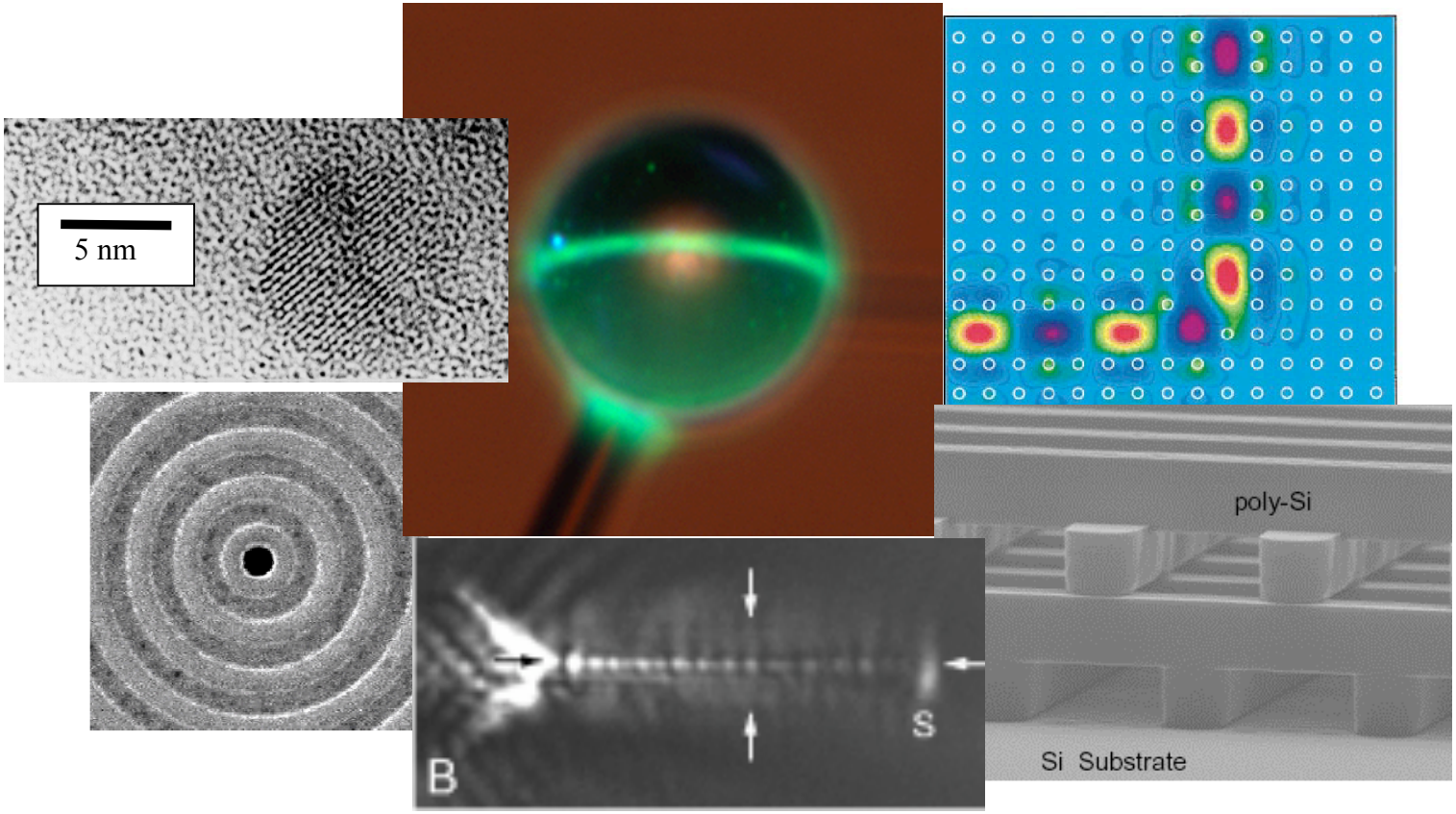
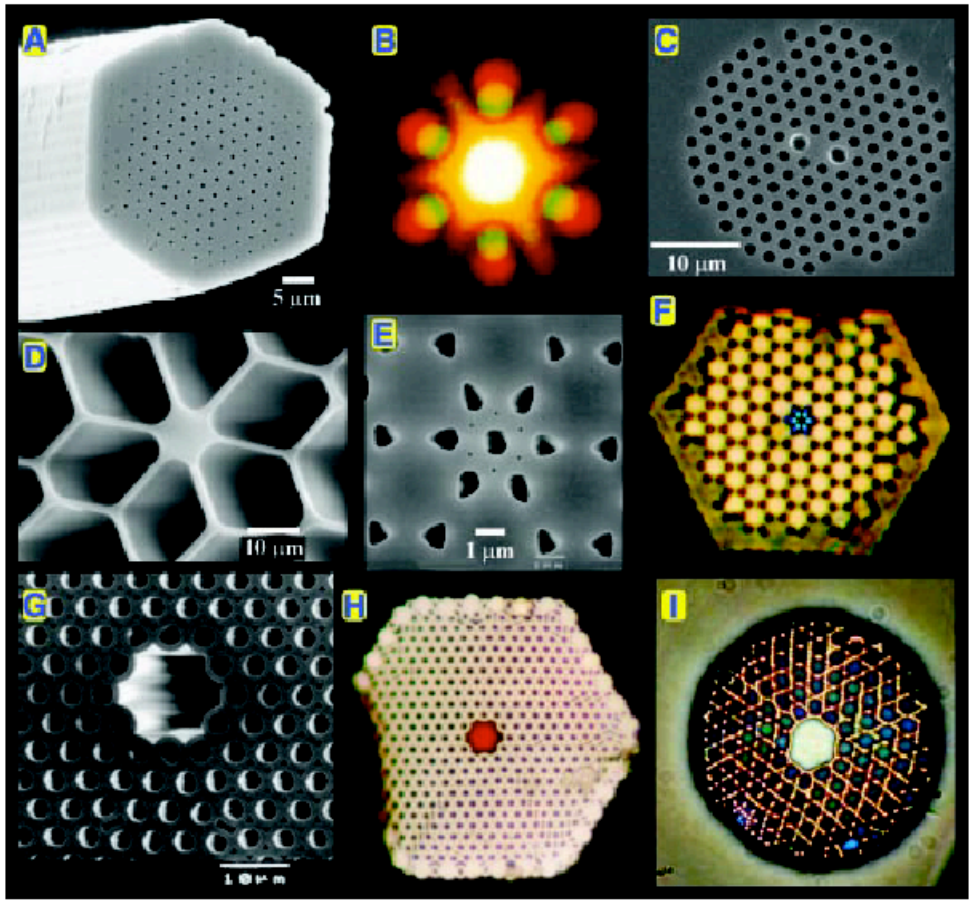
Lecture 8: Photonic Crystals Fibers



