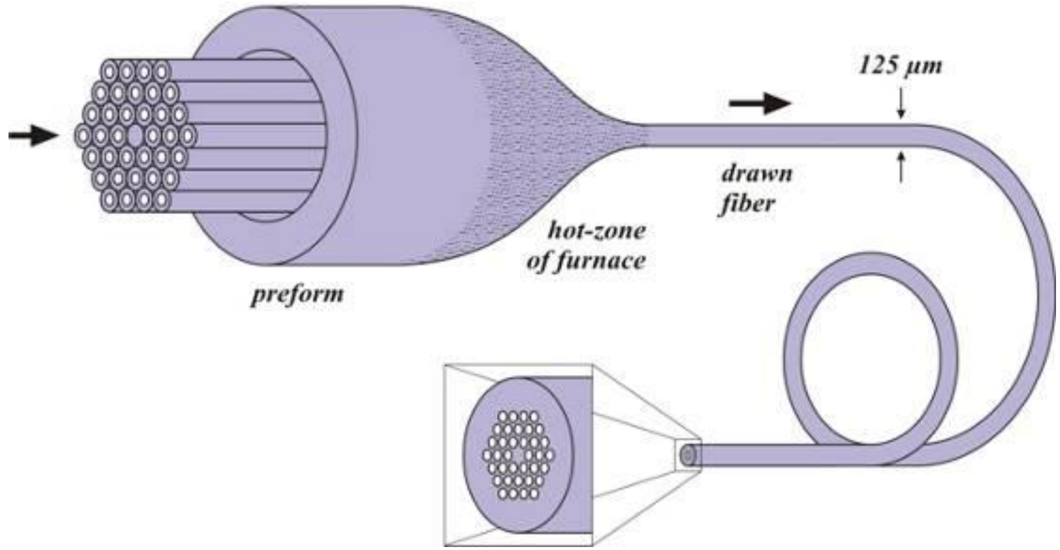
Photonic Crystal Fibres (PCFs)
Benefits & Applications



Randhir Bhatnagar, Chief Scientist
CSIR-Central Scientific Instruments Organisation, Chandigarh
email: rbh5@csio.res.in

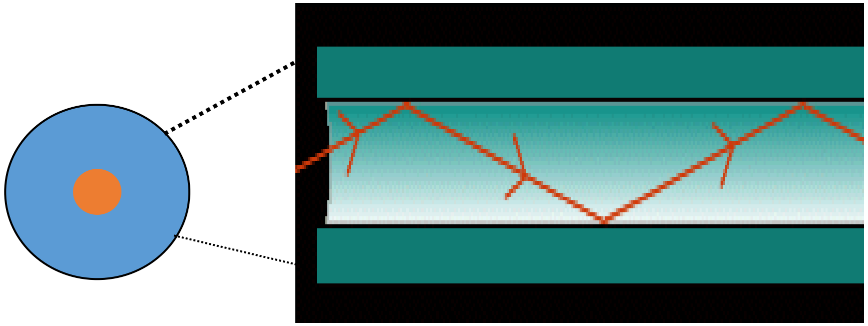
22nd December 2017

Lecture Outline

- **Conventional Optical Fiber**
- **Photonic Crystal Fibers**
- **PCF Fabrication techniques**
- **Application of PCF as Sensor,**

  Supercontinuum generation and High Power delivery

Classical Optical Fiber



Total Internal Reflection

- Total internal Reflection
- Multi-mode fibers(MMF)

  - Short range

  - many paths allowed
- Single-mode fibers(SMF)

  - Long range

  - Modal dispersion less

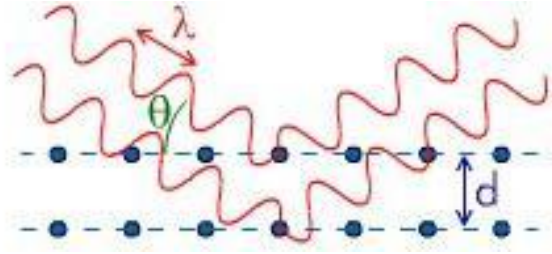
Limitation of Classical Optical Fiber

- **Linear effects – a function of the fiber length**
  - **Limited bend radius ~ 30 mm**
  - **Dispersion – broadens the optical pulse over length of a fiber**
- **Non-Linear effects**
  - **Self phase modulation (Nonlinear phase modulation of a beam, caused by its own intensity via the Kerr effect)**
  - **Guidance of high power is not possible**

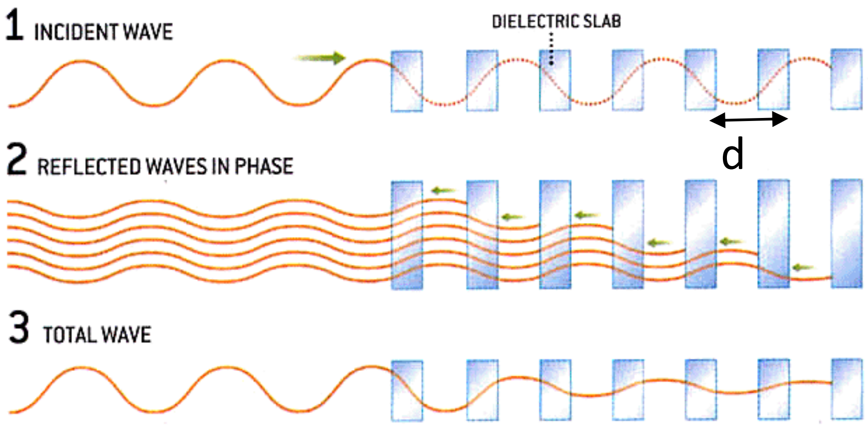
Bragg's Law

- Periodic objects reflect incident waves when wavelength and interplanar spacing, satisfy Bragg's Law

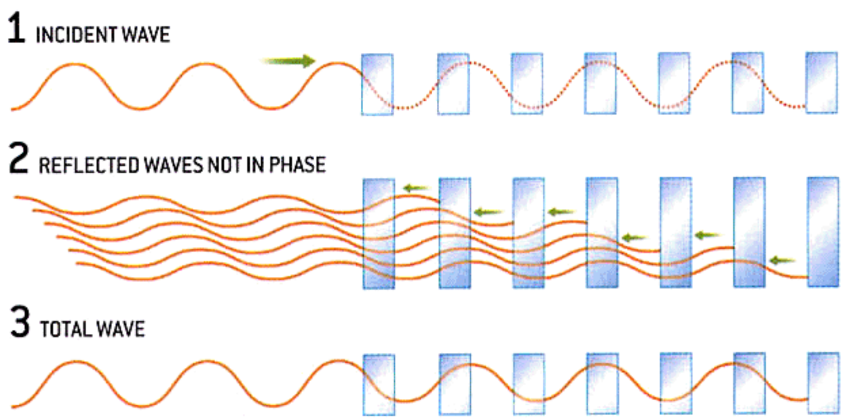
$$n \lambda = 2 d \sin(\theta)$$



One dimensional Photonic Crystal: Bragg grating



- Wavelength corresponds to the period.
- Reflected waves are in phase.
- Wave does not propagate inside.



- Wavelength does not correspond to the period
- Reflected waves are not in phase.
- Wave propagates through.

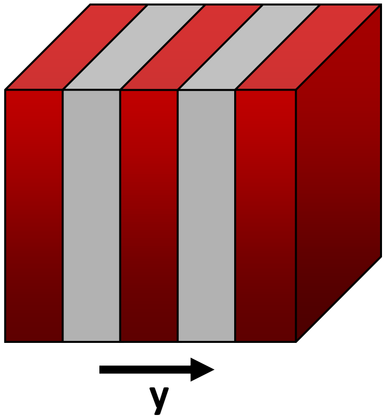
Yablonovitch, Sci.Am. 2001

Photonic Crystals (PhCs)

Novel class of optical media represented by natural or artificial structures with periodic modulation of the refractive index.

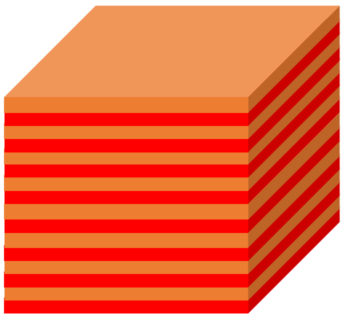
<u>Depending on geometry of the structure</u>, PhCs can be divided into three broad categories:

1-D Photonic Crystal

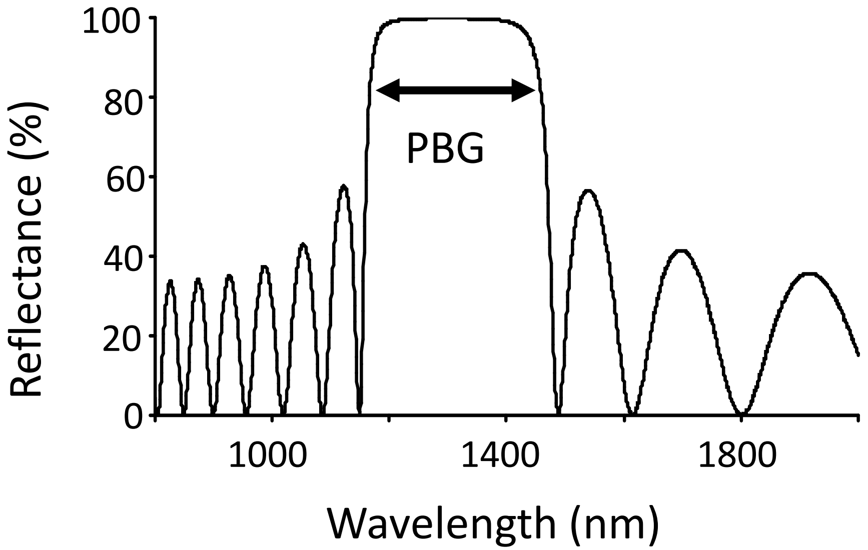


The periodic modulation of the permittivity occurs in one direction only, while in other two directions structure is uniform e.g. <u>Bragg grating and antireflecting</u> optical coatings.

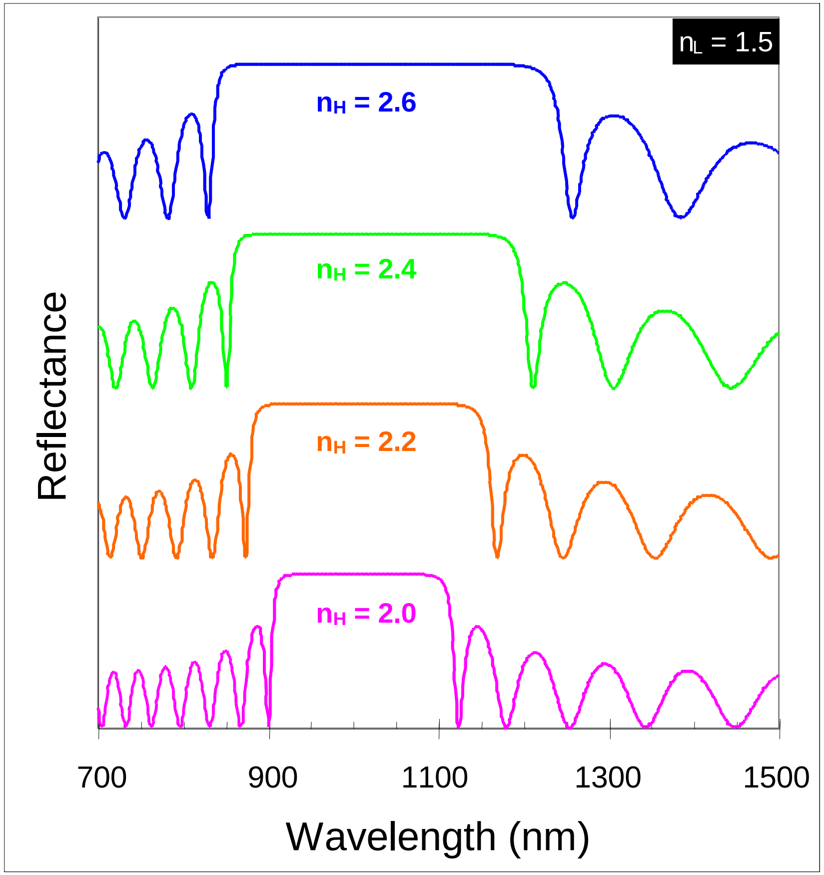
Bragg mirrors (1-D Photonic Crystal)



- **Consists of alternating quarter wavelength optical thickness high and low refractive index materials**



Propagation of light over a particular wavelength range is forbidden (called photonic band gap – PBG)

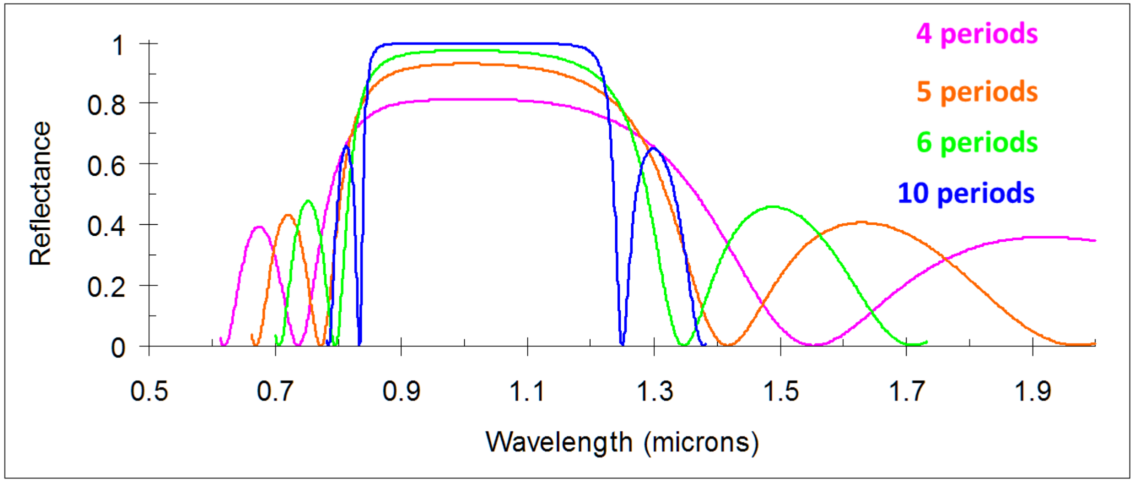


Stopband width increases as index ratio of n_H/n_L increases

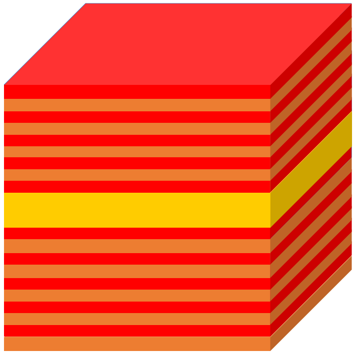
Bragg mirrors (1-D Photonic Crystal)

