Photonics Crystal Fibers:
from origin to actual applications

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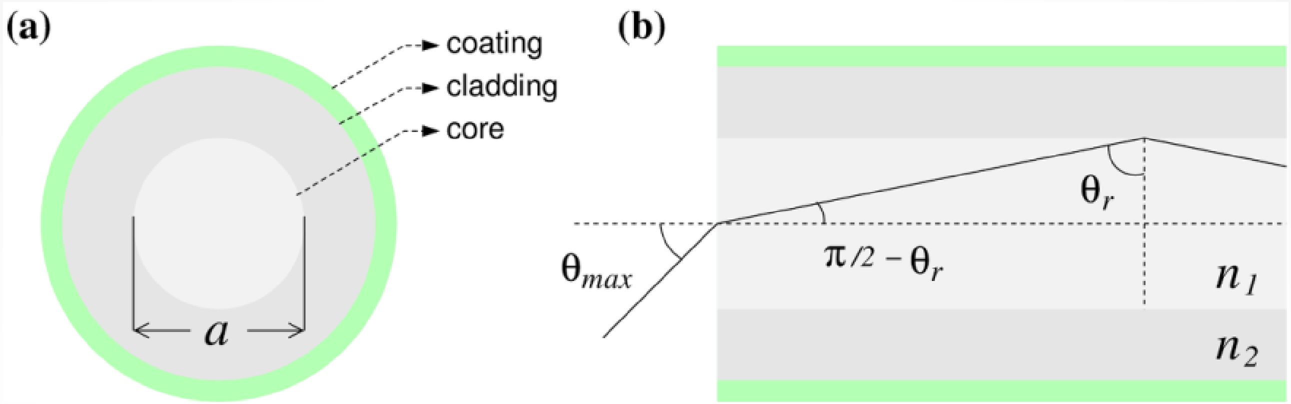
Outline

- Brief introduction to optical fibers
- Photonic Crystal Fibers (PCFs)
- Properties of PCFs
- Applications of PCFs

Outline: Brief introduction to optical fibers

- **Brief introduction to optical fibers**
  - Step Index Fibers: principles of guidance
  - Manufacturing and materials
  - Optical fibers in telecommunications
  - Different applications

Step Index Fibers: principles of guidance



- Optical fiber: **dielectric waveguide with cylindrical symmetry**.
- The most simple design involves a **core** with higher refractive index n_1 surrounded by a **cladding** with lower index n_2 , **(Step Index fiber - SIF).**
- Principle of guidance is based on Snell Law and **Total Internal Reflection (TIR).**
- Defining:

$$\bar{e}(x,y,z) = \bar{E}(x,y)\, e^{-\beta z}$$

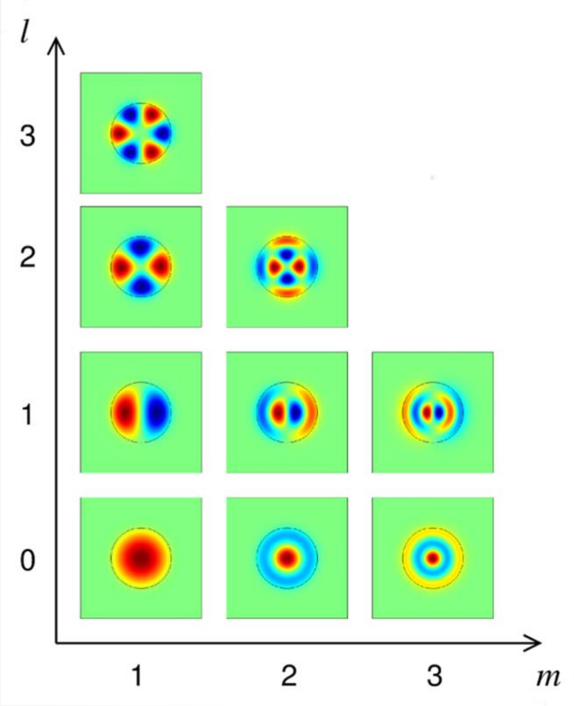
$$\bar{h}(x,y,z) = \bar{H}(x,y)\, e^{-\beta z}$$

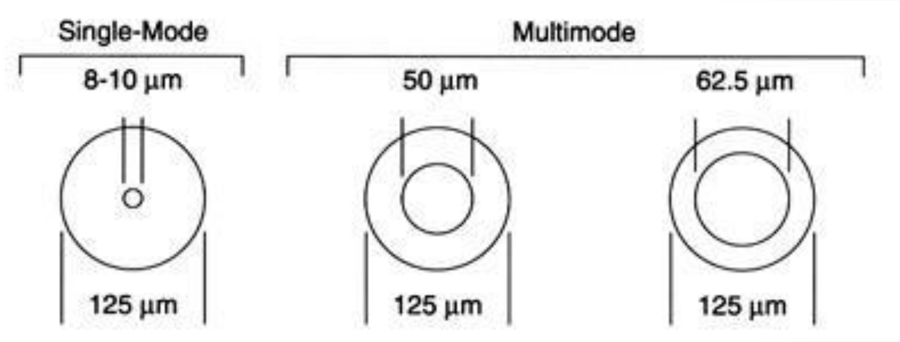
Modes

Modes are guided in the core when:

$$n_2 k_0 < \beta_{mode} < n_1 k_0$$

Step Index Fibers: principles of guidance





- The number of Modes that can be guided depends on the **V-number.**

$$V = \frac{2\pi a}{\lambda}\boxed{\sqrt{{n_1}^2 - {n_2}^2}} \rightarrow$$ Numerical Aperture - **NA**

- **Single mode operation** is obtained when $V < 2.405$ in a SIF.

Manufacturing and materials

- A **preform** (1-10 cm thick and 1 m long) is drawn with a controlled temperature, till it reaches the final diameter.
- The most common fibers is made of **silica proper doped** to obtain the desired index profile.
- GeO_2 or Al_2O_3 are used to raise the refractive index while F_2 or B_2O_3 are used to decrease the index.

- **Rare-earth dopants** can be used in fiber amplifiers (Er^{3+}, Nd^{3+}, Yb^{3+}, Tm^{3+} …)
- Materials other than Silica can also be used:
  - Fluoride glasses (ZEBLAN) (Mid-IR)
  - Chalcogenide glasses (sulfides, tellurides…) (Mid-IR)
  - Plastic materials (PMMA, polycaronates) (Visible)

Note: Silica is optimum in the Near-IR region.

