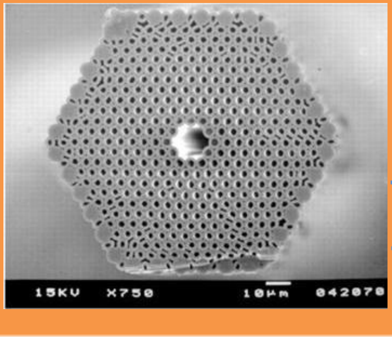
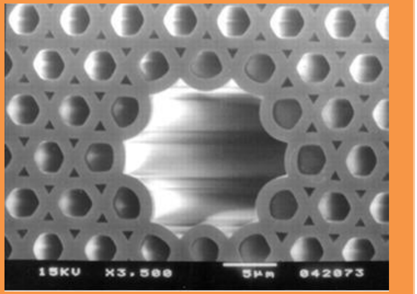


بلورهای فوتونی
Photonic Crystals



3.2. Photonic Crystal Fibers (PCFs)

زاهدان- دانشگاه سیستان و بلوچستان- دانشکده مهندسی برق و کامپیوتر-
گروه مهندسی الکترونیک- محمدعلی منصوری بیرجندی

mansouri@ece.usb.ac.ir

mamansouri@yahoo.com

Outline

- A brief history of PCF
- Physical properties
  - Effective refractive index
  - Filling factor
  - Attenuation
  - Dispersion
  - Nonlinearities
- Fabrication techniques
  - Capillary stacking
  - Extrusion
- Applications
  - Supercontinuum generation
  - All-fiber gas cells

A brief history…

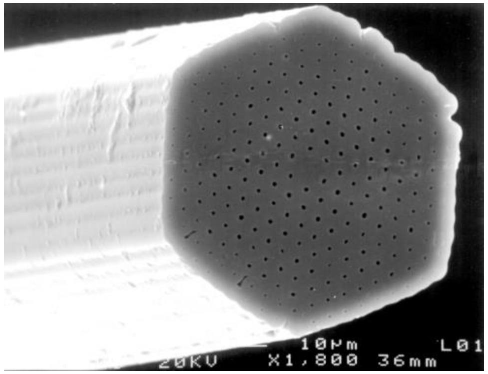
- 1970: idea that a cylindrical Bragg waveguide can guide light
- 1991: idea that light could be trapped inside a 2D PhC made of silica capillaries.

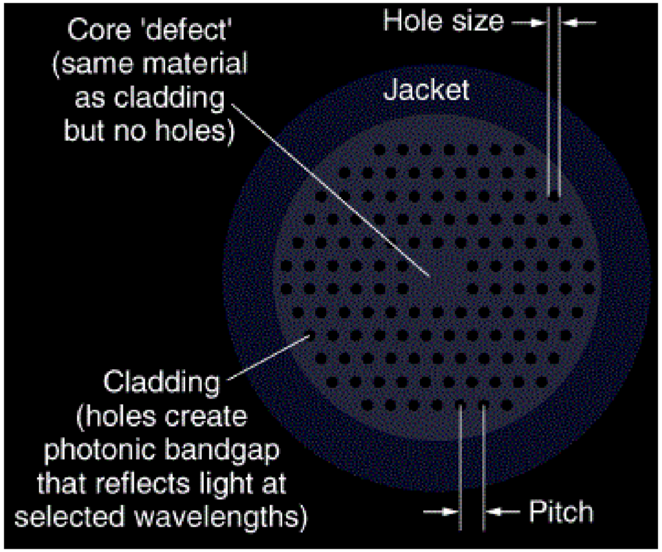
    How? By drilling microscopic holes inside a silica rod, then drawing to fiber.

- 1995: Theoretical proof that bandgap guiding is possible
- 1996: First PCF prototype

    How? By stacking silica capillaries, then drawing to fiber

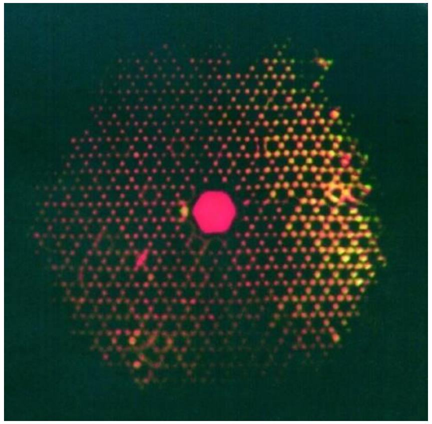
    index guidance. d_{hole}/pitch=0.2

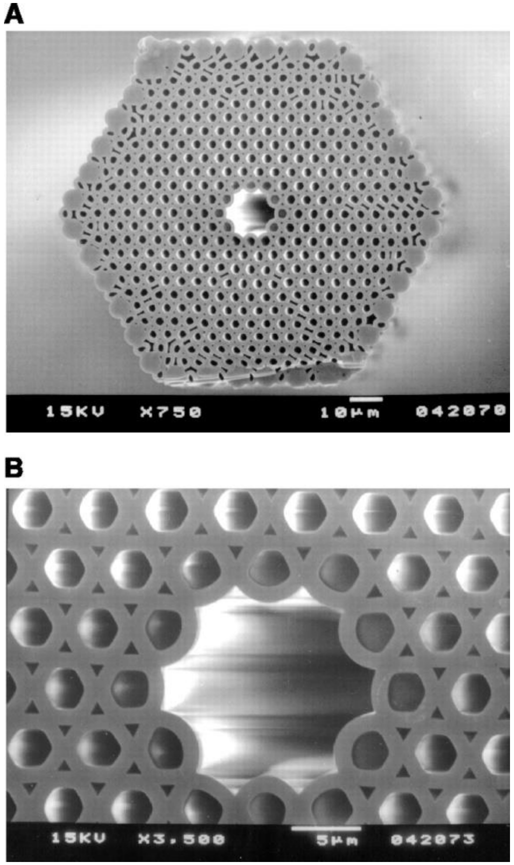




A brief history…

- 1999: first HC PCF
  - Photonic bandgap guidance
  - Stack-and-draw technique
  - 3 cm long!
  - When illuminated with white light:



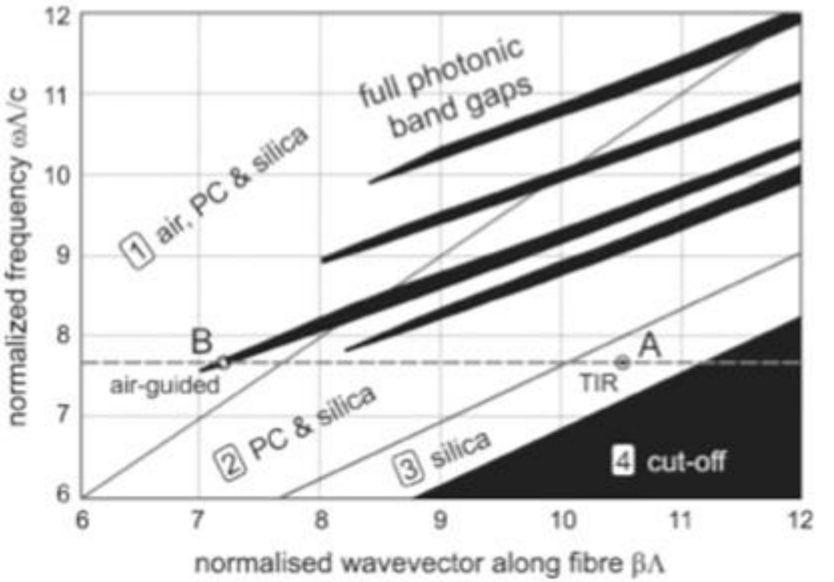


R. F. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. St. J. Russell, P. J. Roberts, D. C. Allan, "Single-ode Photonic Band Gap Guidance of Light in Air”, Science **285,** 1537 - 1539 (1999)

Guiding characteristics

- Where propagation occurs:
  - Region #1: everywhere
  - Region #2: everywhere in fiber
  - Region #3: in silica

- Two different propagation regimes.
  - Point A: TIR
  - Point B: Bandgap

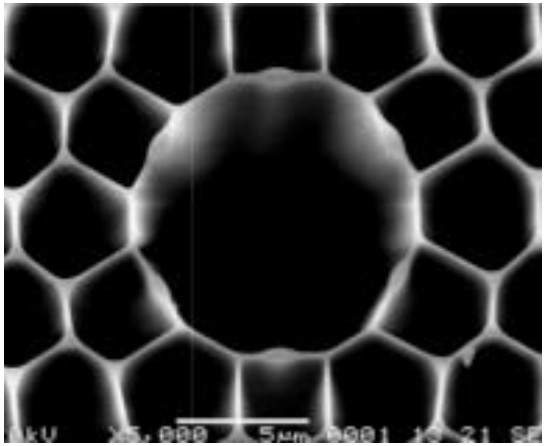


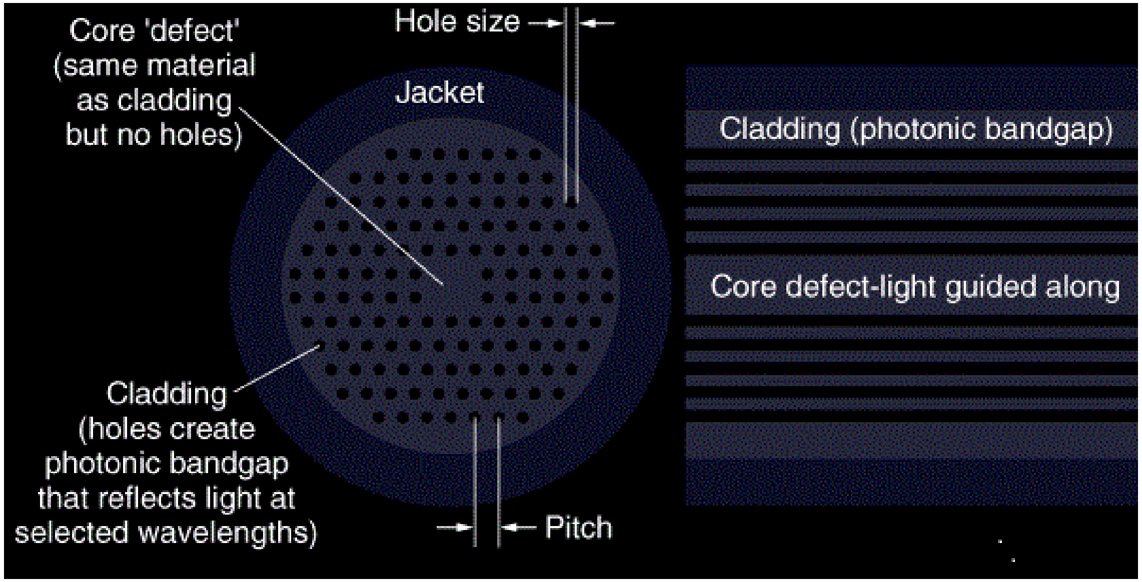
Propagation diagram for a PCF with 45% air-filling fraction. Note the different regions where light is (1) able to propagate in all regions, (2) able to propagate also in the photonic-crystal cladding, (3) able to propagate only in silica glass, and (4) cut off completely. The "fingers" indicate the positions of full 2-D photonic band gaps .

