The Glass Ceiling: *Limits of Silica*

Loss: amplifiers every 50–100km

…limited by Rayleigh scattering (molecular entropy)

…cannot use "exotic" wavelengths like 10.6μm

Nonlinearities: after ~100km, cause dispersion, crosstalk, power limits

(limited by mode area ~ single-mode, bending loss)

also cannot be made (very) **large** for compact nonlinear devices

Radical modifications to dispersion, polarization effects?

…tunability is limited by low index contrast

Long Distances

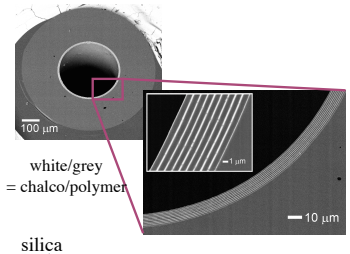
High Bit-Rates

Dense Wavelength Multiplexing (DWDM)

Compact Devices

Breaking the Glass Ceiling: Hollow-core Bandgap Fibers

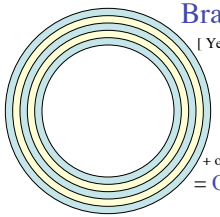
[figs courtesy Y. Fink *et al.*, MIT]



white/grey = chalco/polymer

Bragg fiber

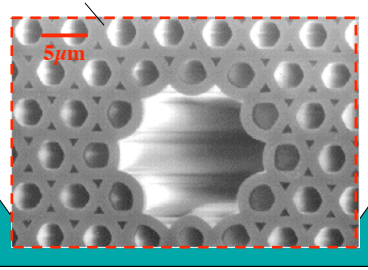
[Yeh *et al.*, 1978]

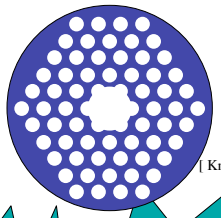


+ omnidirectional = OmniGuide fibers

[R. F. Cregan *et al.*, *Science* **285**, 1537 (1999)]

silica

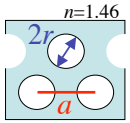




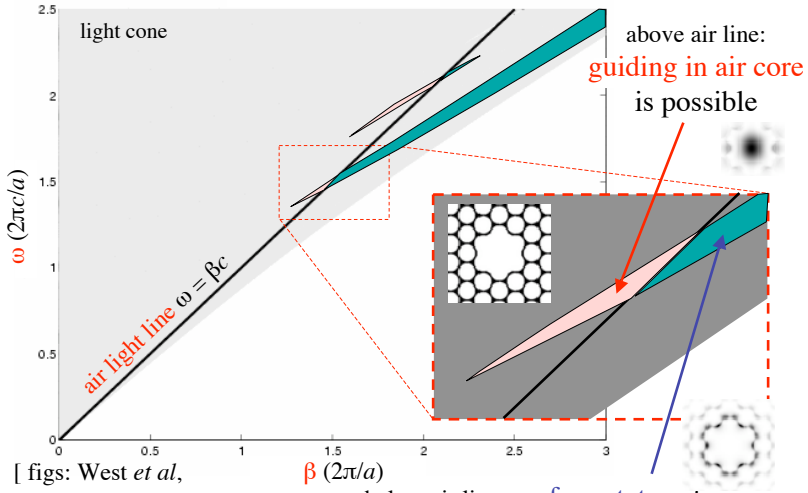
PCF

[Knight *et al.*, 1998]

PCF: Holey Silica Cladding



$r = 0.45a$



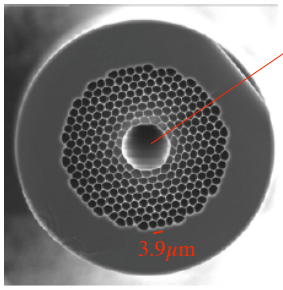
above air line: guiding in air core is possible

below air line: surface states of air core

[figs: West *et al*, *Opt. Express* **12** (8), 1485 (2004)]