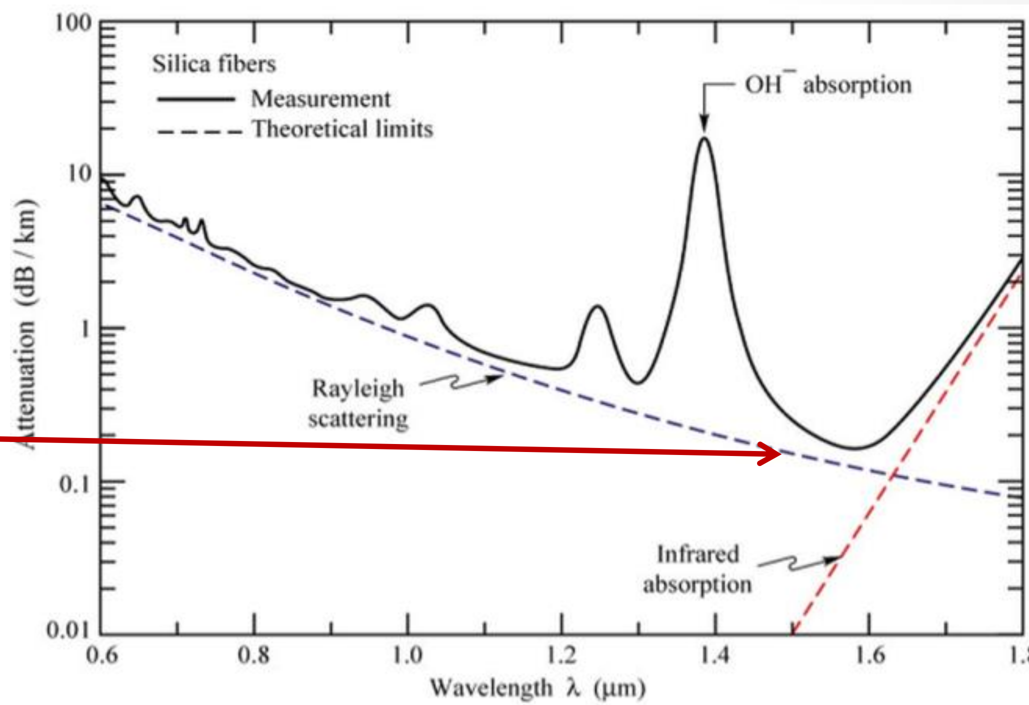
Optical fiber in telecommunications

- The main application of silica SIF is in **long distance communications**:
  - huge capacity of fibers for data transmission, (large number of channels multiplied),
  - huge transmission rate achievable,
  - possibility to re-amplify in a single fiber amplifier.
  - low costs,
  - electromagnetic immunity,
  - very low attenuation.

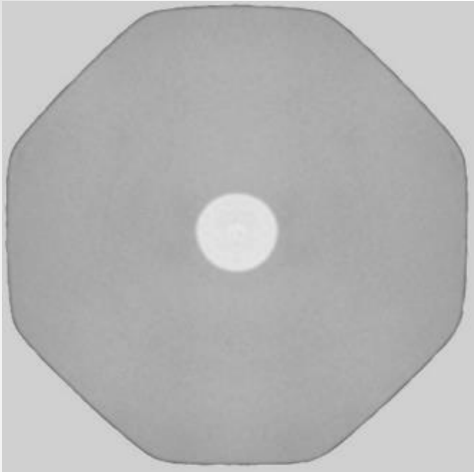
0.2 dB/km

at

1550 nm



Different applications



- **Fiber Lasers**: fiber amplifiers can be used as a cavity to onset lasing effects. Fiber lasers show excellent properties in term of emission quality.
- Efficient pumping using **Double Cladding (DC)** fibers
- More power delivered with **Large Mode Area (LMA)** fibers.

- **Sensors:** a large amount of physical, environmental factors can change the light propagation in fibers (temperature, bending, mechanical traction…)

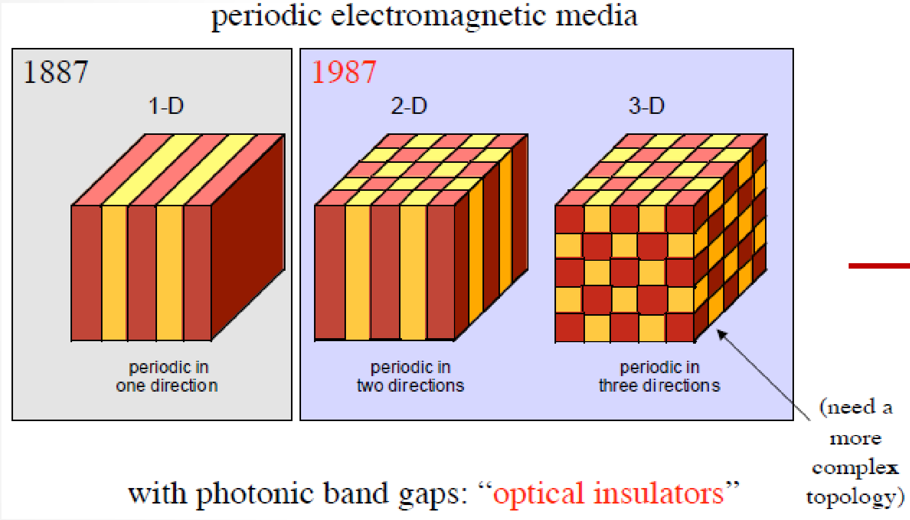
- **Illumination sources for imaging** (endoscopy, microscopy…)

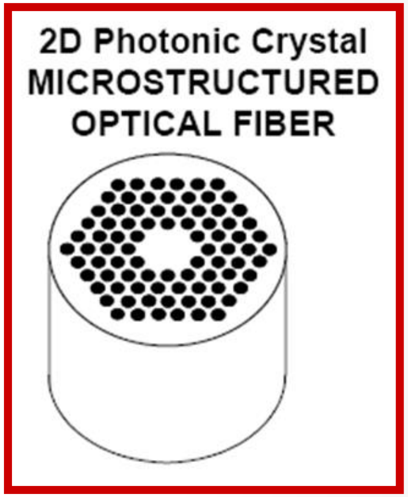
Outline: Photonic Crystal Fibers (PCFs)

- **Photonic Crystal Fibers (PCFs)**
  - Overview on Photonic Crystals
  - Birth of PCFs
  - Propagation diagram
  - Guidance: modified Total Internal Reflection
  - Guidance: Photonic Band Gap
  - Manufacturing and materials
  - Numerical charecterization

Overview on Photonic Crystals

- **Photonic Crystals** is a periodic optical structure that affects the photons transport..
- Photonic Crystals can be artificially created in 1, 2 or 3 dimensions.