Multilayer Mirrors: Number of Periods

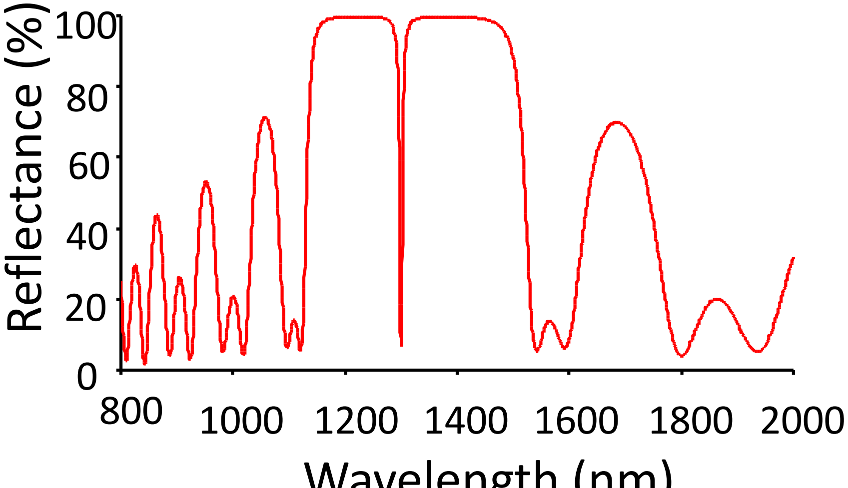
Height of high reflectance stopband increases with the number of periods



Microcavities

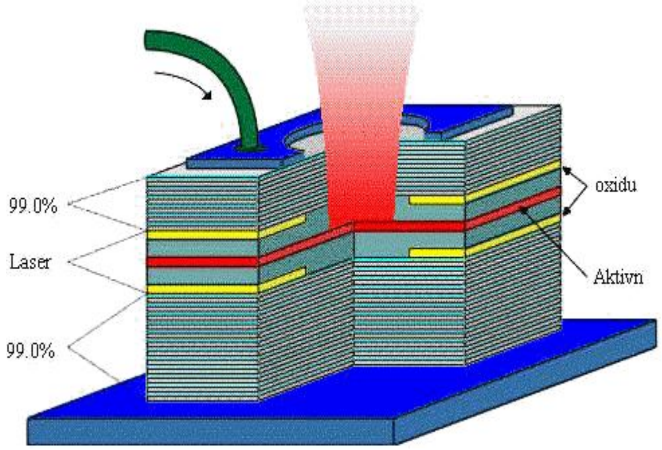


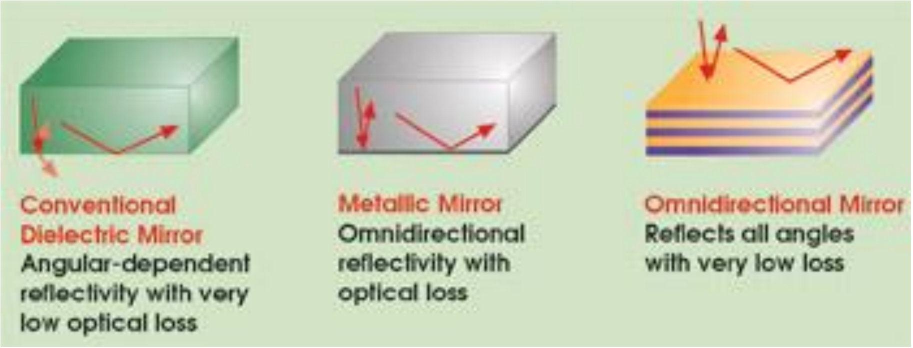
- **Defect layer breaks periodicity of dielectric function and introduces allowed mode into PBG**

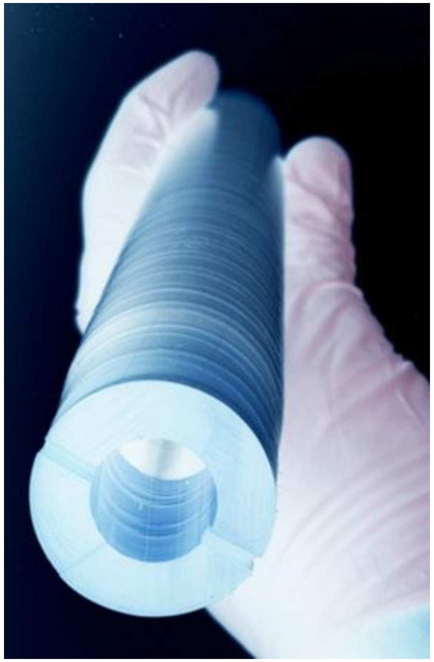


Examples of 1-D Photonic Crystals

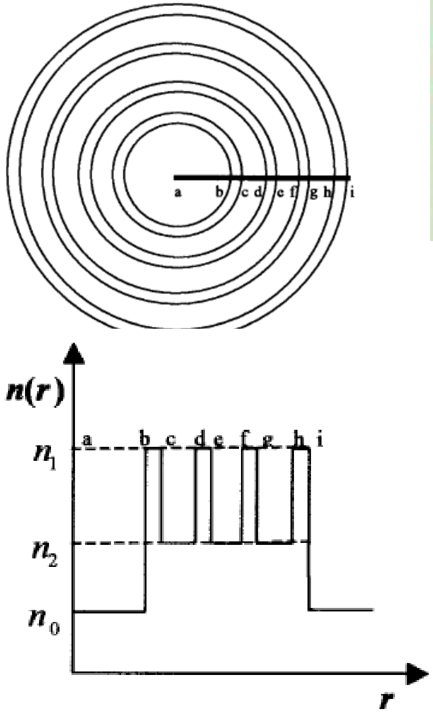
- **Bragg mirrors**
- **VCSELs** (**vertical cavity surface emitting lasers**)
- **Omnidirectional mirrors**







Omniguide

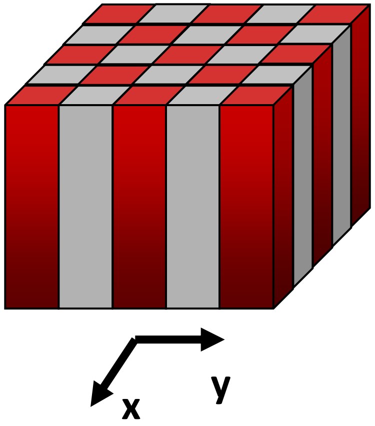


OMNIGUIDE:

Light guided in air core of hollow tube. Confinement based on multilayer films that constitute the cladding

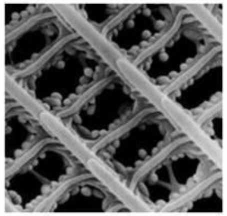
Y. Fink *et al.*, J. Lightwave Technology **17**, 2039 (1999)

2-D Photonic Crystal



Dielectric constant is periodic in two directions and homogeneous in third.

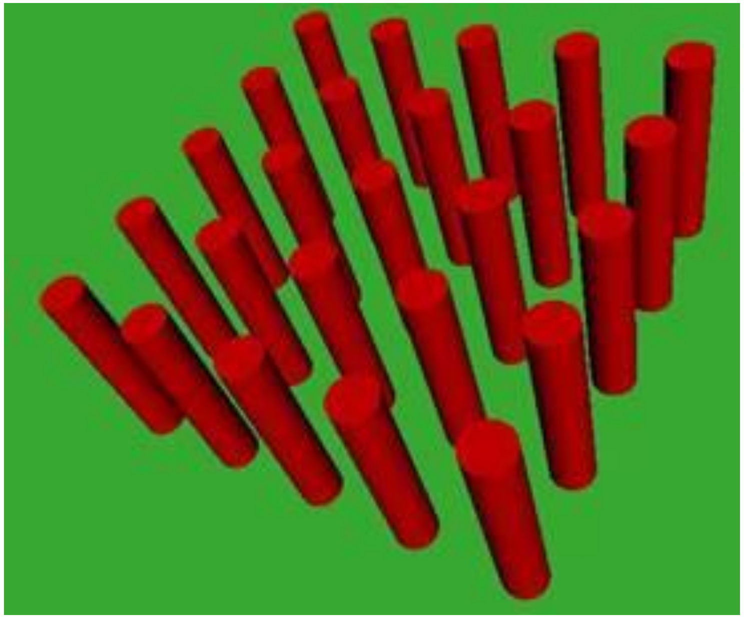
The pattern on the butterfly’s wing and its rainbow play is caused by the light reflection from the microstructure on the wing.



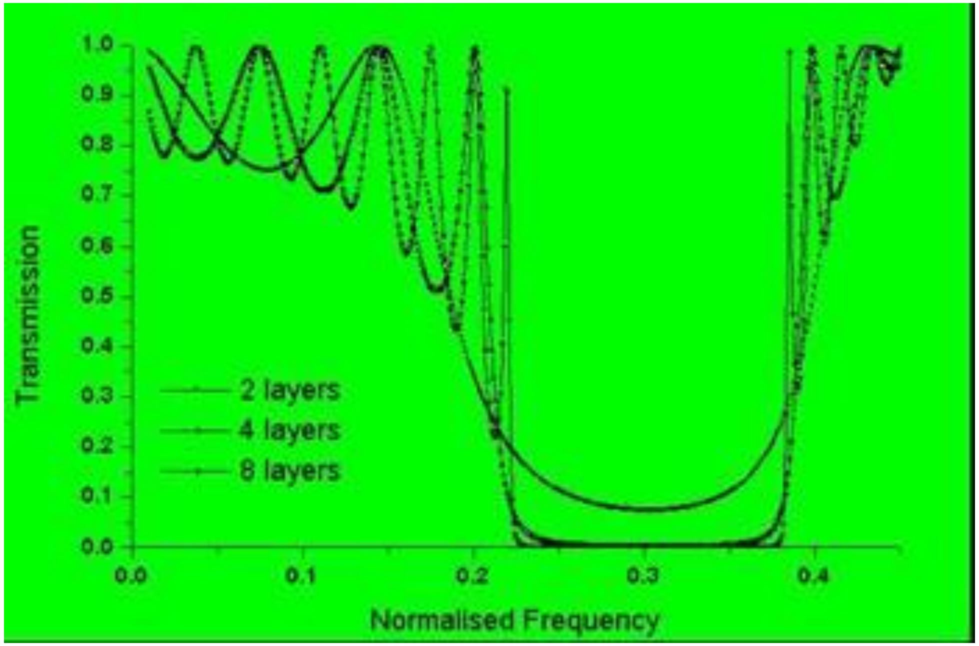
Examples of 2-D Photonic Crystals

- **Waveguides**
- **Photonic crystal lasers**
- **Photonic crystal fiber**
- **Add/drop filters**

2D PBG Crystals

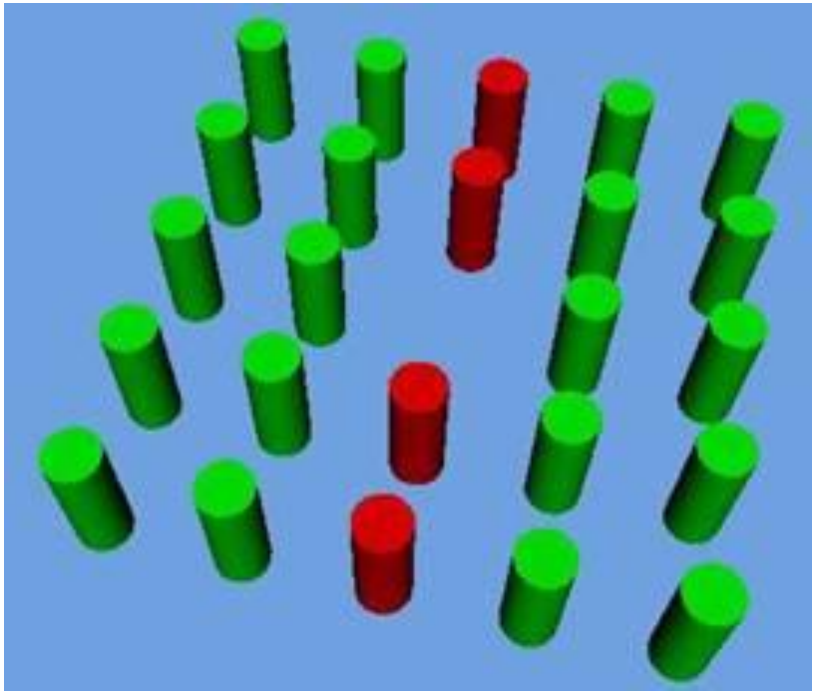


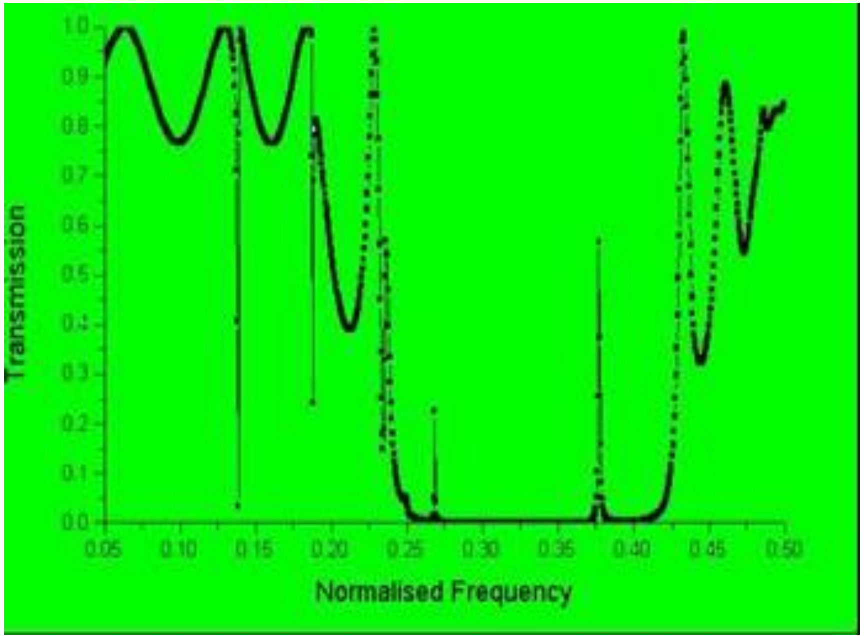
A periodic array of dielectric cylinders in air forming a two-dimensional band gap.



Transmission spectrum of this periodic lattice. A full 2D band gap is observed in the wavelength range 0.22 microns to 0.38 microns.

