Photonic Crystal Fibers

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I. What are Optical Fibers?

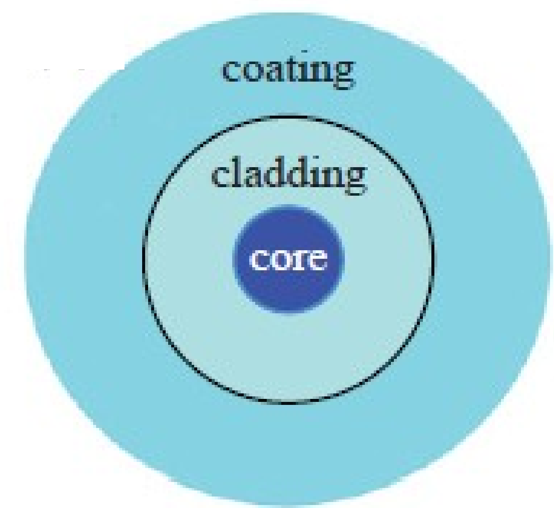
- Optical microstructures
  with special features
- Confine light in
  microscopical dimensions
  while guiding it over macroscopical distances
- Highly versatile devices for bio-chemical sensing, adaptive optical elements, telecomunications..

II. Light guiding in optical fibers

Different guiding mechanisms:

- Reflection at a dielectric interface (total internal reflection)
- Reflection at a dielectric multilayer
- Guiding in a photonic crystal structure.

II a. Total internal reflection



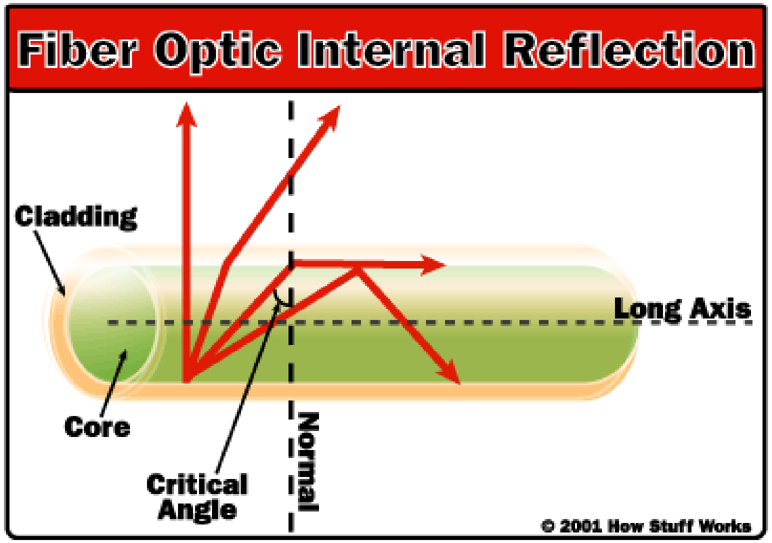
- Requires a dielectric boundary between materials of different refractive index

- Condition $n_{core} > n_{clad}$

- Important aspects: Numerical aperture and Factor V

$$NA = \sqrt{n_{Core}^2 - n_{Cladding}^2}$$

$$V = \frac{2\pi r}{\lambda}\sqrt{n_{Core}^2 - n_{Cladding}^2}$$

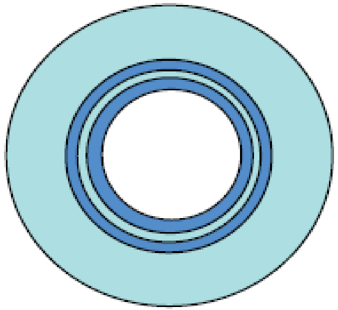


III. Design possibilities for optical fibers

Fiber properties such as dispersion are important.

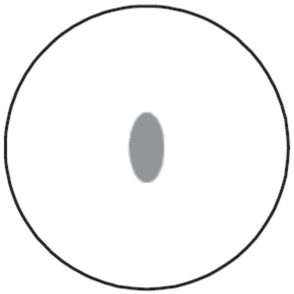
Fiber´s Modifications:

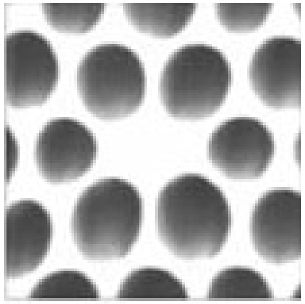
- Multilayered structured fibers
  with several different refractive index values.



Another modification concerns the shape of the core:

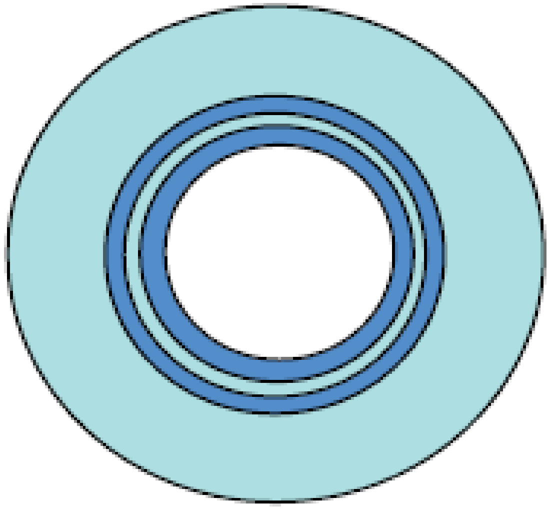
- Asymetrically core. Polarizing fibers.





III b. Dielectric Multilayer

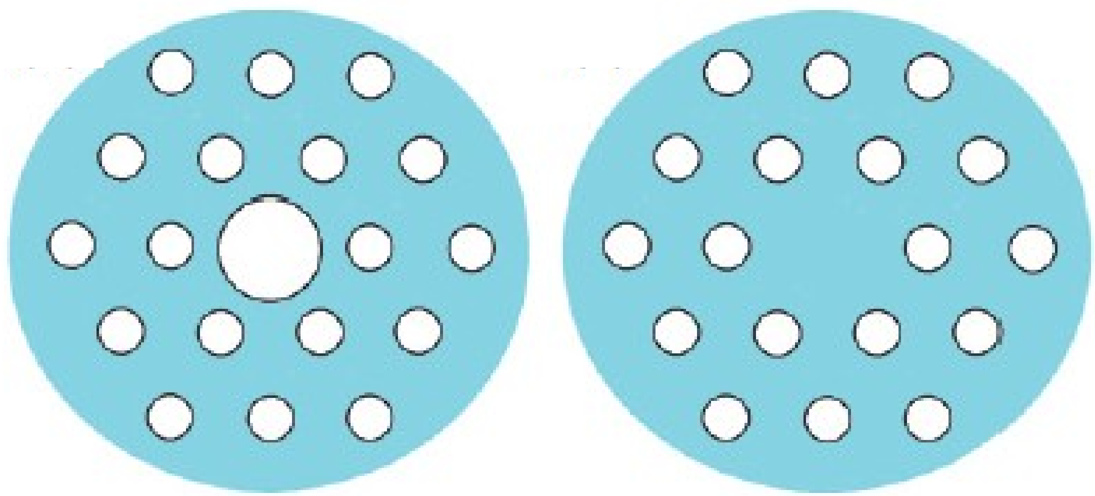
- Consisting of materials with different refractive index values similar to optical interference filters
- Braggs Reflection
- Hollow core posible.