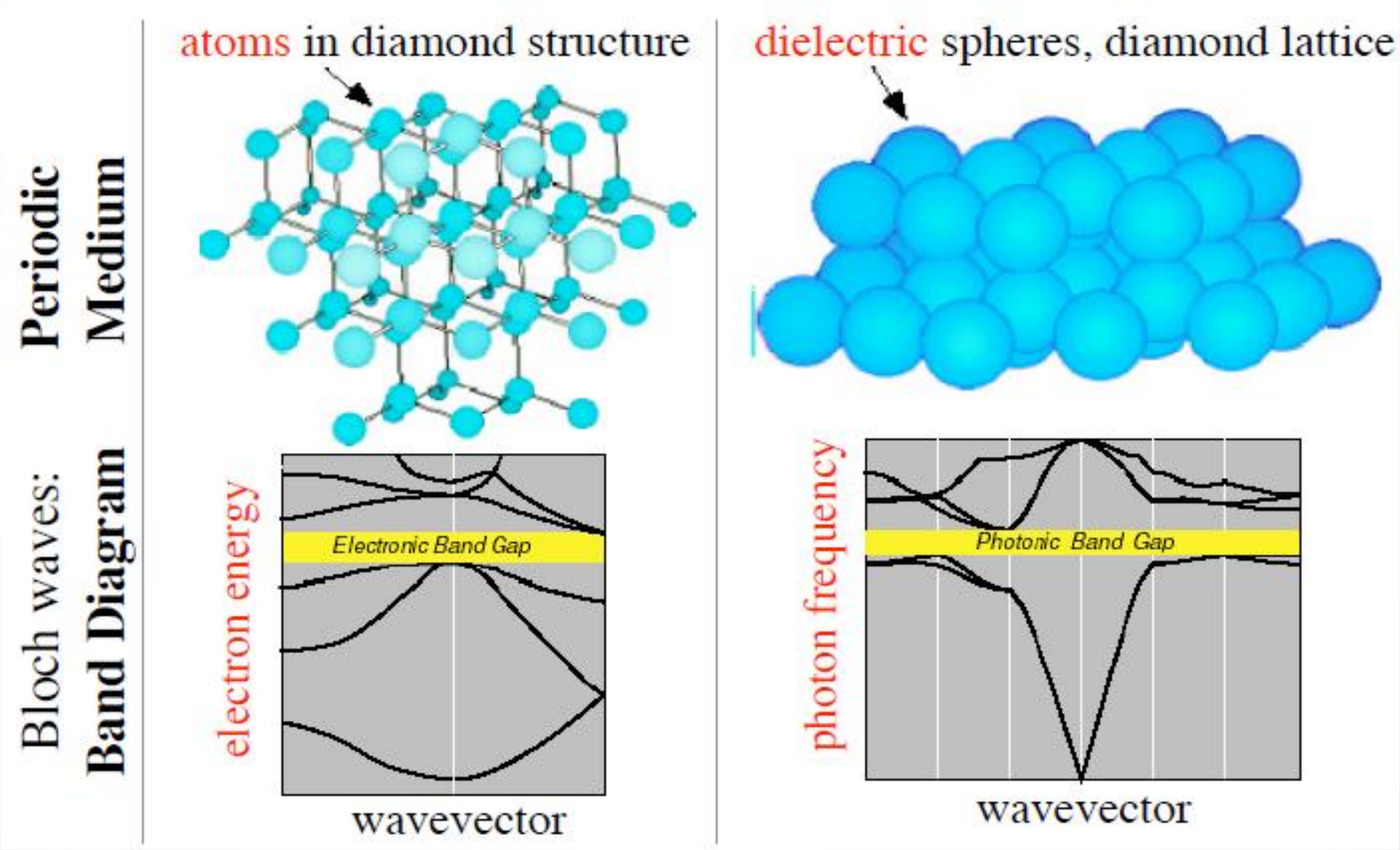




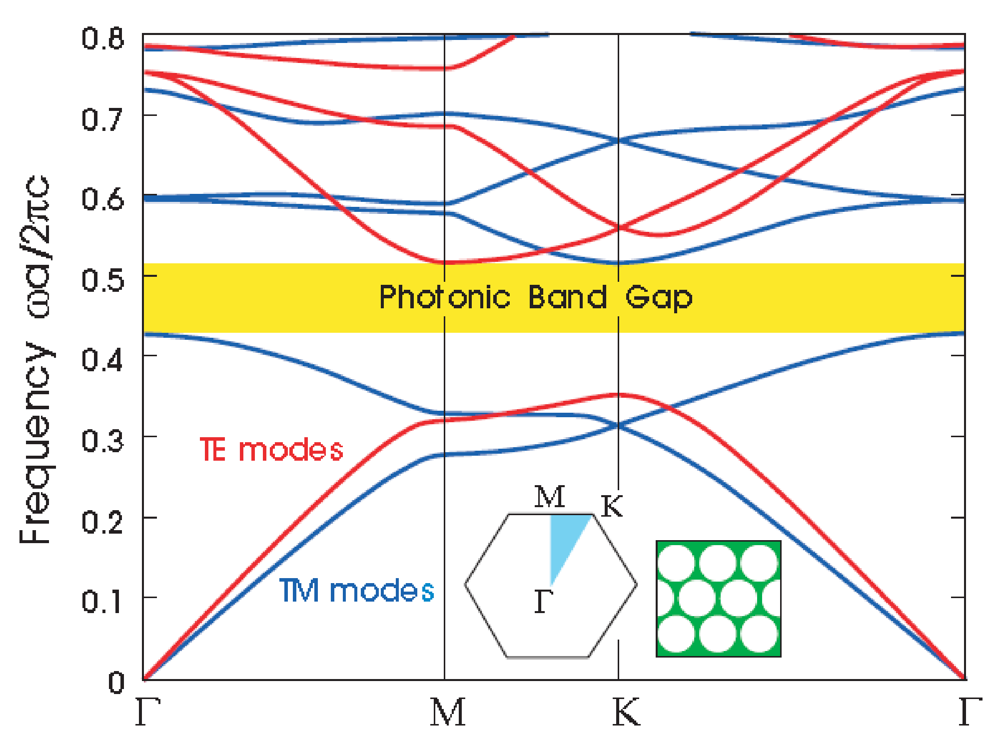
- Natural Photonic Crystals, give the color properties of peacock feathers and translucence of opals.

Overview on Photonic Crystals

- In a Photonic Crystals electromagnetic wave propagation is affected in the same way that the periodic atom lattice of a crystal affects electron motion by defining allowed and forbidden electronic energy bands.



Overview on Photonic Crystals



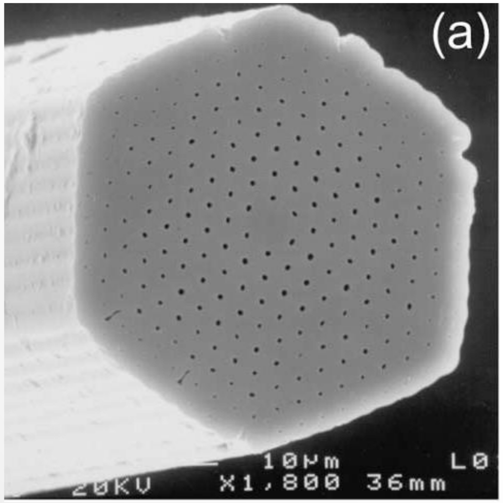
- It is possible to trap the light in a photonic crystal by introducing a point defect (or a line defect, in more elaborated structures).

- In a PCF the properties of the **photonic crystal cladding** (2-D periodic defect-free material with its own well-defined band structure) determine the behavior of the guided modes that form in the **core** (structural defect)
- Properties of guided mode are, therefore, mainly determined by the pitch Λ between holes and by their diameter **d** .

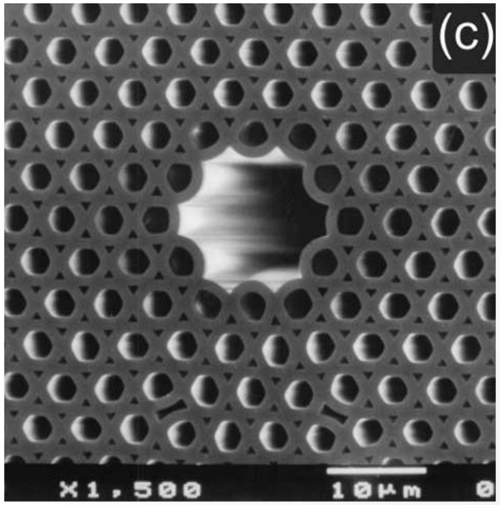
Birth of PCFs

- PCFs (alternative names: Micro-structured Fibers or Holey Fibers) born in 1991 from an idea of **Philip St. Russell,** to create a new kind of dielectric waveguide able to trap light in a hollow core by means of a 2-D photonic crystal made of microscopic air capillaries running along the entire length of a glass fiber,
- This means, fibers with a **periodic transverse microstructure** for guiding light by means of a **2-D Photonic Band Gap (PBG).**

