Photonic Crystals:

Periodic Surprises in Electromagnetism

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MIT

A Long and Winding Road

Photonic-Crystal Fibers

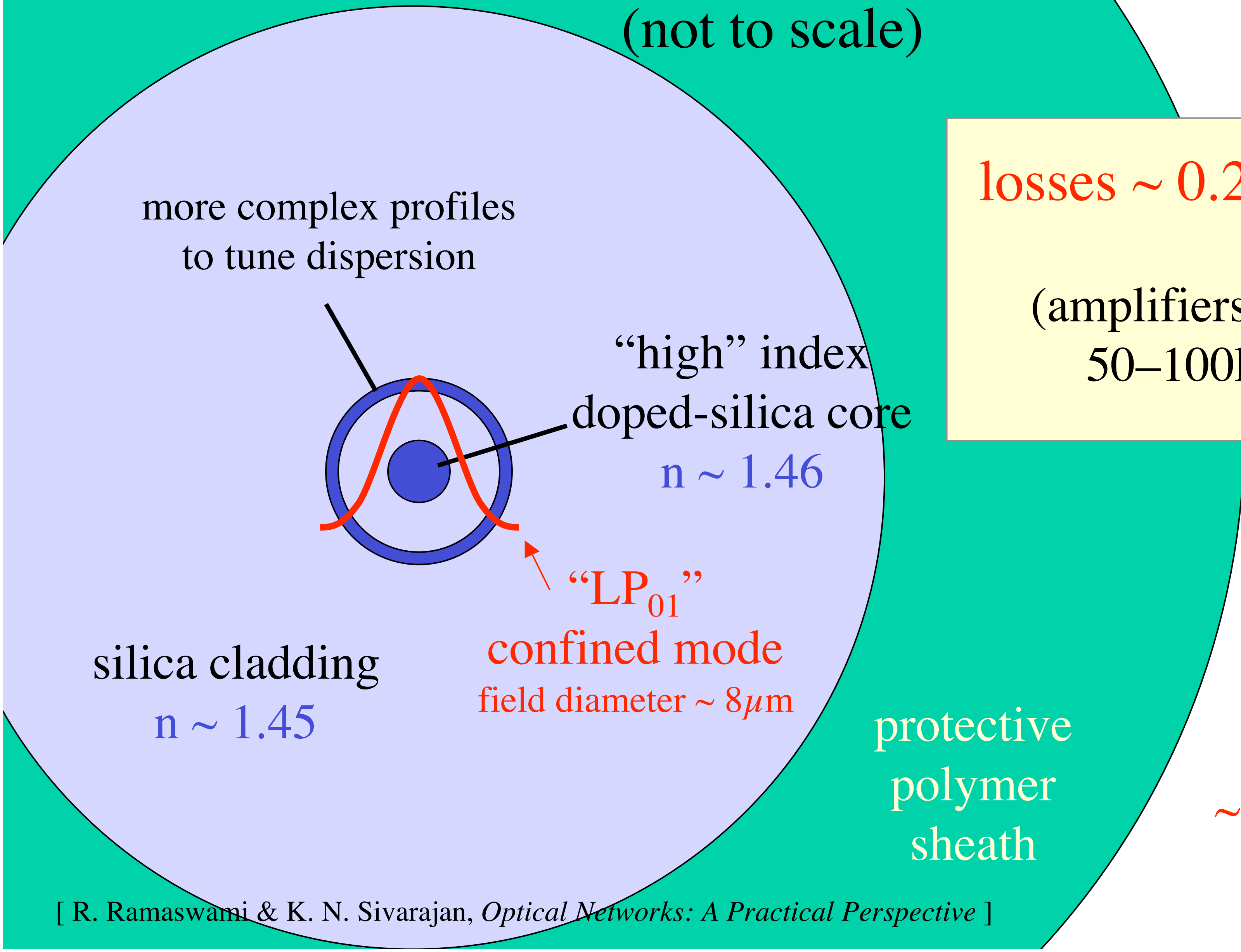
1/31/02 INSPEC literature search:

14810 hits   458604 hits   87652 hits

Bloch's theorem is more important than Maxwell's equations ;^)

Optical Fibers Today

(not to scale)



losses ~ 0.2 dB/km

(amplifiers every
50–100km)

but this is
~ as good as
it gets…

[R. Ramaswami & K. N. Sivarajan, *Optical Networks: A Practical Perspective*]

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

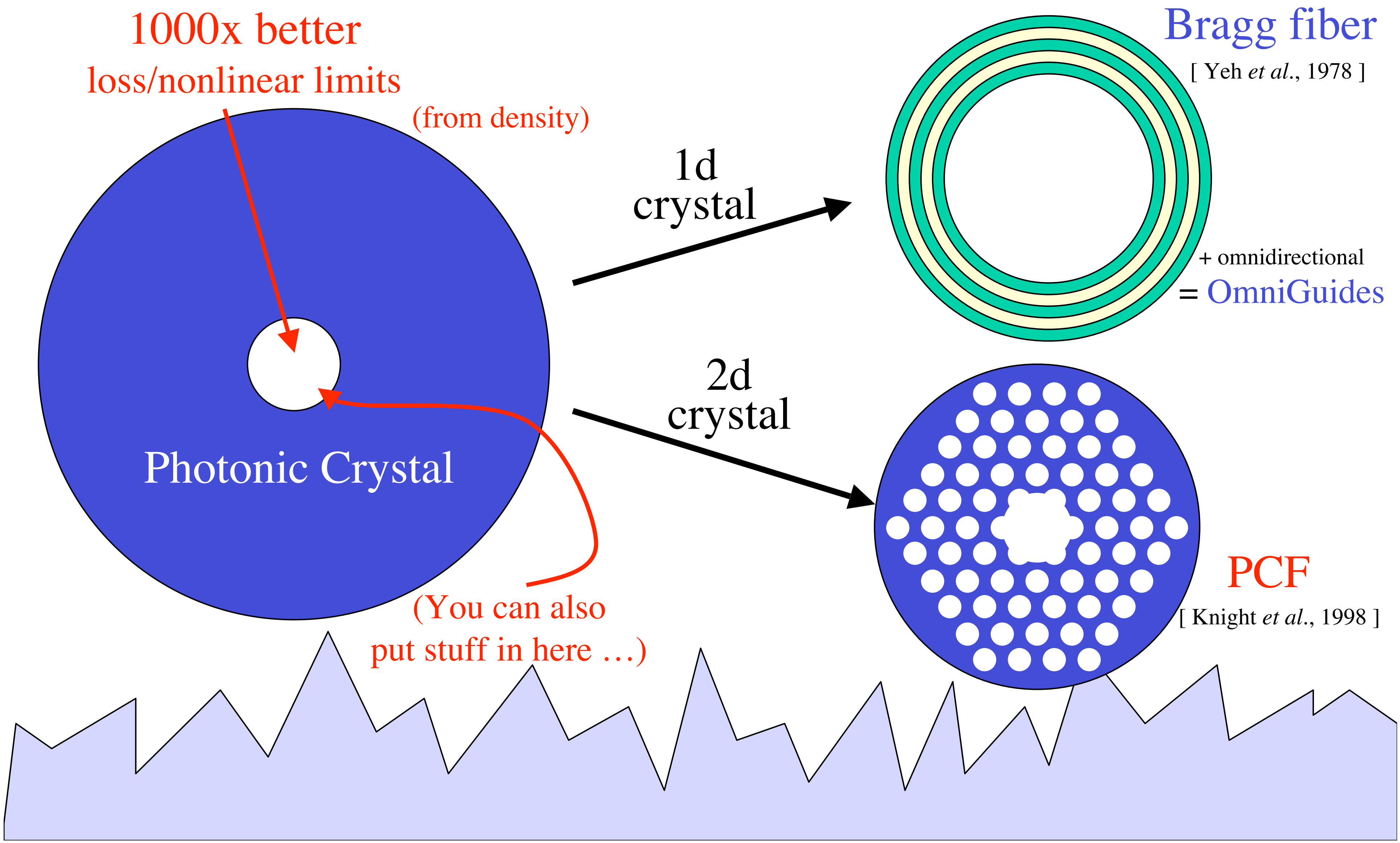
Long Distances

High Bit-Rates

Dense Wavelength Multiplexing (DWDM)

Compact Devices

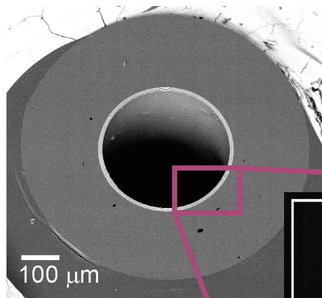
Breaking the Glass Ceiling:
Hollow-core Bandgap Fibers

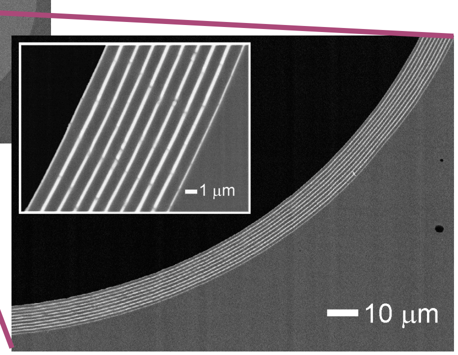


Breaking the Glass Ceiling:

Hollow-core Bandgap Fibers

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

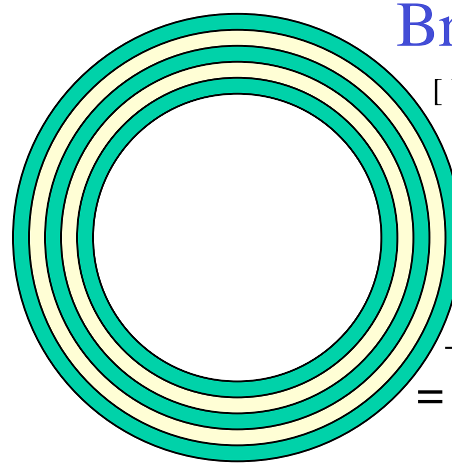




white/grey
= chalco/polymer

Bragg fiber

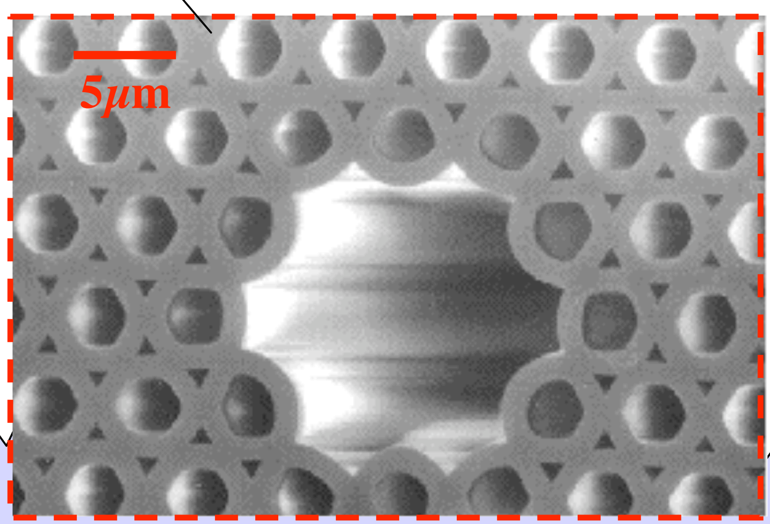
[Yeh *et al.*, 1978]

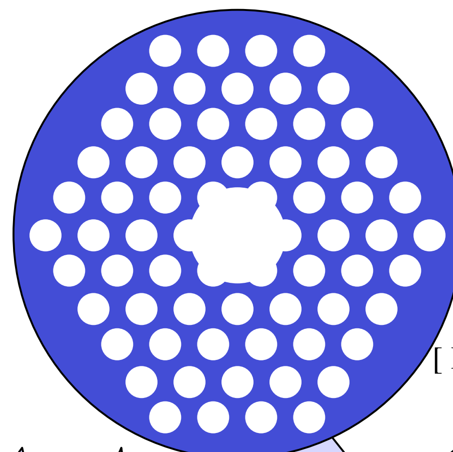


+ omnidirectional
= OmniGuides

silica

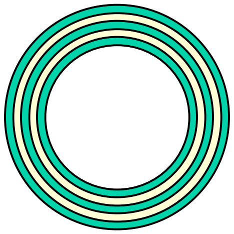
[R. F. Cregan
et al.,
Science **285**,
1537 (1999)]



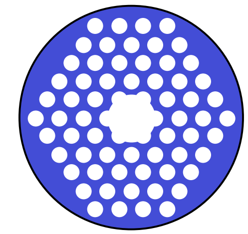


PCF

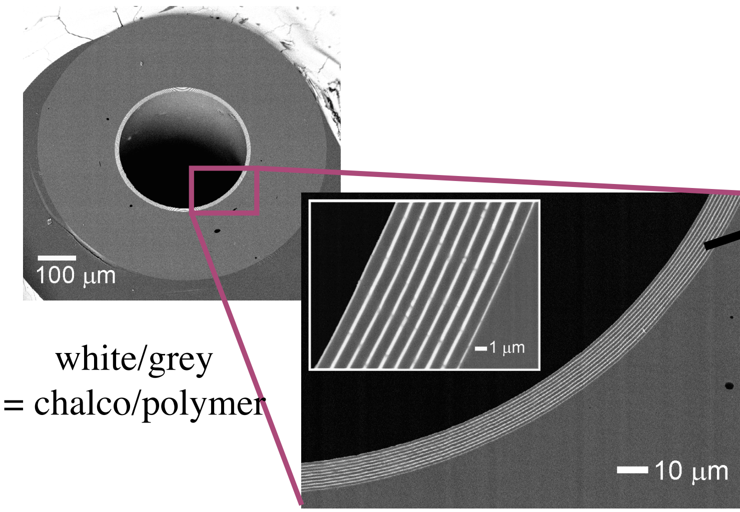
[Knight *et al.*, 1998]



Breaking the Glass Ceiling:
Hollow-core Bandgap Fibers



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

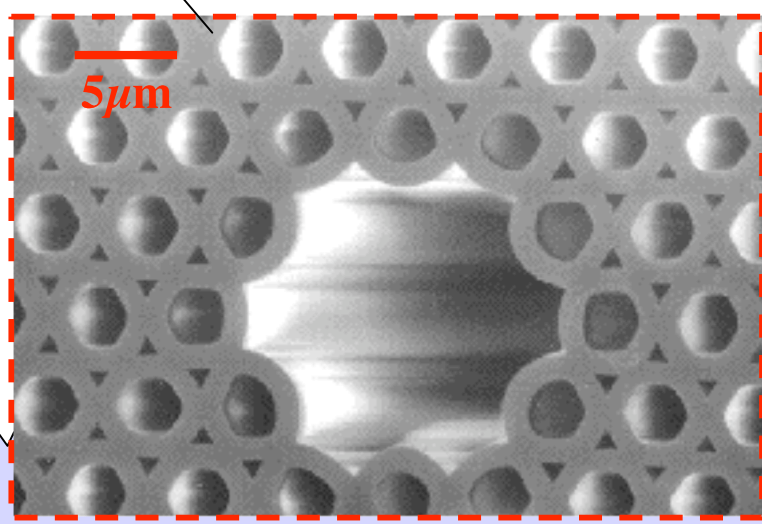


white/grey
= chalco/polymer

Guiding @ 10.6μm
(high-power CO_2 lasers)
loss < 1 dB/m
(material loss ~ 10^4 dB/m)

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

silica



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

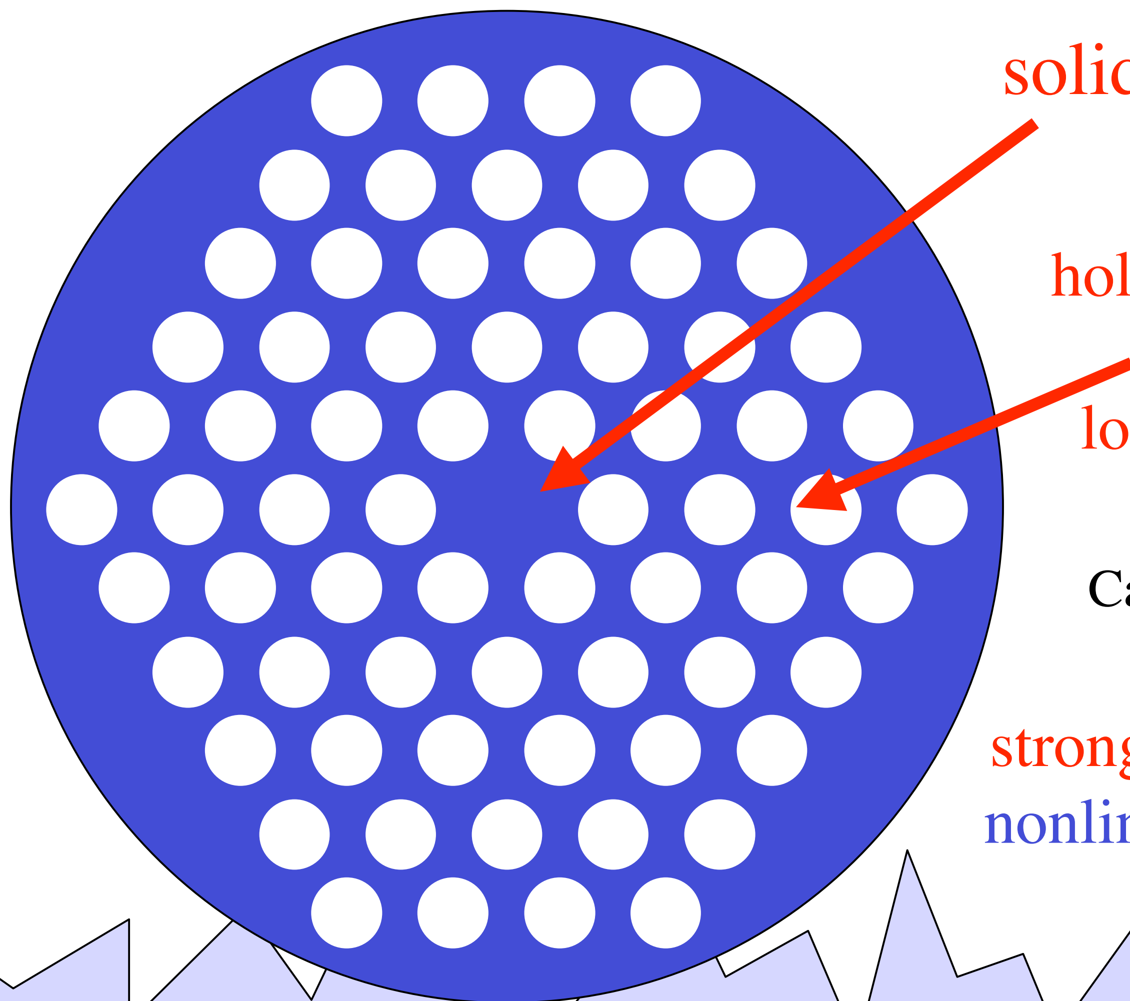
Guiding @ 1.55μm
loss ~ 13dB/km

[Smith, *et al.*,
Nature **424**, 657 (2003)]

OFC 2004: 1.7dB/km
BlazePhotonics

Breaking the Glass Ceiling II:

Solid-core Holey Fibers



solid core

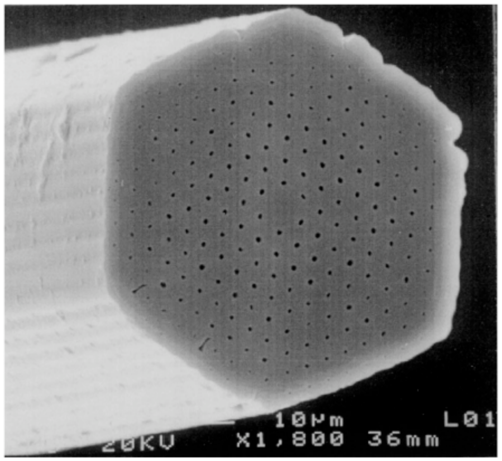
holey cladding forms
effective
low-index material

