“Photonic crystal fibers guide light by corralling it within a periodic array of microscopic air holes that run along the entire fiber length….”

Stack and Draw Technique

Macroscopic “preform” with the required periodicity

Furnace to soften the silica gas

Photonic crystal fiber
A brief overview of conventional fiber structure

Silica cladding: $n_1 = 1.44$ to $1.46$

Silica core doped with Germanium, Boron or Titantium

$$\frac{n_2 - n_1}{n_2} = 0.001 \sim 0.02$$

Core diameter for single mode fiber about $8 \mu m$. 
Propagation loss in conventional optical fiber

Rayleigh scattering: from random localized variation of the molecular positions in glass which creates random inhomogeneities in index.
Infrared absorption: from vibrational transitions.

Absolute minimum at 1.55 micron, at 0.16dB/km, about 3.6% per km.

Saleh and Teich, Fundamentals of Photonics, 1991
Fiber optical amplifier for long distance communication

Er, gain maximum close to 1.55 micron
Usable bandwidth limited by the amplifier bandwidth to be approximately 30nm

Improving bandwidth by removing amplifiers, guiding in air?
Guiding mode exists between the light line of the cladding and light line of the core.

Band diagram for conventional fibers

Light-line of cladding
\[ \omega = c k / n_1 \]

Radiation modes

Guided modes

Light-line of core
\[ \omega = c k / n_2 \]
Lower and higher order modes

The $V$-number determines the number of modes in the fiber

$$V = \frac{2\pi a}{\lambda} \left( \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2} \right)$$
Conventional vs Photonic Crystal Fibers

Conventional fiber
Core diameter 9 micron

Dielectric-core PCF
Core diameter 5 micron

Air-core PCF
Core diameter 9 micron
Endless single mode photonic crystal fiber

Solid core photonic crystal fiber.

Solid core region nominally 4.6 μm wide

The fiber supports a single mode over the range of at least 458-1550 nm

Compare with conventional fibers:

Single mode \( V < 2.4 \)
Multimode \( V > 2.4 \)

\[
V = \frac{2\pi a}{\lambda} \left( \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2} \right)
\]

Knight et al, Opt. Lett. 21, 1547, 1996
The cladding as a mode sieve

The lower modes can not escape as the wire mesh are too narrow.

The higher order modes can leak through the narrow strip.

Increasing the relative size of the diameters of holes (d) with respect to the pitch (\(\Lambda\)) leads to the trapping of higher modes

Single mode behavior occurs when \(d/\Lambda < 0.4\)

Knight et al, Opt. Lett. 21, 1547, 1996
Much larger room for dispersion management.

State-of-art loss figure at 0.58dB/km

No complete band gap at $\beta = 0$ for silica/air type of index contrast.

At finite $\beta$, band gap can appear. Band gaps arise from multiple reflection at the interfaces. At finite $\beta$, the reflectivity goes up, effectively increasing the in-plane index contrast.

In order to achieve guiding in air, the criteria is to find a band gap above the light line of air.

Requires fairly large air holes ($r \sim 0.47\Lambda$)

Possible region for air guiding
Air core photonic band gap fibers, experiments

13 db/km in propagation loss, comparable to early days of conventional optical fiber.

Loss primarily due to the coupling of core modes to surface modes, and likely can be further reduced significantly in newer design.

Core modes vs. surface modes in air-core PCF

Super Continuum Generation

Nonlinear interaction of incident pulse with fiber results in spectrally broad output spectrum.

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.

The Bragg fiber

Using multilayer-film reflection to replace metal and create a light pipe.

The boundary condition for EM field at the boundary of core-film boundary can be designed to be rather similar to that at the metal boundary.

All dielectric co-axial waveguide

Single polarization mode in dielectric waveguide, similar to the TEM mode
Asymptotic single mode guiding behavior

For TE\textsubscript{01} mode, the fraction of the power in cladding scales as \(1/R^3\).

For TM and mixed polarization mode, the fraction of the power in the cladding scales as \(1/R\).

S. G. Johnson et al, Opt. Express. 9, 748 (2001)
Hollow optical fiber, experiments

Guiding of intense CO2 laser light at 10 micron wavelength range for high power applications