III c. Microstructured fiber

- Microstructured optical fibers (MOFs) or photonic crystal fibers extended the design possibilities of optical fibers

- Holey structures are introduced in the fiber cladding area



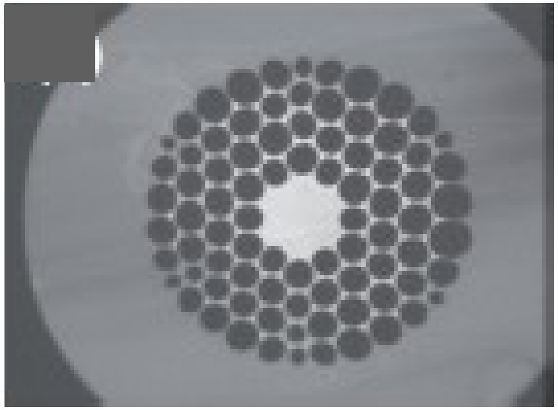
Advantages compared to conventional fibers:

- Light guiding can be achieved from a single material
- Optical guiding properties can be modified precisely over a wide parameter range
- Asymmetrical fiber properties can be introduced in a simple way
- Solid core or hollow core
- Single-mode propagation is possible independent of the applied wavelength

VI. Light guiding in MOFs

Different principles are possibles:

1. Effective index guiding: the averaged index of the solid material and the holey fraction has to fulfil the condition of total internal reflection.



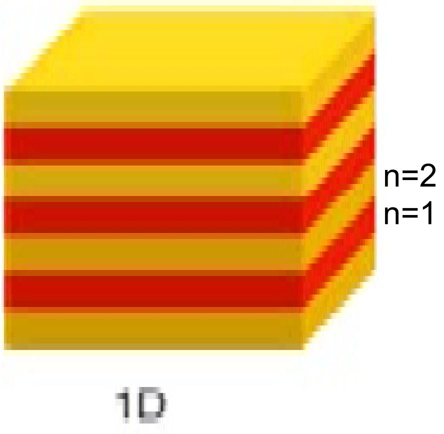
Caracteristics of this case:

- strict periodicity of holes is not necessary
- guiding is efficiently possible over a wide wavelength range. V-parameter value can be introduced in analogy to conventional fibers

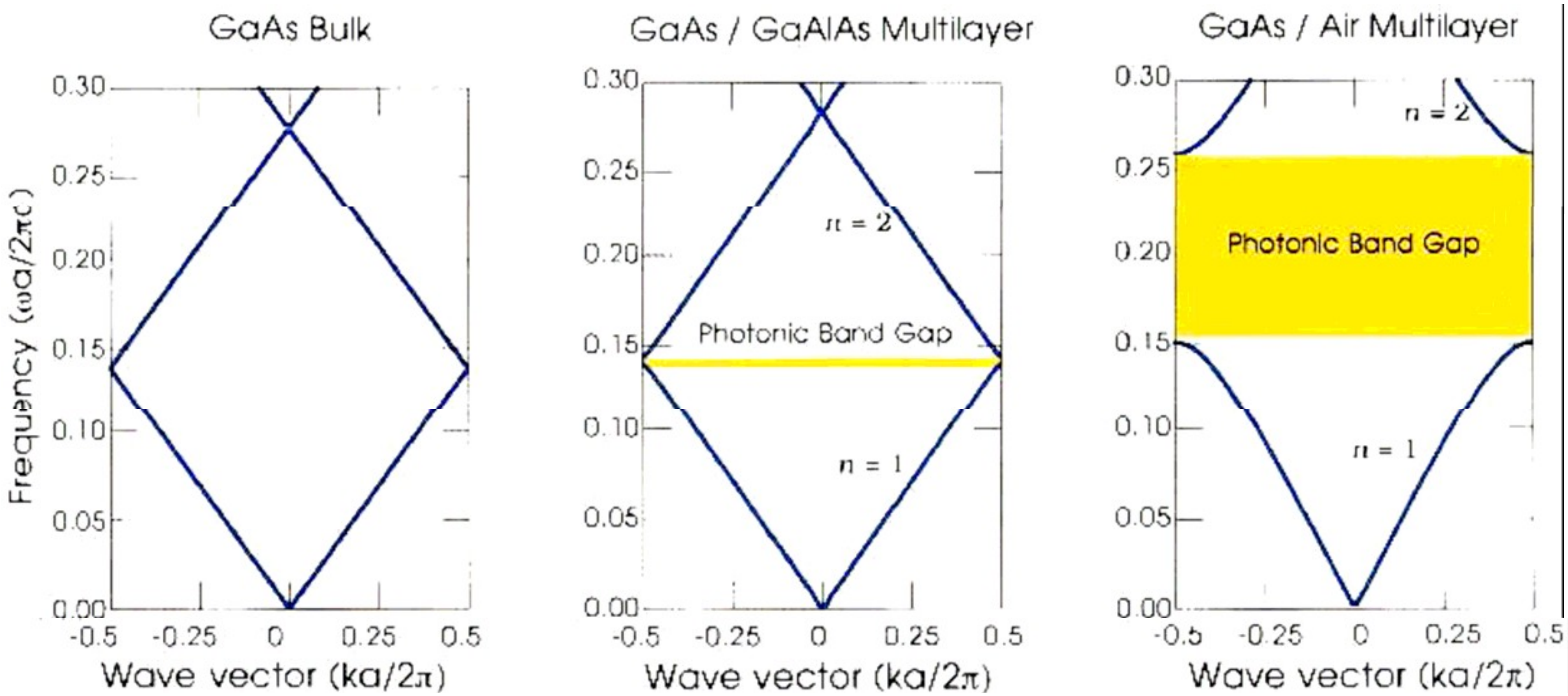
2. Origin of Band gap effect

- Simplest photonic crystal: multilayer film (Braggs mirror).
- Traditional analysis: plane waves propagate through the material and multiple reflections and refractions at each interface occur.
- New approach: band structures.