Hollow-core fibres

- Attenuation: 10 dB/km

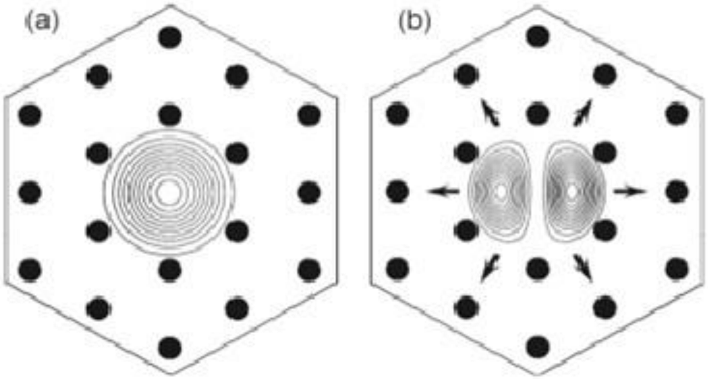
  SMF = 0.2 dB/km
- λ_c=1535nm, $\Delta\lambda$=100nm
- n_{eff}~0.99
- f ~ 10%



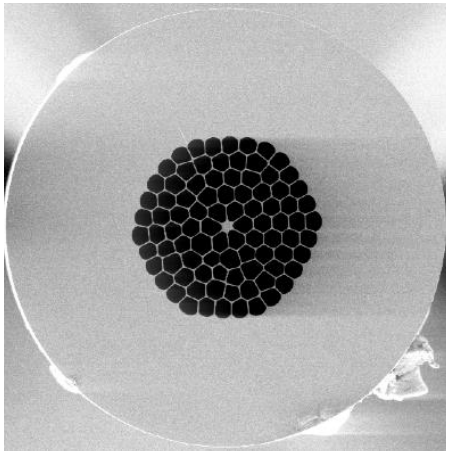


Solid-core PCF

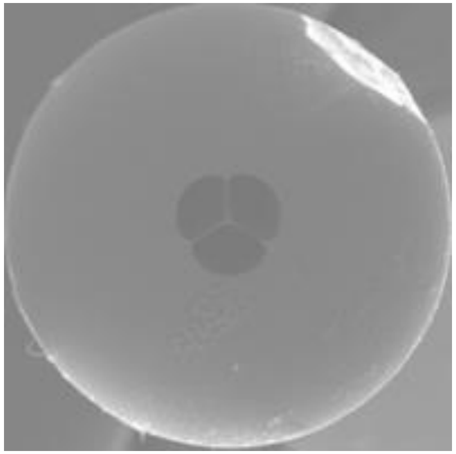
- Attenuation: 0.5 dB/km
- n_{eff}~1.4
- Φ_{air}=1-15%
- Index guiding -> robustness



Modal filtering in a solid-core PCF. (a) Fundamental mode is trapped. (b) Higher order modes leak away through the gaps between the air holes.



D_{core}=3μm



D_{core}=1.2 μm

d_{hole}/pitch < 0.43

$$V_{\text{gen}} = k\Lambda\sqrt{n_1^2 - n_2^2}$$

$N_{modes}=V_{gen}^2/2$

Attenuation mechanisms

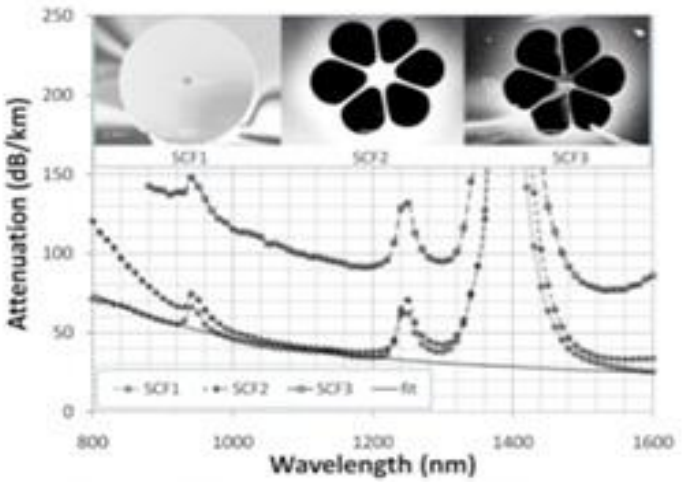
- Insertion loss:

$$\alpha = \text{-}20\log\left(2\omega_{PCF}\,\omega_{SMF} \Big/ \left(\omega^2_{PCF} + \omega^2_{SMF}\right) \right)$$

- Confinement loss:

$$\text{Confinement loss [dB/m]} = \frac{20 \times 10^6}{\ln 10}\,\frac{2\pi}{\lambda[\mu\text{m}]}\,\text{Im}\{n_{eff}\}.$$