Can have much higher contrast
than doped silica…

strong confinement = enhanced
nonlinearities, birefringence, …

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

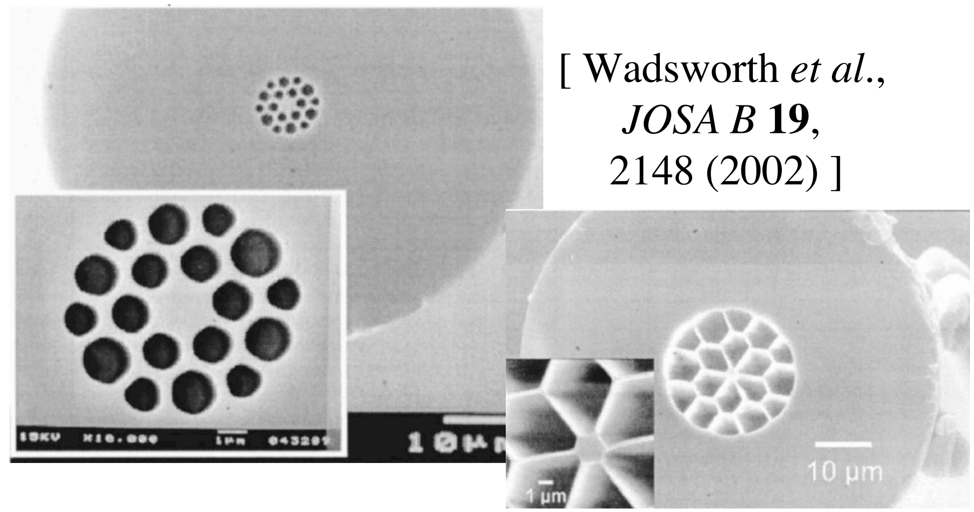
Breaking the Glass Ceiling II:
Solid-core Holey Fibers



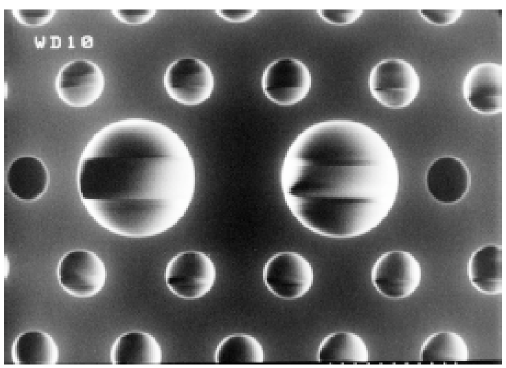
endlessly single-mode

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

nonlinear fibers

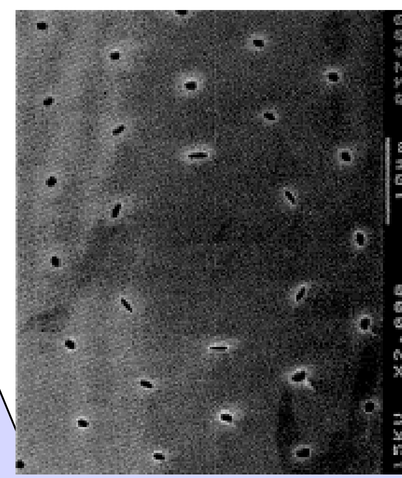


[Wadsworth *et al*., *JOSA B* **19**, 2148 (2002)]



polarization -maintaining

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



low-contrast *linear* fiber (large area)

[J. C. Knight *et al*., *Elec*. *Lett*. **34**, 1347 (1998)]

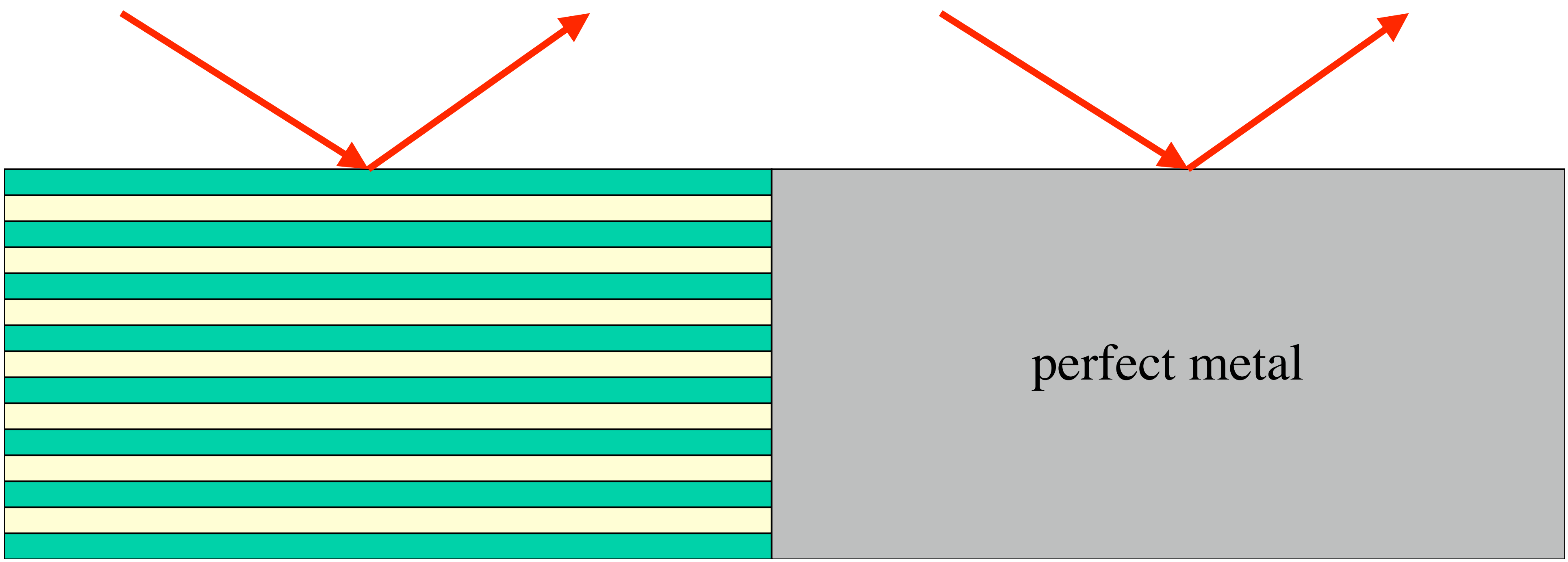
Omnidirectional Bragg Mirrors

a 1d crystal can reflect light from
all angles and polarizations

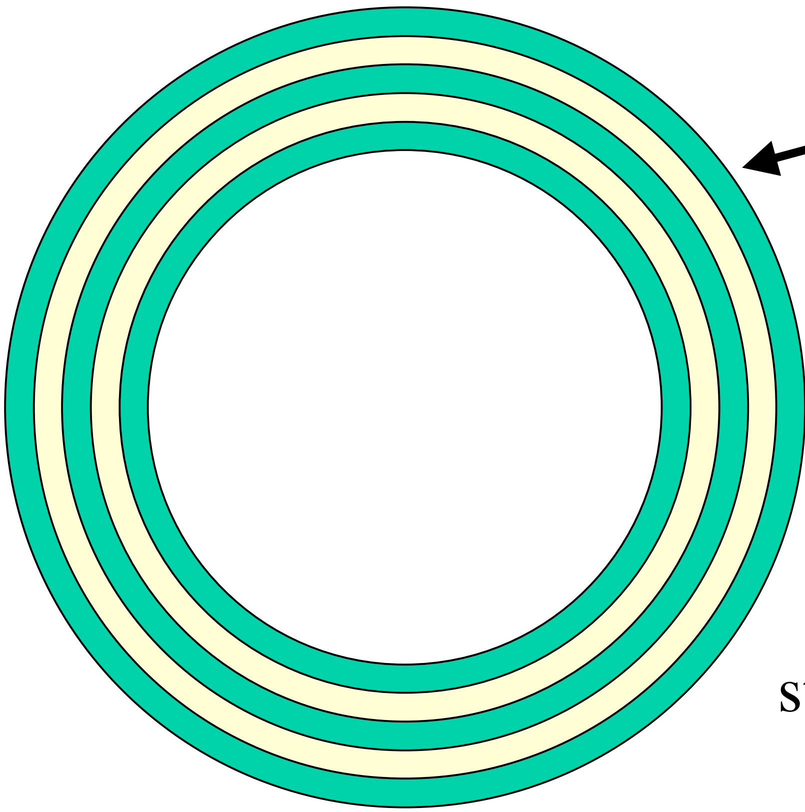
[Winn, Fink *et al*. (1998)]

…it behaves
like a metal

(but at any wavelength)