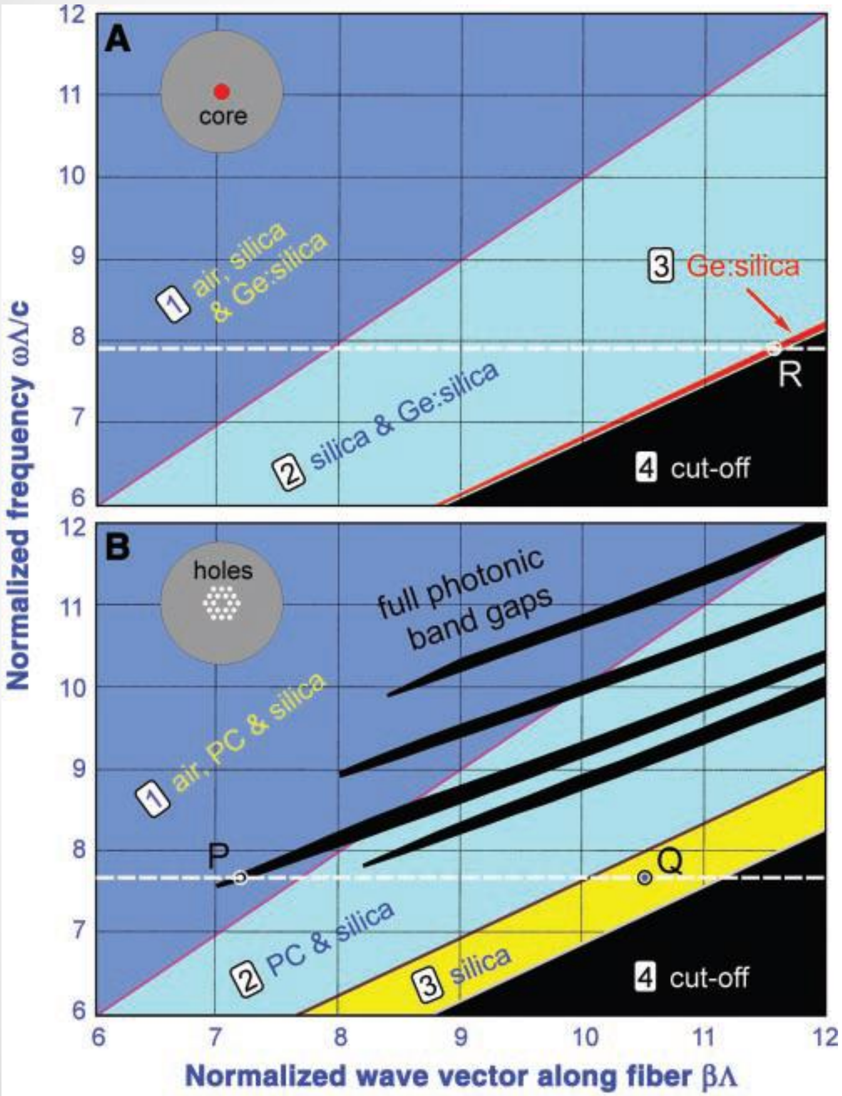
1st solid-core PCF (1995)



1st hollow-core PCF (1999)



Propagation diagram



- **Propagation diagram:** map of the ranges of frequency and axial wavevector component β where light is evanescent.
- **A:** SIF diagram, where propagation is allowed in the red stripe (TIR)
  $$(n_2 k_0 < \beta < n_1 k_0)$$
- **B:** PCF diagram, when $\beta < k_0$ light can propagate everywhere, when $k_0 < \beta < n_g k_0$ light can propagate only in the silica.
- **Black region:** light is cut-off from propagating.
- **P:** Band gap guidance.
- **Q:** modified-TIR guidance.

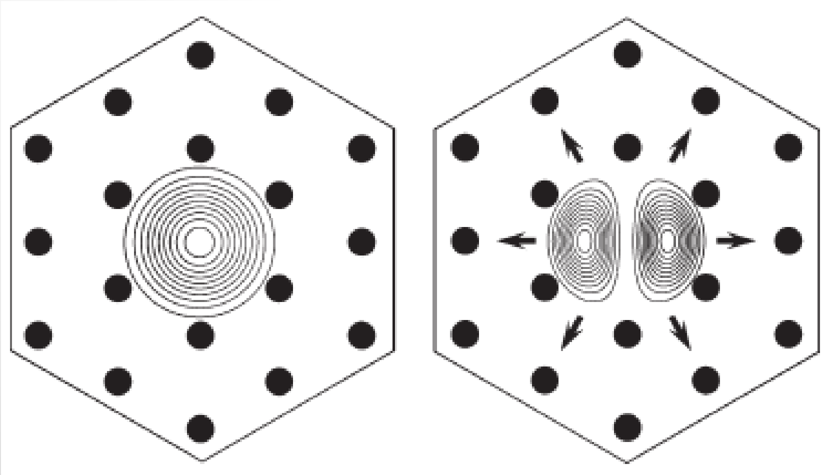
Guidance: modified Total Internal Reflection

- **Modified Total Internal Reflection (m-TIR)** appears in some respects similar to **conventional TIR**:

$$(n_{cl}k_0 < \beta < n_1 k_g)$$

where n_{cl} is the virtual reflective index of the periodic structure, n_{cl} is strongly dependent on the wavelength.

- Solid core PCFs show the unique property to be **Endlessly Single Mode (ESM).**
- When single mode operation is obtained setting $\boldsymbol{d/\Lambda}$ $(d/\Lambda < 0.43)$, it is independent from λ.
- **Mode sieve interpretation**:

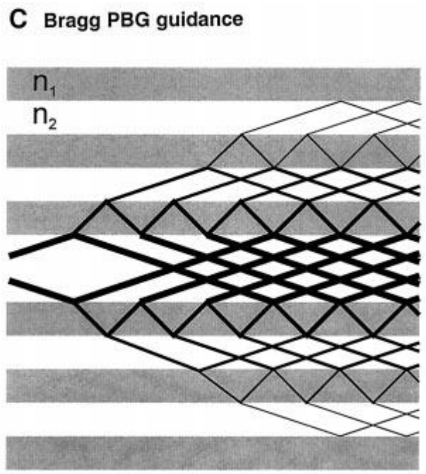


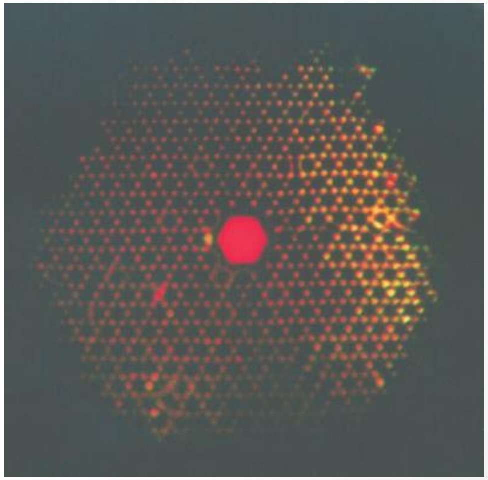
- In SIFs at short λ, the fiber becomes multimode
- Possibility of **increasing the core area**
- Possible anti-guiding behavior at short wavelength when a down-doped core is used.

Guidance: Photonic Band Gap

- Typical of PCFs with negative core-cladding index difference, TIR is not possible
- The mechanism involves the possibility of light to propagate in air, when it is prevent to penetrate the cladding because the presence of the band gap.
- In a air - silica PCFs
  - **large air-filling fraction**
  - **small hole-to-hole spacing**

  are necessary to achieve PBGs in the region $\beta < k$.
- Since PBGs are quite narrow, the hollow core must be sufficiently large to permit a guided mode.

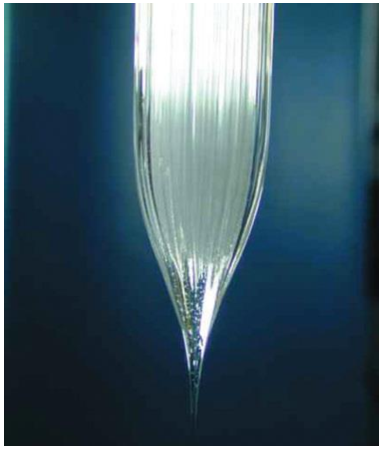


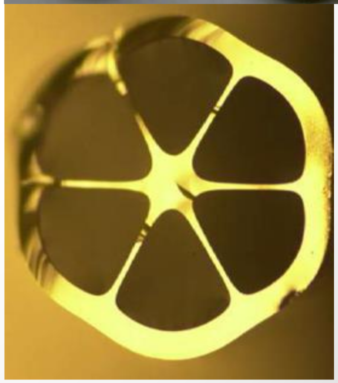


Manufacturing and materials

- Passive PCFs are typically made of pure silica.
- The same dopant used in SIF can be applied in the solid core of PCFs (rare earth for active fibers, amplifiers)
- Also different substrate materials can be used (fluoride, telluride, polymers...)