- Propagation loss:
  - Rayleigh scattering (dopants) λ^{-4}
  - Roughness of the glass-air interface λ^{-3}



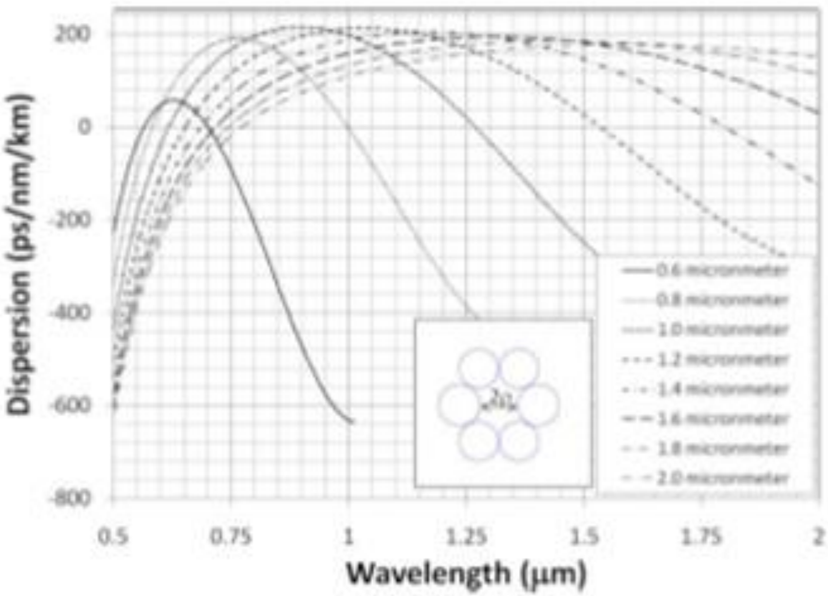
Measured loss for three fibers: SCF1: 2ρ=2.3μm, no germanium in the core; SCF2: 2ρ=2.3μm, germanium doped center of ~60% core radius, graded refractive index with NA=0.275. SCF3: 2ρ=1.27μm, with germanium-doped center similar to SCF2. Close up of SCF1 is essentially the same as SCF2. A global view is used to show the whole fiber instead. The solid line fit is of the formula: $A+B/\lambda^3$.

Advantages of PCFs

- Many physical properties can be engineered (power fraction, chromatic dispersion,…)
- Fill with gases or liquids

W. H. Reeves, J. C. Knight, P. St.J. Russell, and P. J. Roberts, "Demonstration of ultra-flattened dispersion in photonic crystal fibers", *Opt. Express*, vol. 10, no. 14, pp. 609-613, Jul. 2002.

L. Dong, B. K. Thomas, and L. Fu, "Highly nonlinear silica suspended core fibers", *Opt. Express*, vol. 10, no. 14, pp. 609-613, Jul. 2002.



(a). Waveguide dispersion for SCFs with various core diameters. Inset shows the fiber structure studied, six air holes in a hexagonal grid with d/Λ=0.99. Core diameter 2ρ is given in the legends.

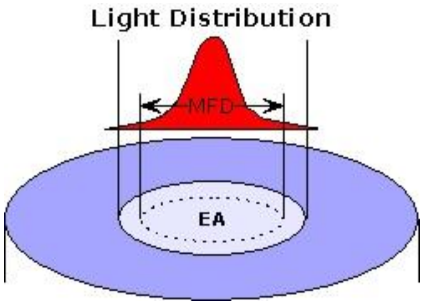
nonlinearities

- Effective nonlinearity:

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}},$$

n_2: nonlinear n

A_{eff}:



- In step-index fibers: γ_{max} ~ 30 (W.kr

$$V = k a_{eff}\underbrace{\sqrt{n_{co}^2 - n_{FSM}^2}}_{NA},$$

- In solid-core PCF: γ_{max} ~ 550 $(W.km)^{-1}$
-
  - a_{min} is function of NA: low A_{eff}

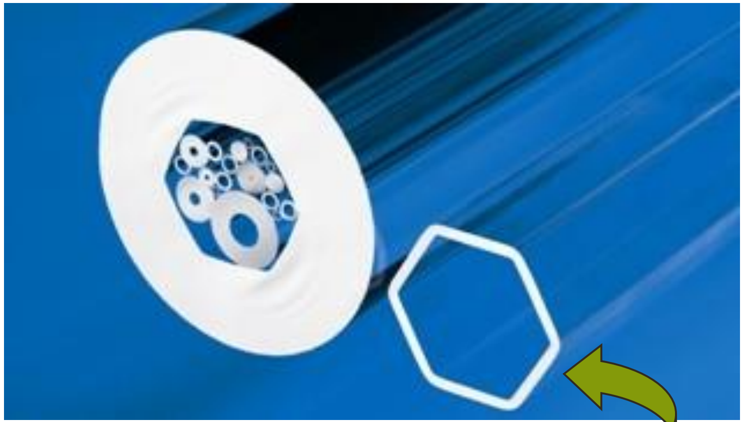
a:core radius

- In hollow-core fibers: γ_{min} ~ 0.01 $(W.km)^{-1}$-> very attractive for high power delivery applications

