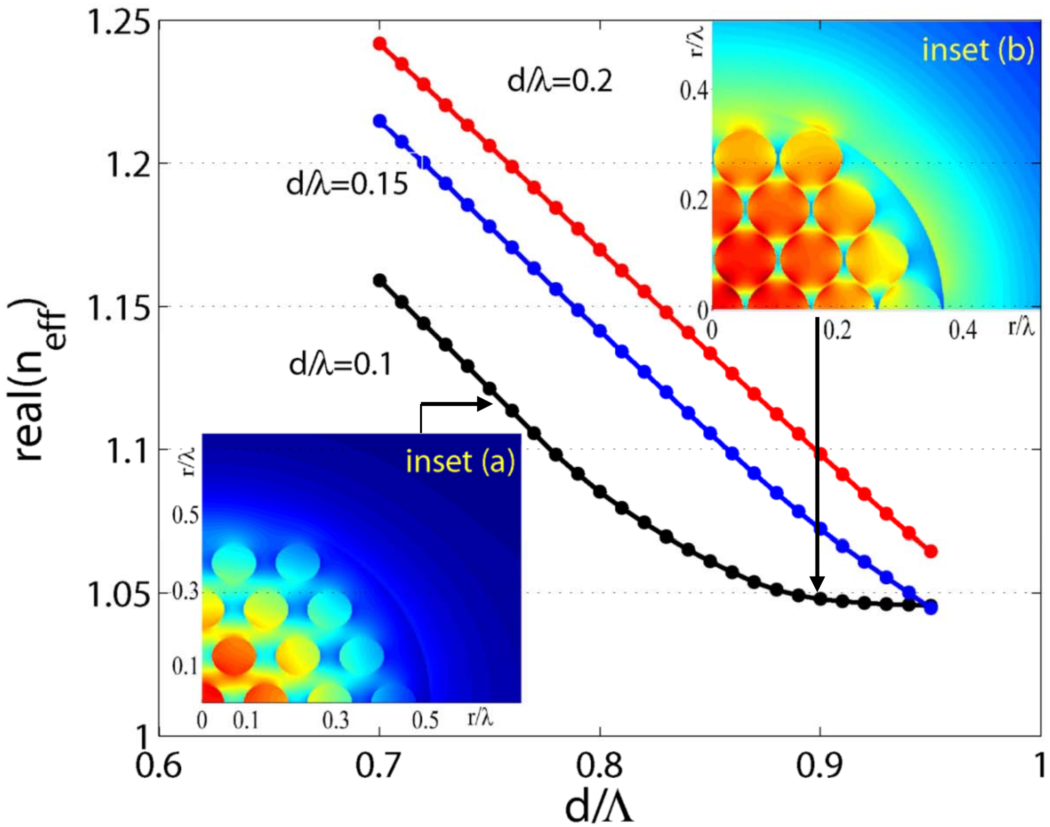




A. Hassani, A. Dupuis, and M. Skorobogatiy, "Low Loss Porous Terahertz Fibers Containing Multiple Subwavelength Holes," Appl. Phys. Lett, vol. 92, 071101 (2008).

A. Dupuis, J.-F. Allard, D. Morris, K. Stoeffler, C. Dubois, and M. Skorobogatiy, "Fabrication and THz loss measurements of porous subwavelength fibers using a directional coupler method," Opt. Express, vol. 17, pp. 8012–8028 (2009).