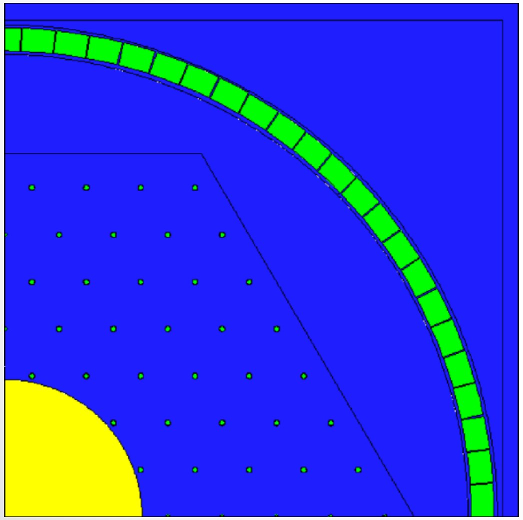
- Manufacturing of preforms is more complicated due to the geometrical complexity:
  - **stacking of capillaries and rods**
  - extrusion (telluride, fluoride)
  - sol-gel casting
  - injection molding
  - drilling (soft-glass, polymers)

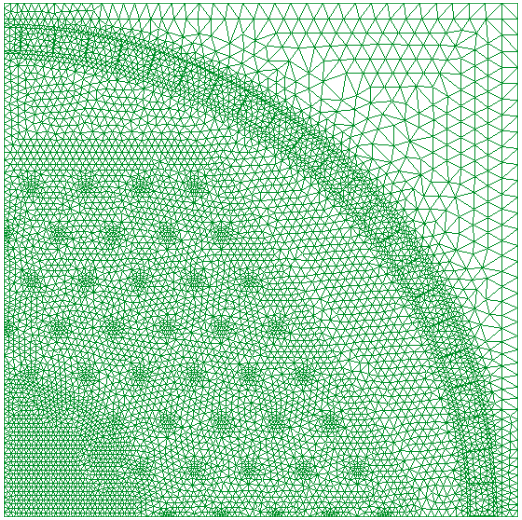


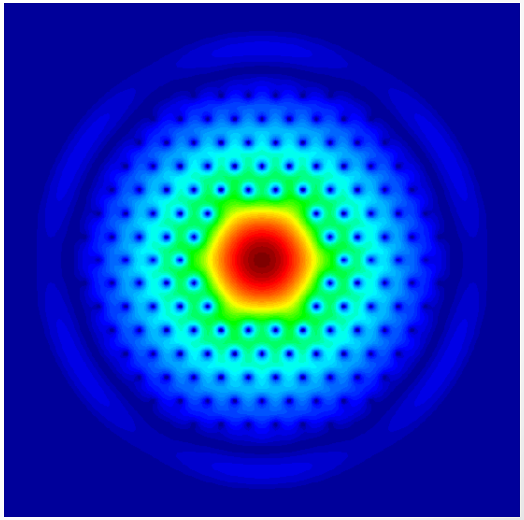


Numerical characterization

- The **complex structure** of PCF (large refractive-index difference between glass and air) makes its electromagnetic analysis challenging.
- Although standard optical fiber analyses and a number of approximate models are occasionally helpful, these are only useful as rough guidelines to the exact behavior unless checked against accurate numerical solutions
- Maxwell's equations must usually be solved numerically using one of a number of specially developed techniques
- **Finite Element Method (FEM)** approach.







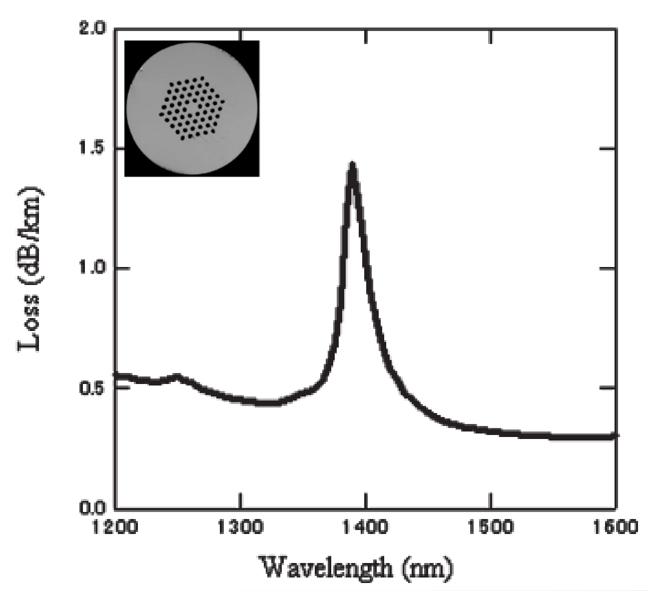
Outline: Properties of PCFs

- **Properties of PCFs**
  - Attenuation
  - Birefringence
  - Chromatic dispersion
  - Nonlinearity

Attenuation

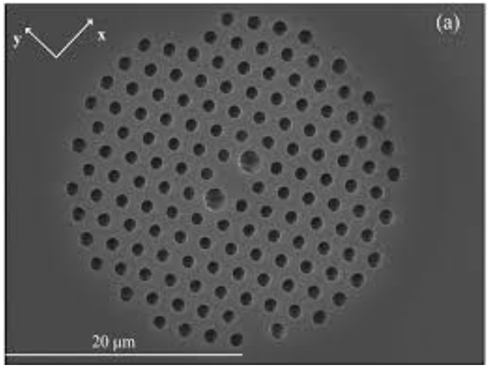
- In PCFs, **losses** are given by two main effects:
  - **fraction of light in glass**: attenuation of silica, it can be controlled by a proper design, close to 100% for solid-core fibers, less than 1% in the best hollow-core fibers.
  - **roughness** at the glass–air interfaces (typical of PCFs), this unwanted effect is the main reason that why PCFs cannot reach the SIF ultra-low attenuation.
- **In particular HC-PCFs** (which theoretically can have lower losses) are affected by this drawback.

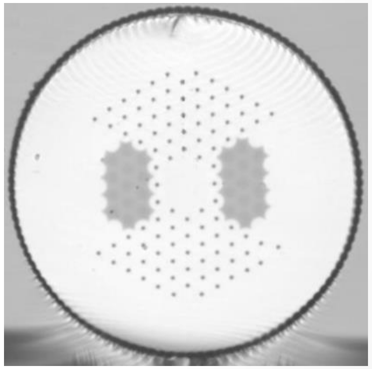
- Now-a-day the best results obtained are:
  - **0.28 dB/km** at **1550 nm** for solid core PCFs
  - **1.2 dB/km** at **1900 nm** for hollow core PCFs



Birefringence

- An ideal PCF do not present birefringence. Accidental distortions in the structure yield a degree of birefringence, due to the large glass–air index difference
- If the cladding structure, and consequently the core, is deliberately distorted to become two-fold symmetric, **extremely high values of birefringence** can be achieved (some ten times larger than in conventional fiber)
- Substituting some holes in the PCFs cladding with stress inducing boron doped glass can be also effective.