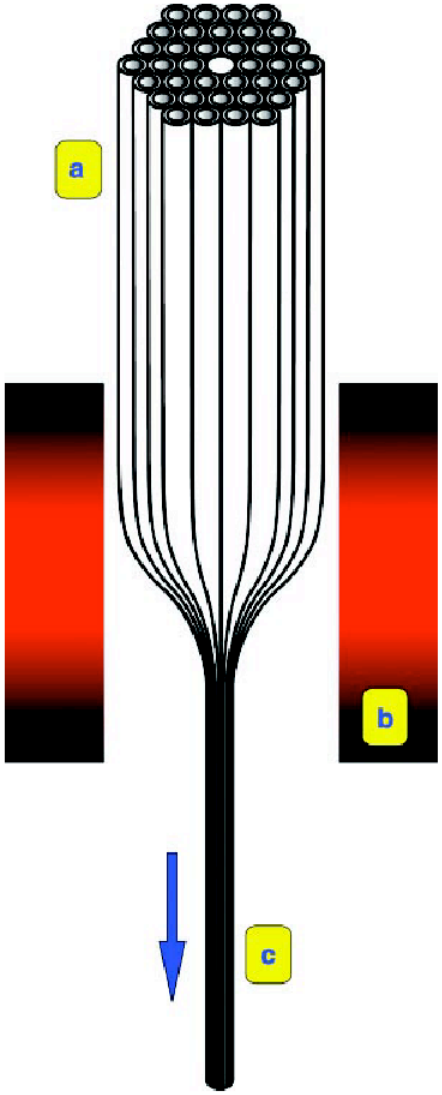
Photonic crystal fibers



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

P. Russell, Science, 299, 358, 2003

Stack and Draw Technique

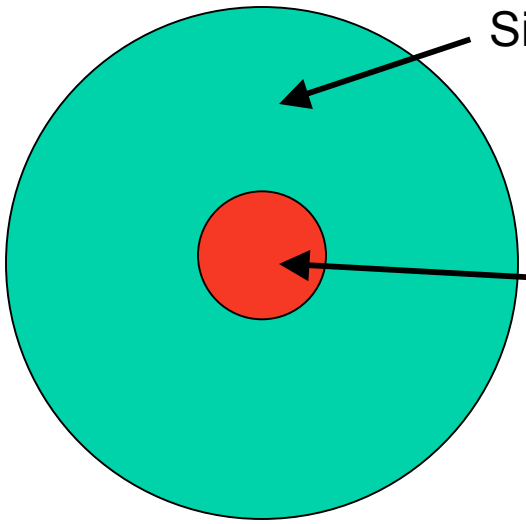


Macroscopic “preform” with the required periodicity

Furnace to soften the silica gas

Photonic crystal fiber

A brief overview of conventional fiber structure



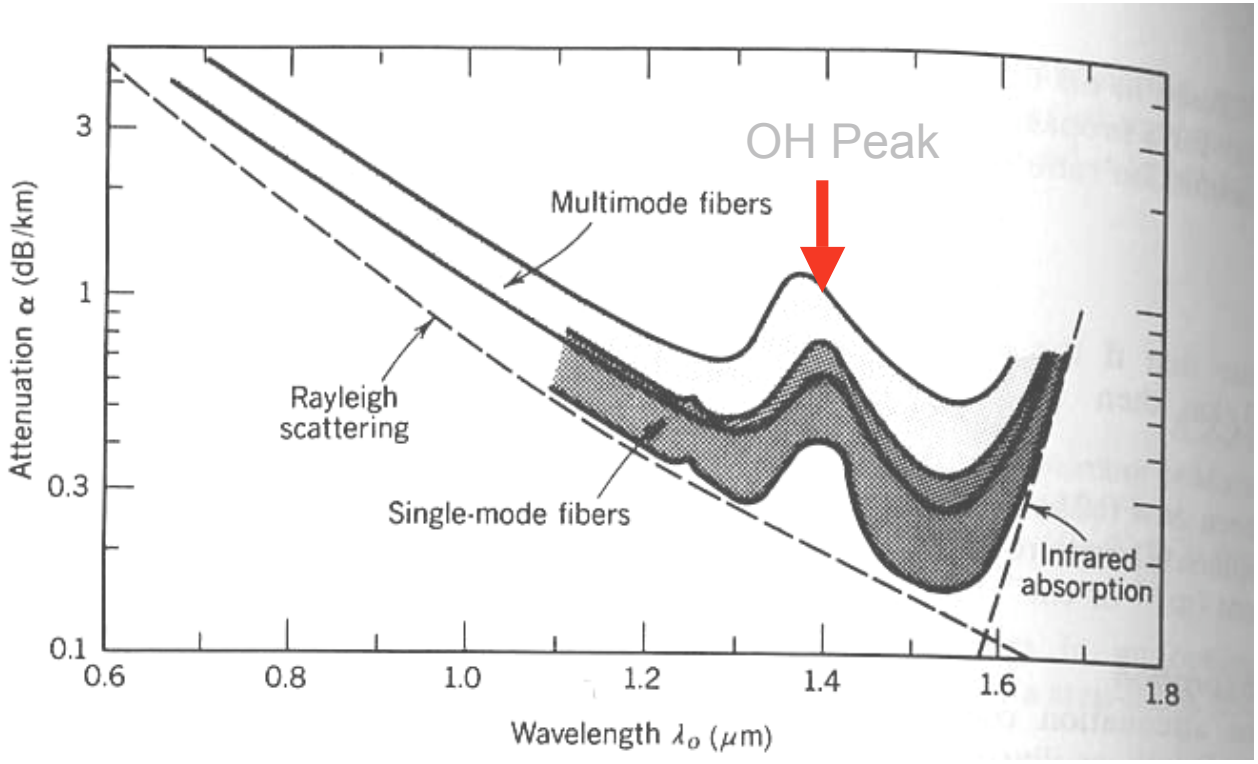
Silica cladding: n_1 = 1.44 to 1.46

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 μm.