OmniGuide Fibers



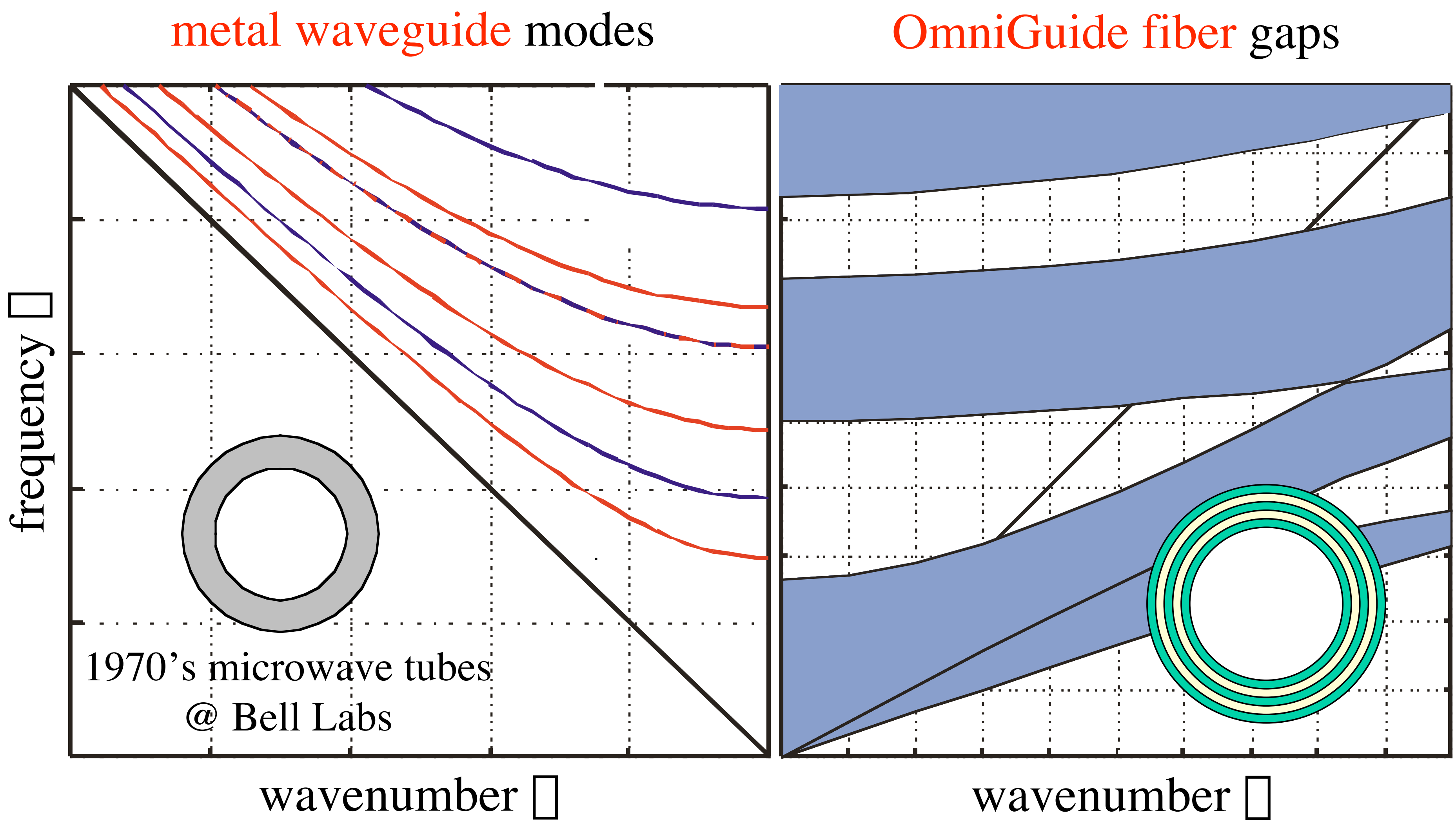
omnidirectional mirrors

c.f. Photonic Bandgap Fibers
& Devices Group @ MIT

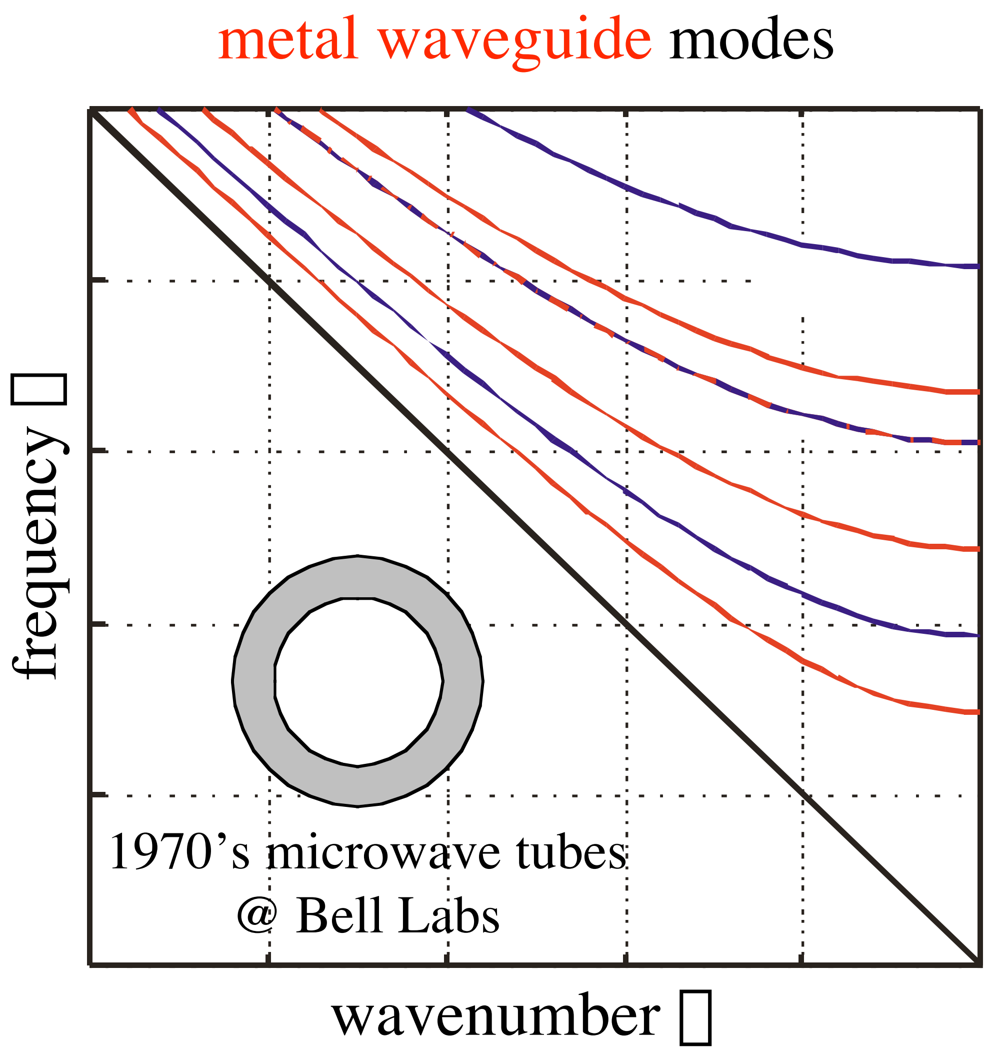
(also a Cambridge MA
start-up: `www.omni-guide.com`)

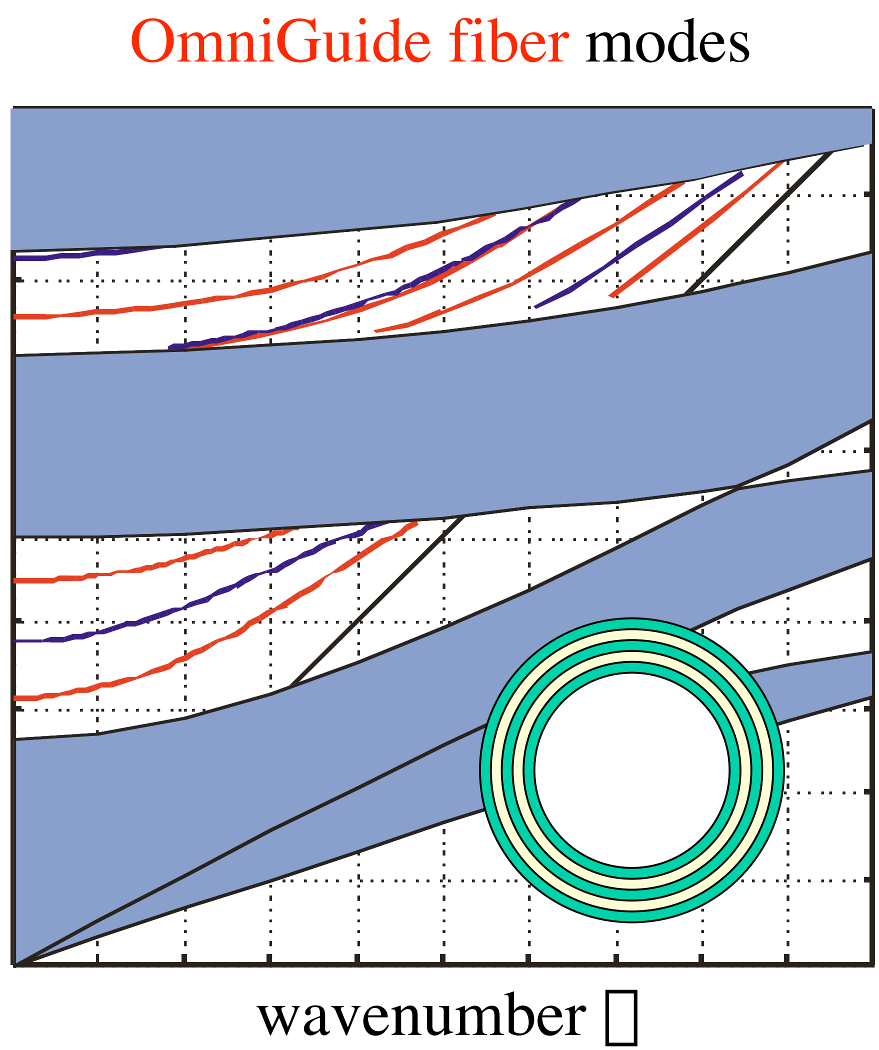
[S. G. Johnson *et al.*, *Opt. Express* **9**, 748 (2001)]