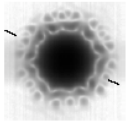
State-of-the-art air-guiding losses

[Mangan, *et al.*, OFC 2004 PDP24]



hollow (air) core (covers 19 holes)

guided field profile: (flux density)



1.7dB/km

BlazePhotonics

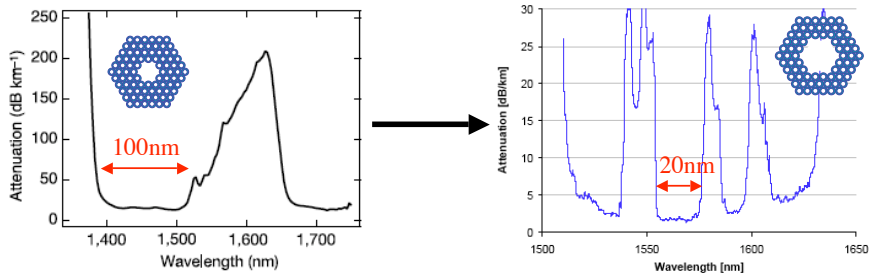
over ~ 800m @1.57μm

State-of-the-art air-guiding losses

larger core = more surface states crossing guided mode

… but surface states can be removed by proper crystal termination

[West, *Opt. Express* **12** (8), 1485 (2004)]



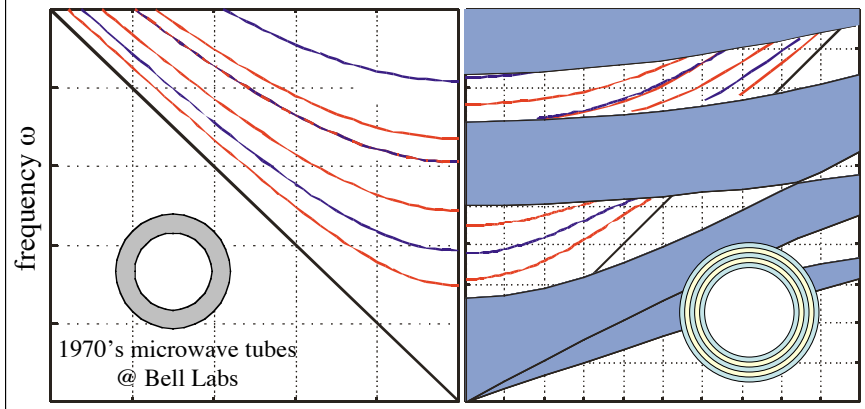
13dB/km
Corning
over ~ 100m @1.5μm
[Smith, *et al.*, *Nature* **424**, 657 (2003)]

1.7dB/km
BlazePhotonics
over ~ 800m @1.57μm
[Mangan, *et al.*, *OFC 2004* PDP24]