Propagation loss in conventional optical fiber

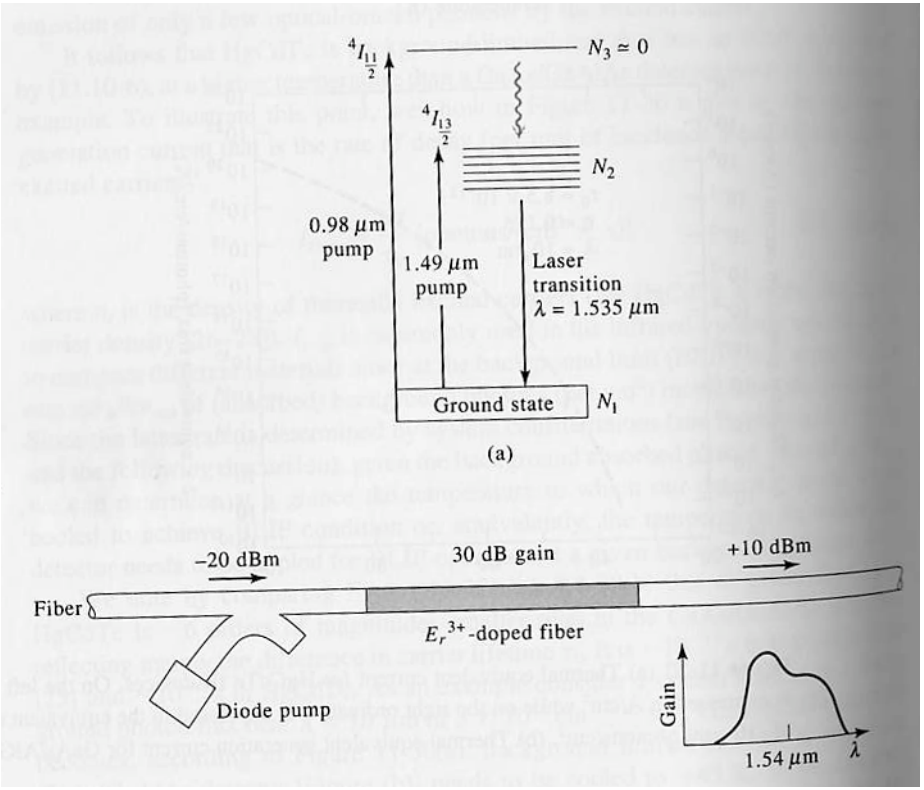


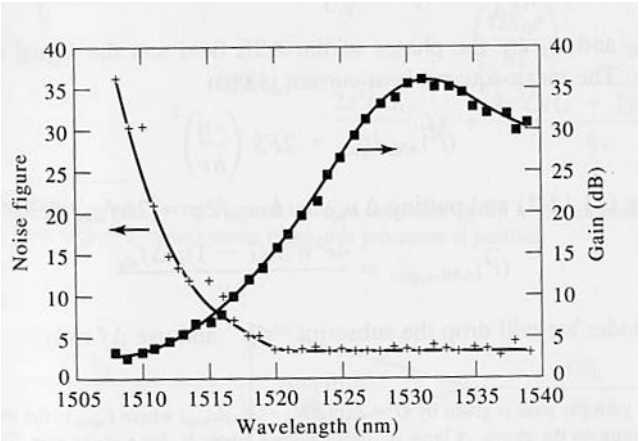
Rayleigh scattering: from random localized variation of the molecular positions in glass which creates random inhomogeneities in index.
Infrared absorption: from vibrational transitions.