Hollow Metal Waveguides, Reborn



Hollow Metal Waveguides, Reborn

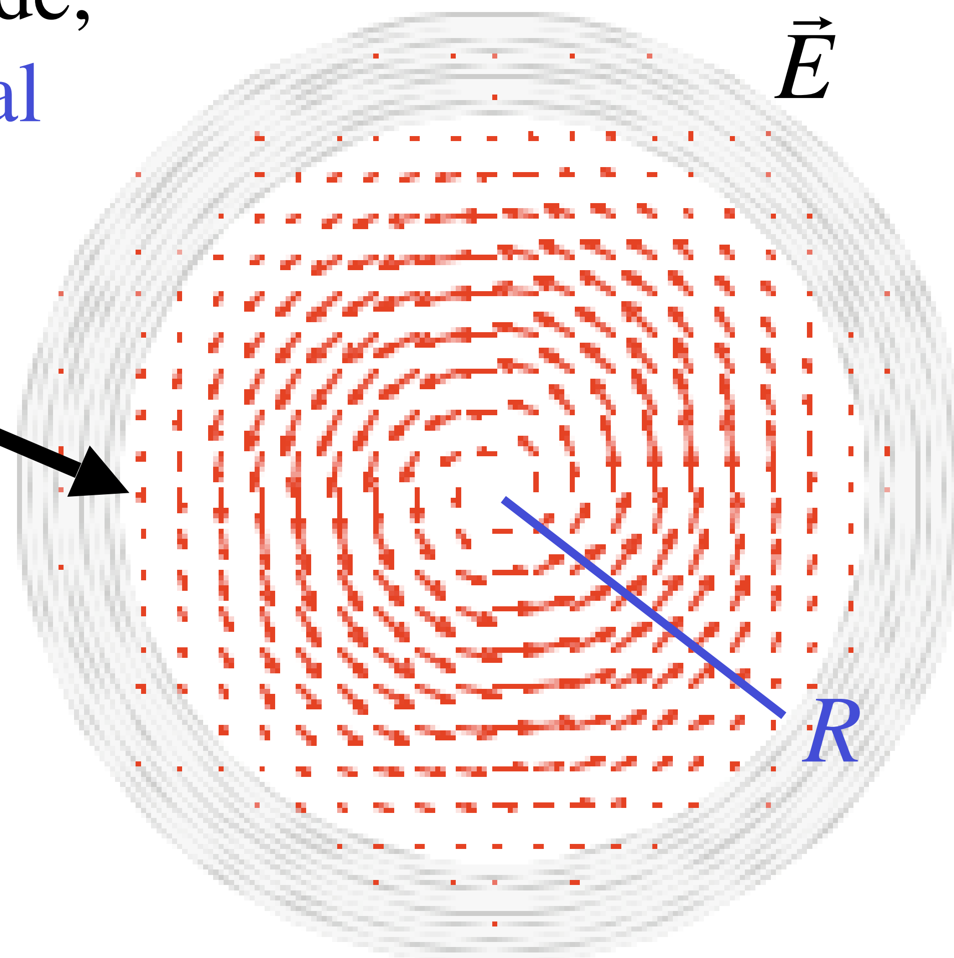




modes are directly analogous to those in hollow metal waveguide

An Old Friend: the TE_{01} mode

lowest-loss mode,
just as in metal



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

from metal:
optimal R ~ 10□

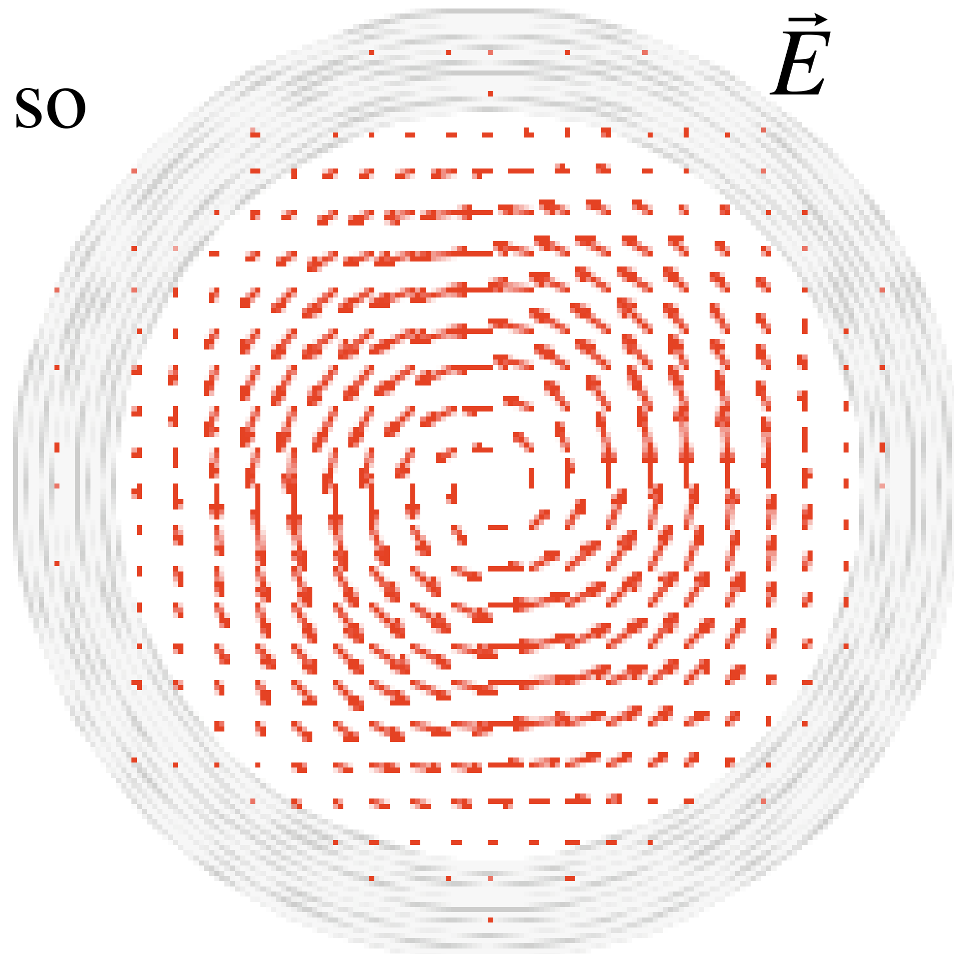
Here, use R=13μm for □=1.55μm … n=4.6/1.6 (any omnidirectional is similar)

TE_{01} vs. PMD

non-degenerate mode, so
cannot be split

i.e. immune
to birefringence

i.e. PMD is zero



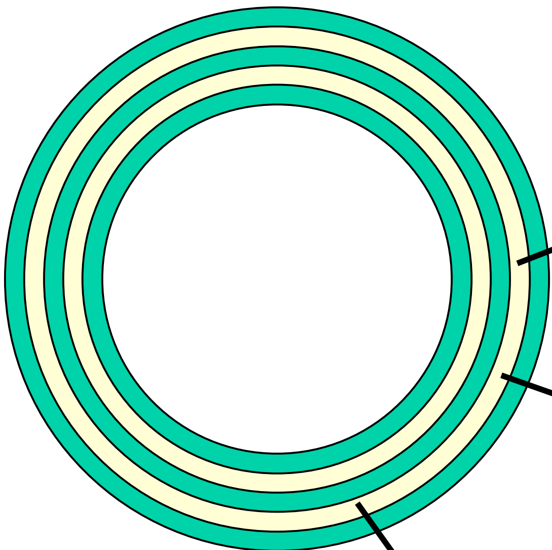
Let's Get Quantitative

…but what about the cladding?

…*some* field penetrates!

& may need to use very "bad" material to get high index contrast

Let’s Get Quantitative



Absorption (& Rayleigh Scattering)

= small imaginary □□

Nonlinearity

= small □□~ $|E|^2$

Acircularity, bending, roughness, …

= small perturbations

Hard to compute *directly*

… use Perturbation Theory

Perturbation Theory

Given solution for ideal system
compute approximate effect
of small changes

…solves hard problems starting with easy problems

& provides (semi) analytical insight

Perturbation Theory

for Hermitian eigenproblems

given eigenvectors/values: $\hat{O}|u\rangle = u|u\rangle$

…find change Δu & $\Delta|u\rangle$ for small $\Delta\hat{O}$

Solution:

expand as power series in $\Delta\hat{O}$

$$\Delta u = 0 + \Delta u^{(1)} + \Delta u^{(2)} + \ldots$$

$$\& \ \Delta|u\rangle = 0 + \Delta|u\rangle^{(1)} + \ldots$$

$$\boxed{\Delta u^{(1)} = \frac{\langle u|\Delta\hat{O}|u\rangle}{\langle u|u\rangle}}$$

(first-order is usually enough)

Perturbation Theory

for electromagnetism

$$\Delta\omega^{(1)} = \frac{c^2}{2\omega}\frac{\langle \vec{H} | \Delta\hat{\varepsilon}^{-1} | \vec{H} \rangle}{\langle \vec{H} | \vec{H} \rangle}$$

$$= -\frac{\omega}{2}\frac{\int \Delta\varepsilon |\vec{E}|^2}{\int \varepsilon |\vec{E}|^2}$$

…e.g. absorption gives imaginary $\Delta\varepsilon$ = decay!

$$\Delta\beta^{(1)} = \Delta\omega^{(1)} / v_g \qquad v_g = \frac{d\omega}{d\beta}$$