Defect in a 2D PBG Crystal



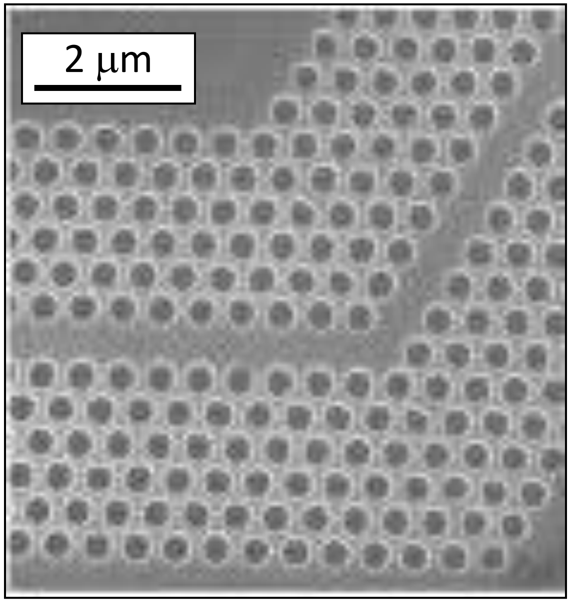


A defect is introduced into the system by removing one of the cylinders. This will lead to localization of a mode in the gap at the defect site

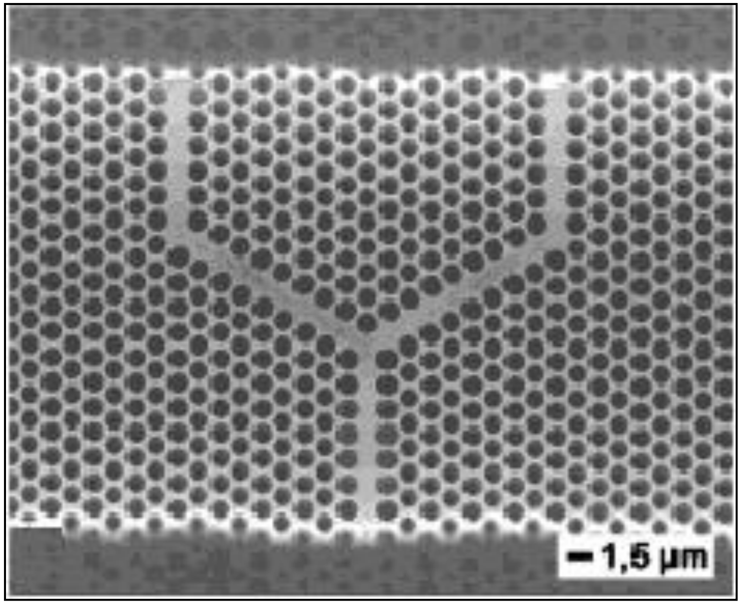
Transmission peak is observed in the forbidden band. This corresponds to the defect state which leads to spatial localization of light

2-D PBG Waveguides

- Silicon waveguides fabricated by a combination of lithography and electrochemistry



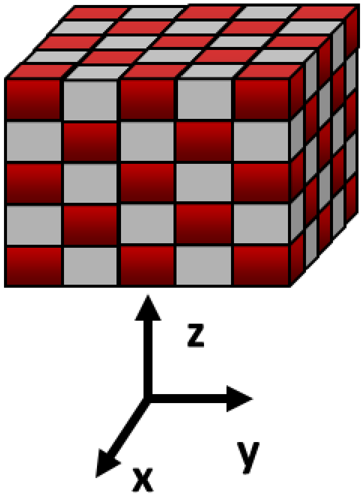
M. Loncar *et al.,* Appl. Phys. Lett. 7**7**, 1937 (2000)

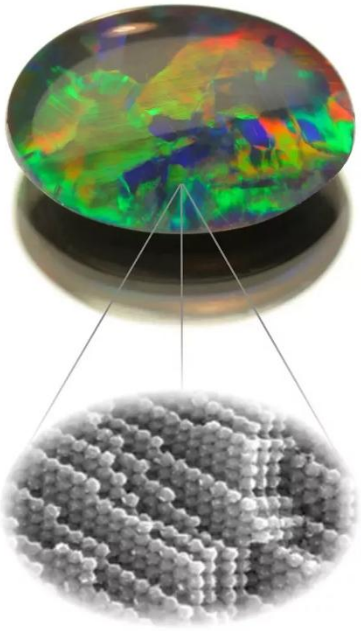


F. Muller *et al.,* J. Porous Materials **7**, 201 (2000)

3-D Photonic Crystals

- True optical analog of traditional semiconductor crystal lattice
  - <u>Dielectric function periodic in all three directions</u>
- Very few periodic arrangements of two materials gives rise to complete 3-D PBG
- Opal stone

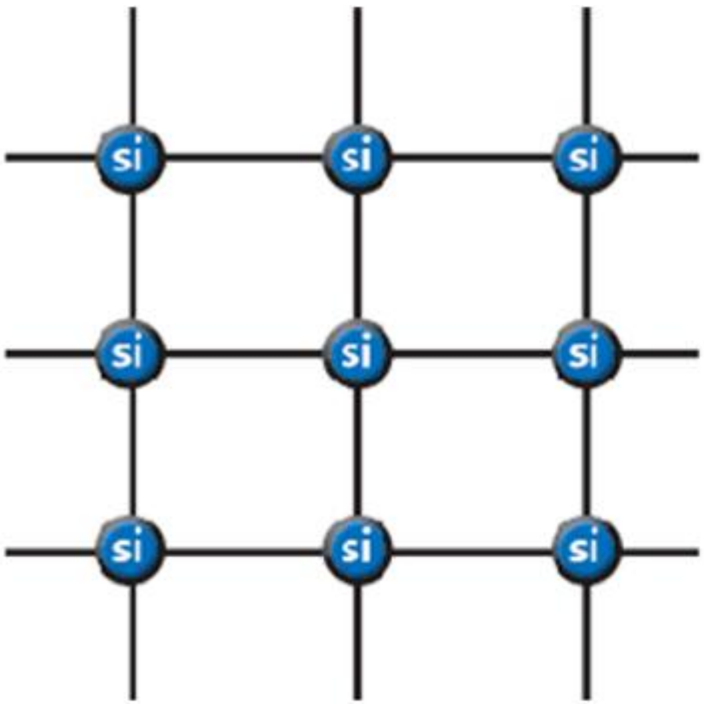




The optical properties of PhCs are determined by the existence of the periodic modulation of the refractive index of the medium.

Photonic Bandgap (PBG) Concept

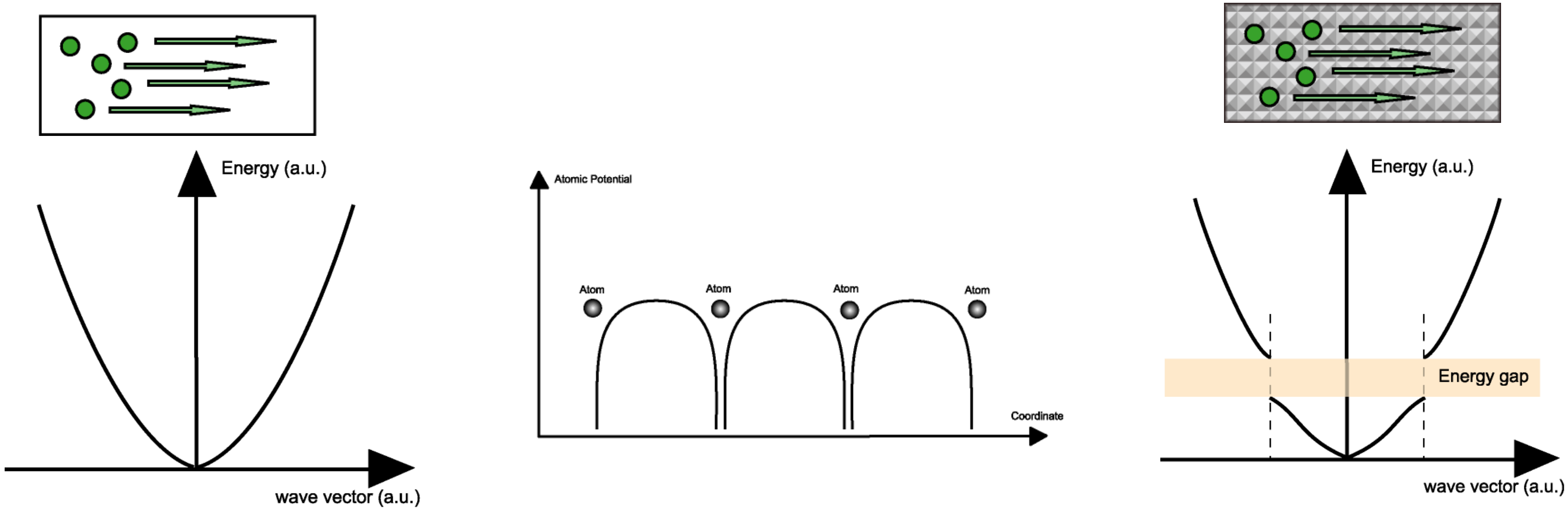
The behavior of light in a photonic crystal is similar to the movement of electrons and holes in a semiconductor.



If the periodicity of the lattice is broken by a missing Si atom or by <u>various impurity, an electron can have enough energy to be in the band gap.</u>

The same for photons in a photonic lattice, photons move in a transparent dielectric material that contains tiny air holes arranged in a lattice pattern.

Energy gap in Semiconductor

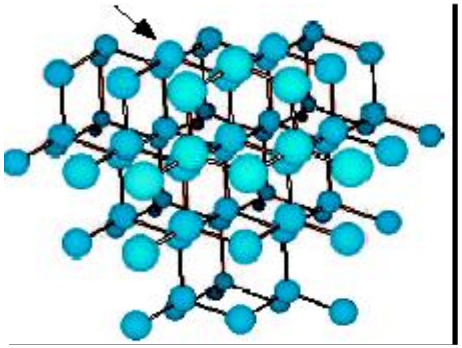


Gap in energy spectra of electrons arises in periodic structure

Photonic Crystals – Semiconductors of light

Semiconductors

Periodic array of atoms (0.5nm)



Atomic length scales

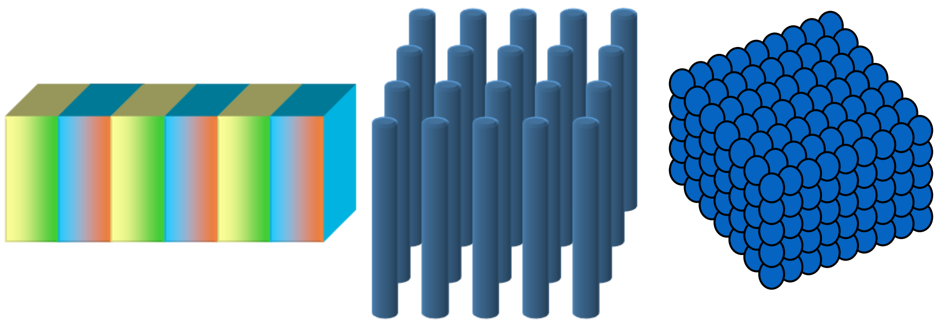
Natural structures

Control electron flow

1950's electronic revolution

Photonic Crystals

Periodic variation of dielectric Constant (0.5micron)



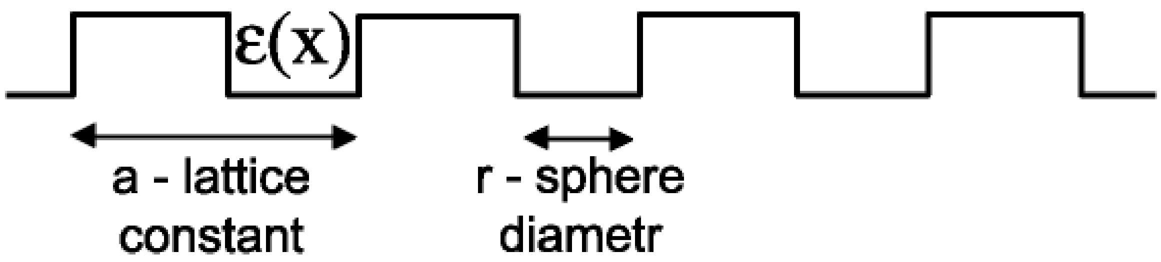
Length scale ~ λ

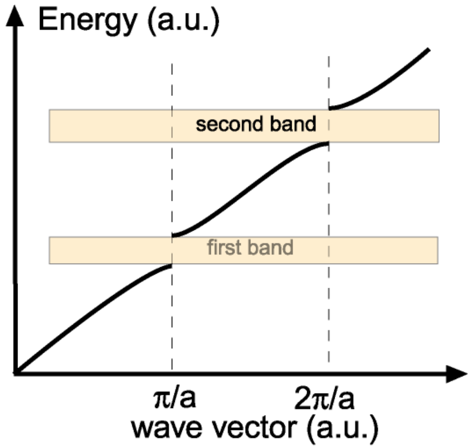
Artificial structures

Control E.M. wave propagation

New frontier in modern optics

PBG formation





- **PBG formation can be regarded as the synergetic interplay between two distinct resonance scattering mechanisms.**
- **The first is the "macroscopic" Bragg resonance from a periodic array of scatterers. This leads to electromagnetic stop gaps when the wave propagates in the direction of periodic modulation when an integer number, m=1,2,3…, of half wavelengths coincides with the lattice spacing, a, of the dielectric microstructure.**
- **The second is a "microscopic" scattering resonance from a single unit cell of the material. The maximum backscattering occurs when precisely one quarter of the wavelength coincides with the diameter, 2r, of a single dielectric well of refractive index n.**
- **PBG formation is enhanced by choosing the materials parameters a, r, and n such that both the macroscopic and microscopic resonances occur at the same frequency.**

Size scales

Wavelength range of photonic band gap directly related to feature size of photonic crystal

Refractive index periodicity	Photonic band gap wavelength
1 millimeter	THz
1 micron	Mid IR
0.5 micron	Near IR
0.1 micron	Visible

PBG materials

Materials used for making a PBG:

- **Silicon**
- **Germanium**
- **Gallium Arsenide**
- **Indium Phosphide**

A brief history…

1970: **Idea that a cylindrical Bragg waveguide can guide light**

1991: **Idea that light could be trapped inside a 2D PhC made of silica capillaries.**

1995: **Theoretical proof that bandgap guiding is possible**

1996: **First PCF prototype**

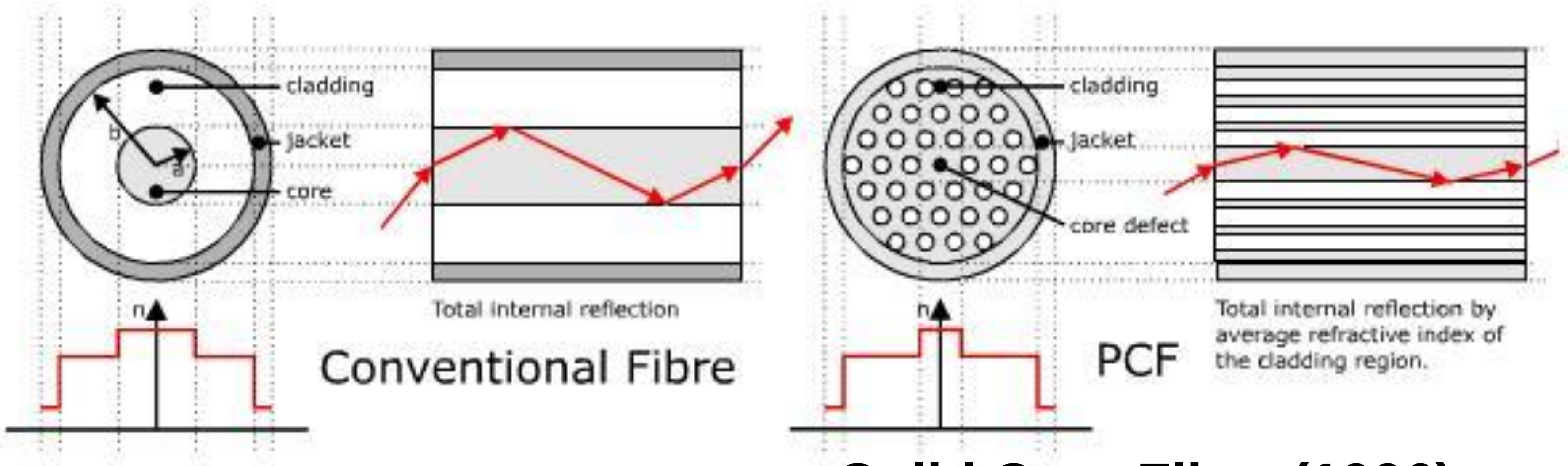
- **By stacking silica capillaries, then drawing to fiber**
- **Index guidance. d_{hole}/pitch=0.2**