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

Saleh and Teich, Fundamentals of Photonics, 1991

fiber optical amplifier for long distance communication



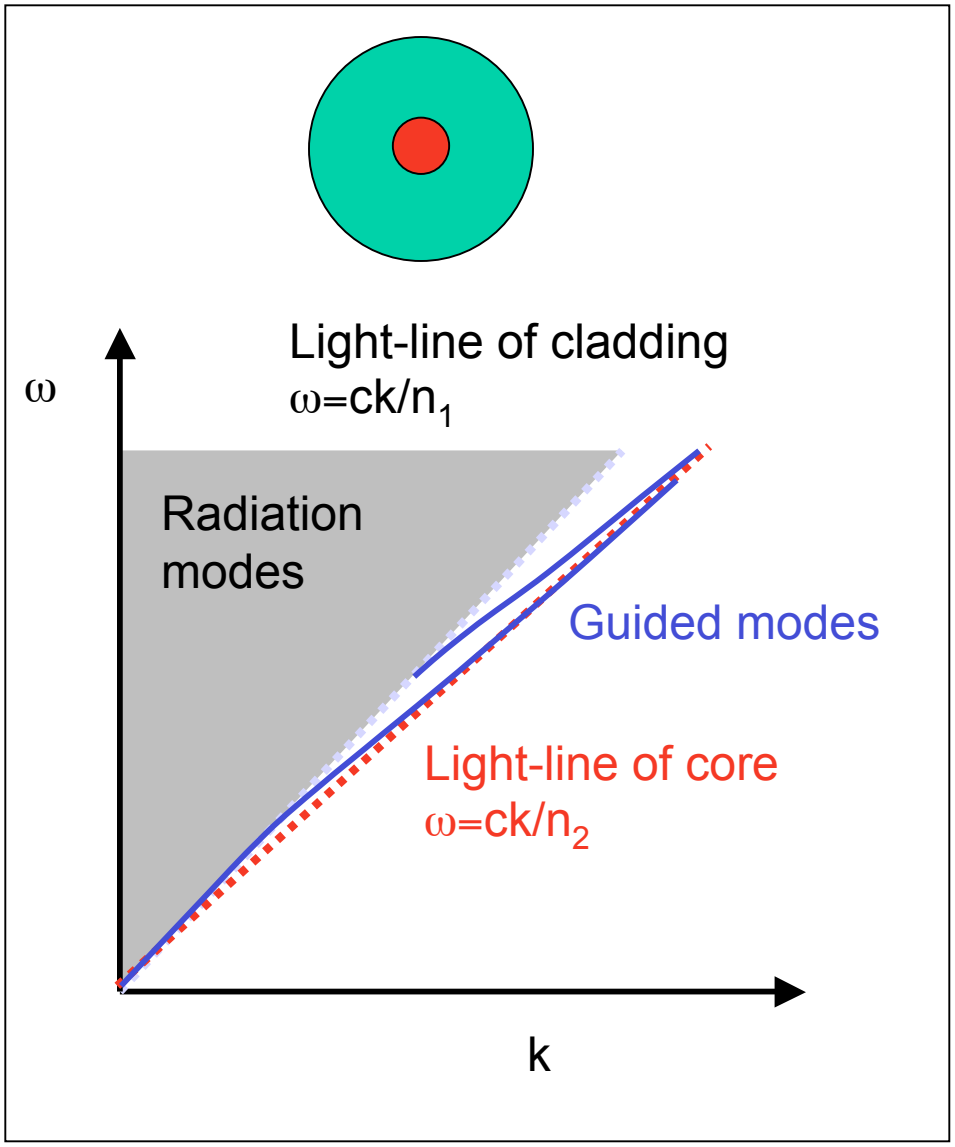


Er, gain maximum close to 1.55 micron

Usable bandwidth limited by the amplifier bandwidth to be approximately 30nm

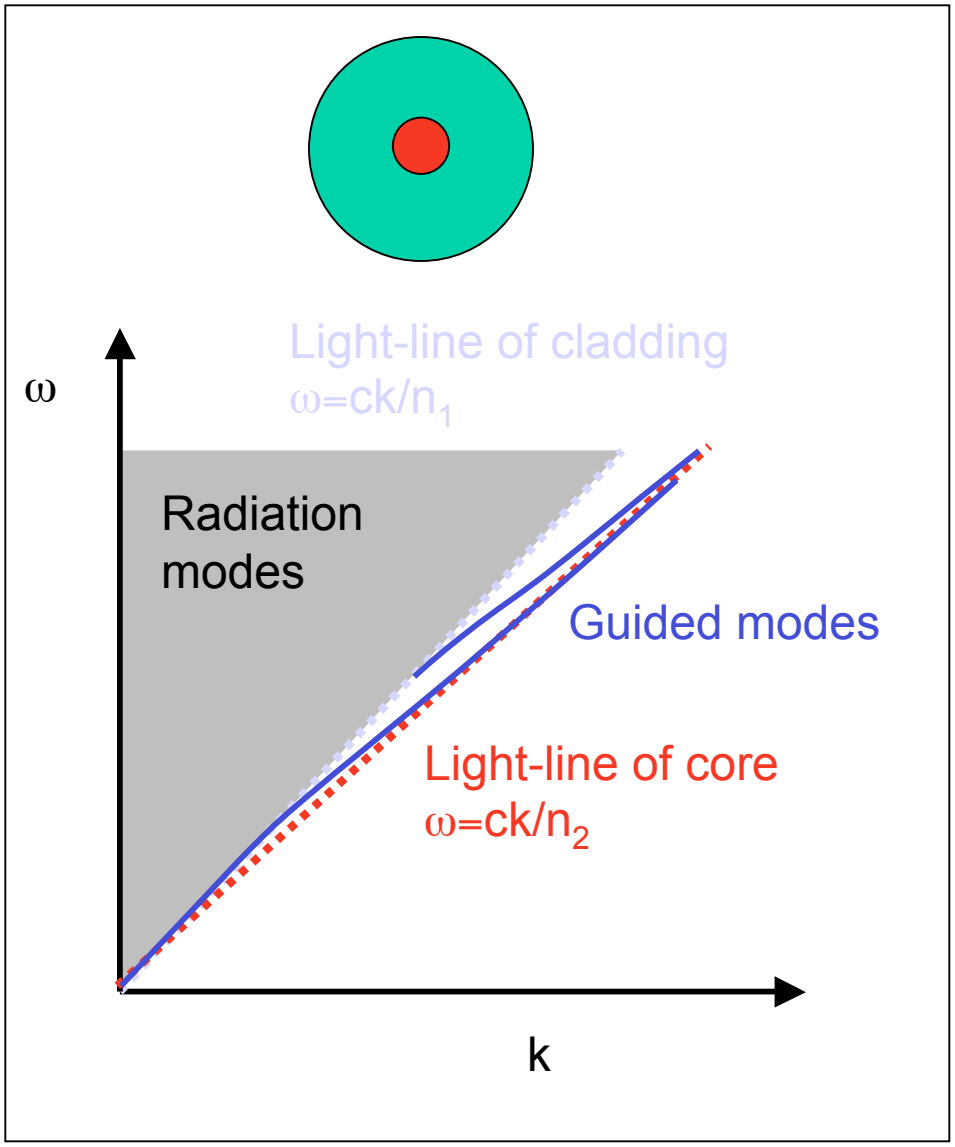
<u>Improving bandwidth by removing amplifiers, guiding in air?</u>

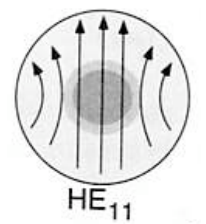
Band diagram for conventional fibers



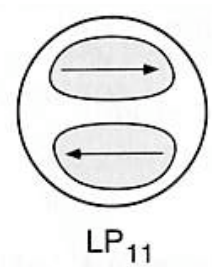
Guiding mode exists between the light line of the cladding and light line of the core.