  Generalized for two- and three-dimensions



- Consider wave propagating only in z direction: $k_z = k$
- Band diagram plotted for three different multilayers films. Dielectric mediums with periodicity of a.



Why does band gap appear?

- We can understand the physic by considering the electric field mode profile for the states immediately above and below the gap.
- Gap between bands occurs at k= $\pi/2$. For k= $\pi/2$ the modes have a wave length of 2a, twice the crystal spacial period or lattice constant.
- Two possibilities to centre a mode:

  Positions of the nodes in lower dielectric layers or in higher dielectric layers.

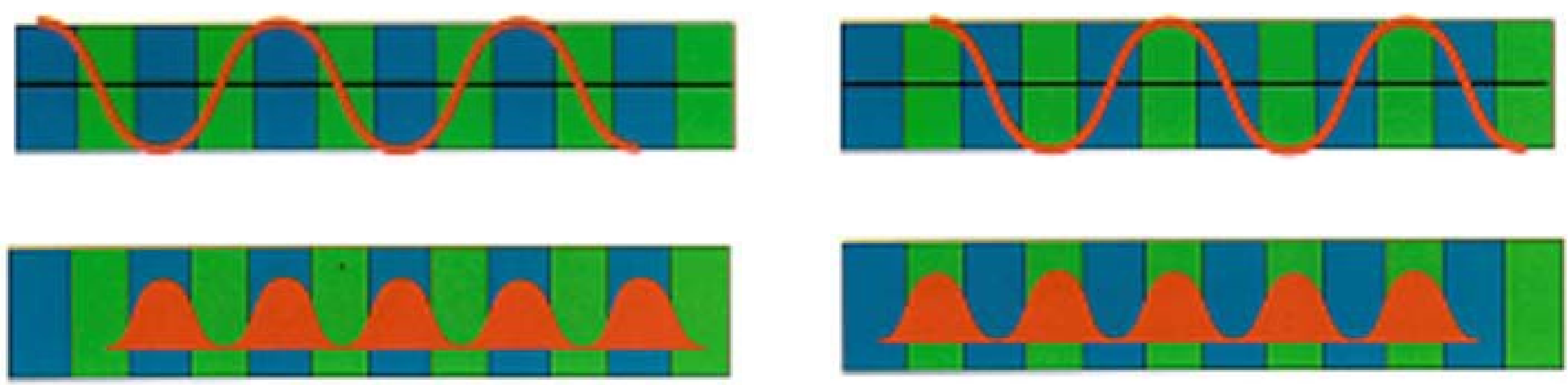
  Other position violate the symmetry of the unit cell about its centre.

- low frequency modes concentrate their energy in high dielectric regions (dielectric modes) and high frequency modes in low dielectric regions (air modes).

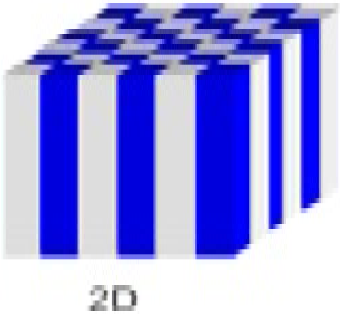
Frequency difference → Band Gap

- Bands below and above band gap distinguished by where energy modes are concentrated