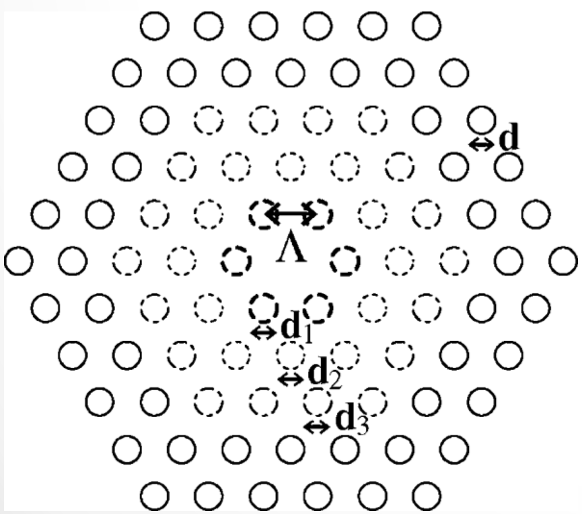


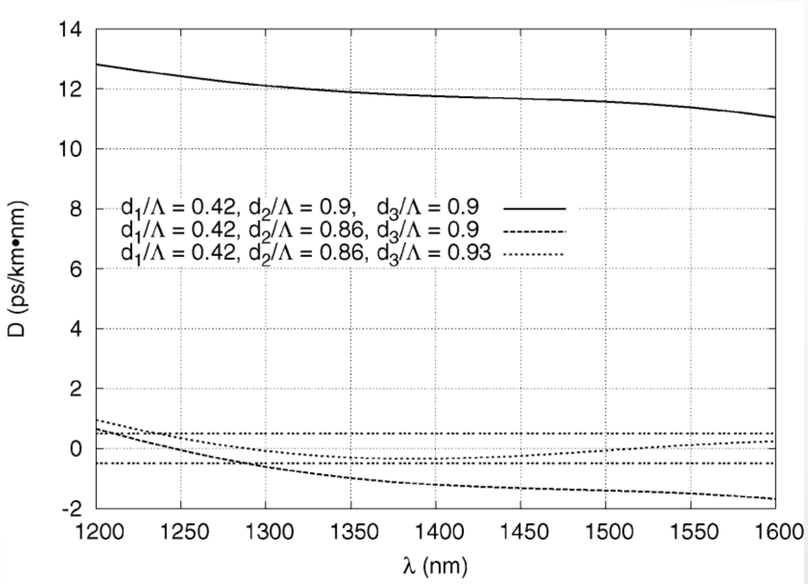


- Hollow-core PCF with moderate levels of birefringence ($\sim 10^{-4}$) can be realized either by: forming an elliptical core or adjusting structural design of core surround

Chromatic dispersion

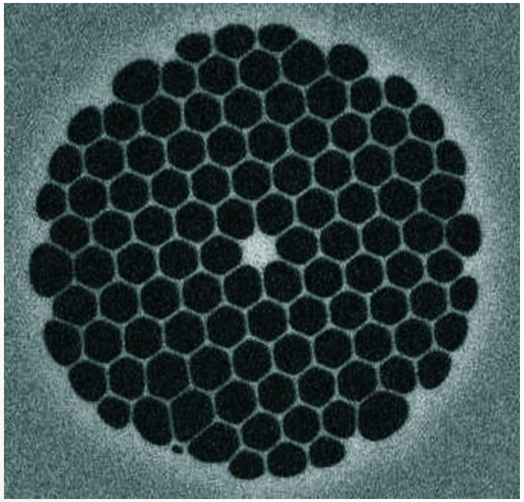
- **SIF**: as the optical frequency increases, chromatic dispersion changes sign from anomalous ($D > 0$) to normal ($D < 0$) (1300 nm, roughly).
- **PCFs** offers much more control of the magnitude and sign of the chromatic dispersion D
- Varying the core dimension, the hole diameter and their arrangement in a PCF structure, zero dispersion wavelength **(ZDW)** can be shifted to the visible.
- By a proper design, the wavelength dependence of chromatic dispersion can be reduced in PCFs with lower air-filling fractions **(flattened *D* profiles).**

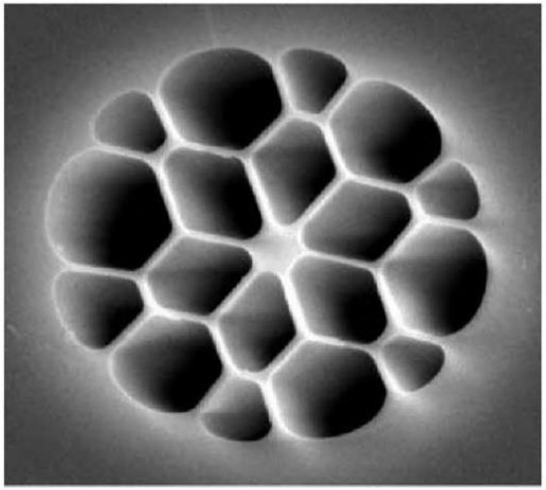




Nonlinearity

- PCFs are a powerful platform for studyng of nonlinear effects (i.e. self-phase modulation, stimulated Raman scattering, four-wave mixing…)
- Ability to control the nonlinearity (**nonlinearity depends on mode area**)
- Furthermore at the same time it is possible to control, the magnitude and wavelength dependence of the chromatic dispersion.
- Possible **soliton operation**.
- It is necessary to take account of the differing proportions of light in glass and air
- Hollow-core PCFs present in general low levels of nonlinearity due to the small overlap between the glass and the light.





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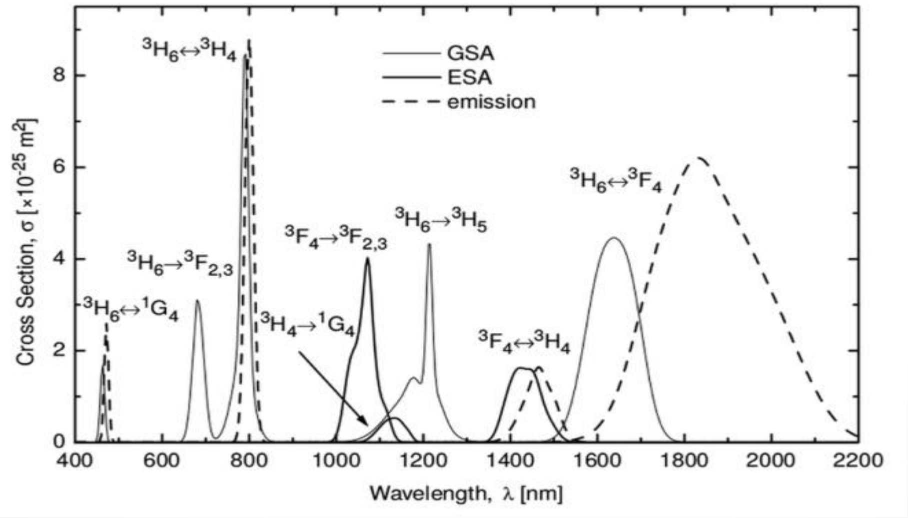
Outline: Applications of PCFs

- **Applications of PCFs**
  - Telecommunications
  - Fiber lasers
  - Power transmission
  - Supercontinuum generation
  - Fiber sensors
  - And more…

Telecommunications

- PCFs show potential also in the field of telecommunications, even if standard telecommunications fibers are doing a great job and are far more cheaper.
- **Solid-core PCFs**, exhibiting similar attenuation properties posses the advantage to be design to have no chromatic dispersion.
- **Hollow core PCFs** with their potential to achieve ultra-low losses, lower than 0.2 dB/km from solid-core SMF can be a realistic competitor for SMF-28™
- Furthermore their operation windows, being centered at 1900 nm, can exploit the large amplification band of Tm-doped fiber amplifiers (1800nm to 2050 nm), permitting an effective wavelength multiplexing.



Fiber lasers

- In the field of fiber laser PCFs, in particular solid core, can outperform traditional fibers..
- The main goal in a fiber laser is to:
  - Deliver more power
  - Maintain a good beam quality
  - Avoid nonlinear effects
- These requirements can be translated in the need of **enlarging the mode area** while **maintaining single mode operation**.
- Large mode area in SIF is impeded by the scaling condition expressed by:

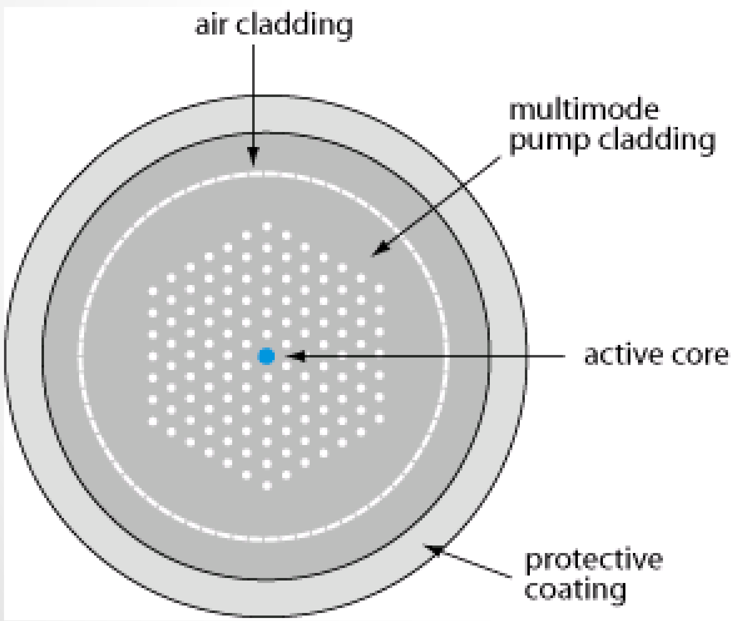
$$V = \frac{2\pi a}{\lambda} \sqrt{{n_1}^2 - {n_2}^2}$$