Lower and higher order modes





Fundamental mode

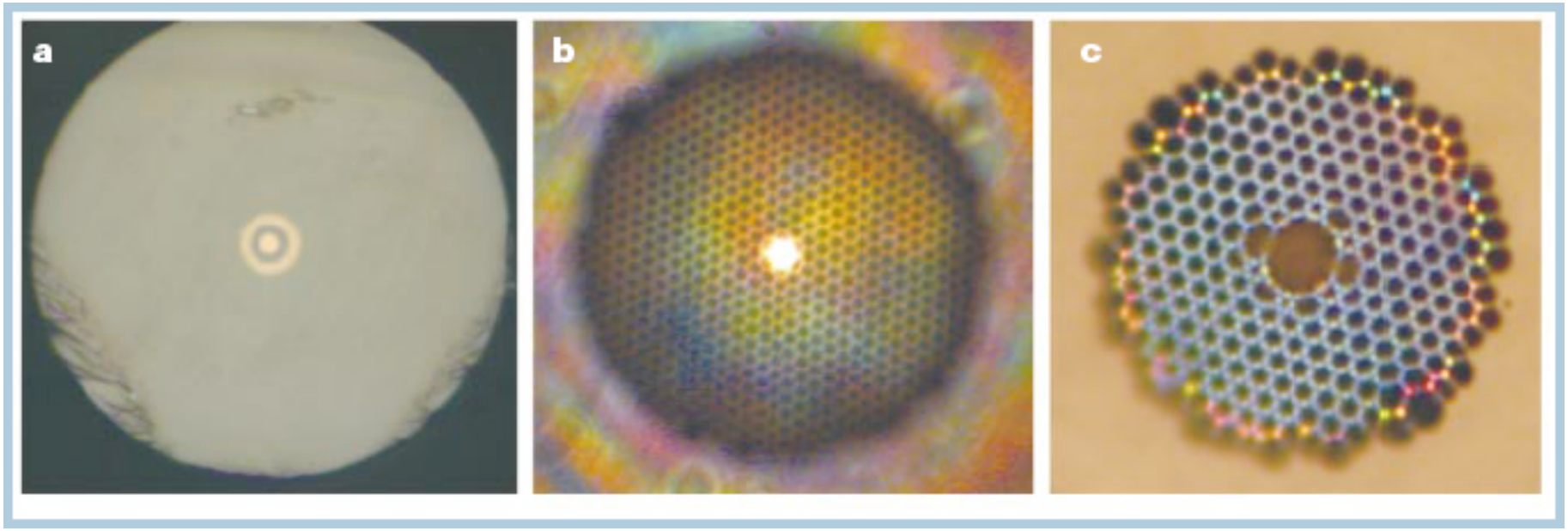


Higher order mode

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

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

Conventional vs Photonic Crystal Fibers



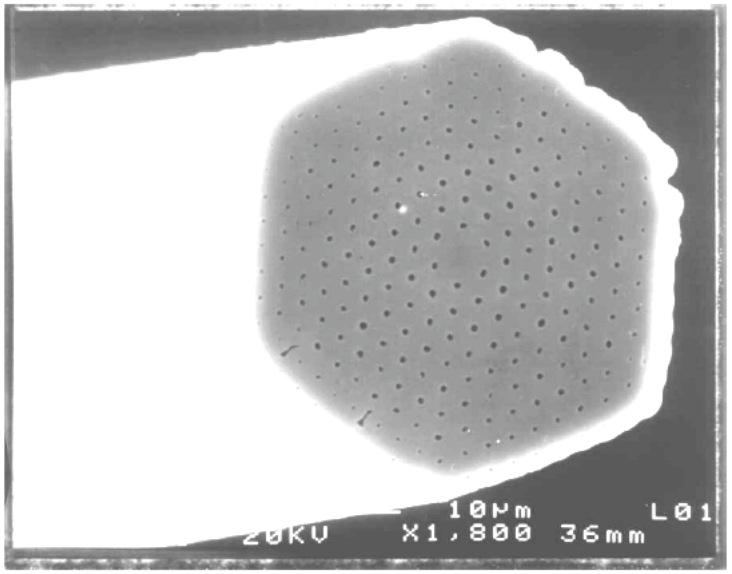
Conventional fiber
Core diameter 9 micron

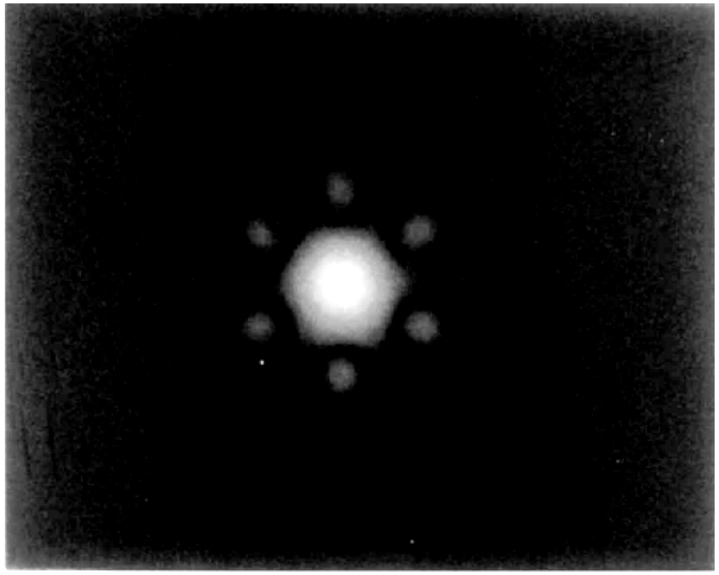
Dielectric-core PCF
Core diameter 5 micron

Air-core PCF
Core diameter 9 micron

Endless single mode photonic crystal fiber

Solid core photonic crystal fiber.



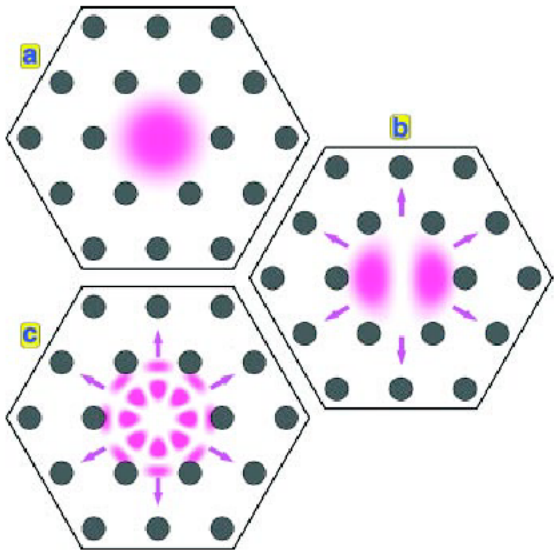


Solid core region nominally 4.6 μm wide

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

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.

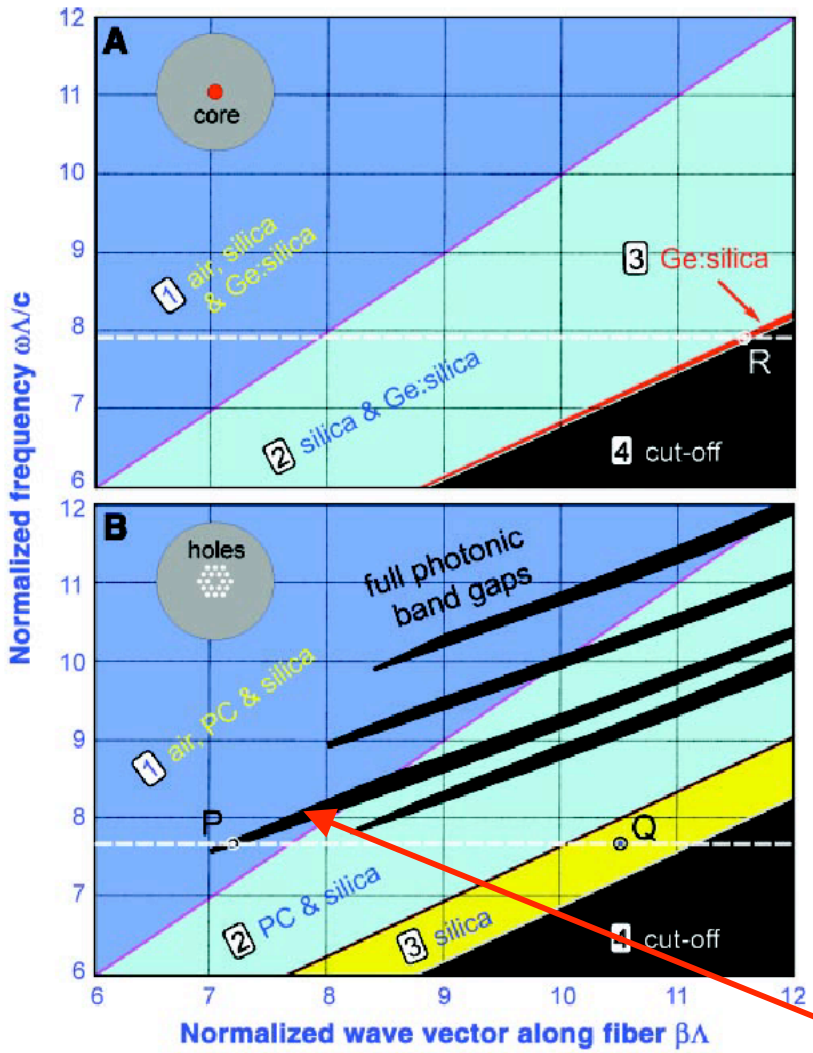
The higher order modes can leak through the narrow strip.