Band 1 Band 2

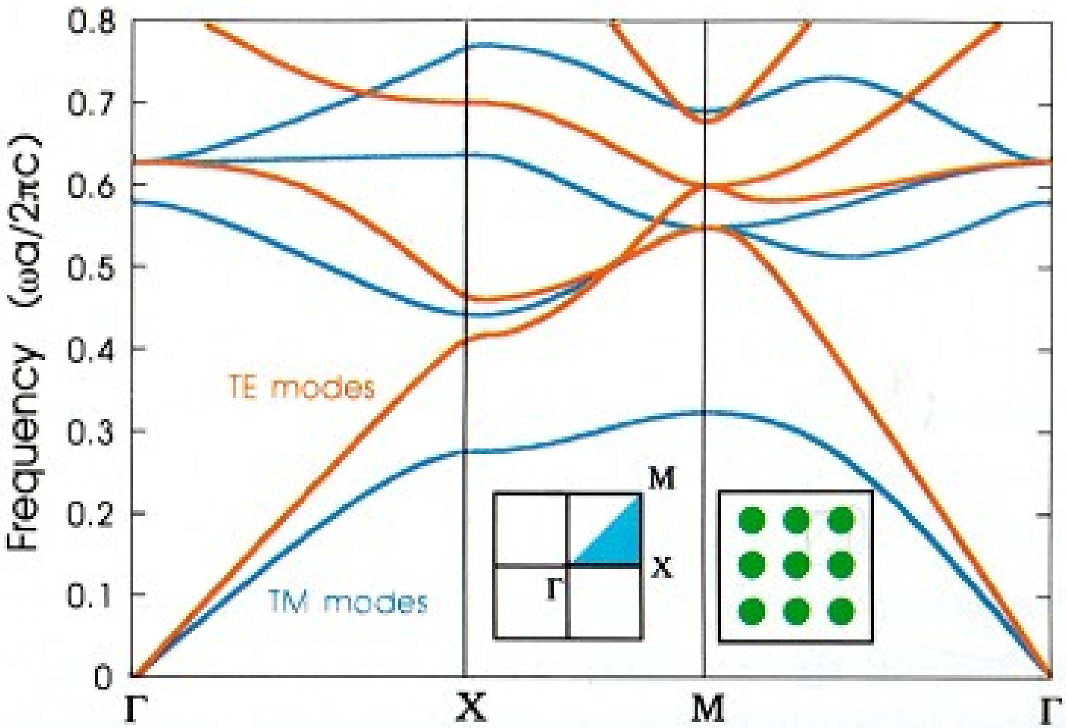


Two dimensions photonic crystal



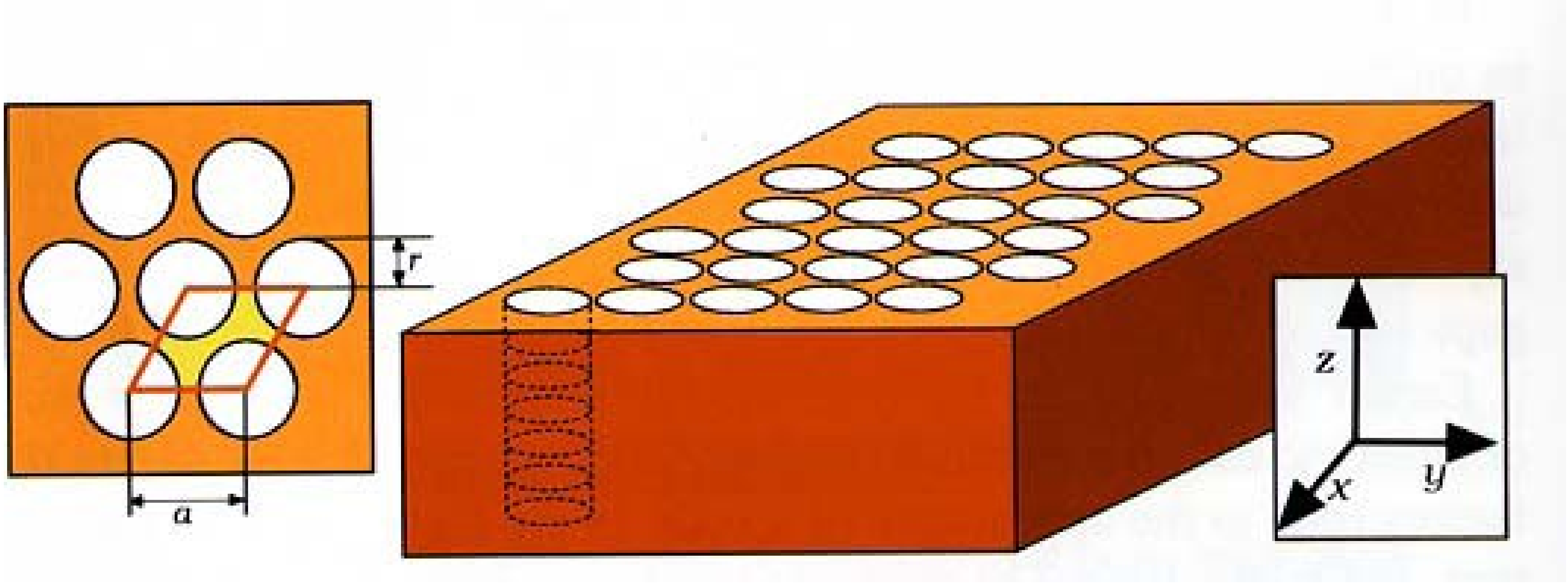
- There are two possible polarizations TE modes and TM modes.
- These two modes have different band structure
- Square grid of dielectric

  There are gaps for TE modes but not for TM modes.

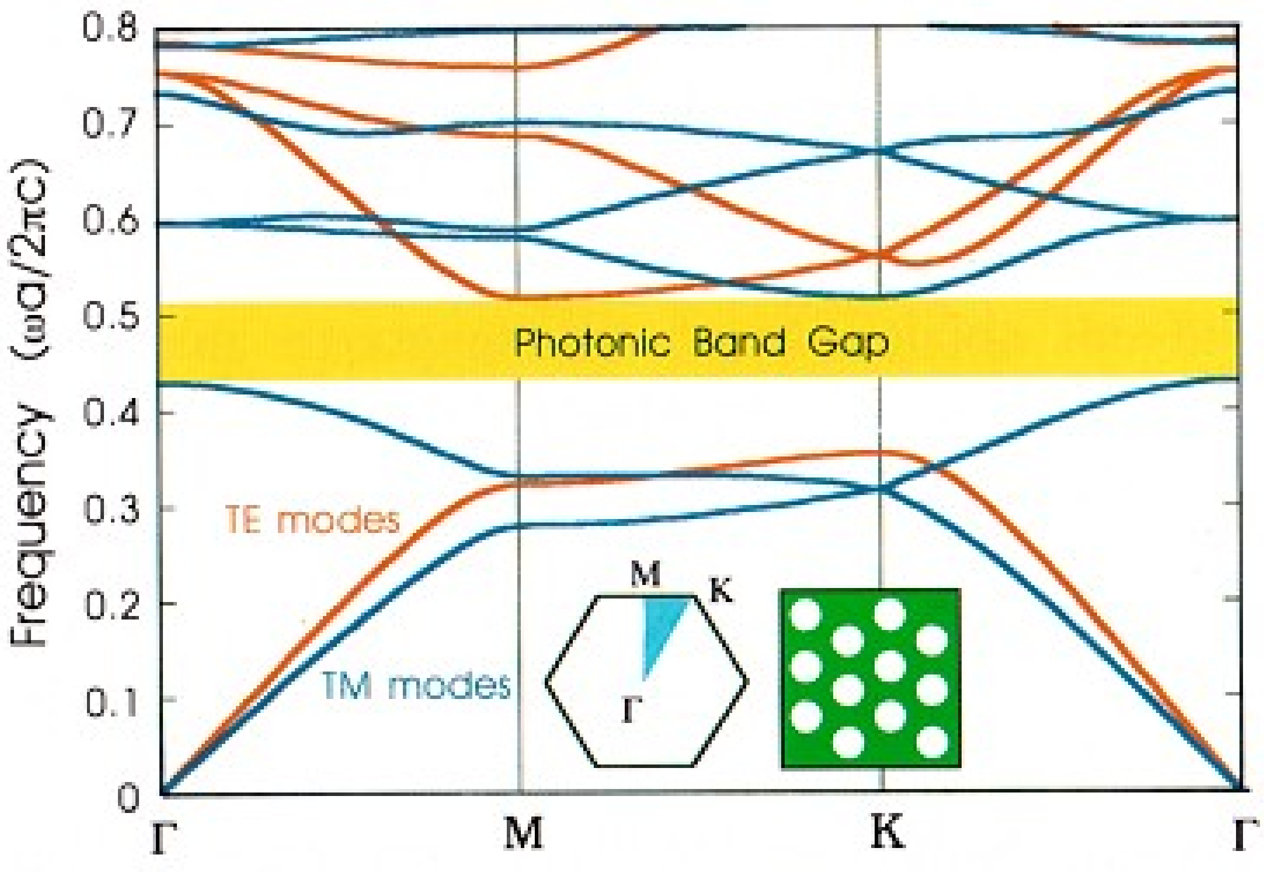


- Possible photonic crystal that has band gap for both polarization adjusting the dimensions of the lattice.
- Example: triangular lattice.