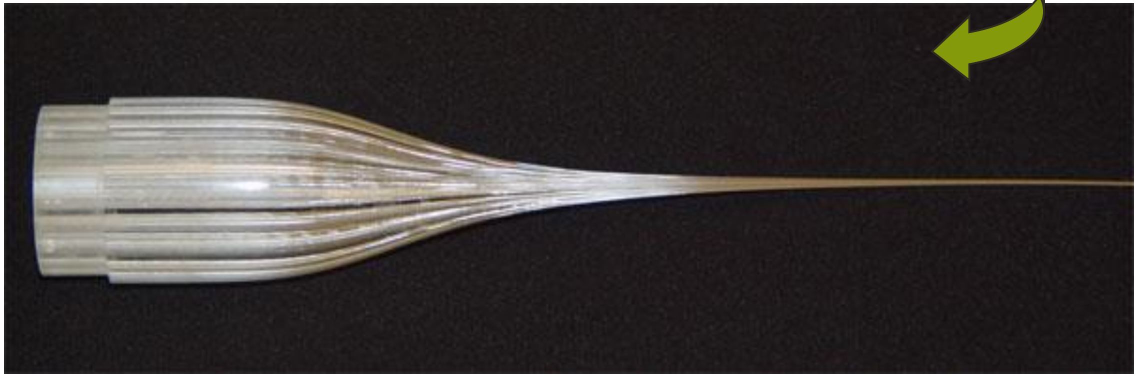
Fabrication

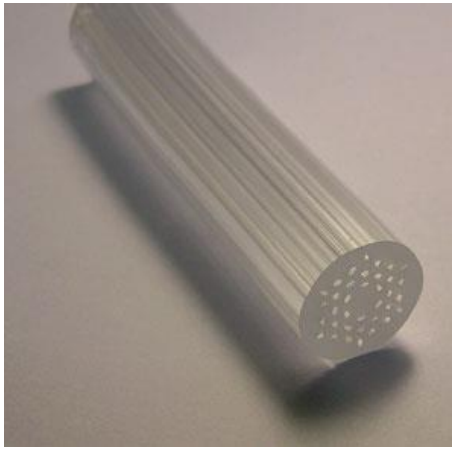
- Capillary stacking: silica
- Drilling
- Extrusion

Soft glasses & polymers



Capillary stacking technique





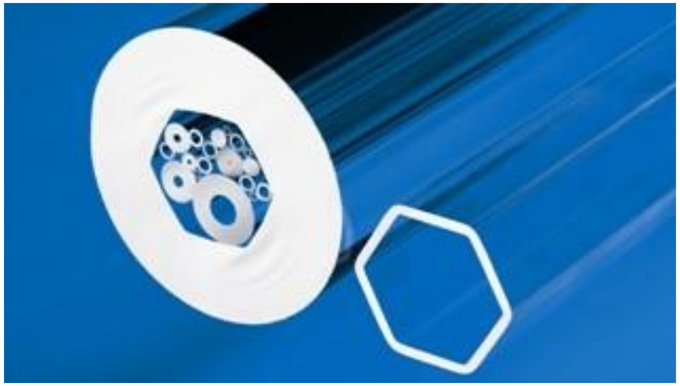
Extrusion technique

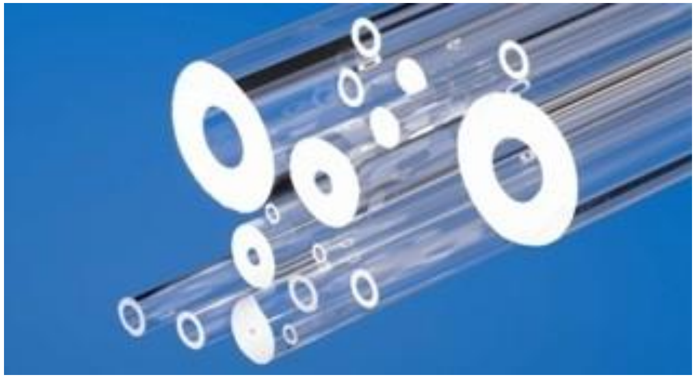
Capillary Stacking

- Reduce the dimensions of silica capillaries from 1-3 cm to ~1mm.

  -> Using a fiber optics drawing tower

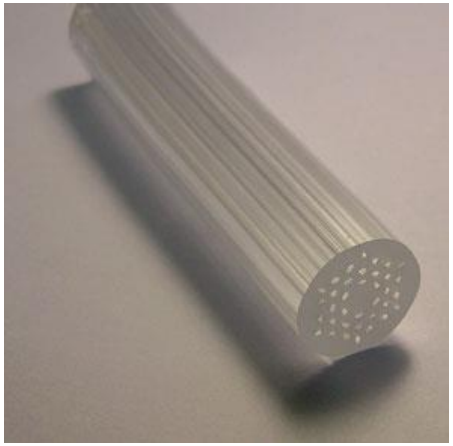
- Horizontally stack in an hexagonal configuration