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

Single mode behavior occurs when $d/\Lambda < 0.4$

Knight et al, Opt. Lett. 21, 1547, 1996

The band structure picture



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.

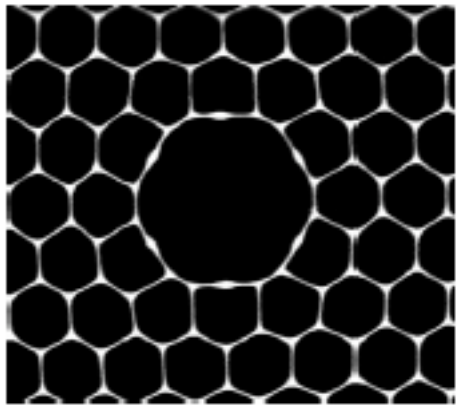
At finite β, band gap can appear. Band gaps arises from multiple reflection at the interfaces. At finite β, the reflectivity goes up, effectively increasing the in-plane index contrast.

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

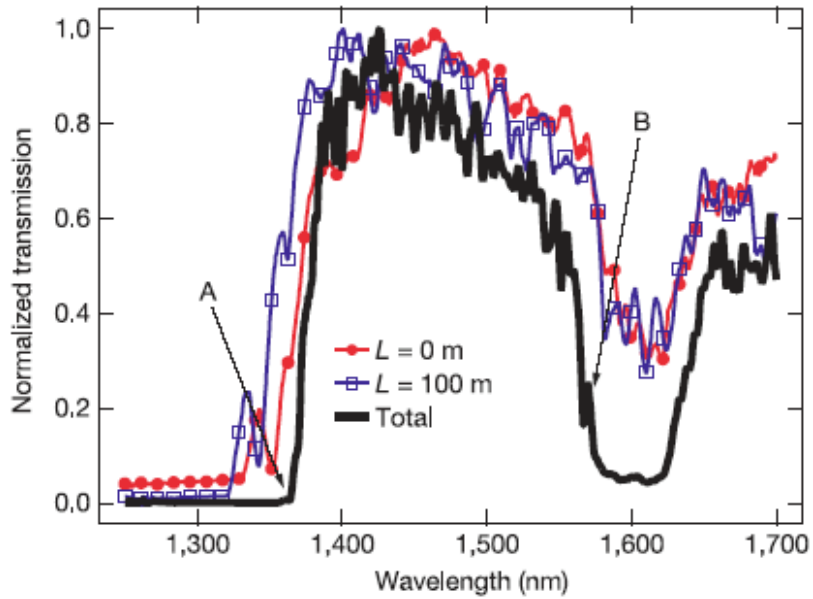
Requires fairly large air holes ($r \sim 0.47\Lambda$)

Possible region for air guiding

Air core photonic band gap fibers, experiments



Transmission through a 100m fiber

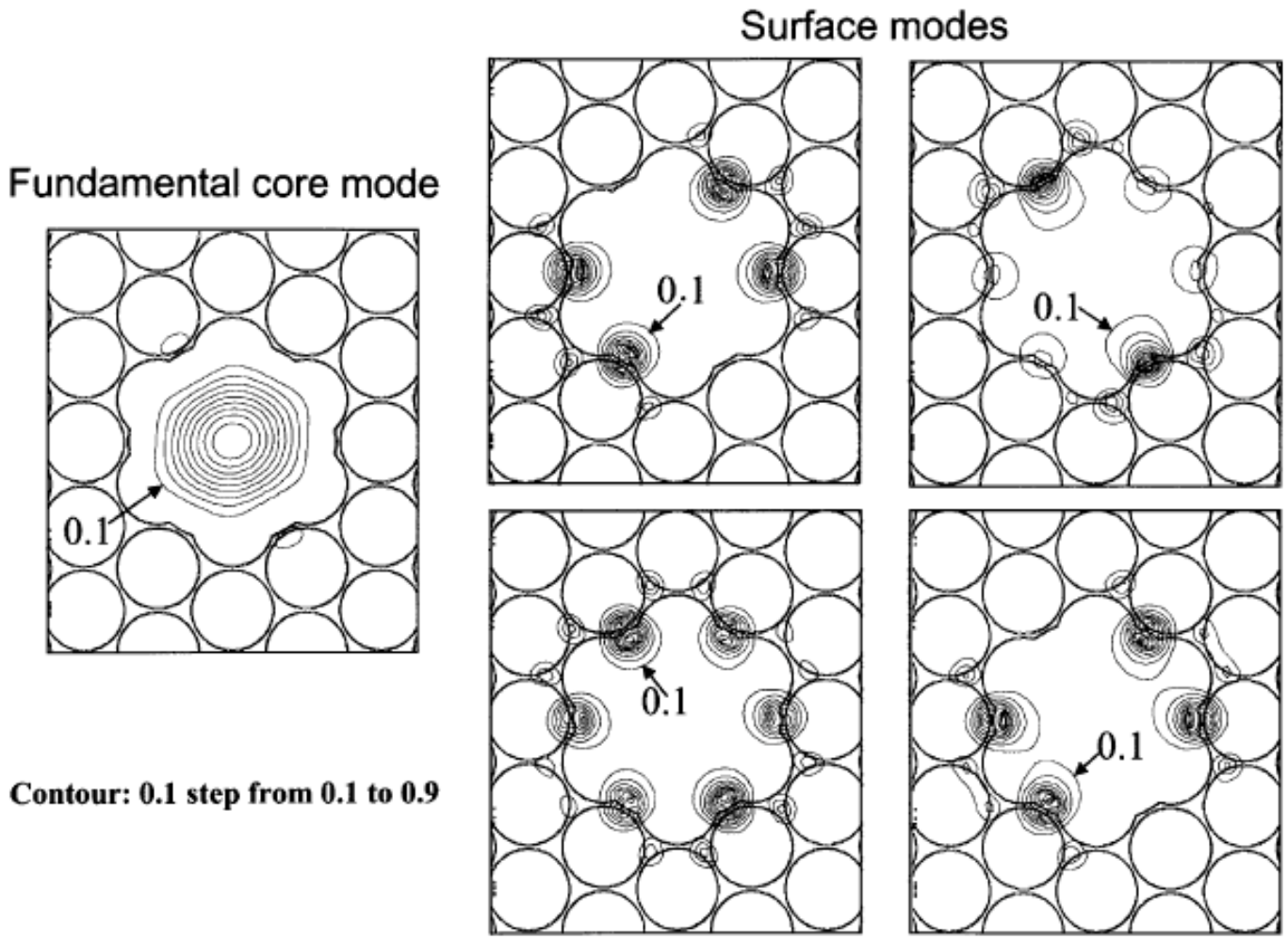


13 db/km in propagation loss, comparable to early days of conventional optical fiber.