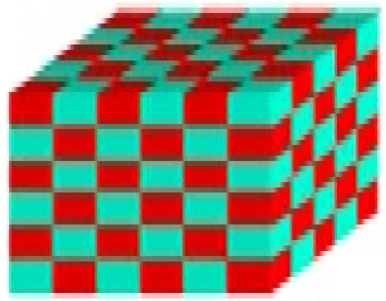
  Low dielectric column inside a medium with high dielectric



- Band gap for both polarizations possible

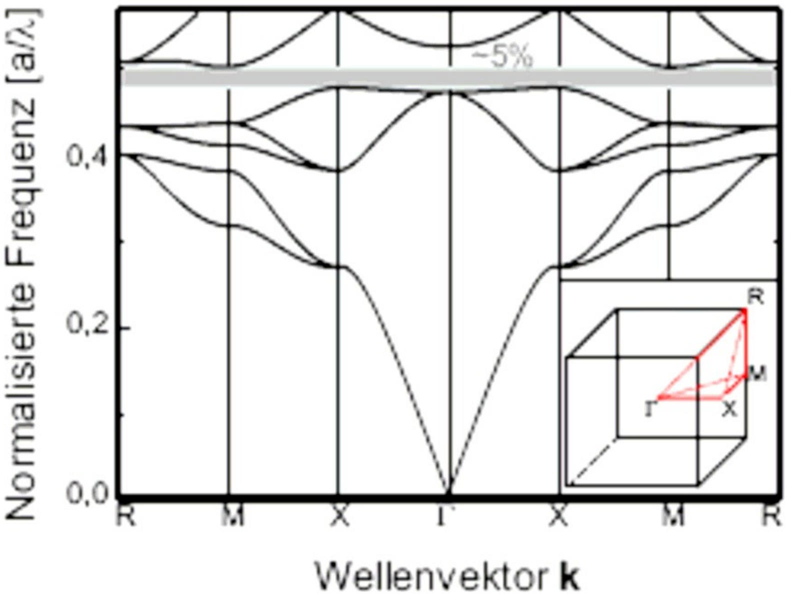


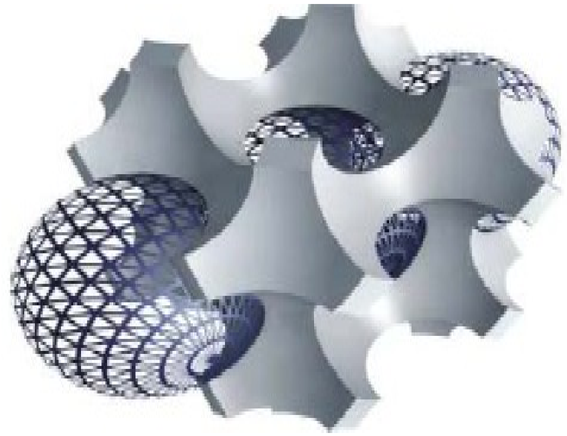
Three dimensions photonic crystal

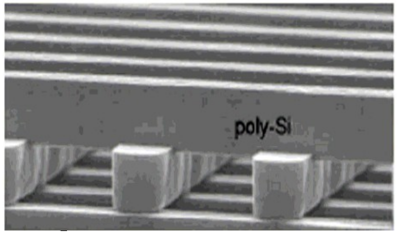


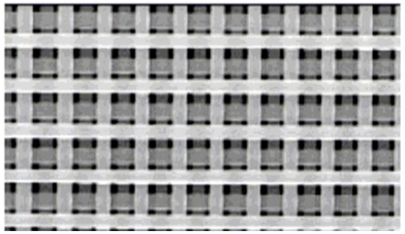
3D

- Band diagram for 3D PC

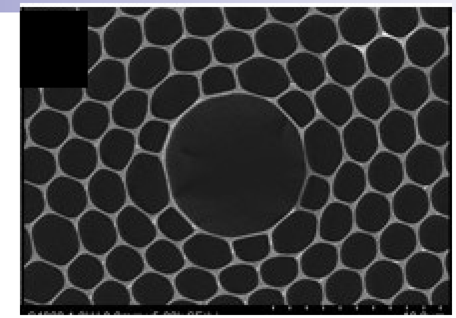




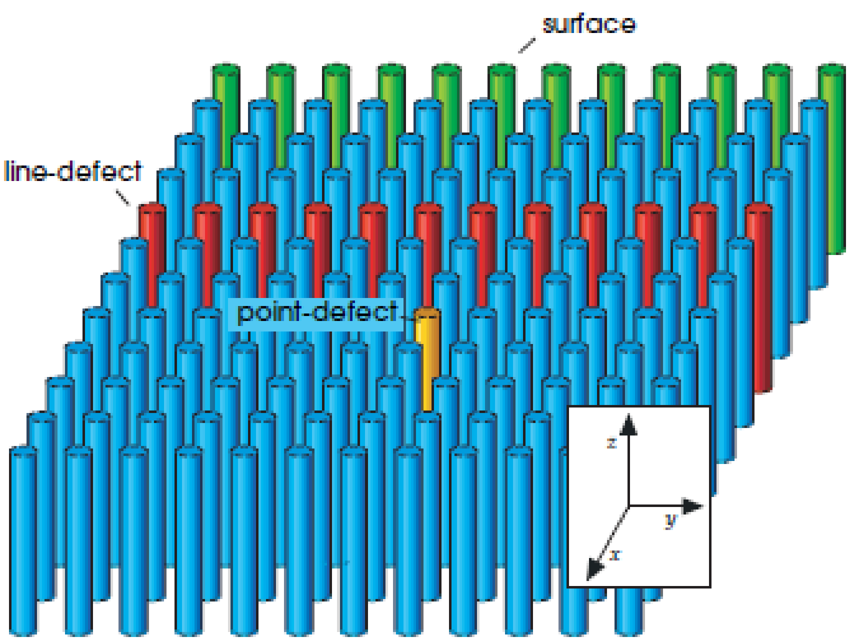


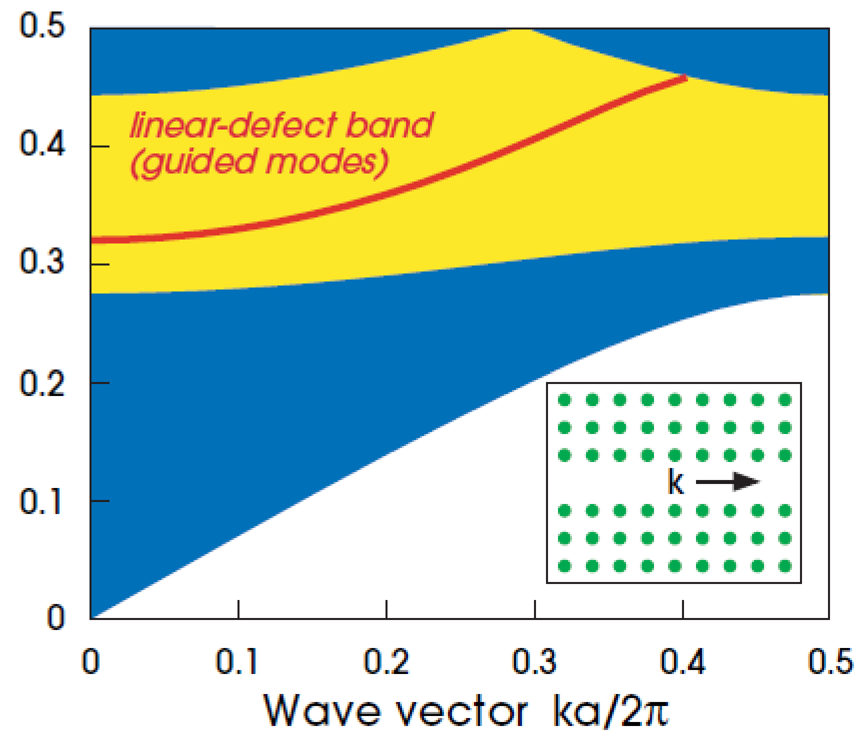


Linear defect band



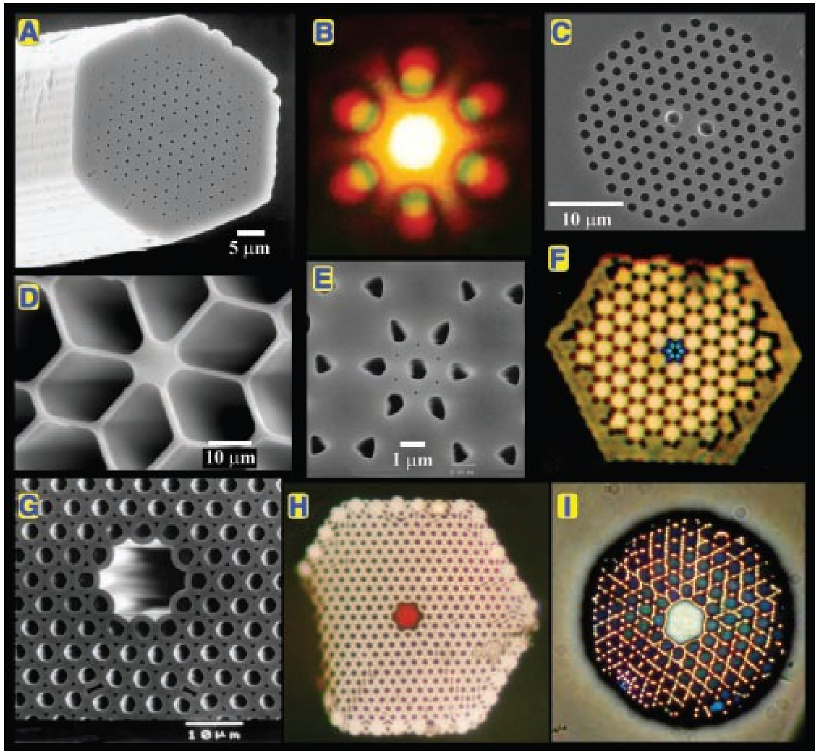