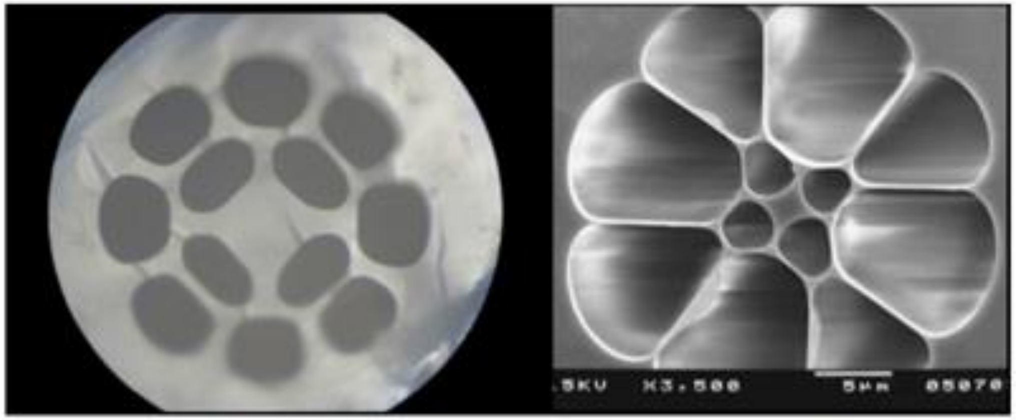




Extrusion

- Used to fabricate the majority of soft glass preforms
  - Tellurite, chalcogenide, lead silicate, bismuthate, …
- Molten material is forced through a die.
- Used to fabricate the first nonlinear solid-core PCF in 2002 (lead silicate glass, T_{soft}=538°C, n=1.805)



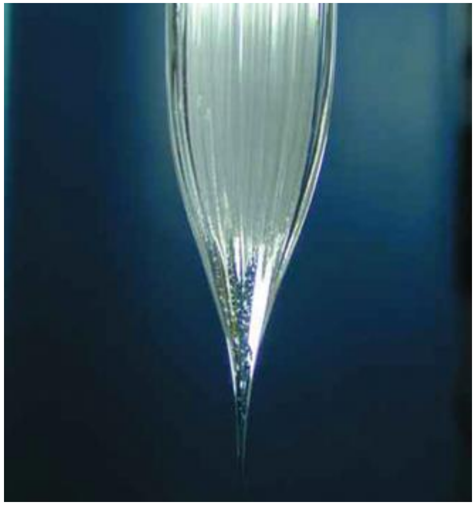


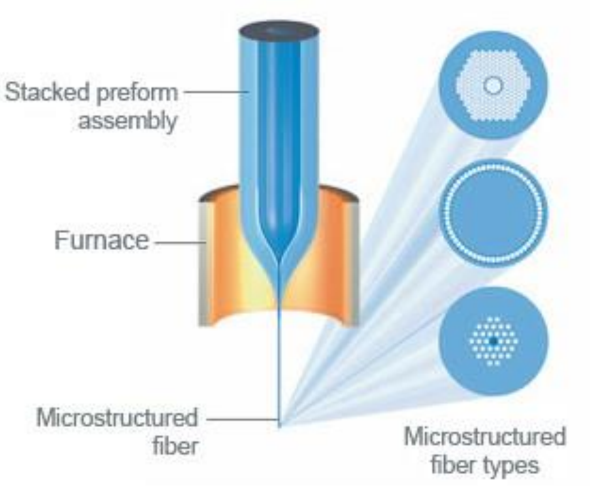
Preform (left, optical micrograph) and fiber (right, electron micrograph) fabricated from SF6 glass by extrusion. The preform (left) is 1mm in outer diameter, and was jacketed prior to drawing the fiber shown on the right. The fiber has a nominal 2.6µm core dimension, and the glass strands in the second ring of air holes are 150nm across and 6µm in length..

V.V. Ravi Kumar, A. George, W. Reeves, J. Knight, P. Russell, F. Omenetto, and A. Taylor, "Extruded soft glass photonic crystal fiber for ultrabroad supercontinuum generation," Opt. Express 10, 1520-1525 (2002)

Draw the preform

- Preform is heated to 2000° C to soften silica
- Collapse ratios of ~50,000
- 1^{st} run: cane of 1mm diameter
- 2^{nd} run: cane is introduced inside a jacketing tube + drawn to the final fiber
- Not a lithographic process!