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

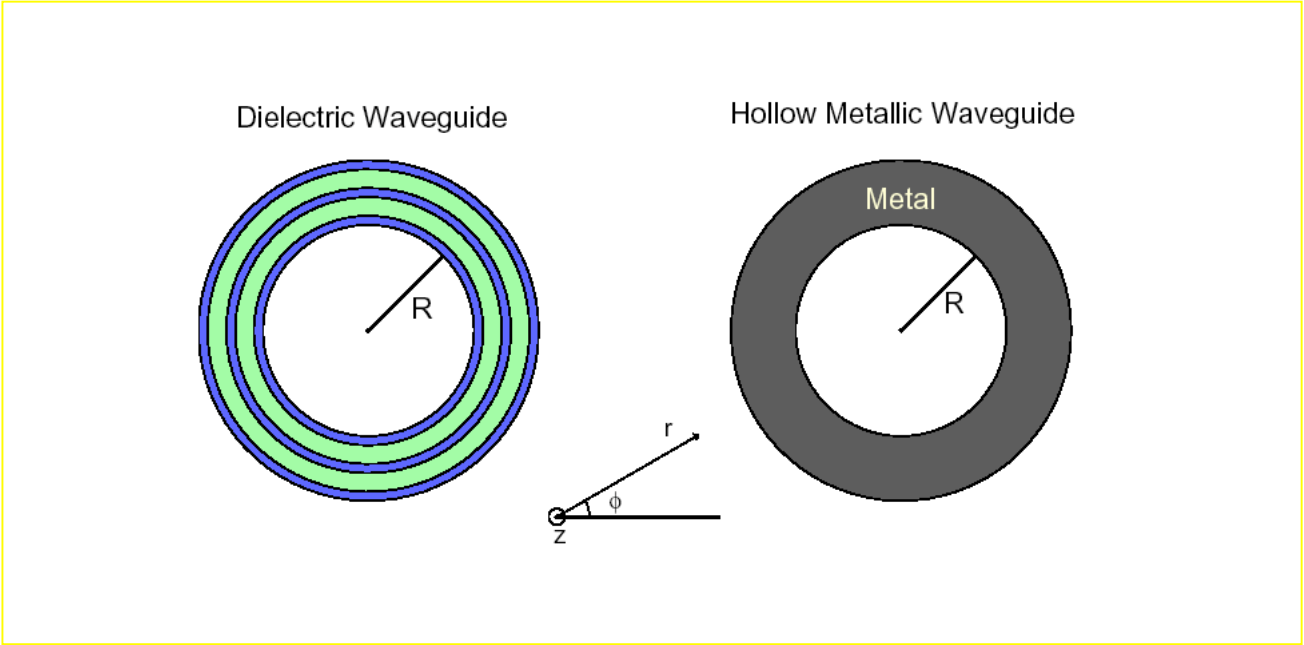
Smith et al, Nature, 424, 657 (2003)

Core modes vs. surface modes in air-core PCF



H. Kim, J. Shin, S. Fan, M. Digonnet, G. S. Kino, IEEE J. Quantum Electronics, 40, 552 (2004)

The Bragg fiber

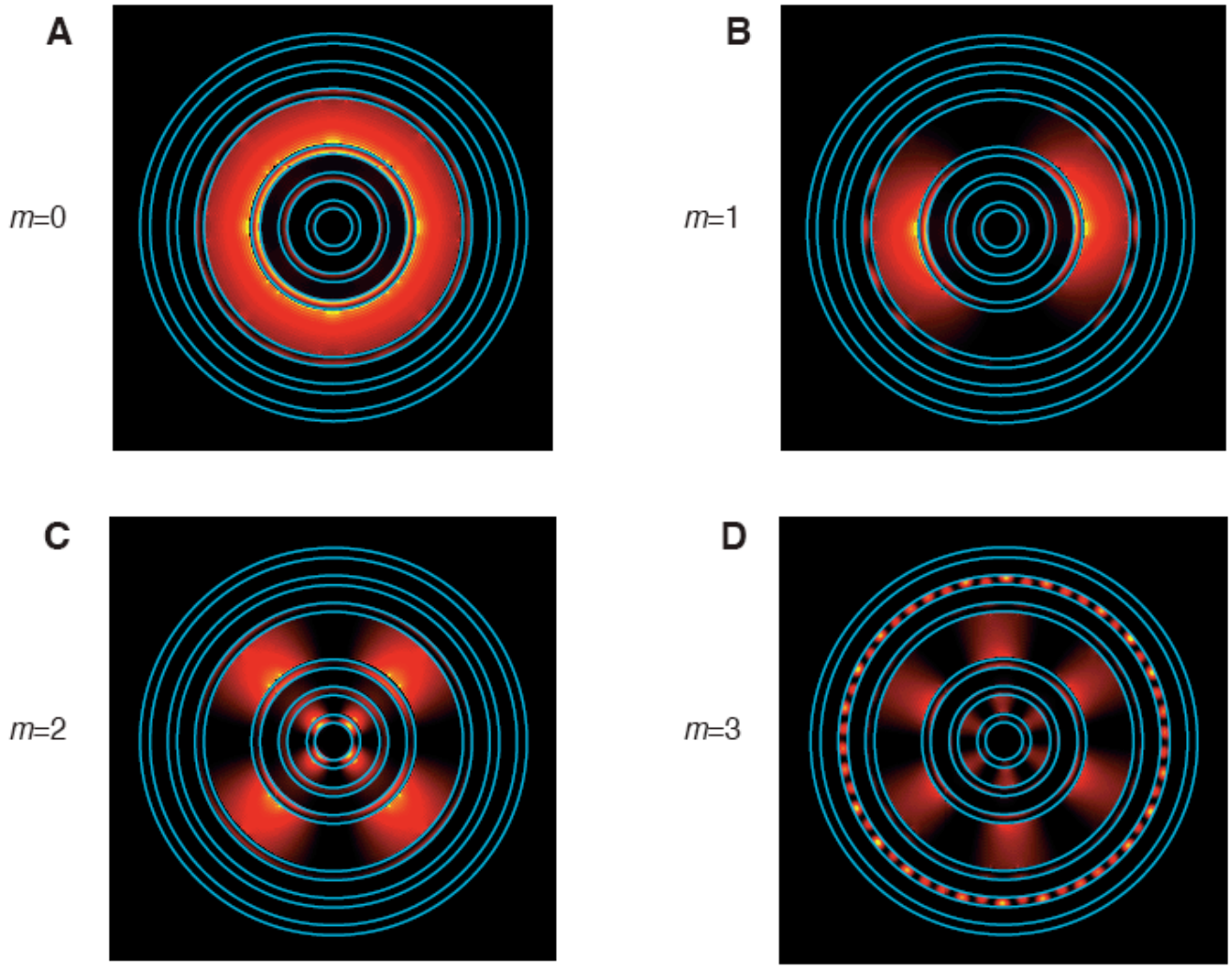


Using multilayer-film reflection to replace metal and create a light pipe.