- Line defect concentrate light in the core of the fiber.



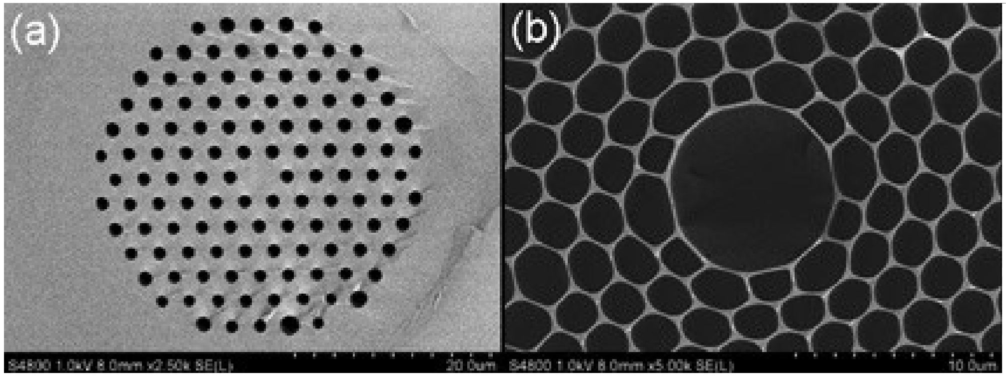


2.1. Band Gap Guiding

- Light trapped inside a hollow fiber core by creating a periodic wavelength-scale lattice of microscopic holes in the cladding glass—a “photonic crystal”

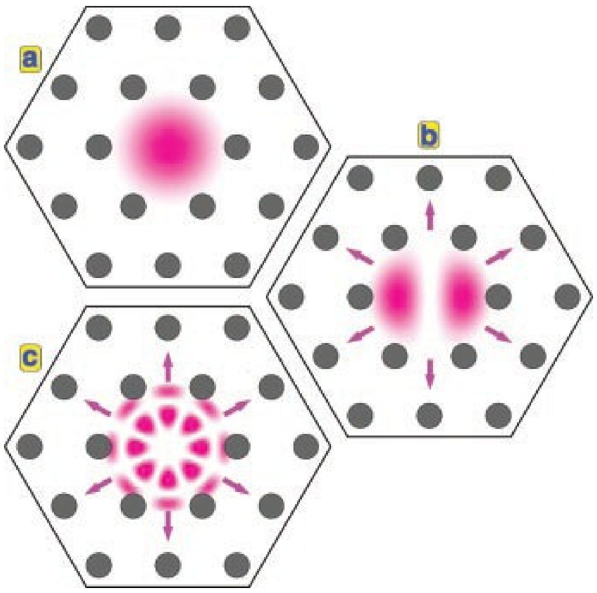


- Appropriately designed, the holey photonic crystal cladding, running along the entire length of the fiber, can prevent the escape of light from a hollow core



(a) Endlessly single-mode PCF; (b) hollow core photonic band-gap PCF

Single mode photonic crystal fibers.