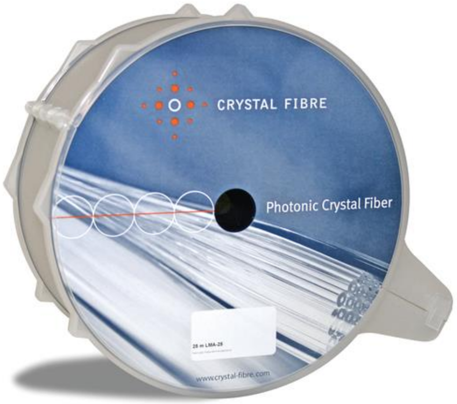


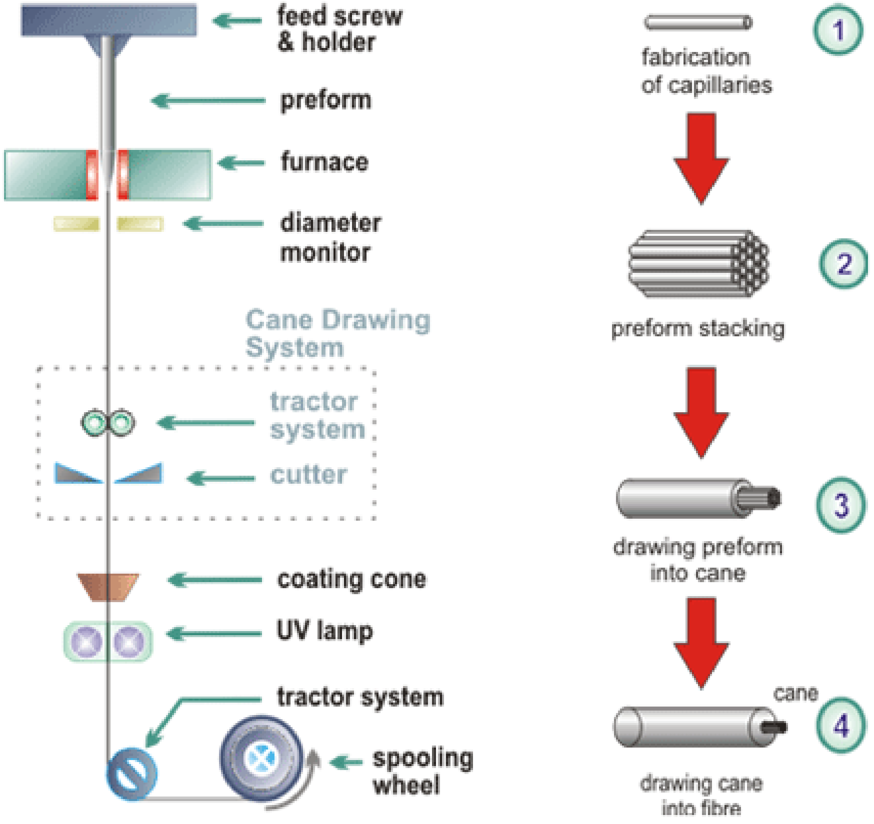
Final steps

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

  -> fiber is coated with a polymer

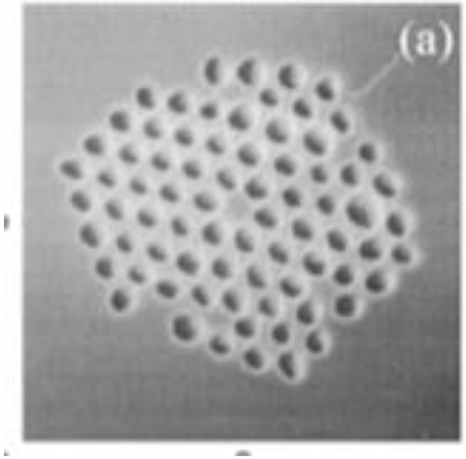
  -> fiber is wound onto spool.

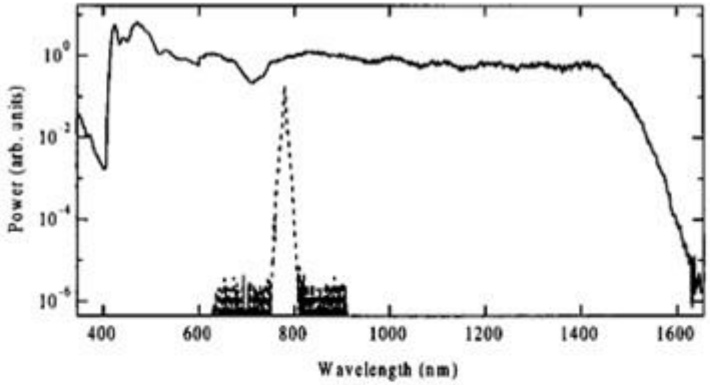




Applications

- **First report of white-light supercontinum generation**:
  - A 100 fs pulse was sent @ λ=800nm. Peak power=kW
  - Dispersion was engineered to have ZDW @ λ=800nm.
  - Small Aeff to enhance nonlinear effects.





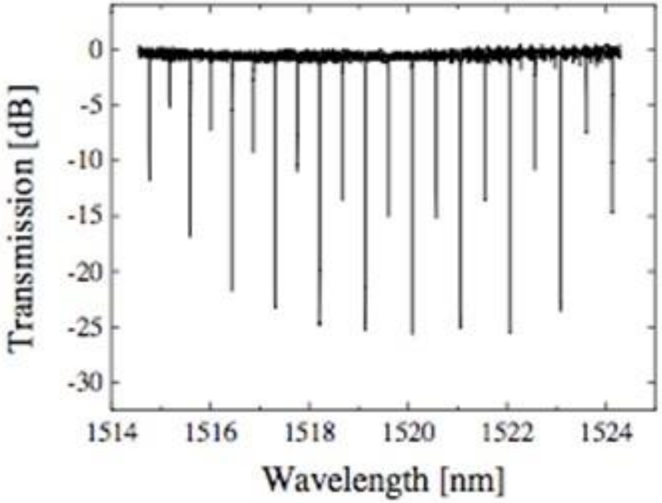
Optical spectrum of the continuum generated in a 75-cm section of microstructure fiber. The dashed curve shows the spectrum of the initial 100-fs pulse.