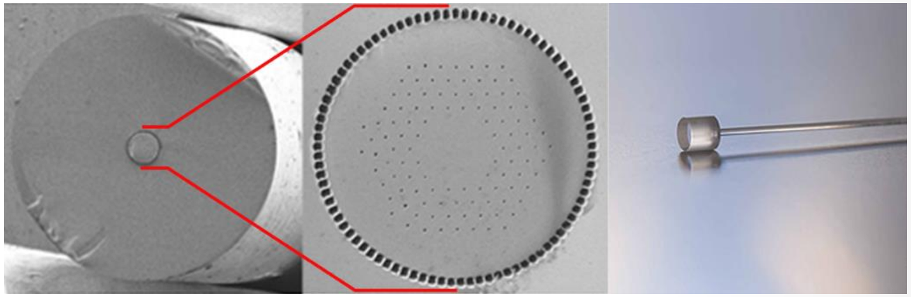
where the increasing of radius a should be compensated by a reduction of NA, which is technologically not feasible.

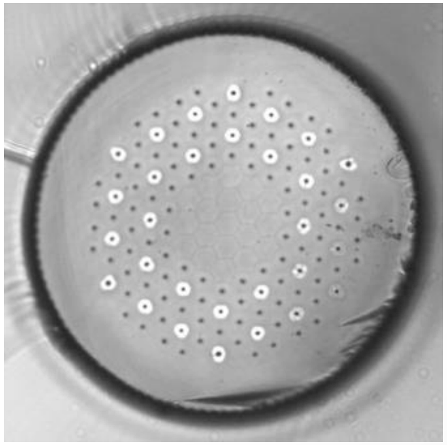
- In a PCF the index contrast is fully determined by the geometrical parameters of the fiber d/Λ, which are much more easier to control.

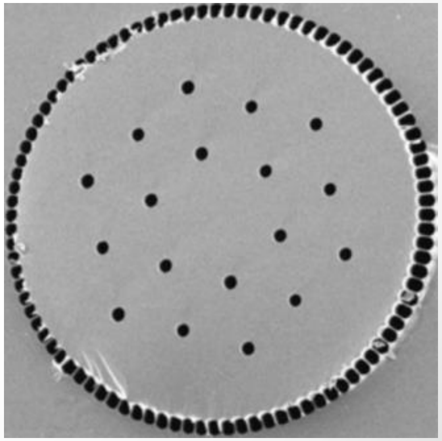
Fiber lasers

- It is possible to dope the solid core of PCFs with **rare earth dopant**.
- A further advantage of PCF technology is the possibility of forming an **air-cladding region for double-cladding fibers**
- Double-cladding PCFs: inner cladding surrounded with a web of silica bridges, which are substantially narrower than the wavelength of the guided radiation



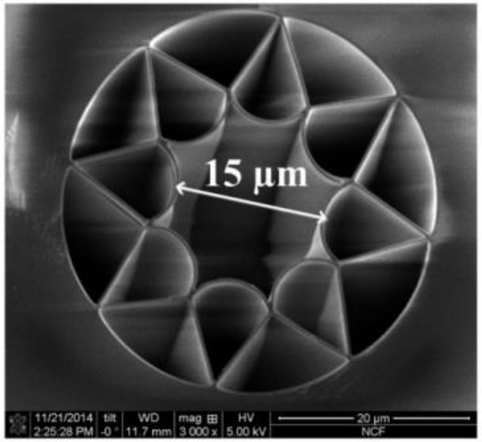






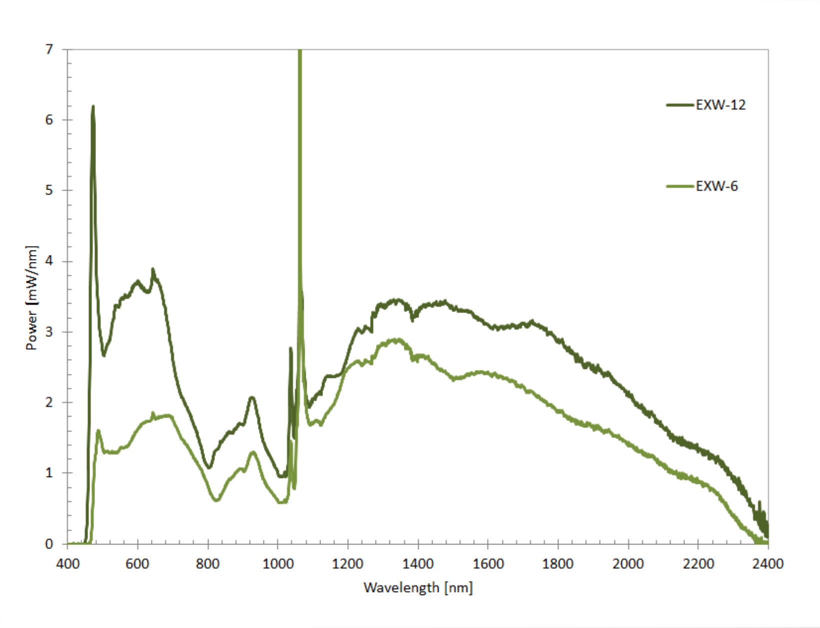
Power transmission

- The ability of PCFs to remain single-mode (ESM) at all wavelengths where they guide, and for all scales of structure, suggests that it should have superior power-handling properties (core area can be increased without the penalty of introducing higher order guided modes)
- The ability to transmit much higher power in a single mode has a major impact in the field of laser machining and high-power fiber lasers and amplifiers.
- Hollow core PCF is also an excellent candidate for transmitting:
    - high continuous-wave power
    - ultra-short pulses with very high peak powers



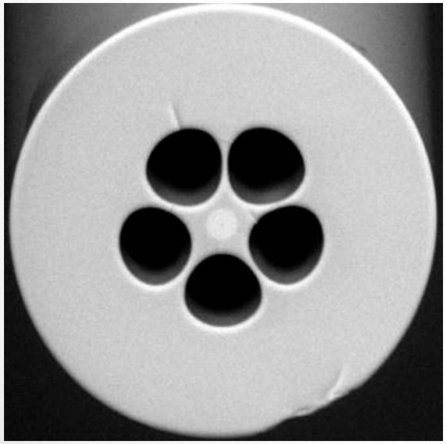
Supercontinuum generation

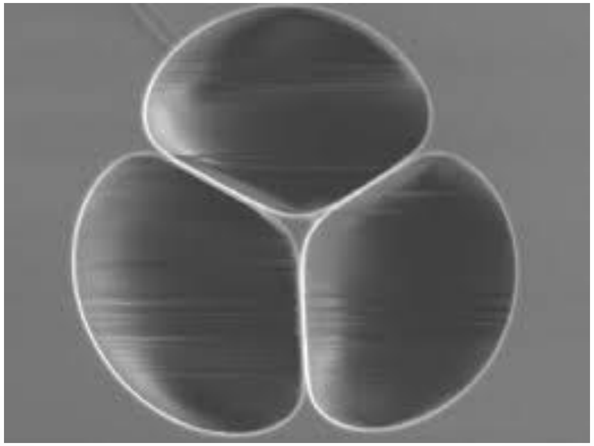
- The most intriguing application of **nonlinear PCF** is to **SuperContinuum (SC) generation** from ps and fs laser pulses.
- When high-power pulses travel through a material, their frequency spectrum can be broadened interconnected nonlinear effects
- In 2000, it was observed that highly nonlinear PCFs, which are designed with zero dispersion wavelength close to 800 nm, massively broaden the spectrum of low-energy (a few nJ) unamplified Ti:sapphire pulses launched into just a few centimeters of fiber .