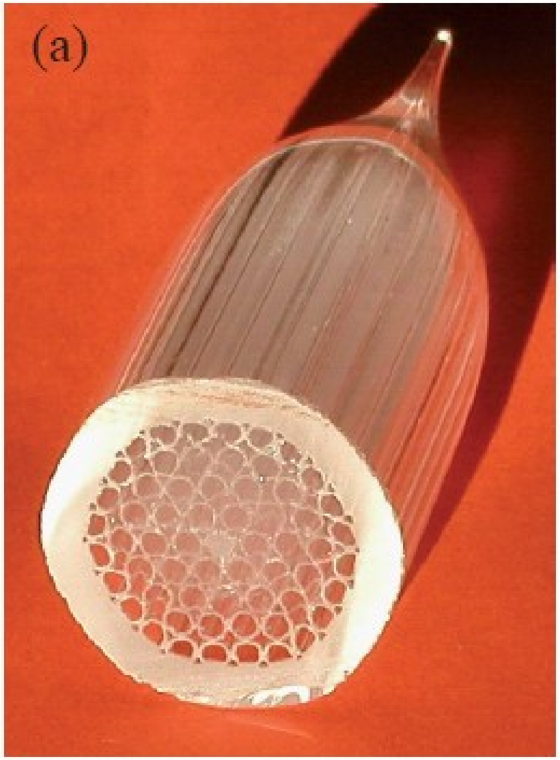


- (a) fundamental mode unable to escape:
  Effective wavelength in the transverse plane is too large.

- (b) and (c), higher order modes able to leak away.
  Transverse effective wavelength is smaller.

Advantages of bandgap fibers compared to multilayer fibers:

- Desgin of dispersion
- Higher Power concentration in core region.

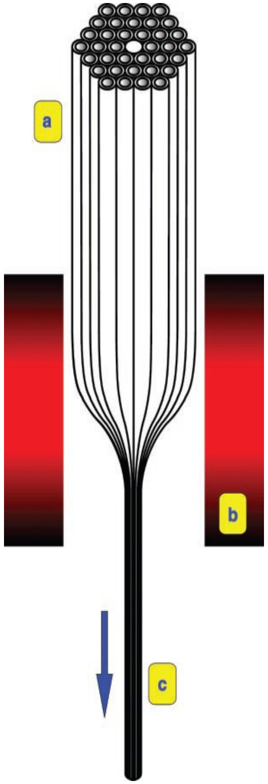


V. Fibers material

Most common material used: Silica glass.

General Characteristics:

- Extremely low attenuation
- Used over a wide spectral range from visible to near infrared wavelengths
- Good mechanical properties in combination with long-term stability



VI. Fabrication technics

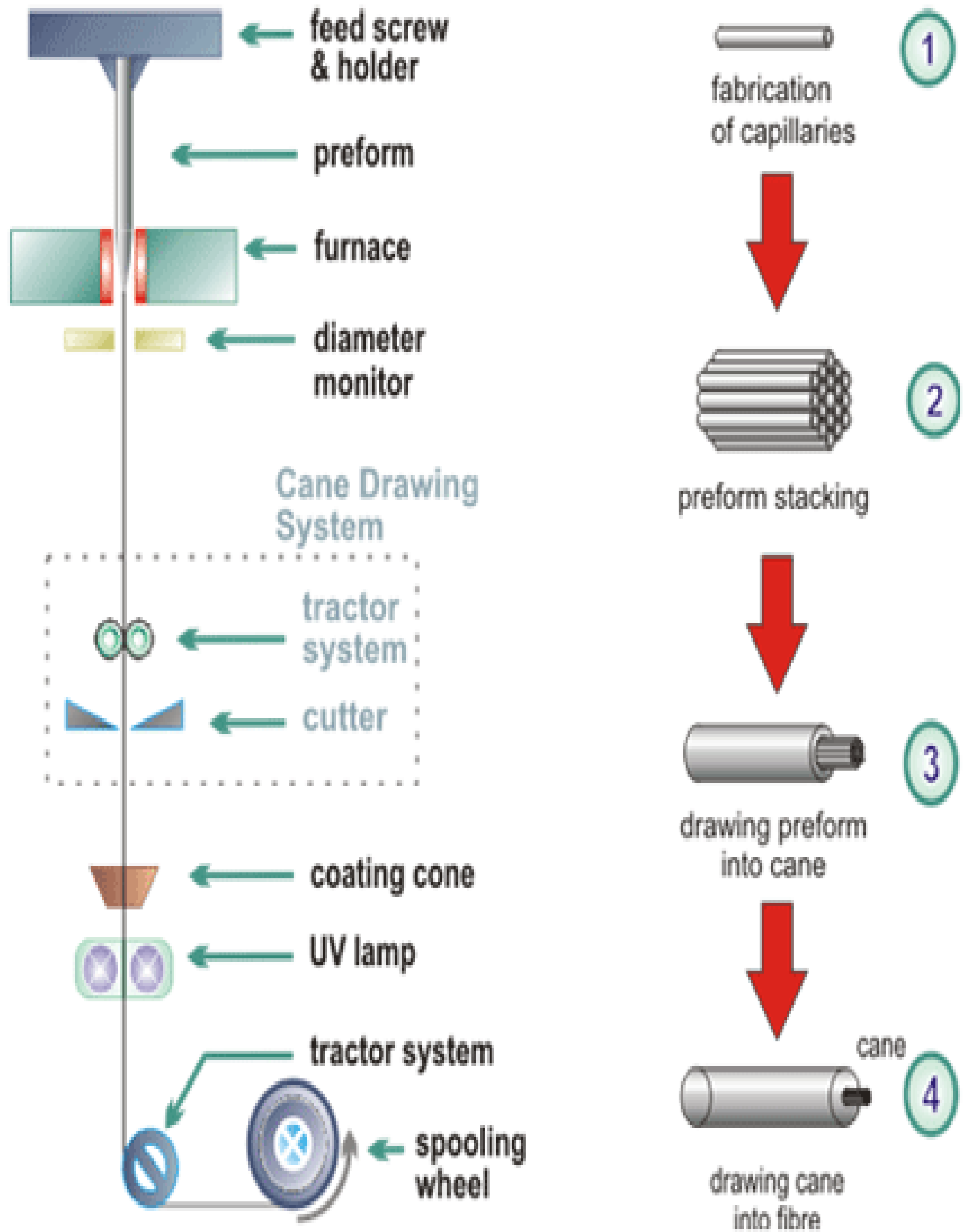
Typical method for fiber fabrication based on fiber preform preparation