- J. K. Ranka, R. S. Windeler, and A. J. Stentz, "Visible continuum generation in air-silica microstructure
- optical fibers with anomalous dispersion at 800 nm," Opt. Lett. **25**, 25-27 (2000)

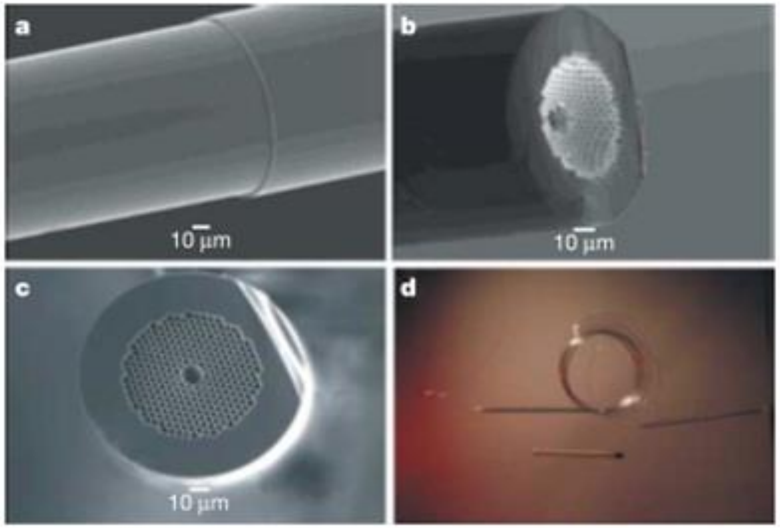
See J.M. Dudley and J.R. Taylor, "Ten years of nonlinear optics in photonic crystal fibres", Nature Photonics **3**, 85 - 90 (2009)

Applications

- All-fiber gas cells



For comparison, the same spectrum recorded using a laser (step size 1 pm) and a reduced pressure of 10 mbar.



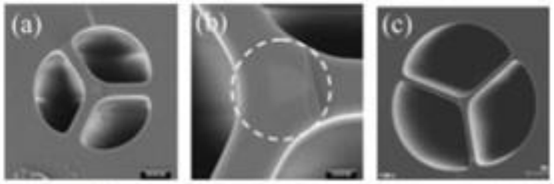
HC-PCF-based gas-cell assembly. **a–c**, Images obtained using a scanning electron microscope. **a**, Side view of a 1,550 nm HC-PCF (the narrower fibre) spliced to an SMF. **b**, End view of an HC-PCF cleaved at the junction of the splice. The recess, which creates an air gap of a few tens of micrometres between the fibre cores, is due to the action of surface tension during fusion. **c**, View of the same piece of HC-PCF as in **a** and **b** but cleaved a few millimetres from the splice, showing clearly the preservation of the microstructural integrity. **d**, Photograph of a 5-m-long hydrogen-filled HC-PCF gas cell, showing its size compared to that of a match.

F. Benabid, F. Couny, J. C. Knight, T. A. Birks & P. St J. Russell, "Compact, stable and efficient all-fibre gas cells using hollow-core photonic crystal fibres", *Nature* **434**, 488-491 (2005)

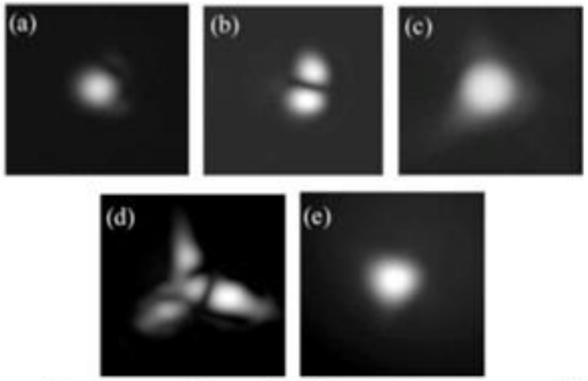
T. Ritari, J. Tuominen, H. Ludvigsen, J. Petersen, T. Sorensen, T. Hansen, and H. Smonsen, "Gas sensing using air-guiding photonic bandgap fibers," Opt. Express **12**, 4080-4087 (2004)1

Applications

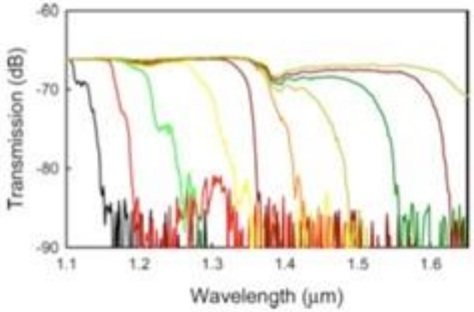
- Temperature sensors



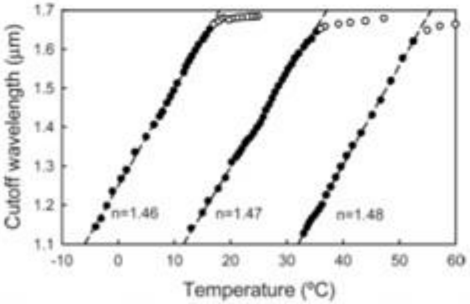
SEM images of fibers (a), (b) 1 and (c) 2.



Experimental near-field intensity pattern of (a) the fundamental and (b) the second mode at 633 nm, and (c) the near-field images of the fiber output at 1550 nm. (a)–(c) are for fiber 1 and empty holes. (d) and (e) are for fiber 2 and show the near-field intensity pattern at 1550 nm when the holes were filled with air and a liquid of RI 1.46, respectively.



(Color online) Transmission spectra of a section of fiber 1 at different temperatures, from 17°C (left) to 41°C (right). The RI of the liquid was 1.47.



Cutoff wavelength as a function of temperature for fiber 2 and three different liquids (nominal RI values are indicated).

S. Torres-Peiro, A. Diez, J. L. Cruz, and M. V. Andrés, "Fundamental-mode cutoff in liquid-filled Y-shaped microstructured fibers with Ge-doped core," Opt. Lett. **33**, 2578-2580 (2008)