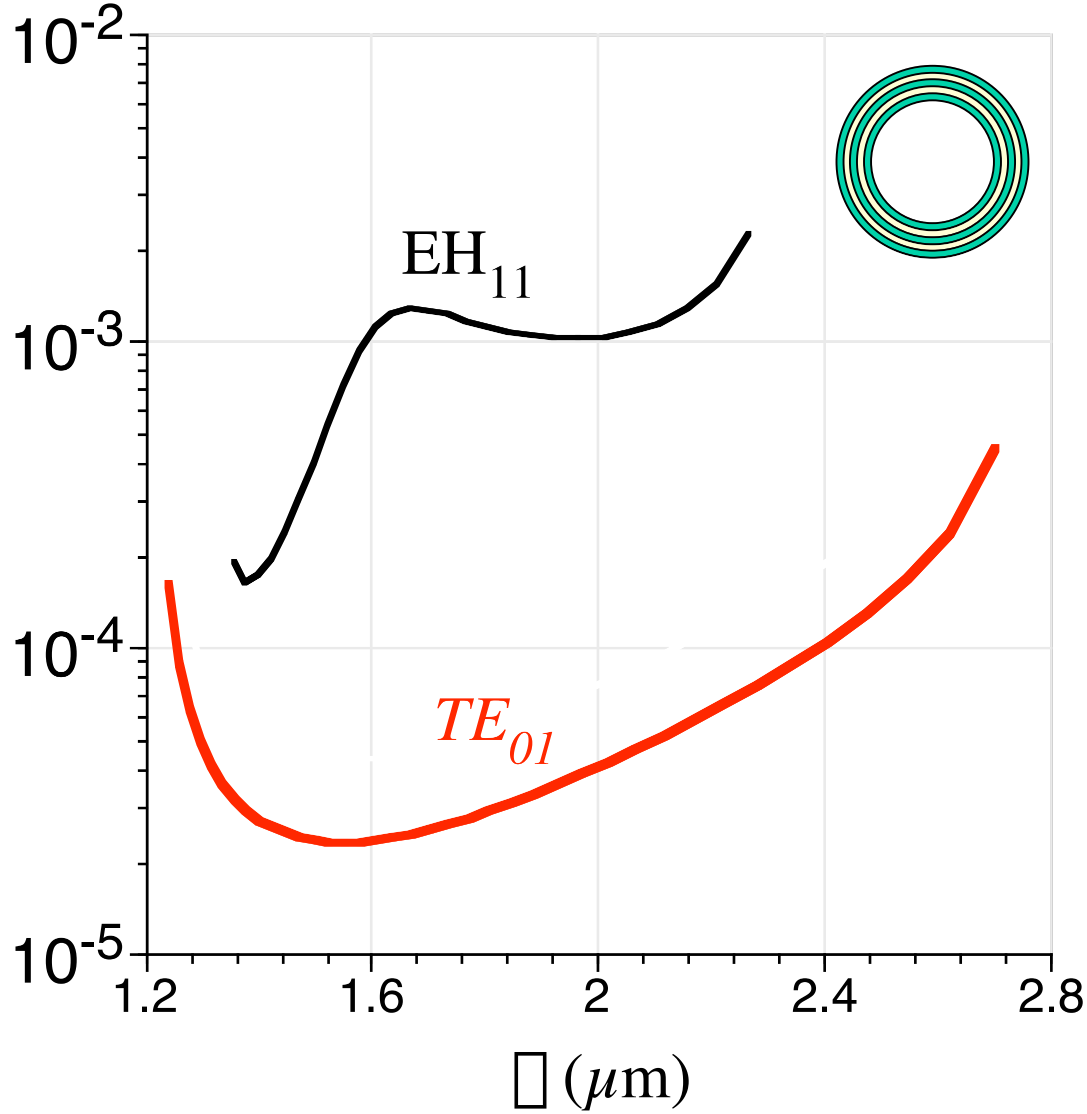
Suppressing Cladding Losses

Mode Losses
/
Bulk Cladding Losses:

Large differential loss

TE_{01} cladding loss
strongly suppressed!

(like ohmic losses)



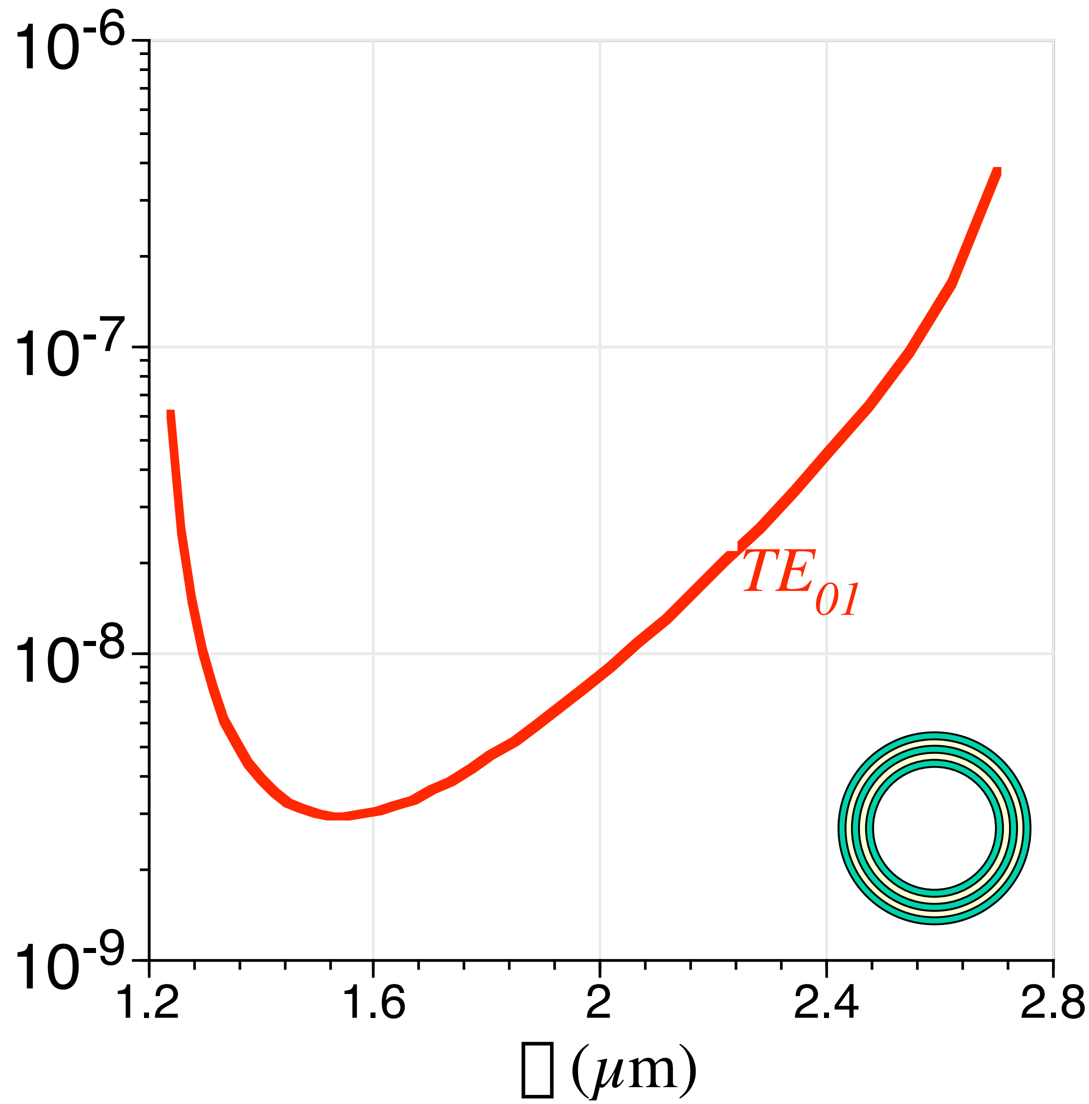
Suppressing Cladding Nonlinearity

Mode Nonlinearity*
/
Cladding Nonlinearity:

Will be dominated by nonlinearity of air

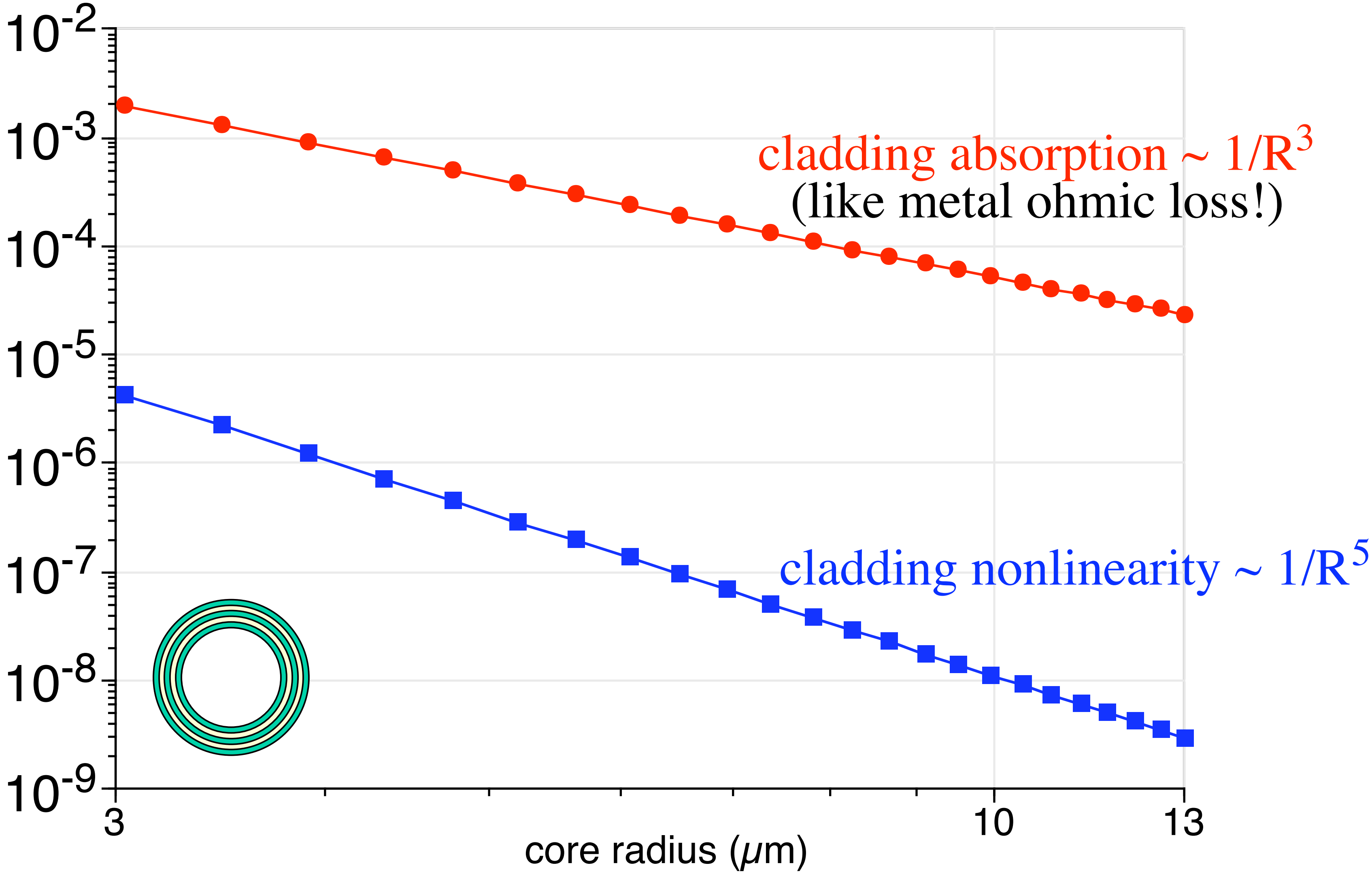
~10,000 times weaker nonlinearity than silica

(including factor of 10 in area)