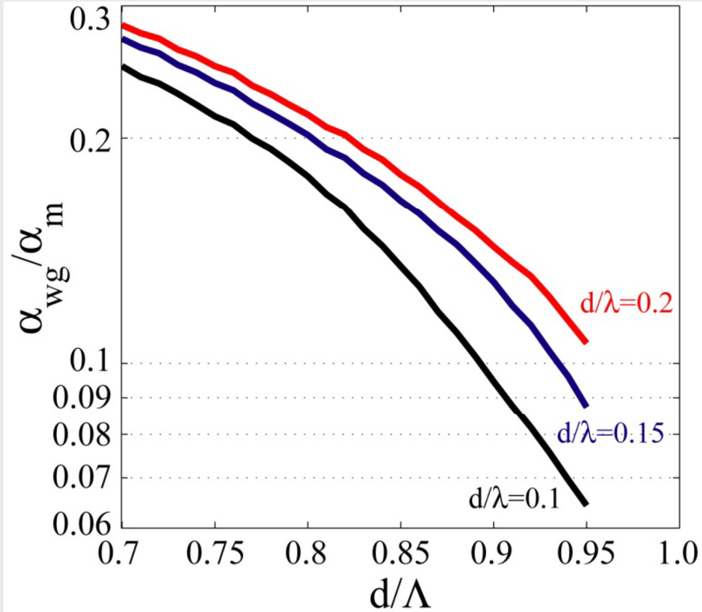
Subwavelength porous fibers



at 1THz, λ=300μm

n_{fiber}=1.5

α_m=1cm^{-1}=435dB/m



To reduce material loss by a factor of 10:

D ~ λ (300μm)

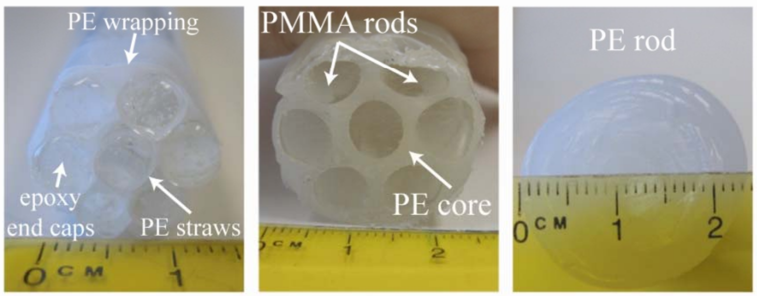
d ~ 0.1λ (30μm)

hvein=Λ-d ~ 0.01λ (3μm)