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.

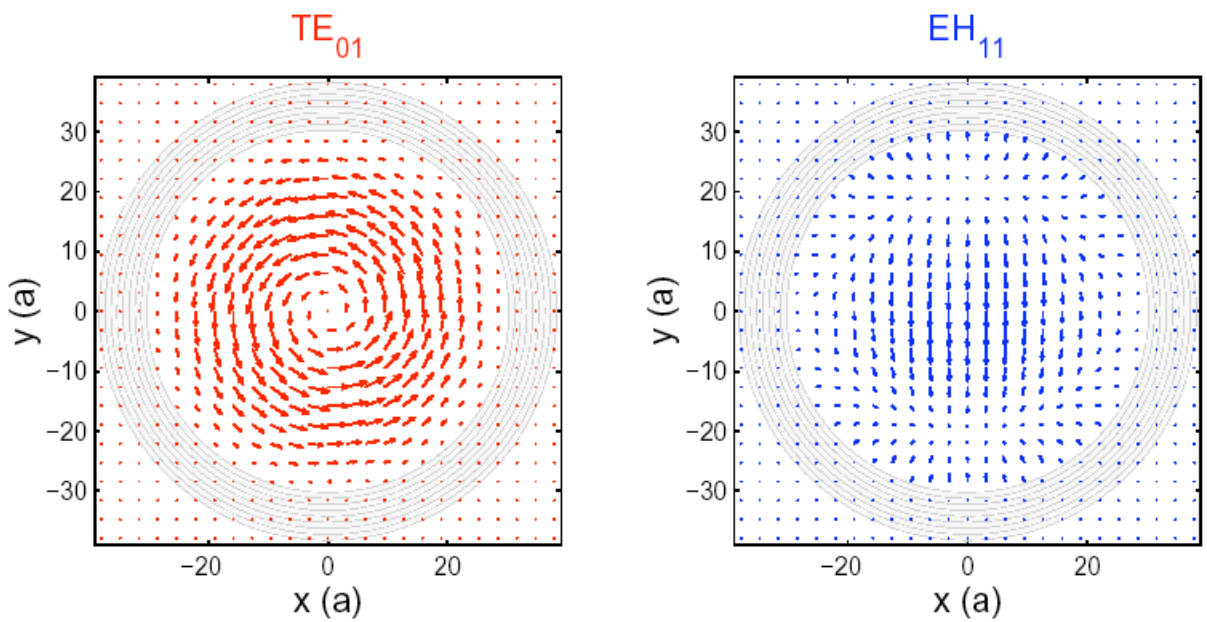
P. Yeh, A. Yariv and E. Marom, J. Opt. Soc. Am. 68, 1196 (1978).

All dielectric co-axial waveguide



Single polarization mode in dielectric waveguide, similar to the TEM mode

Asymptotic single mode guiding behavior

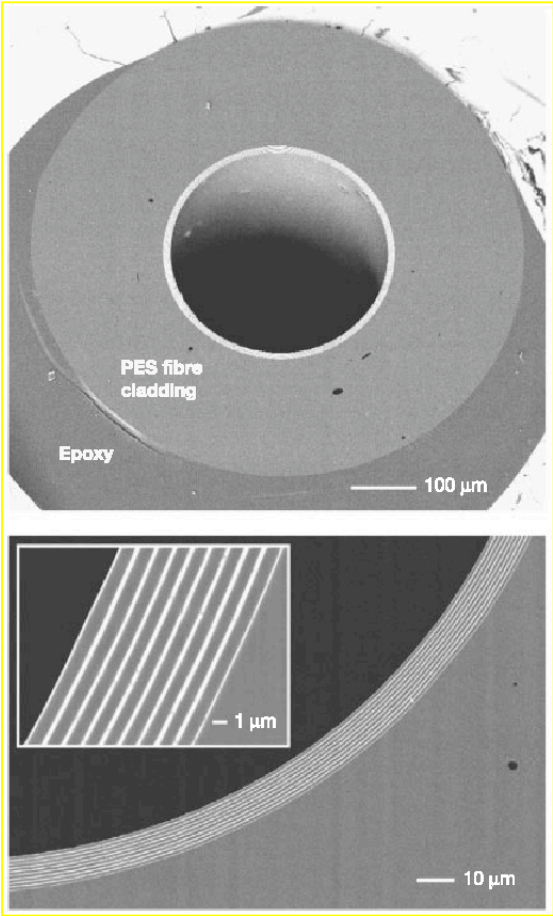


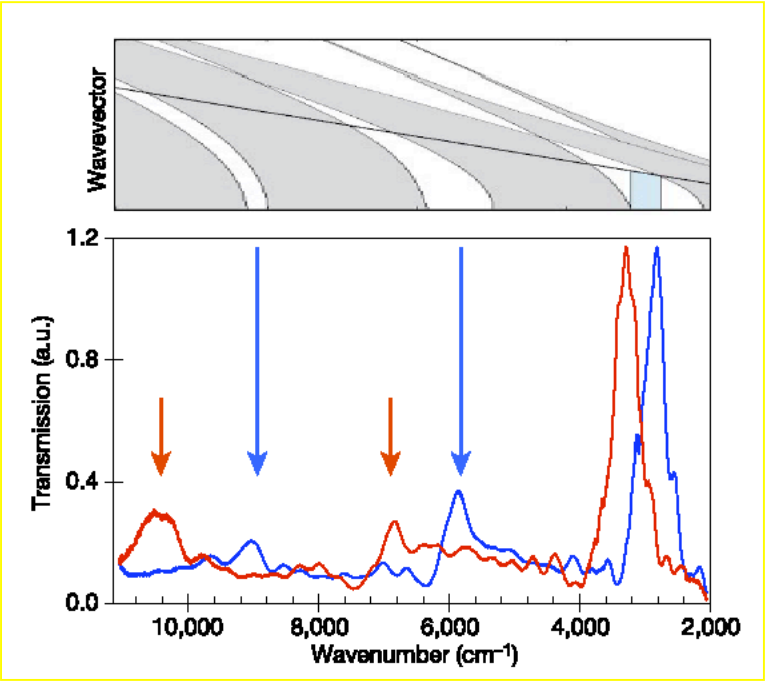
For TE_{0l} mode, the fraction of the power in cladding scales as $1/R^3$.

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

Temelkuran et al, Nature, 420, 650 (2002).