* "nonlinearity" = $\square\square^{(1)} / P$

Absorption & Nonlinearity Scaling

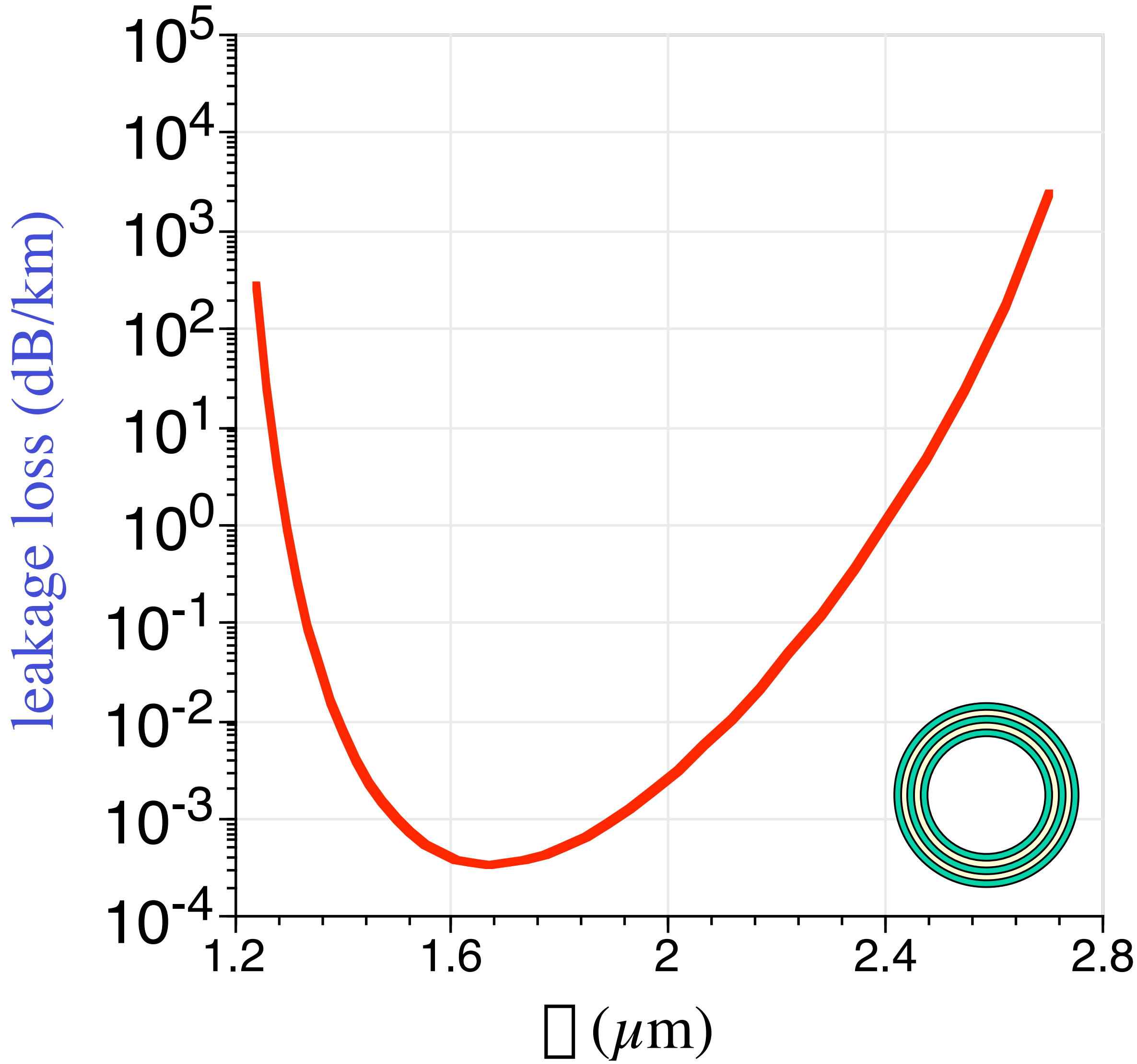


Radiation Leakage Loss (17 layers)

Finite # layers:
modes are "leaky"

loss decreases exponentially with number of layers

(~ $1/R^3$)



Other Losses

Acircularity & Bending

main effect is coupling to lossier modes,
but can be ~ 0.01 dB/km with enough (~50) layers

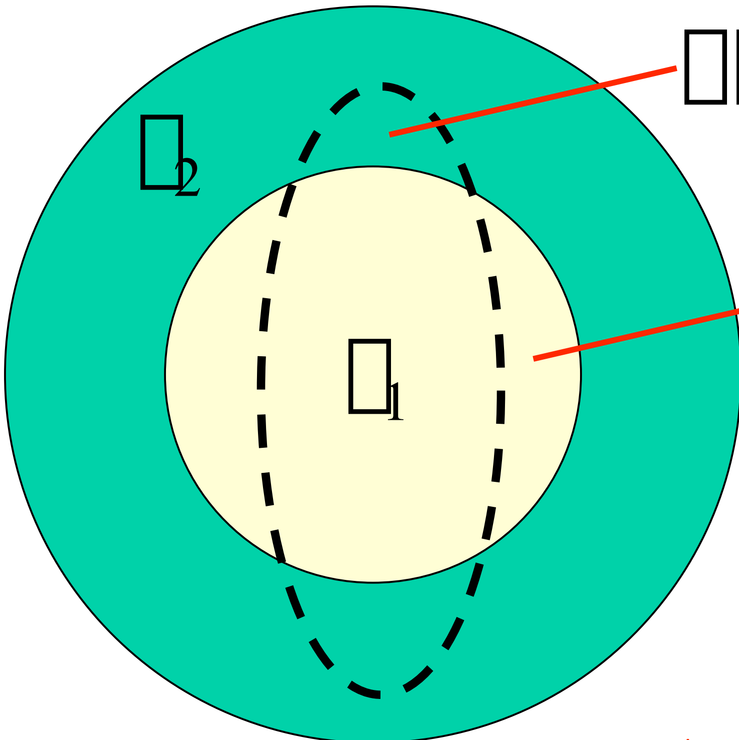
tricky

Surface Roughness

suppressed like absorption

Acircularity & Perturbation Theory

(or any shifting-boundary problem)



$\Delta\varepsilon = \varepsilon_1 - \varepsilon_2$

$\Delta\varepsilon = \varepsilon_2 - \varepsilon_1$

… just plug $\Delta\varepsilon$'s into perturbation formulas?

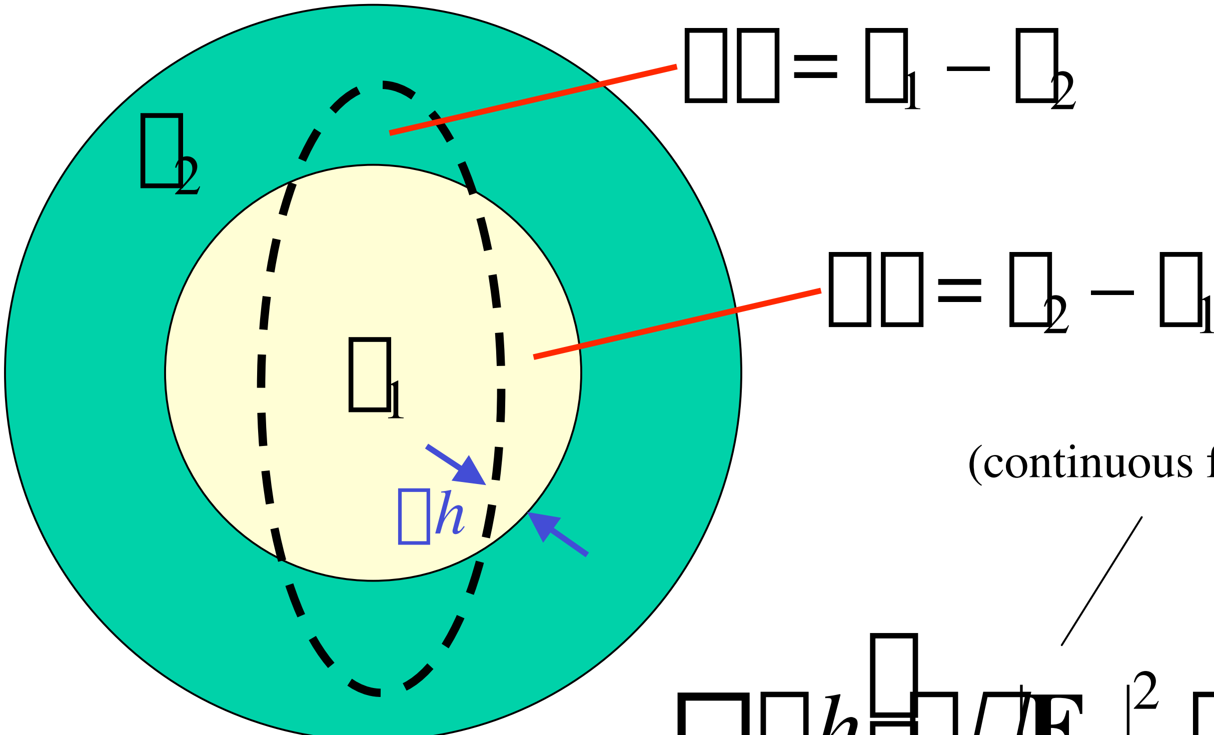
FAILS for high index contrast!

beware field discontinuity…
fortunately, a simple correction exists

[S. G. Johnson *et al.*, *PRE* **65**, 066611 (2002)]

Acircularity & Perturbation Theory

(or any shifting-boundary problem)



(continuous field components)

$$\Delta\omega^{(1)} = -\frac{\omega}{2}\,\frac{\oint_{\text{surf.}} \Delta h \left[\Delta\varepsilon\,|\mathbf{E}_{\parallel}|^2 - \Delta\!\left(\frac{1}{\varepsilon}\right)|D_{\perp}|^2\right]}{\int \varepsilon\,|\mathbf{E}|^2}$$

[S. G. Johnson *et al.*, *PRE* **65**, 066611 (2002)]

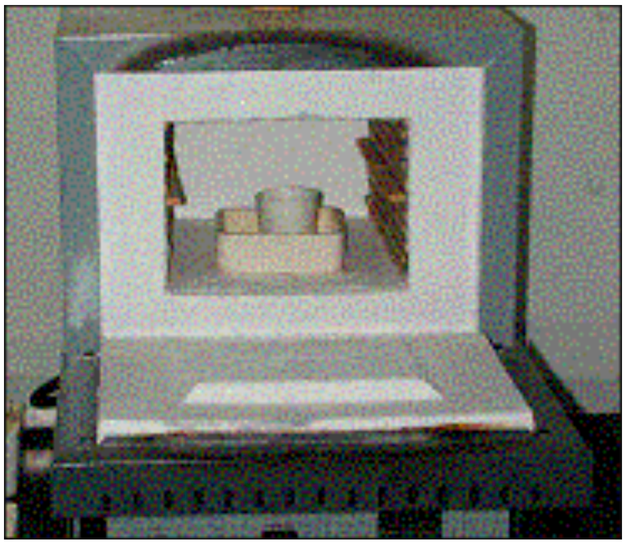
Yes, but how do you make it?