For the preform fabrication different processes can be used:

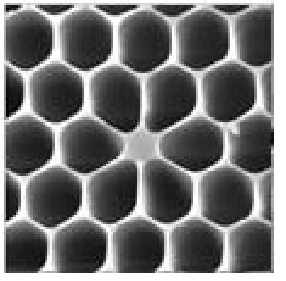
- rod-in-tube
- Modified Chemical Vapor Deposition
- OVD-technology

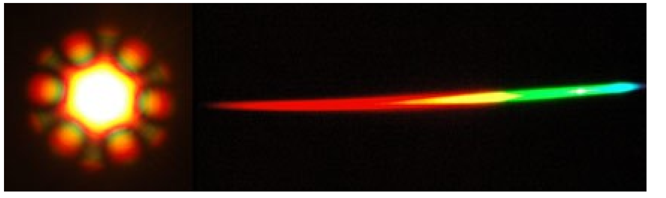
Differents shapes and size are possible.

- Preform is heated and stretched to the final fiber shape
- Final geometrical fiber properties adjusted by proper use of the preform feed speed and the fiber drawing speed
- Fiber is then coated by a protective coating



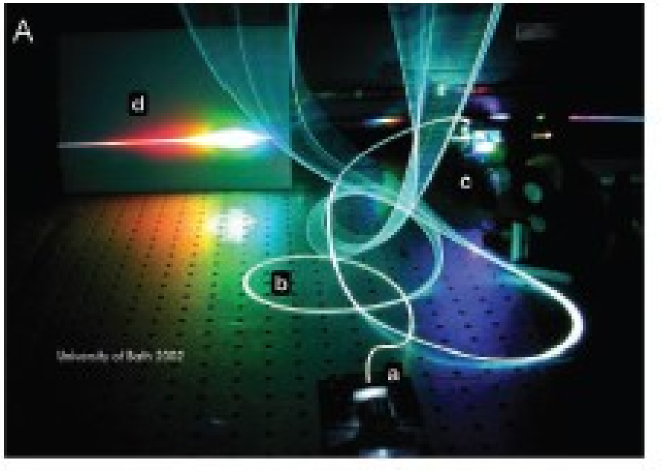
VII. Aplications of Photonic Fibers





- Non-linear effect

  Fibers with capacity to change the wave lenght of the light that cross the fiber.



- Example: Supercontinuous
  When ultrashort, high-energy pulses travel through a material, their frequency spectrum can experience giant broadening due to a range of interconnected nonlinear effects.

Atom and particle guidance

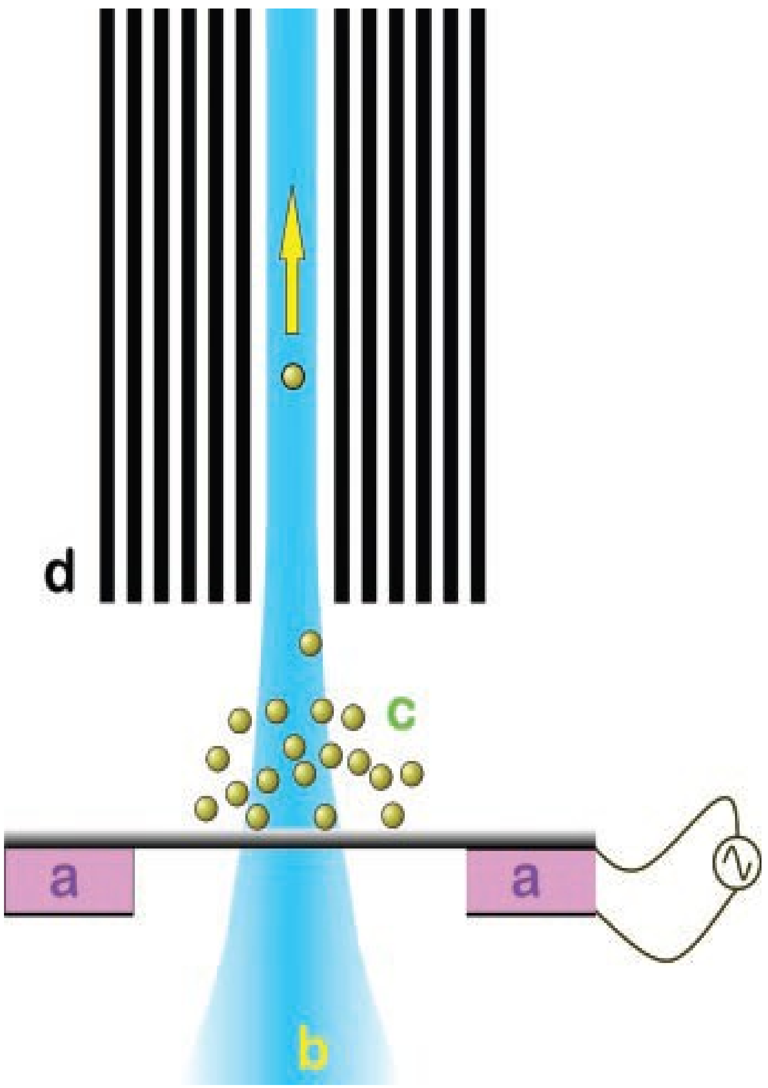
- Small dielectric particles can be trapped, levitated, or propelled in a laser beam using the dipole forces exerted by light.

- Atoms and particles can be transported along hollow capillaries, where the optical dipole forces of a co-guided laser provide the acceleration needed to overcome viscosity.

- Absence of a true guided mode in the capillary severely limits the effectiveness of the technique.

- Large capillaries must be used to avoid leakage, which means that adequate trapping forces can be obtained only at high laser powers.

- Hollow-core PCF provides a neat solution to this problem. In this case, we can use lower laser powers and smaller capillaries diameters.



Vielen Dank¡