Hollow Metal Waveguides, Reborn

metal waveguide modes

OmniGuide fiber modes



wavenumber β

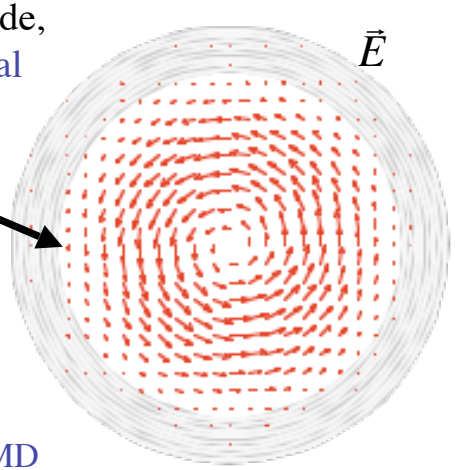
wavenumber β

modes are directly analogous to those in hollow metal waveguide

An Old Friend: the TE_{01} mode

lowest-loss mode,
just as in metal

(near) node at interface
= strong confinement
= low losses



non-degenerate mode
— cannot be split
= no birefringence or PMD

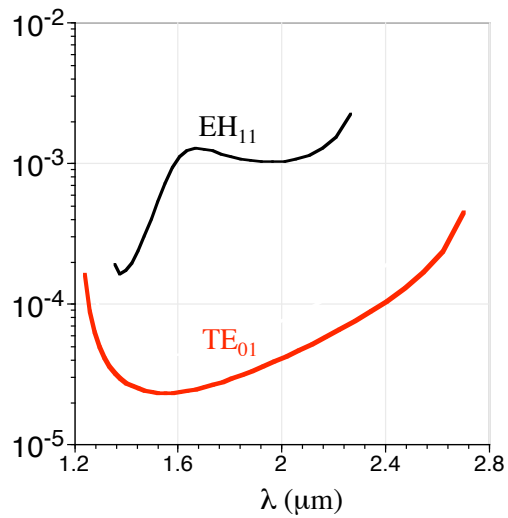
Suppressing Cladding Losses

Mode Losses
÷
Bulk Cladding Losses

Large differential loss

TE_{01} strongly suppresses cladding absorption

(like ohmic loss, for metal)



[Johnson, *Opt. Express* **9**, 748 (2001)]

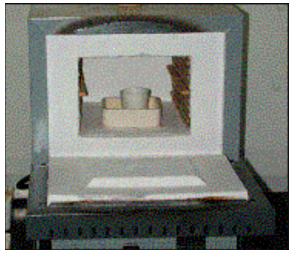
Yes, but how do you make it?

[figs courtesy Y. Fink *et al.*, MIT]

1

find compatible materials

(many new possibilities)



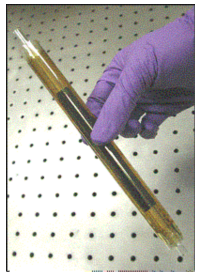
chalcogenide glass, n ~ 2.8

+ polymer (or oxide), n ~ 1.5

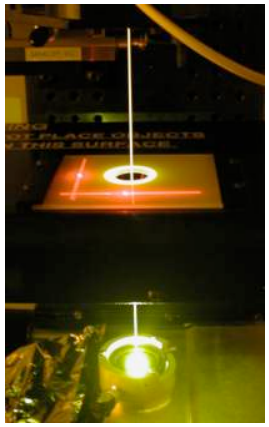
2

Make pre-form

("scale model")



3

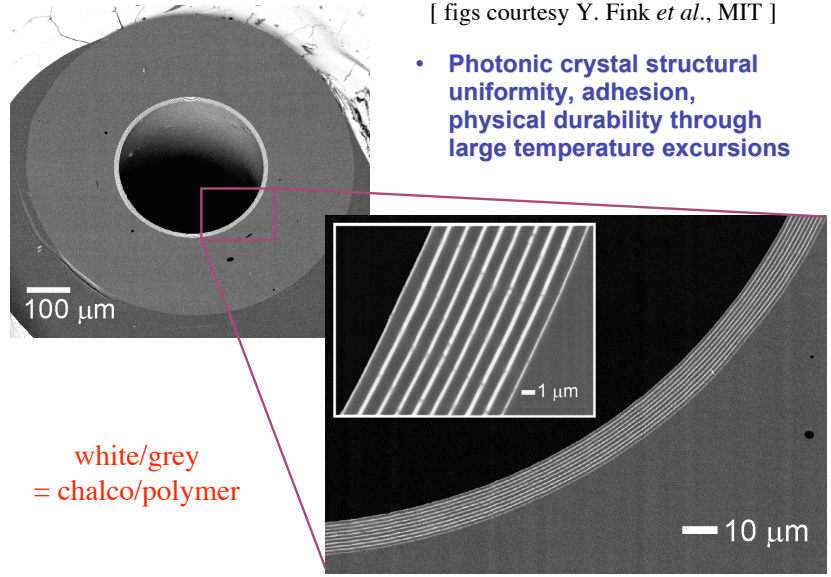


fiber drawing

A Drawn Bandgap Fiber

[figs courtesy Y. Fink *et al.*, MIT]