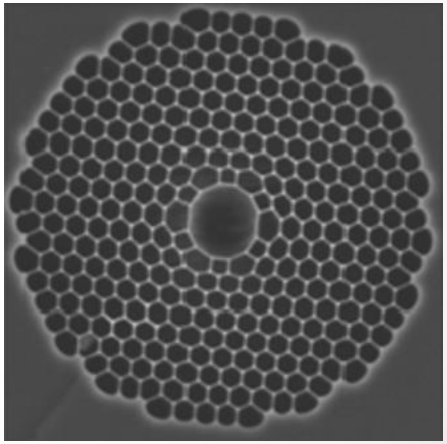


Fiber sensors

- **Sensing** capability offered by PCF is extraordinary, covering many fields. Example: environmental monitoring, structural monitoring and biomedical sensing.
- The key factor in the use of PCFs with respect to conventional SIFs is the presence of the holey structure, which dramatically increase the fiber sensor response.
- In particular Hollow Core PCFs are devices which offer strong interactions of light and gaseous/fluidic samples at path lengths that are much longer than in conventional gas/liquid cells.

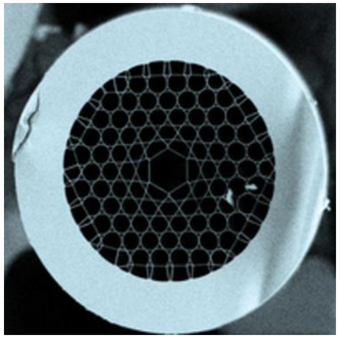


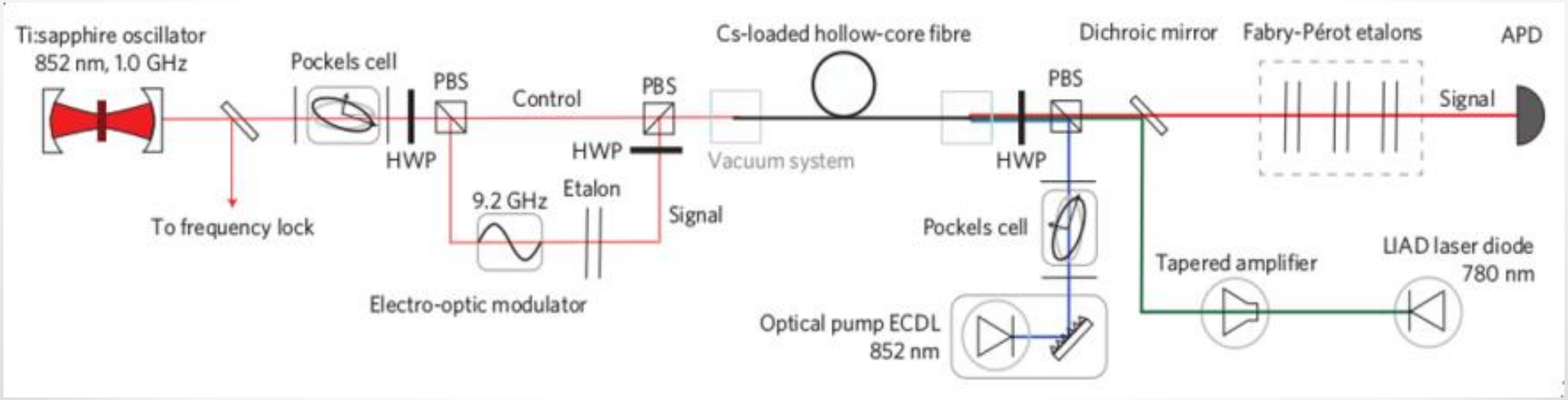




And more…

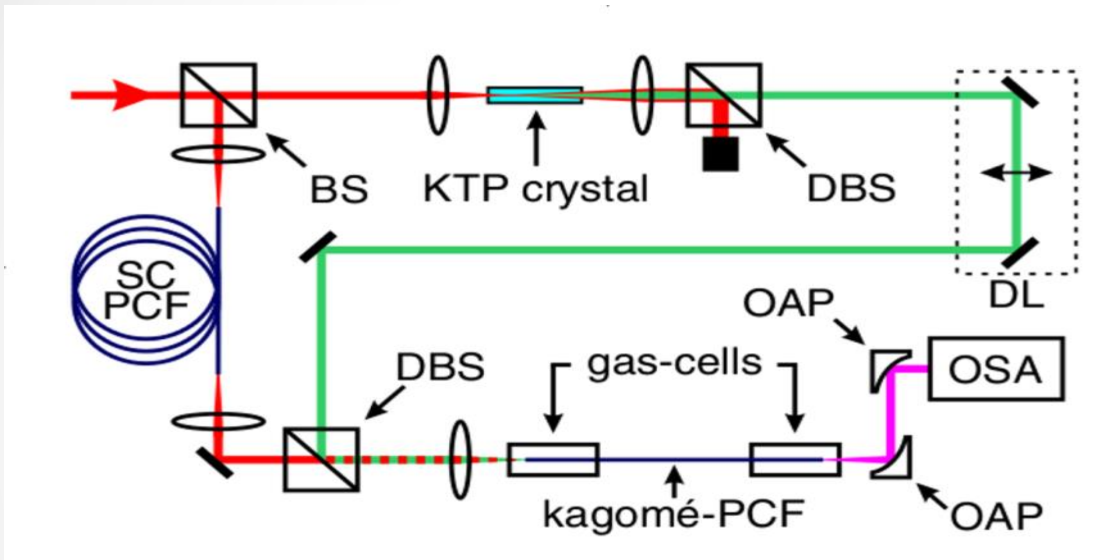
- PCFs can be used also for “exotic” and pioneering applications.
- Example: the experimental demonstration of the first optical quantum memory, where a **Kagome PCF**, filled with cesium gas has been used.

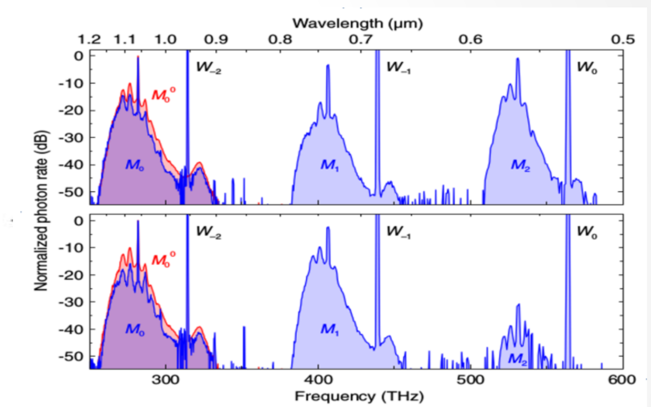


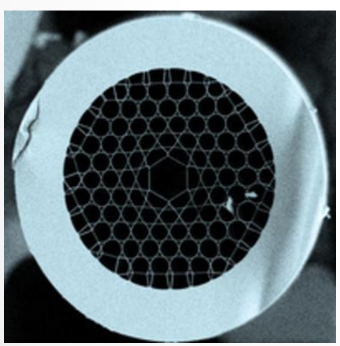


And more…

- Example: a system to achieve broadband LP_{01} mode frequency shifting.







- **Kagome fiber filled with H_2**
- The system exploits Raman scattering effect in H_2
- The system is tunable with gas pressure.

Thanks for your kind attention