1999 : **First HC PCF**

J. C. Knight, T. A. Birks, P. St. J. Russell, and D. M. Atkin, "All-silica single-mode optical fiber with photonic crystal cladding," Opt. Lett. **21**, 1547-1549 (1996)

Photonic Crystal Fiber

- A long thread of silica glass with a periodic air holes running down its length



Solid Core Fiber (1996)

Type 1 - The central hole is absent, high-index defect acts as core (Solid core PCF)

Type 2 - The core has an extra hole, which is a low-index defect (Photonic band gap fiber)

Light is guided along the low refractive index air core by <u>photonic band gap confinement effect</u>

Photonic Crystal Fibers (PCF)

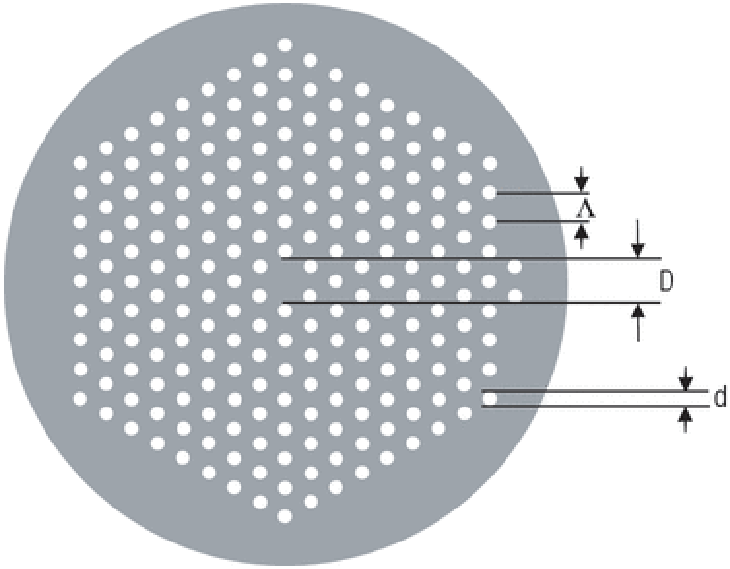
- Contains periodic pattern of micron-sized holes

Core Structure

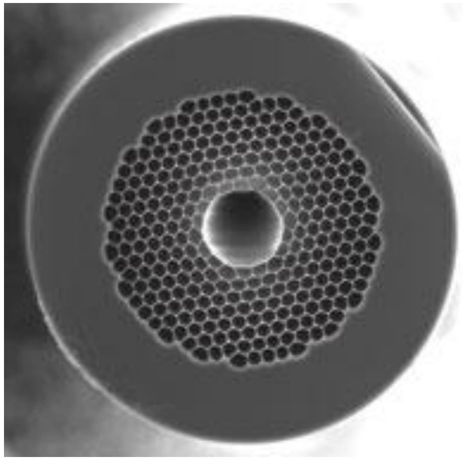
- solid core
- hollow core

Transmission Mechanism

- Index guiding
- Bandgap guiding



Λ: pitch
D: diameter of core
d: diameter of holes

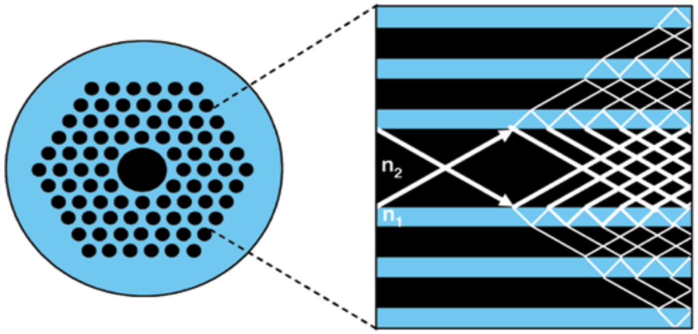


HC-PCF
Index + Bandgap

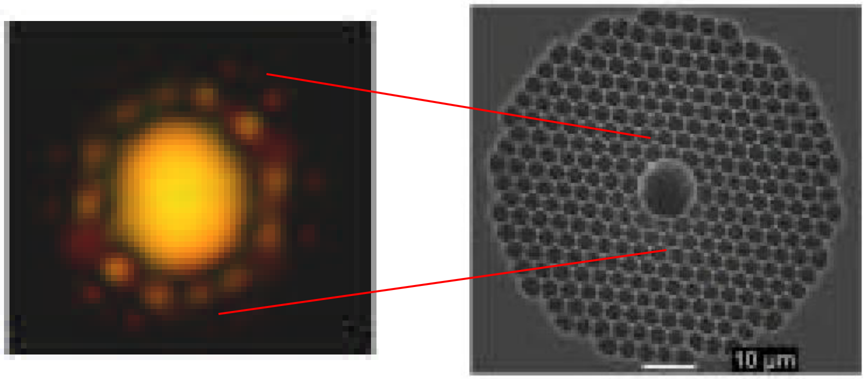
By varying size & location of holes mode shape, dispersion, nonlinearity, etc. can be changed

Hollow Core Photonic Crystal Fiber

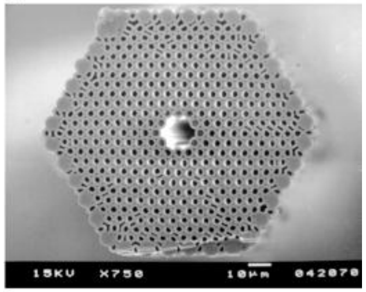
- Light guided in air core instead of traditional high refractive index core
- Allows for lower losses
- 2-D PBG confines light in fiber
- Currently 1.2dB/km (traditional fiber 0.15dB/km)



multiple Interference and scattering at Bragg's condition



A



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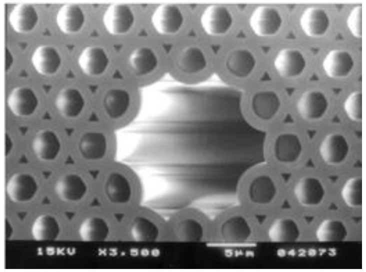
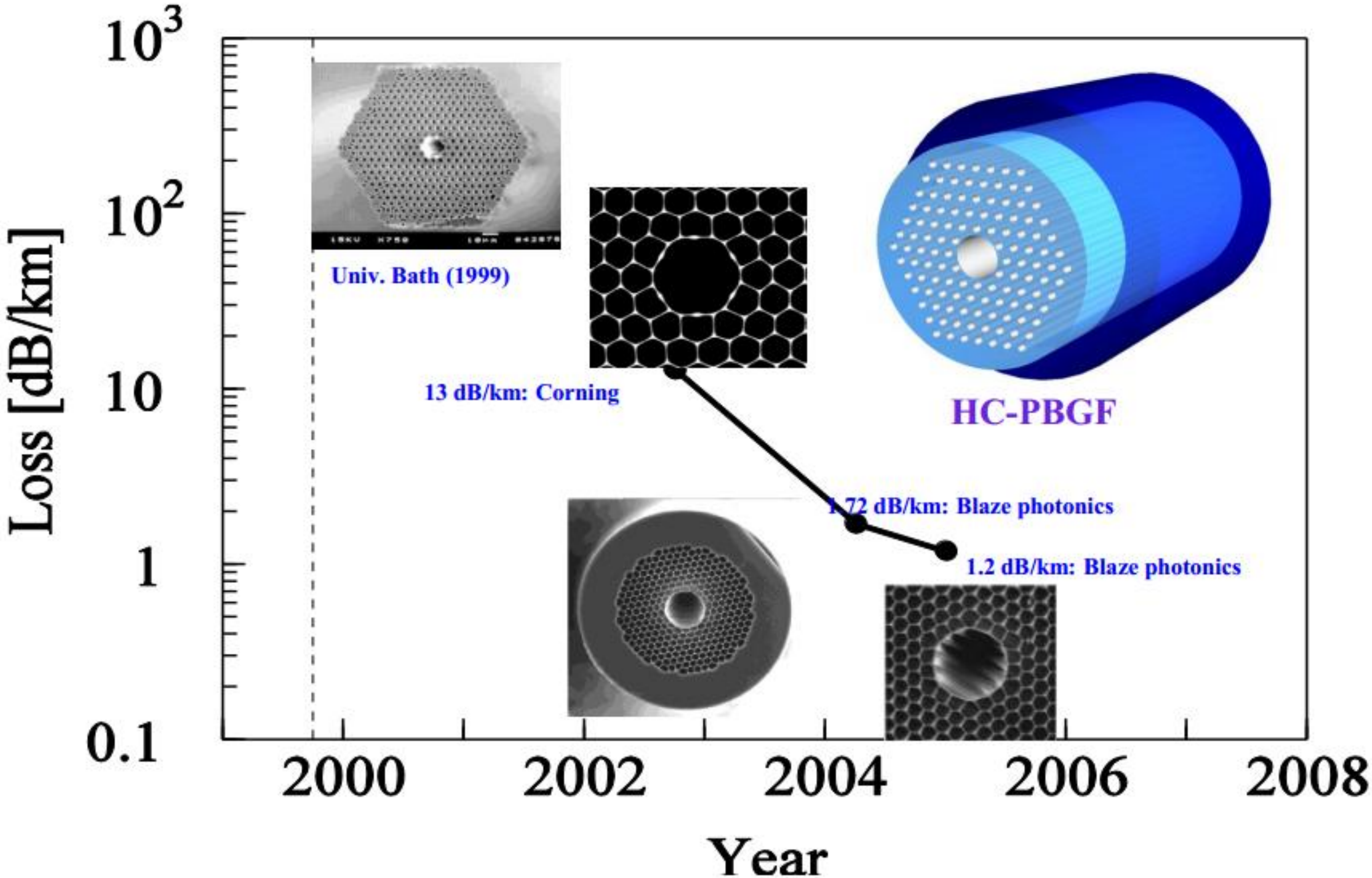


R. F. Cregan *et al.*, Science **285**, 1537 (1999)
P. J. Roberts *et al.*, Opt. Express **13**, 236 (2004)

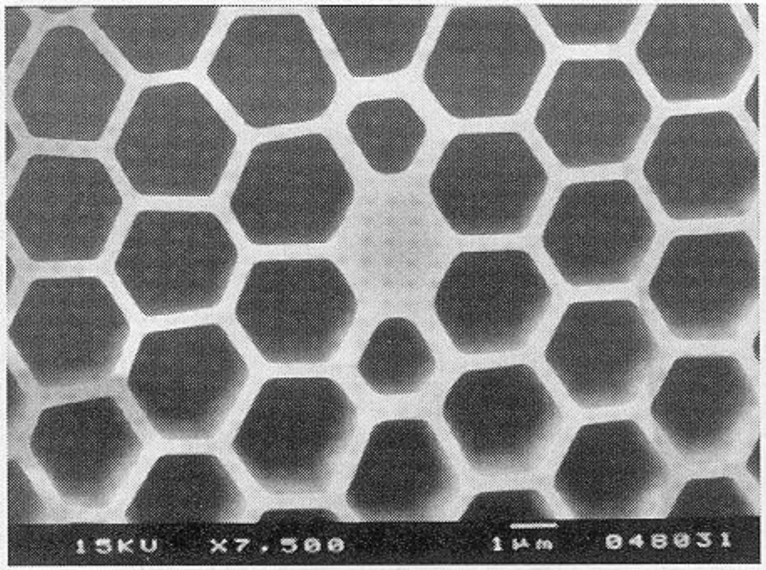
Hollow-core fibres

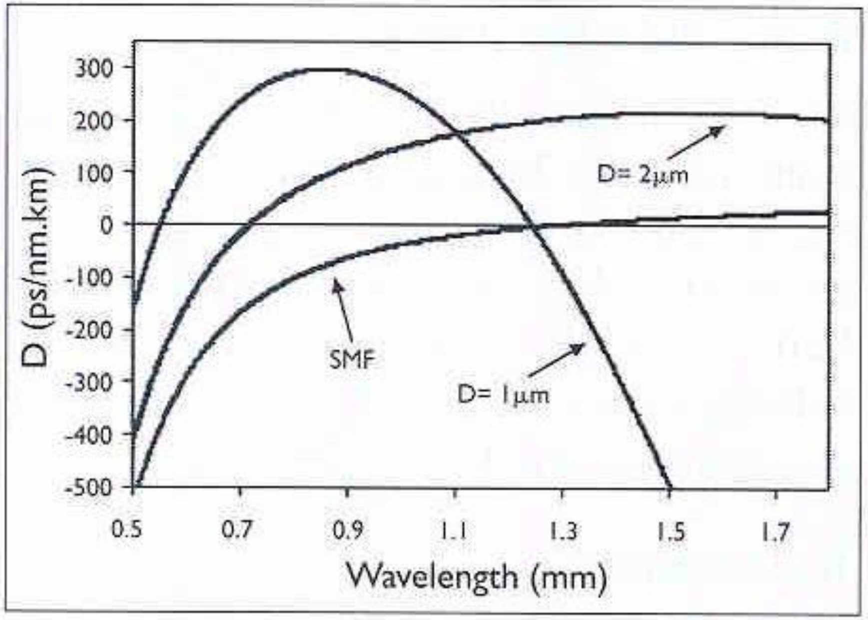
- **Light confinement by photonic band-gap (PBG)**
- **Index of “core” can be lower than that of “cladding”**
- **Light transmitted through “core” with high efficiency even around tight bends**
- **High power transmission without nonlinear optical effects (light mostly in air)**
- **Small material dispersion**
- **Nonlinear interactions in gas-filled air holes**

Hollow core PBGFs have allowed significant advances in chemical sensing, gas-based nonlinear optics, high power delivery , pulse compression, …