- **Photonic crystal structural uniformity, adhesion, physical durability through large temperature excursions**



white/grey

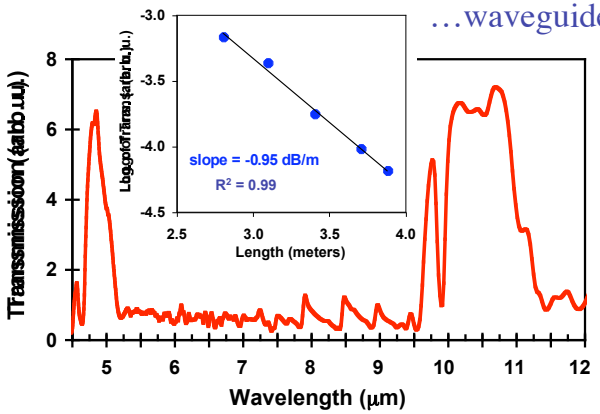
= chalco/polymer

High-Power Transmission

at 10.6μm (no previous dielectric waveguide)

Polymer losses @10.6μm ~ 50,000dB/m…

…waveguide losses < 1dB/m

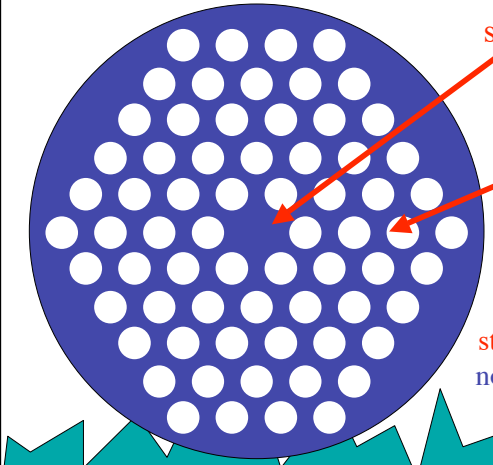


[B. Temelkuran *et al.*, *Nature* **420**, 650 (2002)]

[figs courtesy Y. Fink *et al.*, MIT]

Breaking the Glass Ceiling II:

Solid-core Holey Fibers



solid core

holey cladding forms *effective* low-index material

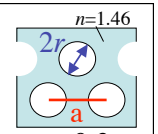
Can have much higher contrast than doped silica…

strong confinement = enhanced nonlinearities, birefringence, …

[J. C. Knight *et al.*, *Opt. Lett.* **21**, 1547 (1996)]

Mode in a Solid Core

small computation: only lowest-ω band!
(~ one minute, planewave)



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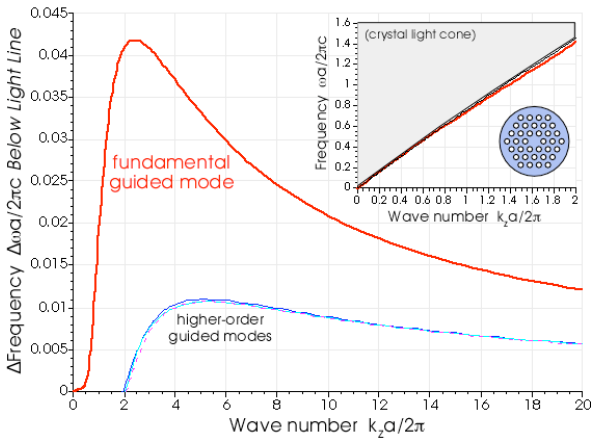
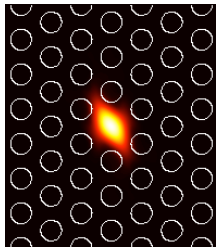


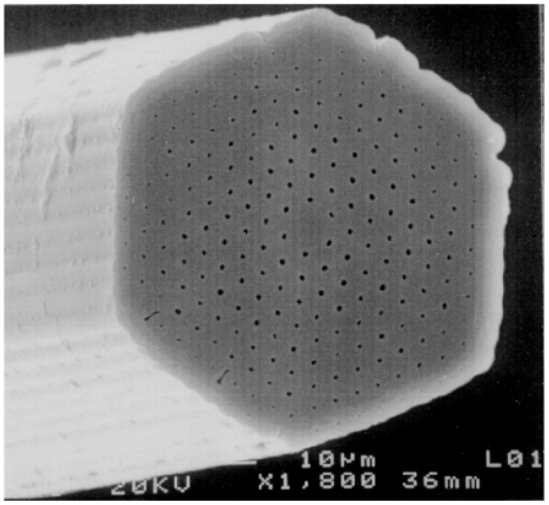
flux density



fundamental mode
(two polarizations)