Subwavelength porous fibers

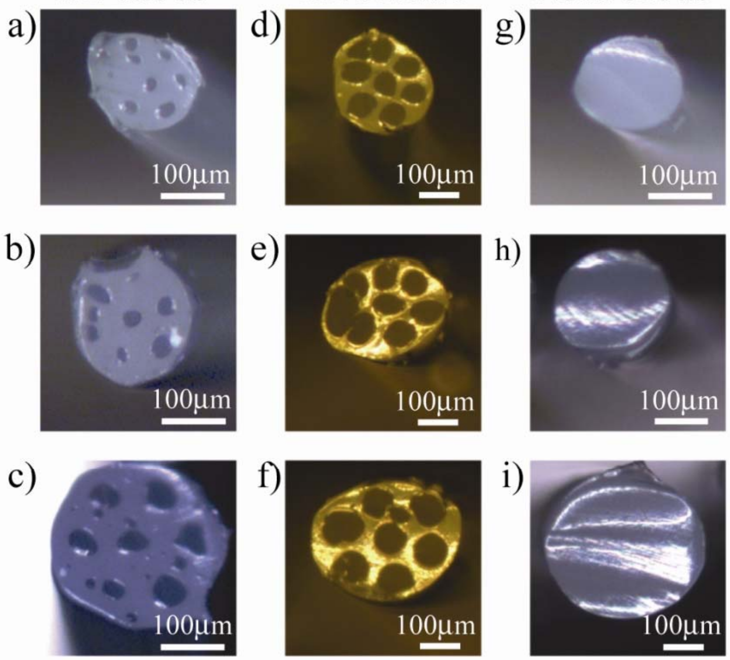
Porous THz Fiber Preforms

PE Tubes | PE/PMMA | Non Porous



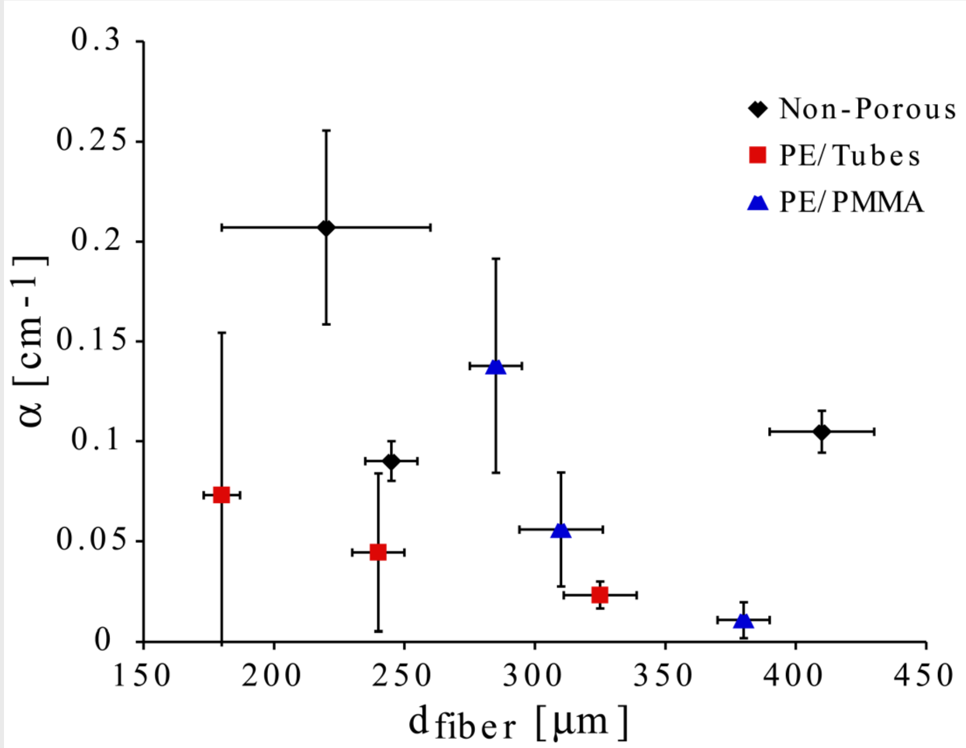
Porous Subwavelength Fibers for THz

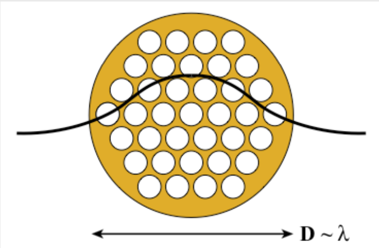
PE Tubes | PE/PMMA | NonPorous

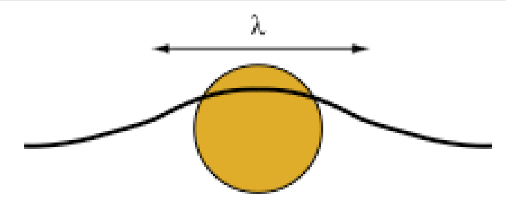


at 1THz, λ=300µm

n_{fiber}=1.5; α_m=1cm^{-1}=435dB/m







Conclusions

- We have discussed three examples of optical fibers whose operation relies on presence of nano-sized structure in the fiber crossection.
- First example was photonic bandgap Bragg fibers containing highly subwavelength layers ($\lambda/10$) to provide **resonant** light confinement in the low refractive index core. Application in sensing, and photonic textiles.
- Second example was photonic crystal fibers containing metallic inclusions. In this configuration, highly localized and lossy **plasmonic modes** ($\lambda/5$) could be coupled to guided core modes. Application in compact and highly sensitive sensors of refractive index.
- Third example was a porous subwavelength fiber that guides light predominantly in the subwavelength air gaps ($\lambda/10$) surrounded by even thinner ($\lambda/100$) material veins (**metamaterial**). Application in low-loss guidance with even highly lossy materials (mid IR, THz).

Acknowledgements

- Prof. C. Dubois
- Prof. J. Berzowska (Concordia U.)
- Designer Kathy Shicker (University of the Arts London)
- Res. Assoc. E. Pone
- PhD N. Guo
- PhD A. Dupuis
- PhD A. Hassani
- MSc B. Gauvreau

- The Natural Sciences and Engineering Research Council of Canada
- Fonds Québécois de la Recherche sur la Nature et les Technologies
- Canada Research Chair Foundation
- Canadian Institute for Photonics Innovations