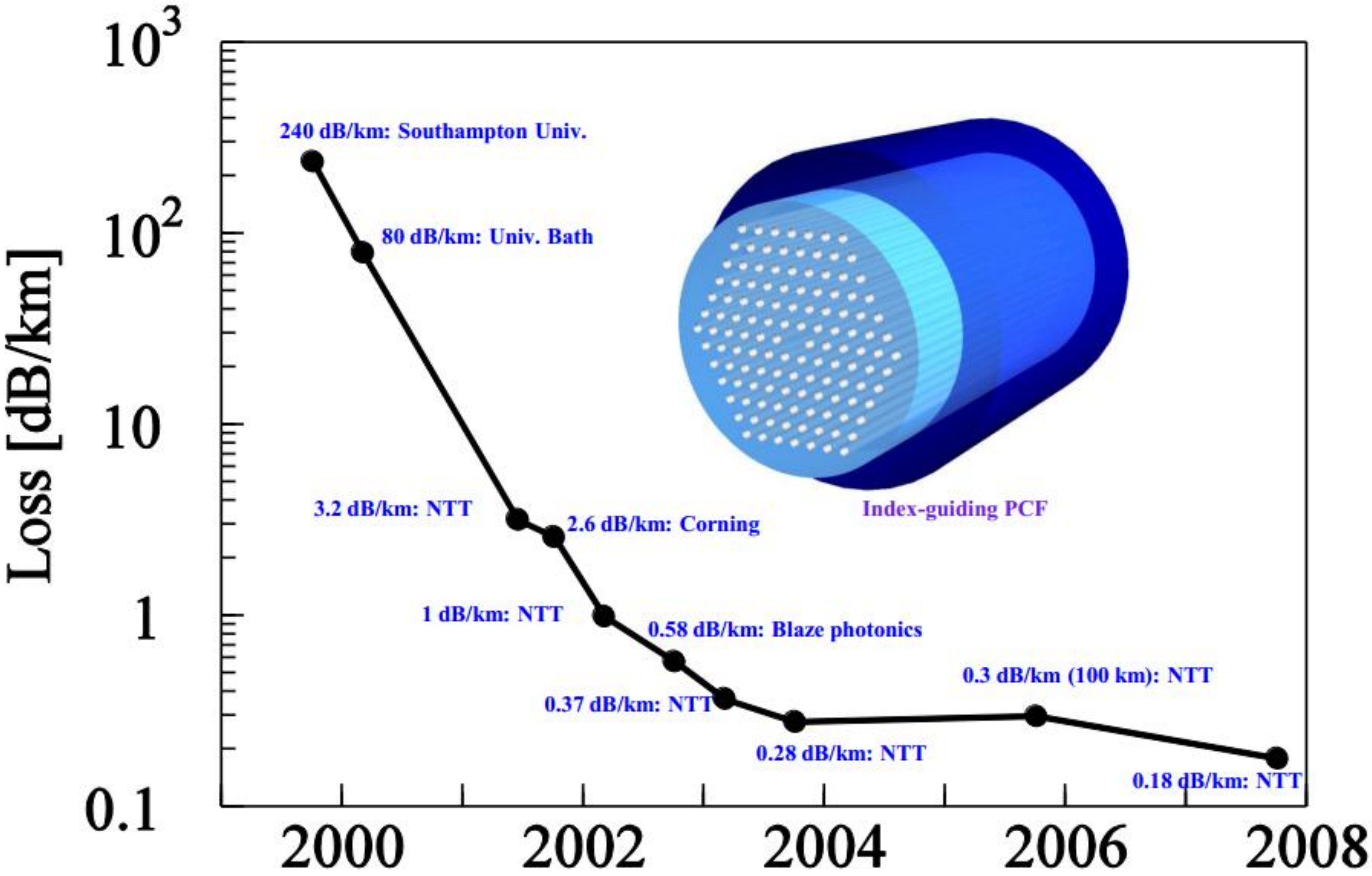
Solid Core PCF fiber





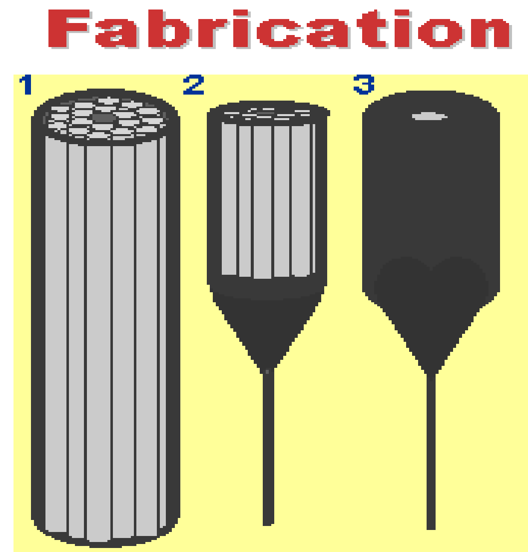
- Effective index of “cladding” is close to that of air (n=1)
- Anomalous dispersion (D>0) over wide λ range, including visible (enables soliton transmission)
- Can taylor zero-dispersion λ for phase-matching in non-linear optical processes (supercontinuum generation)
- Single mode requires V<2.405 (“endlessly single-mode”)
- Single-mode for wide range of core sizes

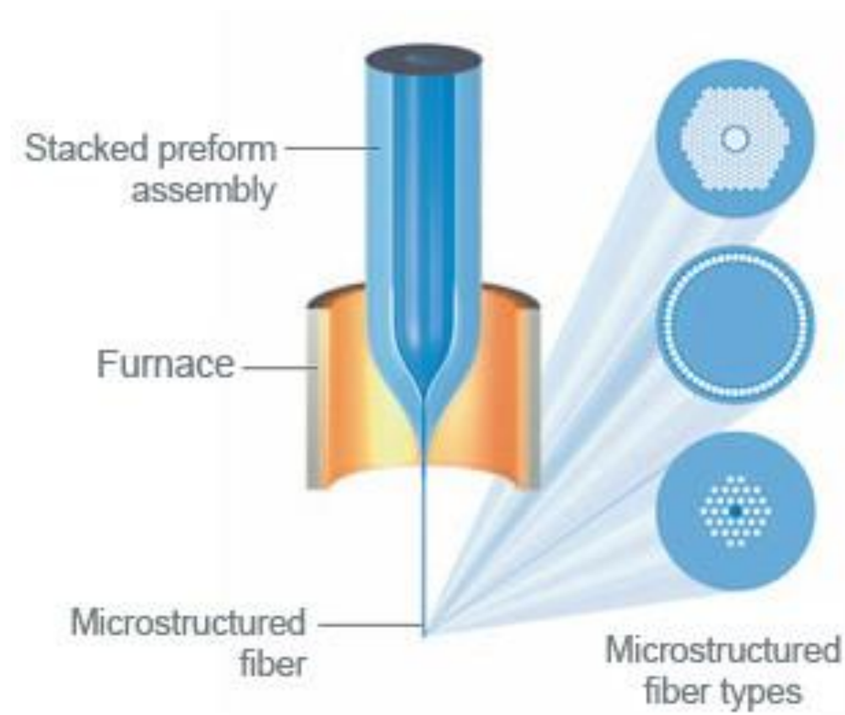
Transmission Loss in Solid core PCF



Fabrication of PCF

- Fabricated by stacking an array of capillaries in a hexagonal configuration around a solid rod which forms the core.
- Preform is heated to 2000°C to soften silica
- The resulting preform is reduced to fibre dimensions using a conventional fibre drawing tower with Collapse ratios of ~50,000
- 1st run: cane of 1mm diameter
- 2nd run: cane is introduced inside a jacketing tube + drawn to the final fiber



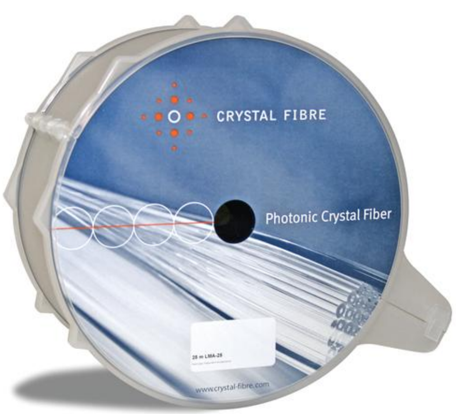


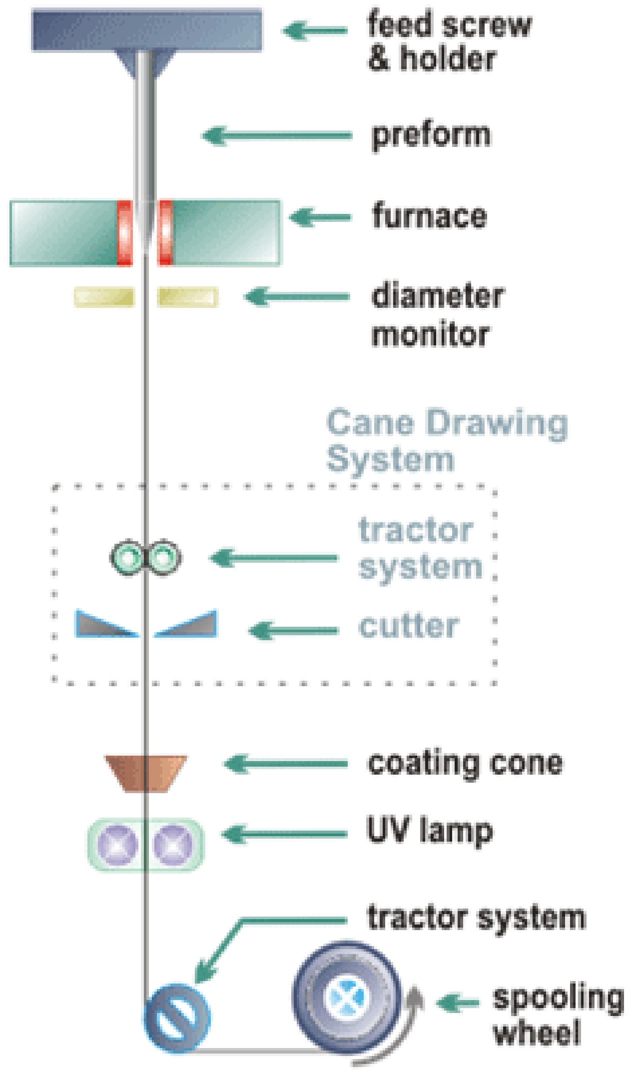
Final steps

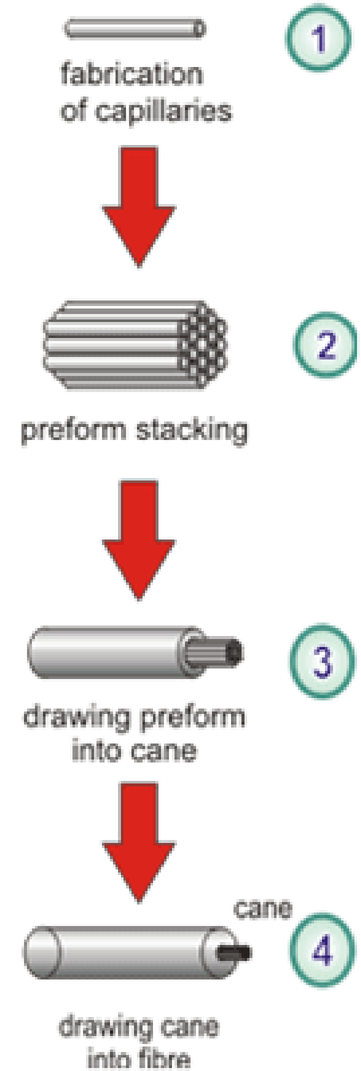
- **Once the final dimensions are reached:**

  -> fiber is coated with a polymer

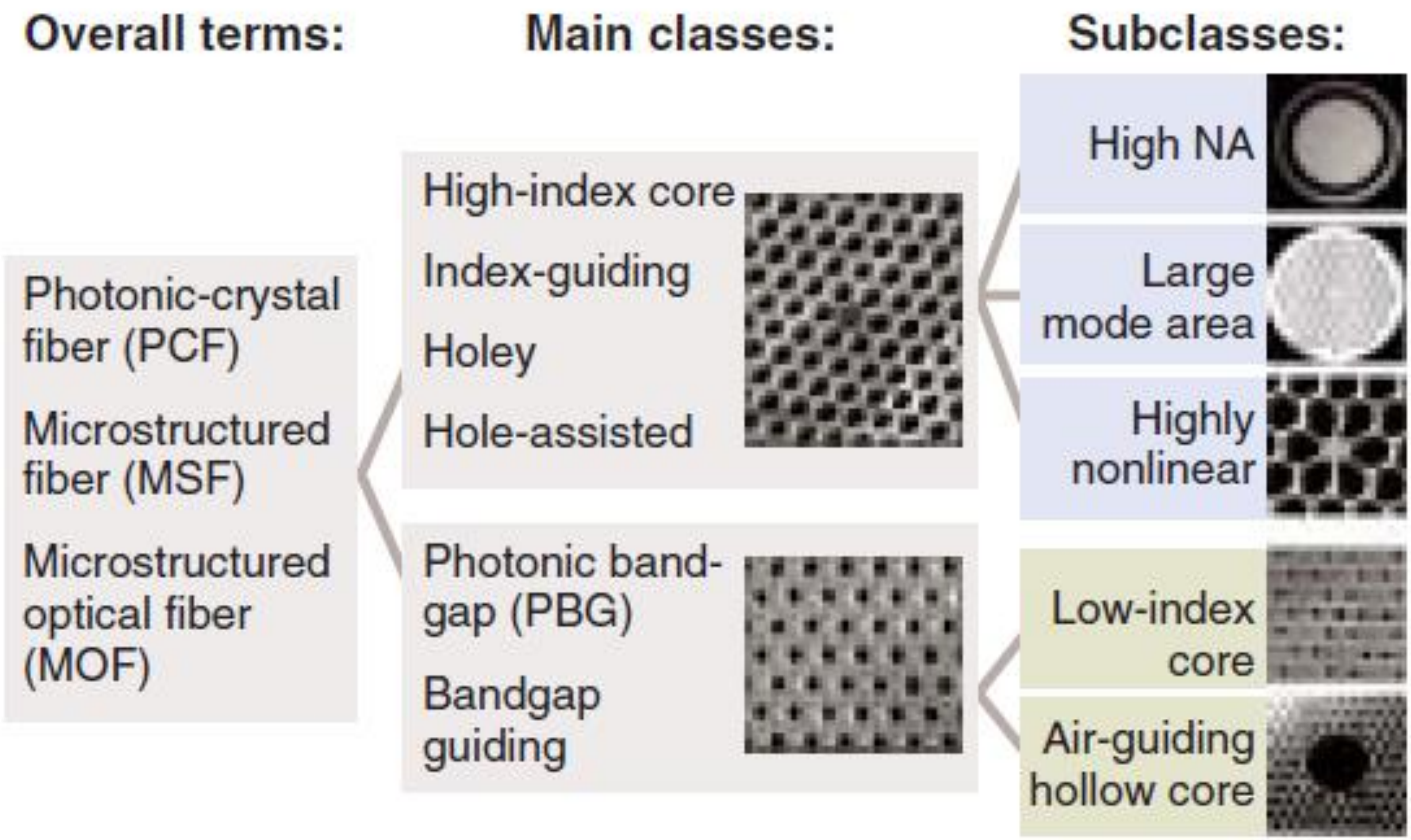
  -> fiber is wound onto spool.