Endlessly Single-Mode

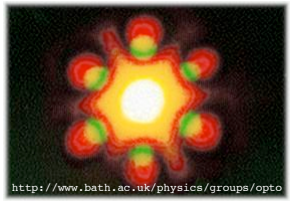
[T. A. Birks *et al.*, *Opt. Lett.* **22**, 961 (1997)]



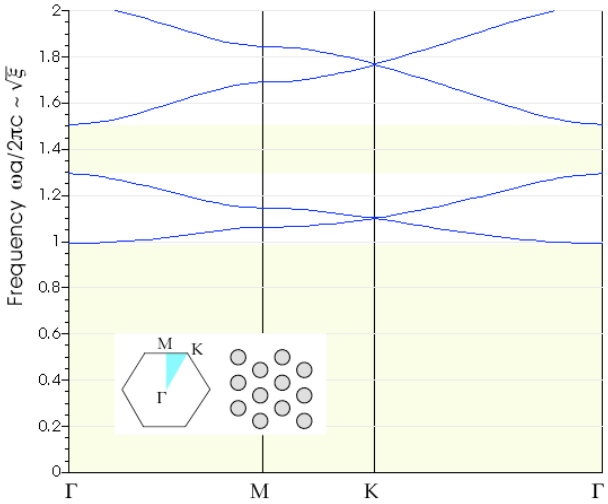
at higher ω (smaller λ), the light is more concentrated in silica

…so the effective index contrast is less

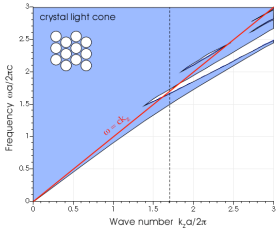
…and the fiber can stay single mode for all λ!

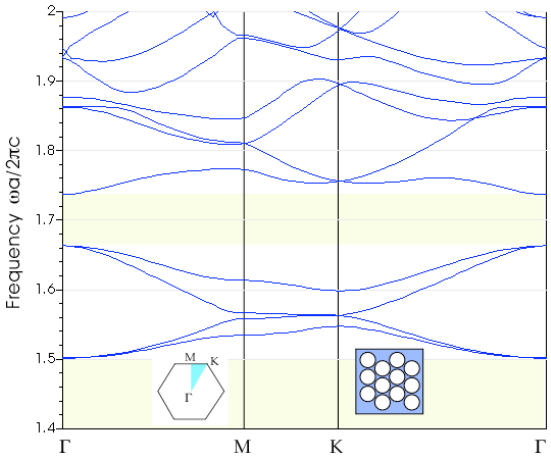


Band Diagram in "Metallic" Limit



Band Gaps from "Metallic" Limit



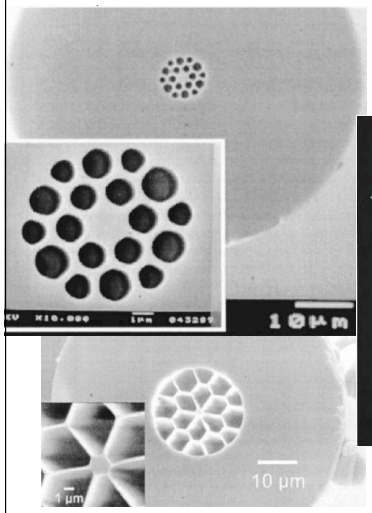


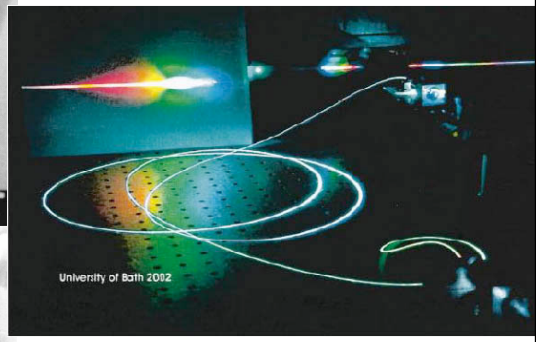
Nonlinear Holey Fibers:

Supercontinuum Generation

(enhanced by strong confinement + unusual dispersion)

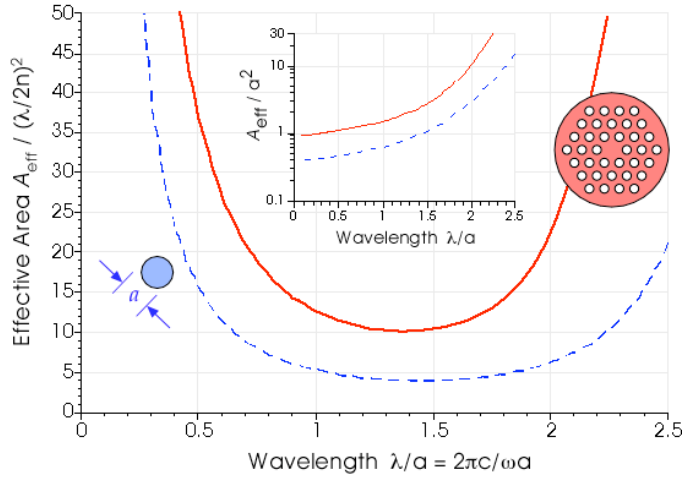
e.g. 400–1600nm "white" light:
from 850nm ~200 fs pulses (4 nJ)



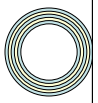


[W. J. Wadsworth *et al.*, *J. Opt. Soc. Am. B* **19**, 2148 (2002)]

Effective Area



Suppressing Cladding Nonlinearity

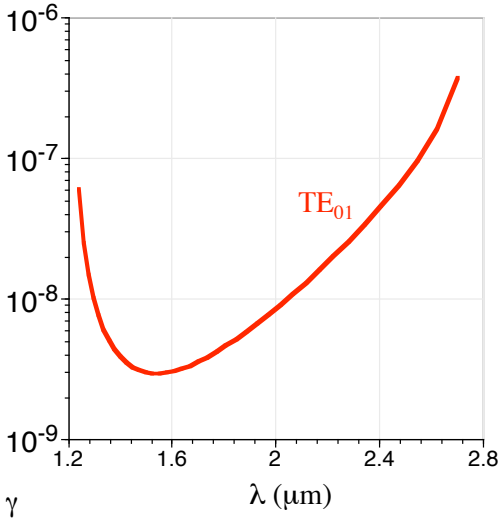


[Johnson, *Opt. Express* **9**, 748 (2001)]

Mode Nonlinearity*
÷
Cladding Nonlinearity

Will be dominated by nonlinearity of air

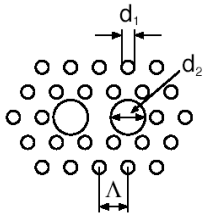
~10,000 times weaker than in silica fiber
(including factor of 10 in area)

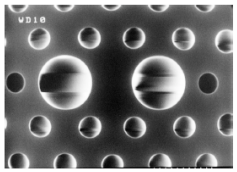


* "nonlinearity" = $\Delta\beta^{(1)} / P = \gamma$

Holey Fiber PMF

(Polarization-Maintaining Fiber)





birefringence $B = \Delta\beta c/\omega$
$= 0.0014$
(10 times B of silica PMF)

Loss = 1.3 dB/km @ 1.55μm
over 1.5km

no longer degenerate with

Can operate in a single polarization, PMD = 0
(also, known polarization at output)

[K. Suzuki, *Opt. Express* **9**, 676 (2001)]