Types of PCF

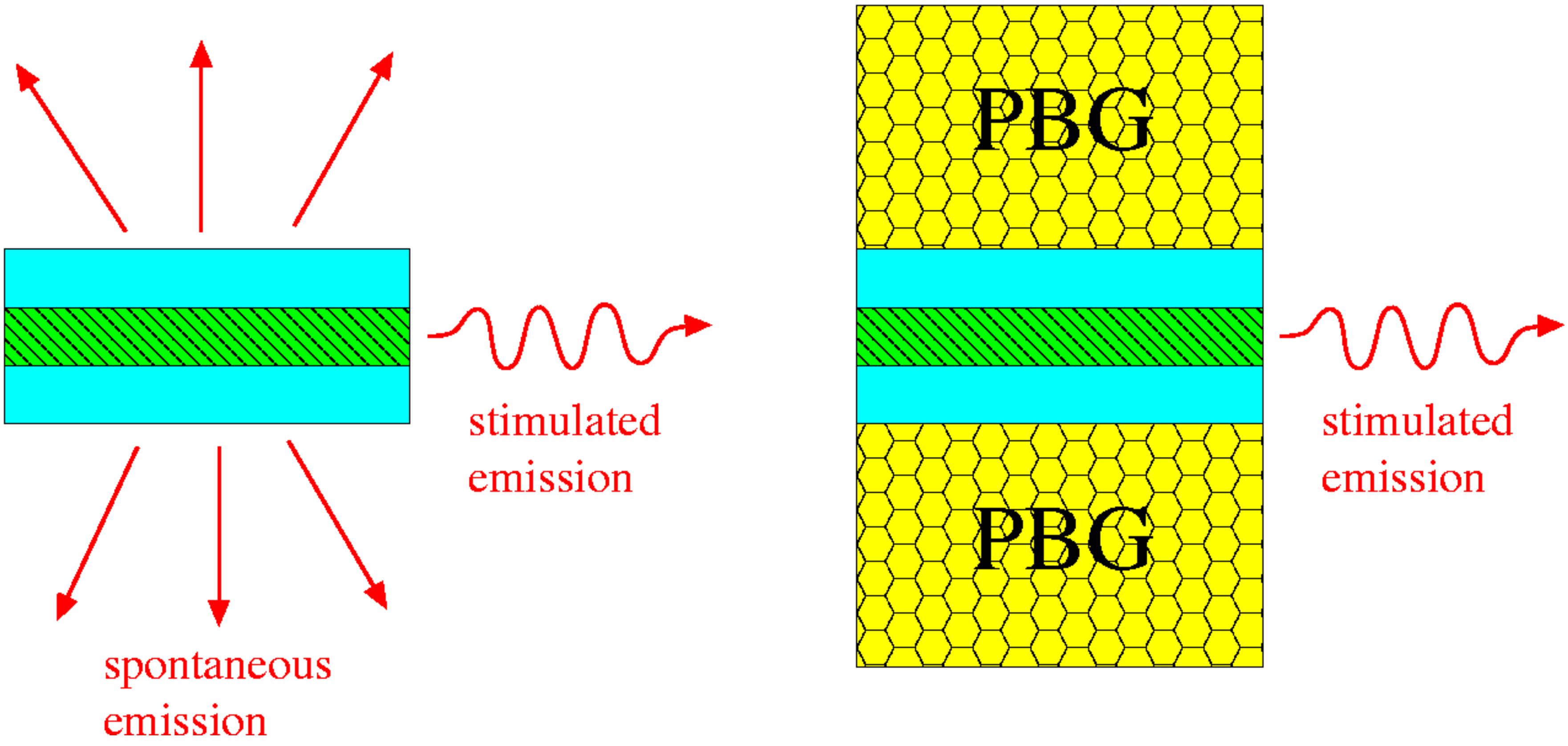

Overall terms:
Main classes:
Subclasses:
Photonic-crystal fiber (PCF)
Microstructured fiber (MSF)
Microstructured optical fiber (MOF)
High-index core
Index-guiding
Holey
Hole-assisted
Photonic band-gap (PBG)
Bandgap guiding
High NA
Large mode area
Highly nonlinear
Low-index core
Air-guiding hollow core

Advantages of PCFs

- **Many physical properties can be engineered (power fraction, birefringence, chromatic dispersion,…)**
- **The waveguide dispersion can be engineered to have the zero dispersion wavelength at any desired wavelength. This is useful for nonlinear applications, where normal dispersion is a limiting factor.**
- **By changing the core diameter of fiber, the Zero Dispersion Wavelength can be shifted to the visible range.**
- **PCF can be filled with gases or liquids for sensing.**

Applications

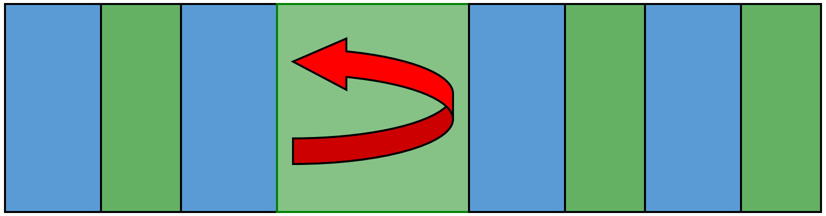
Suppression of spontaneous emission

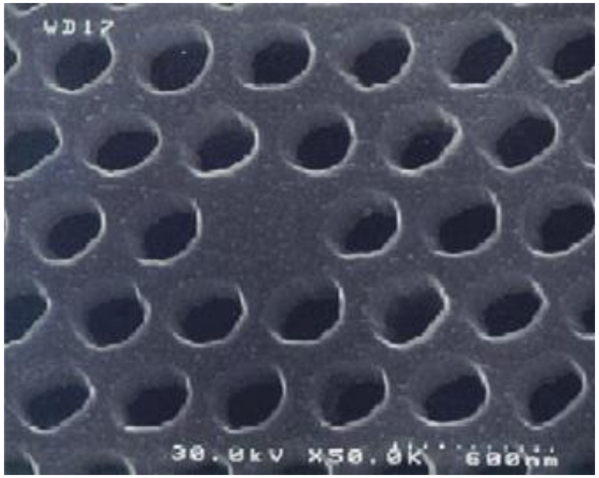


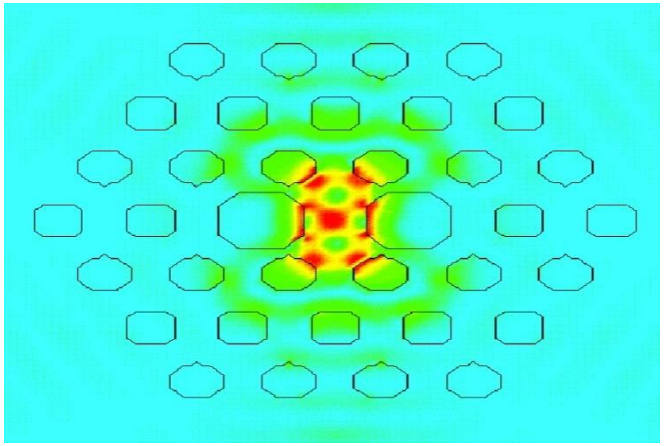
Low-threshold lasers, single-mode LEDs, mirrors, optical filters

Photonic crystals can reflect light very efficiently.

Introduce a defect into the periodic structure



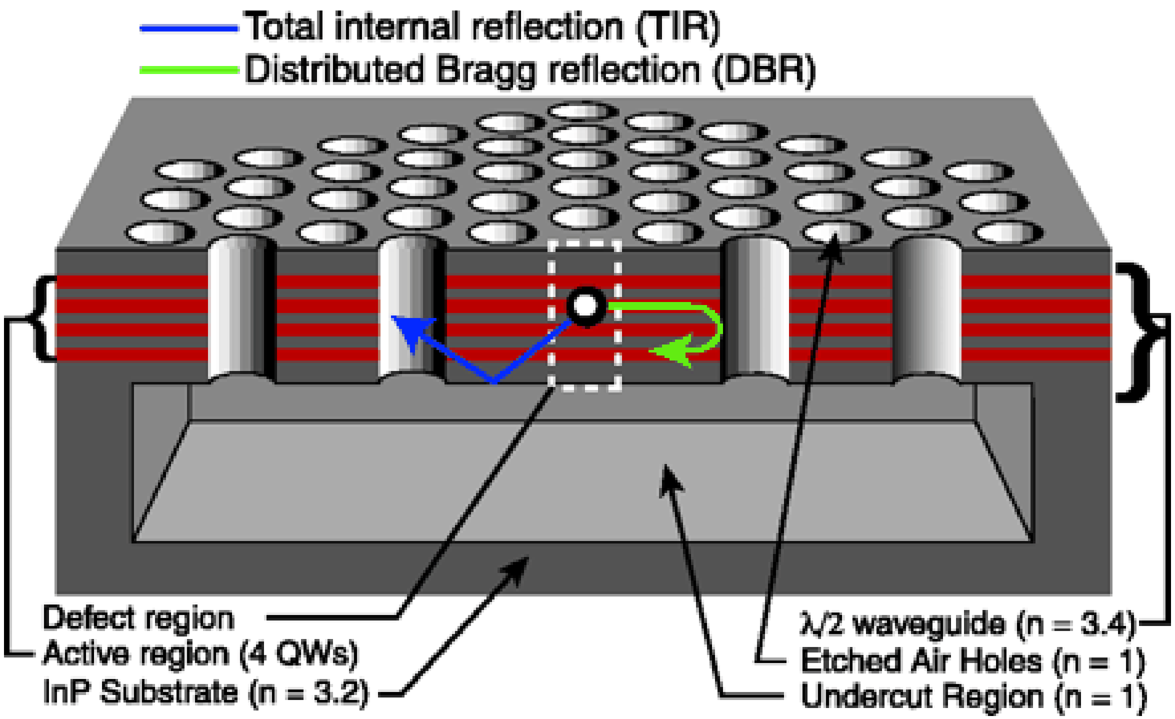


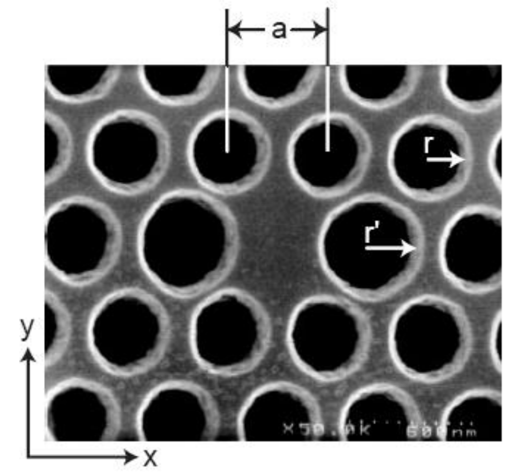


- Creates an allowed photon state in the photonic band gap
- <u>Can be used as a cavity in lasers</u>

Photonic Crystal Lasers

- Incorporation of 2-D photonic crystal with light emitting semiconductor quantum well provides confinement and gain necessary for lasing

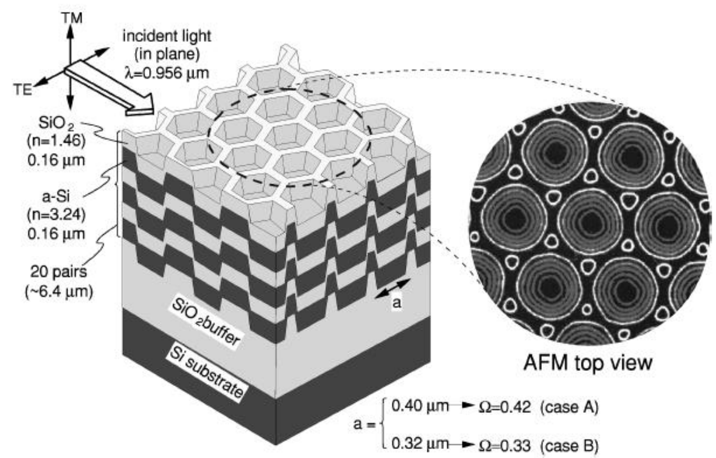


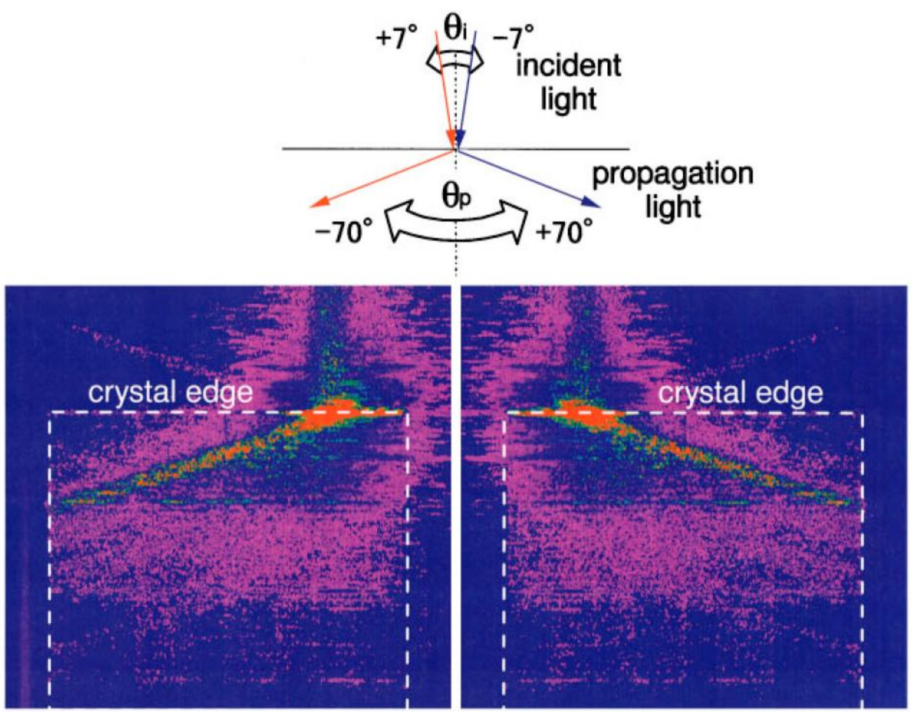


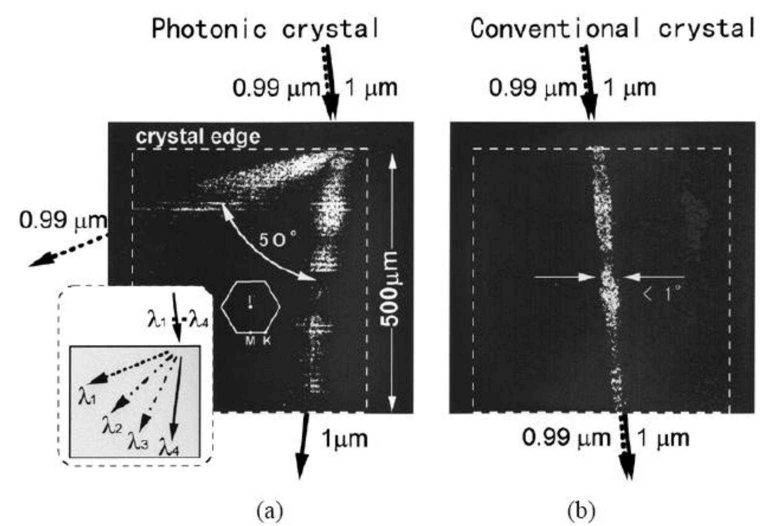
O. Painter *et al.*, Science **284**, 1819 (1999)

Superprism Effect

- **Light path shows a extremely wide swing with a slight change of incident light angle**
- **Based on highly anisotropic dispersion by photonic band (negative refraction)**
- **Wavelength demultiplexer (uses)**



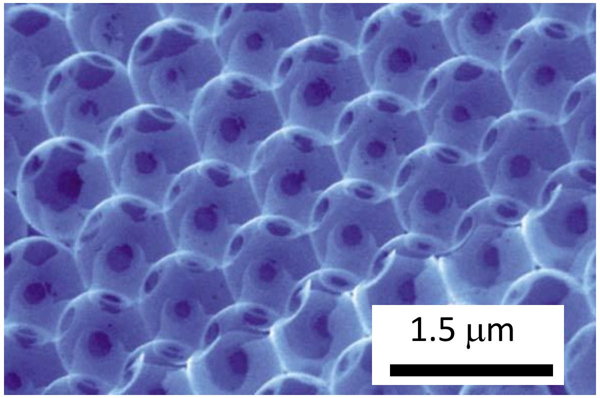




T. Sato *et al.*, Phys. Rev. B **58**, R10096 (1998)

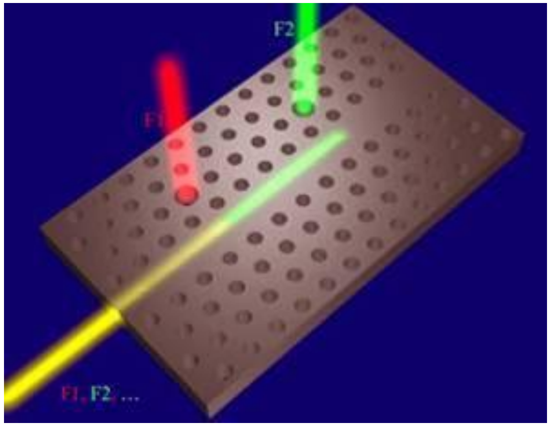
Artificial Opals

- Chemical synthesis using chemical vapor deposition and wet etch to form air spheres surrounded by silicon shells
- Easier to achieve smaller dimensions



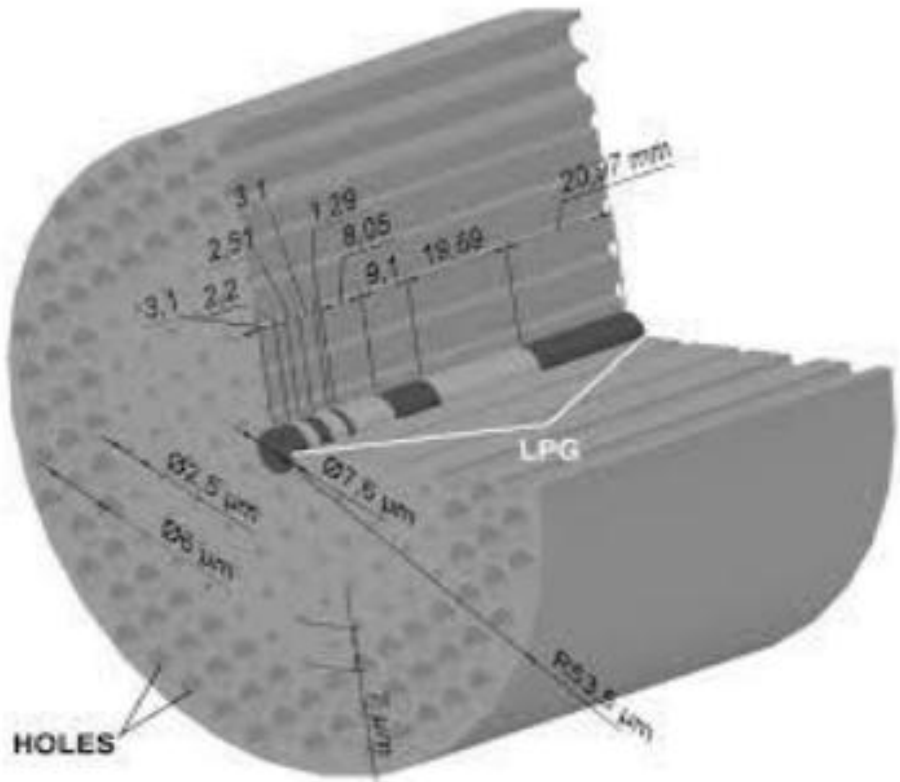
Blanco *et al.,* Nature **405**, 437(2000)

Photonic Crystal Filters



- **Add-drop filter for a dense wavelength division multiplexed optical communication system.**
- **Multiple streams of data carried at different frequencies F1, F2, etc. (yellow) enter the optical micro-chip from an external optical fiber and are carried through a wave guide channel (missing row of pores).**
- **Data streams at frequency F1 (red) and F2 (green) tunnel into localized defect modes and are routed to different destinations.**
- **<u>The frequency of the drop filter is defined by the defect pore diameter which is different from the pore diameter of the background photonic crystal</u>.**

• ***Fiber Grating in the core of PCFs***



Sensing

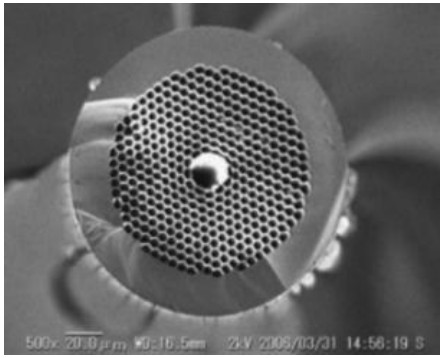
- Strain
- Pressure
- Vibration
- Temperature
- Bio-sensing

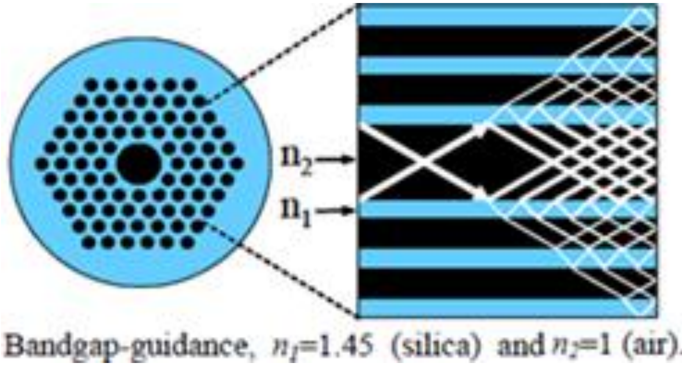
Wang et al. *Photonic Sensors* 3, 193–201 (2013).

HCPCF based Gas sensing

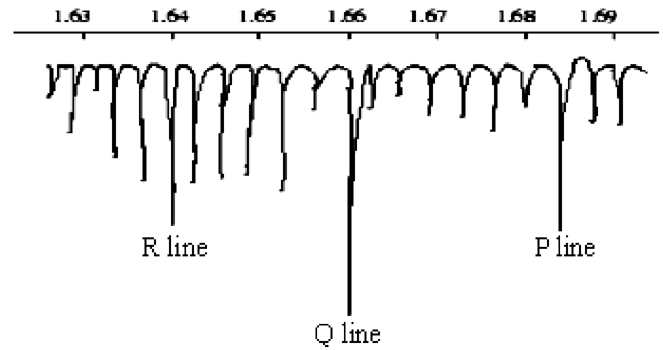
- **Bandgap known HC-PCF**
  - center wavelength must match with absorption band of gases(C_2H_2, NH_3, CO_2) ; around NIR region (~1500nm)
- **Tunable Laser & Photodiode**
  - improving sensitivity
- **Coupling between SMF & PCF to diffuse gas**
  - angled cleaving

Hollow Core Photonic Bandgap Fiber based Methane gas sensor

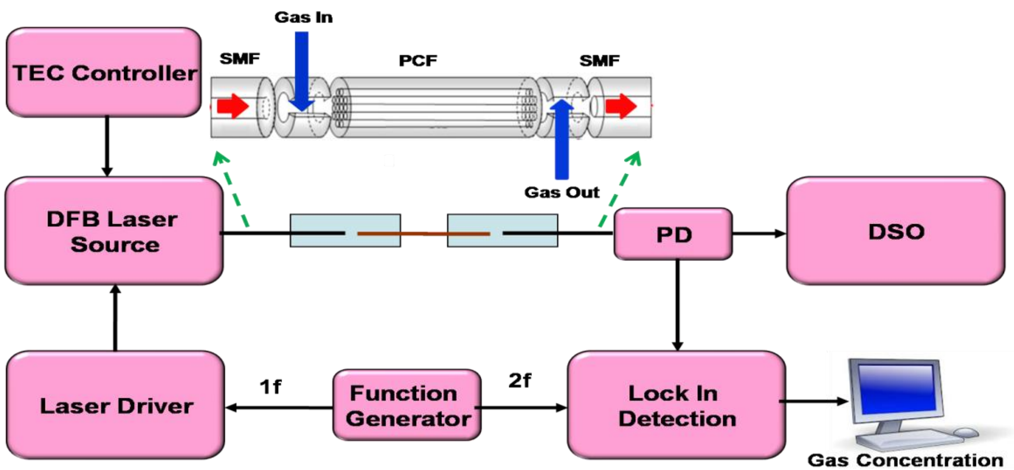




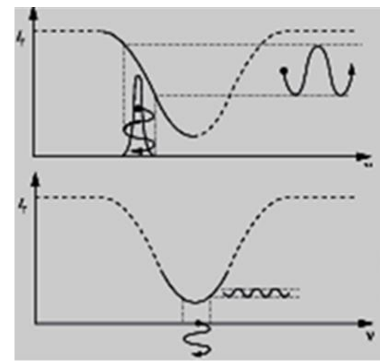
HC-PBG Fiber

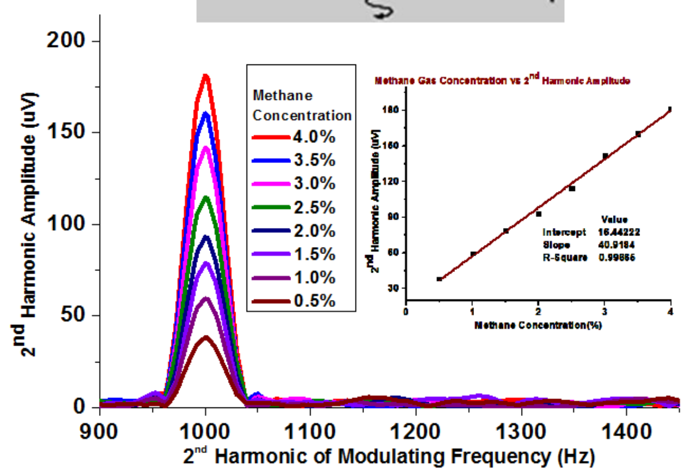


Transmission Spectra of Methane



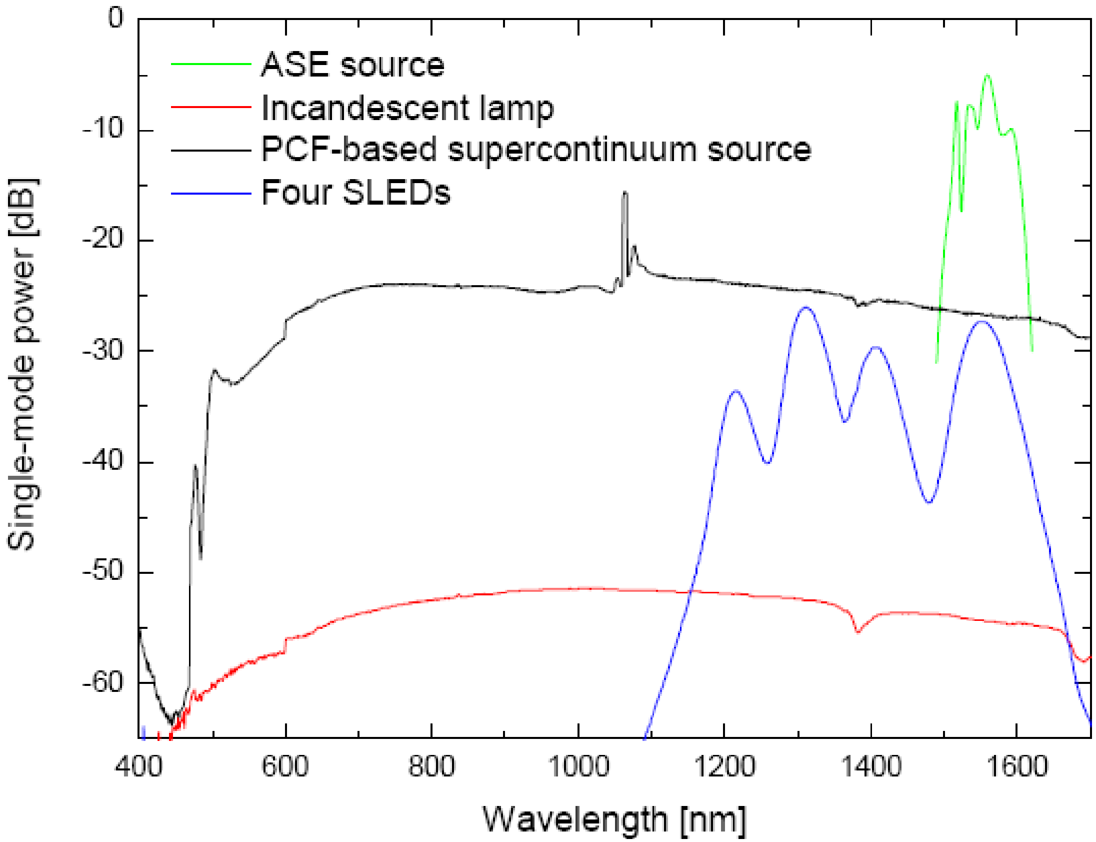
Block Diagram of TDLAS based Gas Detection System





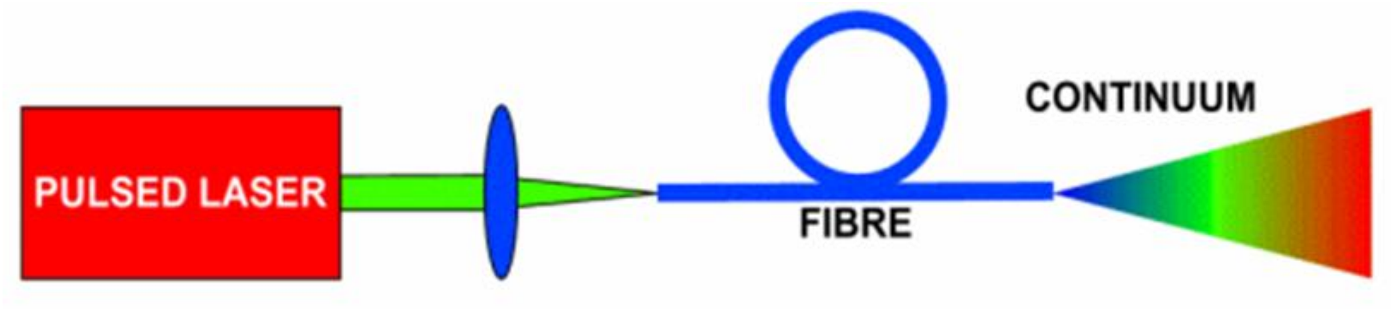
Methane gas detection at 1653.7nm with detection sensitivity of 500ppm.

Supercontinuum Generation



"Supercontinuum generation is the formation of broad continuous spectra by propagation of high power pulses through nonlinear media … The term supercontinuum does not cover a specific phenomenon but rather a plethora of nonlinear effects, which, in combination, lead to extreme pulse broadening."

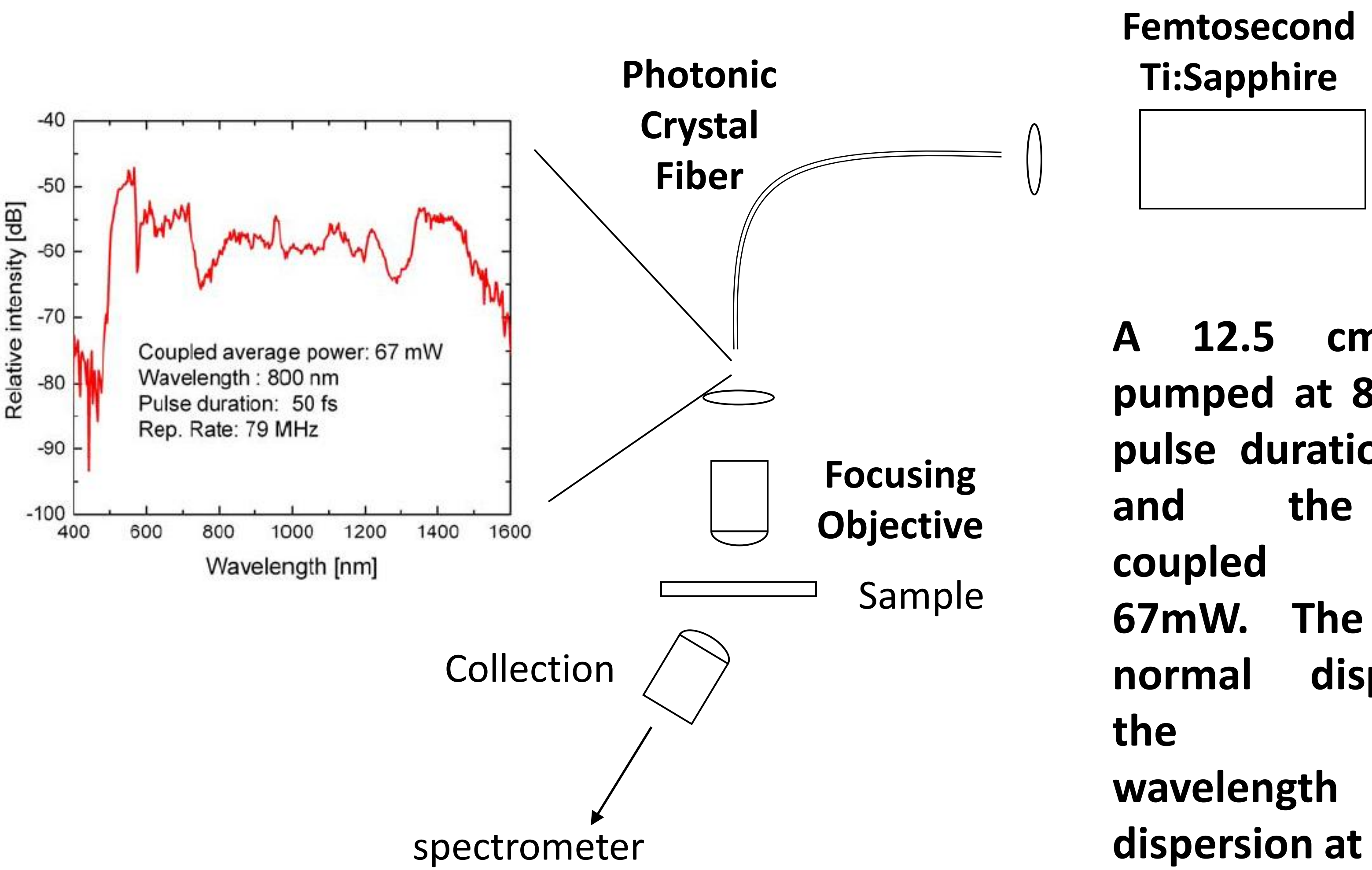
Supercontinuum Generation (SCG)



- **Formation of broad continuous spectra through propagation of short high power pulses through zero-dispersion wavelength of the nonlinear media.**
- **The determining factors for generation of supercontinuam are the dispersion of the fiber relative to the pumping wavelength, the pulse length and the peak power.**
- **SCG is the combined response of various nonlinear effects such as: Self phase modulation (SPM), Raman effect, Four wave mixing (FWM) and Soliton dynamics.**
- **When pumping with femtosecond pulses in the normal dispersion regime, self-phase modulation dominates with Raman scattering broadening to the long wavelength side. The output from the normal dispersion pumping changes dramatically, when the pump is moved closer to the zero-dispersion wavelength, and other nonlinear effects start to participate.**
- **Supercontinuum light can be best described as —broad as a lamp, bright as a laser**

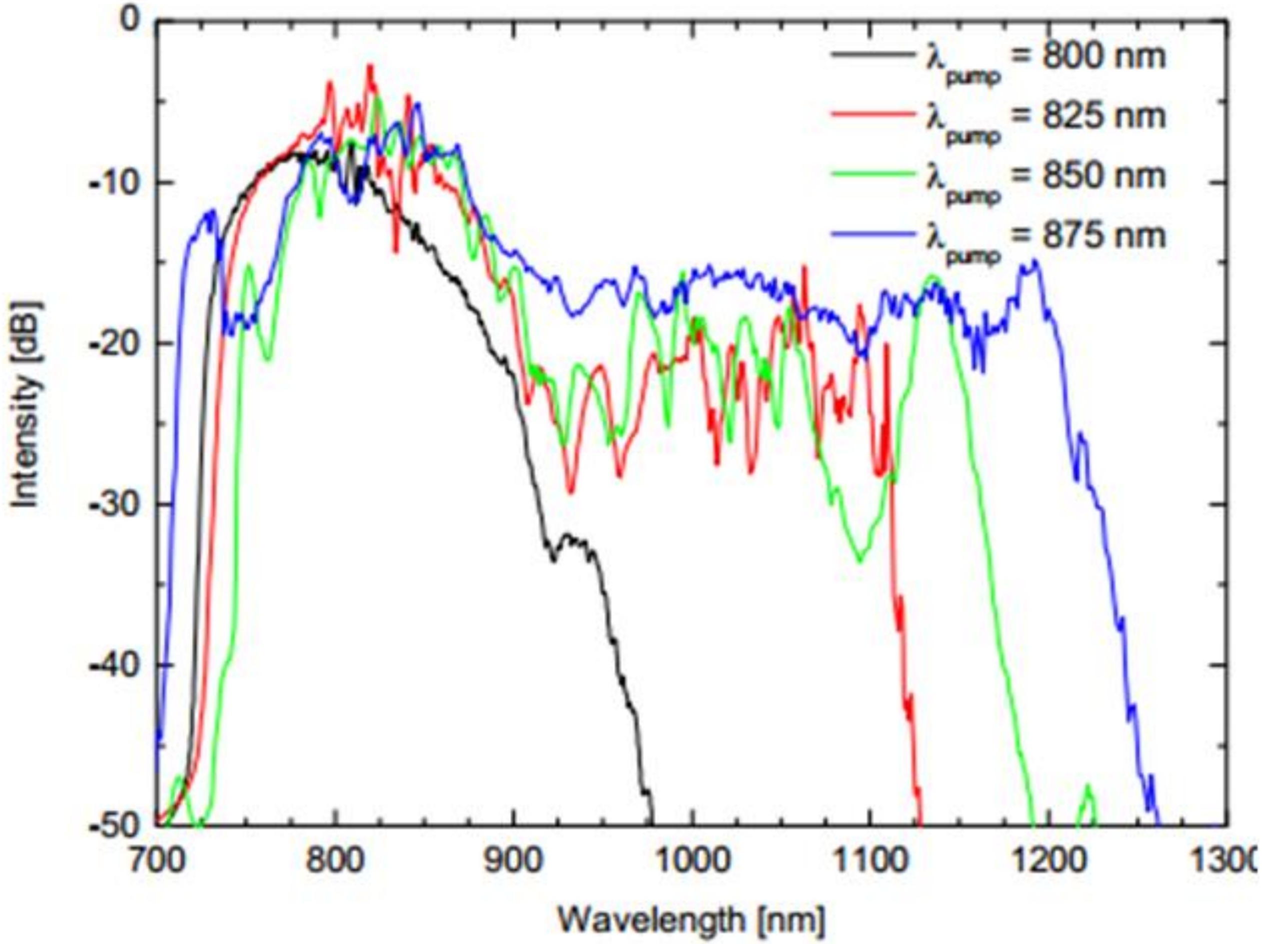
Supercontinuum Generation

Experimental Setup

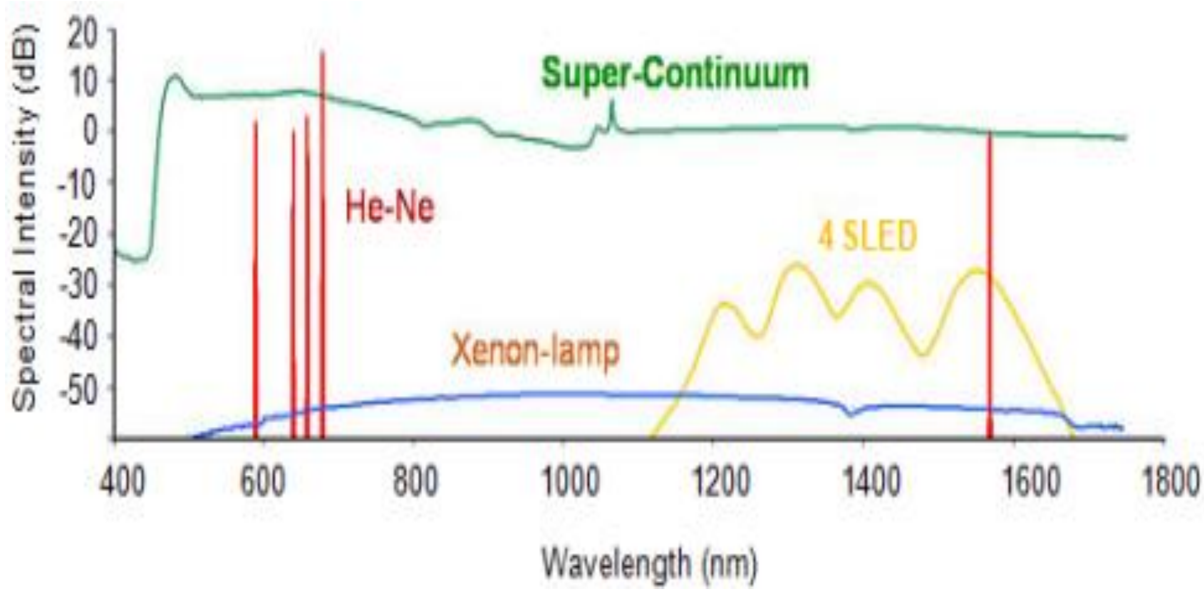


A 12.5 cm fiber is pumped at 800 nm. The pulse duration is 50 fs and the average coupled power is 67mW. The fiber has normal dispersion at the pumping wavelength and zero dispersion at 875 nm.

Hansen & Kristiansen, www.blazephotonics.com,"Application Note: Supercontinuum Generation in PCF"



Supercontinuum formed with pumping at different wavelengths in a fiber with zero dispersion at approximately 900 nm. The fiber is pumped by 100 fs pulses with a repetition rate of 76 MHz.



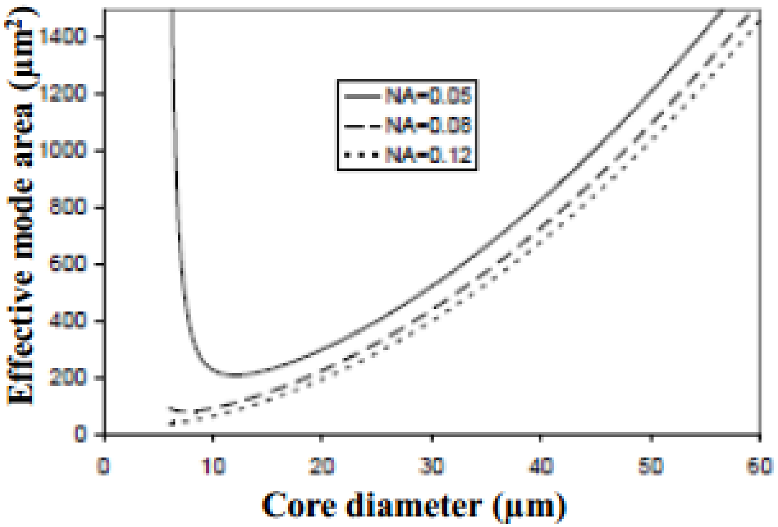
A supercontinuum source provides:

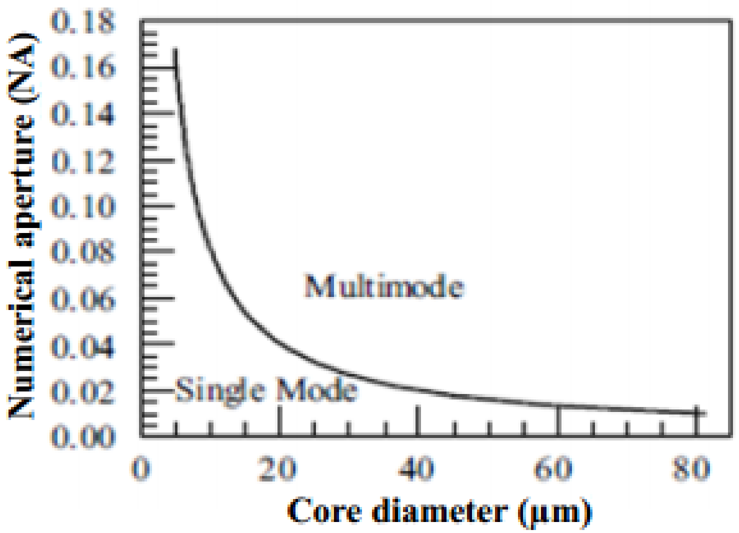
- **Ultra broadband white-light spectrum**
- **Single-mode beam characteristics**
- **Excellent pointing stability**
- **High Brightness**
- **This type of source is required for High resolution imaging: Optical Coherence Tomography (OCT), and Early Cancer Detection**
- **Biophotonics: Flow cytometry**
- **Spectroscopy: Pump probe experiments, Time-resolved spectroscopy**

PCF for High Power Application

Requirements: **Large Mode Area** with **Single-mode** Operation

Challenges:





•*Li et al.* , *"fiber design for higher power laser"*, Proc. Of SPIE Vol. 6469, 64690H, (2007)

- **Core diameter increases** – Effective mode area increases
- **Too large core diameter** – Waveguide become multimode

So, there is a trade off between LMA and SM operation

Designing LMA fibers with SM operation:

- **By controlling the index difference between core and cladding**
- **Tailoring the refractive-index profile inside the core**
- **Using single material Photonic crystal fibers**

Future Applications

- **Highly efficient photonic crystal lasers**
- **High resolution spectral filters**
- **Photonic crystal diodes and transistors**
- **High efficiency light bulbs**
- **Optical computers**

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The excerpts of this lecture are based on the information drawn from following reference.

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6. **Rev. Mod. Phys. 89, 045003 (2017) - Hybrid photonic-crystal fiber**; *https://link.aps.org/doi/10.1103/RevModPhys.89.045003*, by C Markos - 2017

Thank You