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

1

find compatible materials

(many new possibilities)



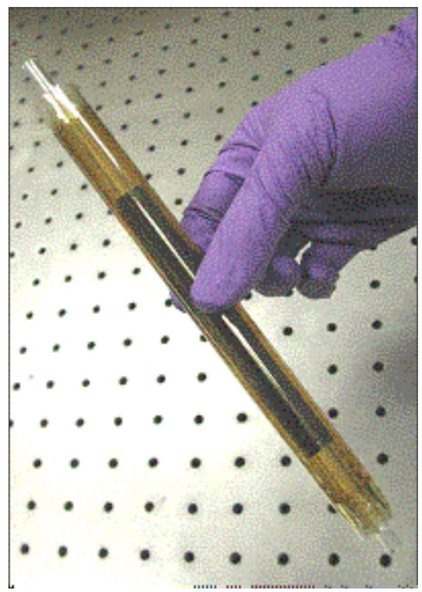
chalcogenide glass, n ~ 2.8

+ polymer (or oxide), n ~ 1.5

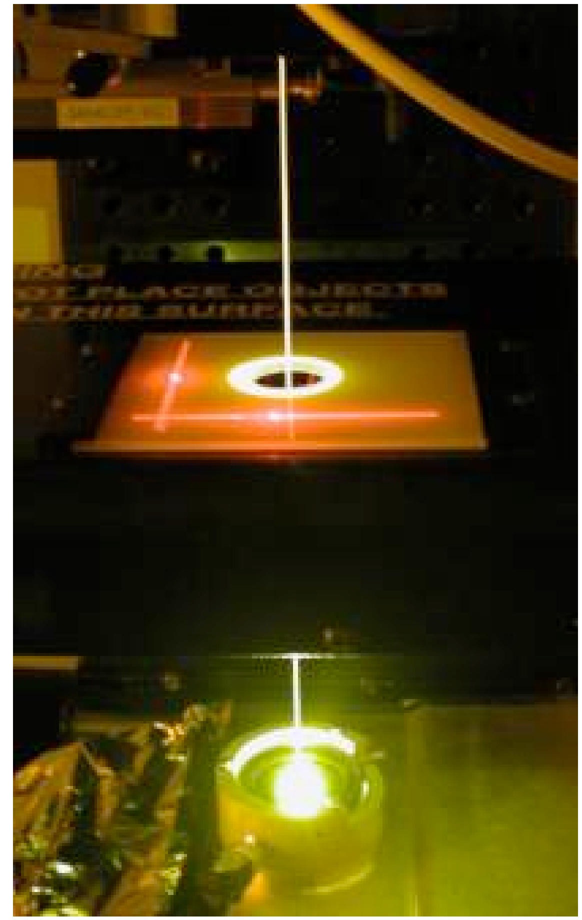
2

Make pre-form

(“scale model”)



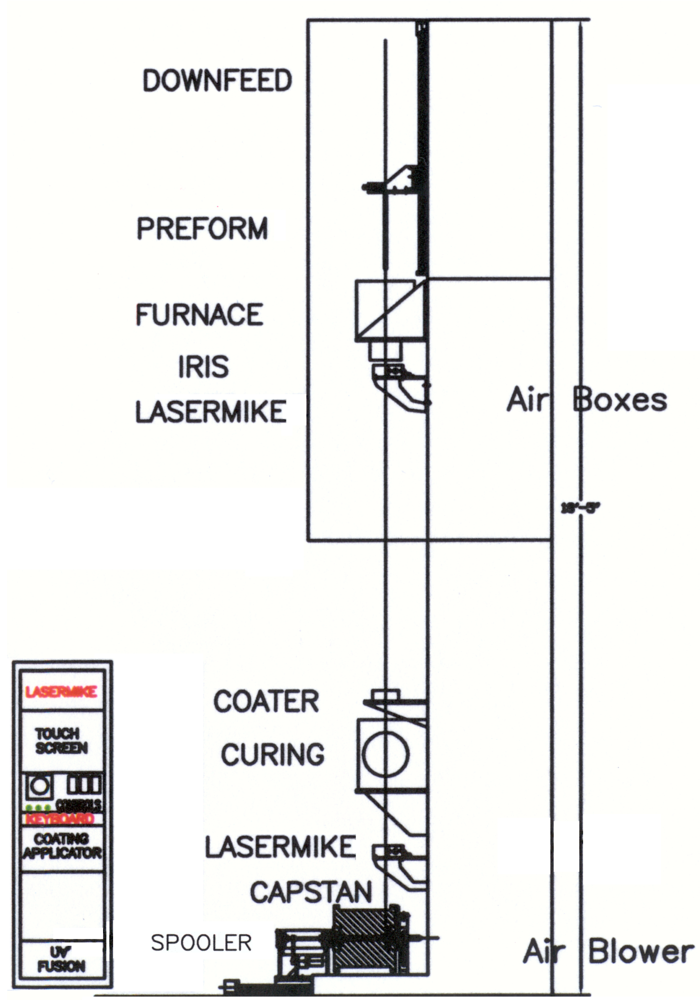
3



fiber drawing

Fiber Draw Tower @ MIT

building 13, constructed 2000–2001



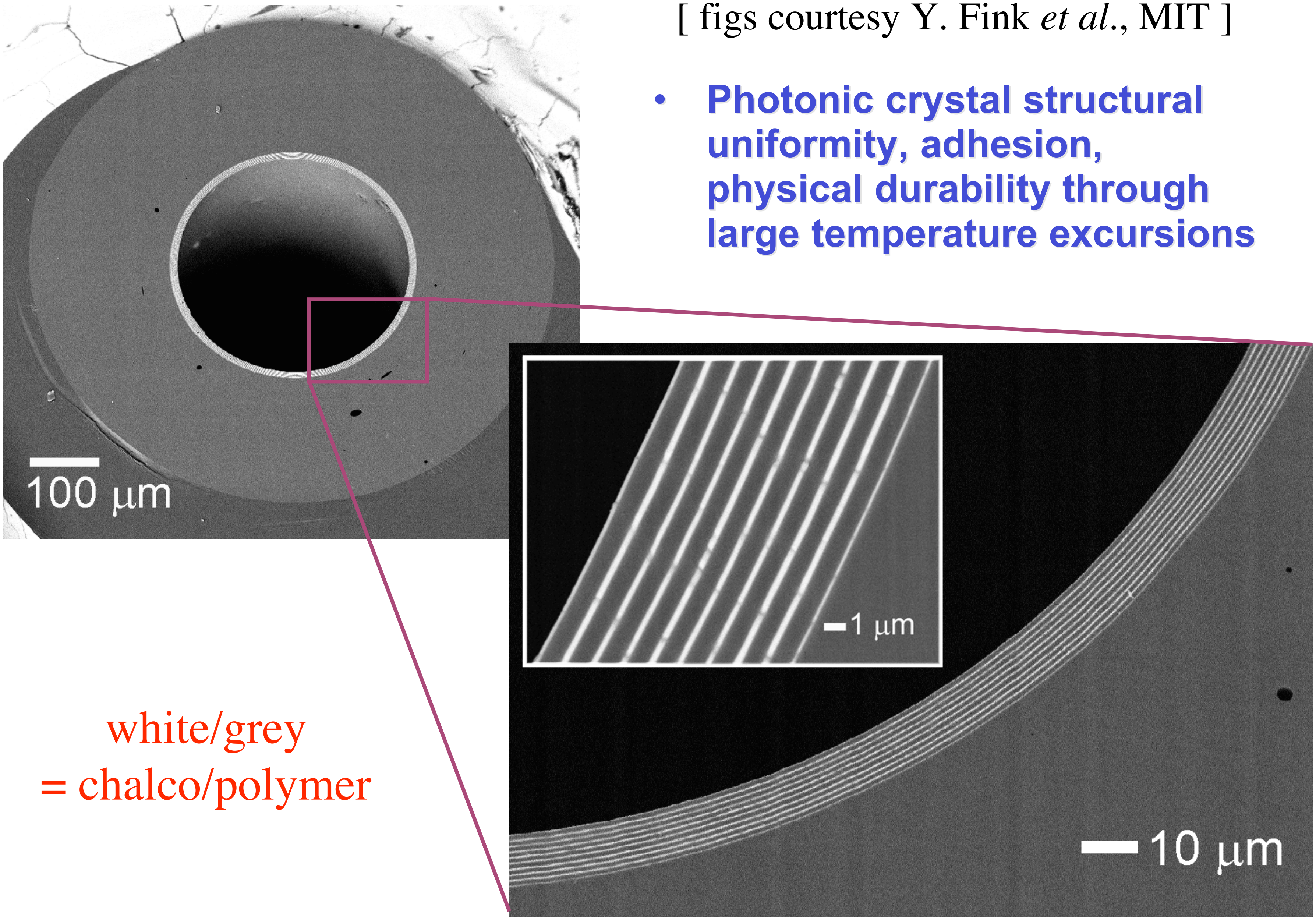
~6 meter (20 feet) research tower

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

A Drawn Bandgap Fiber

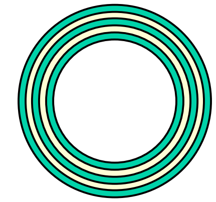
[figs courtesy Y. Fink *et al*., MIT]

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



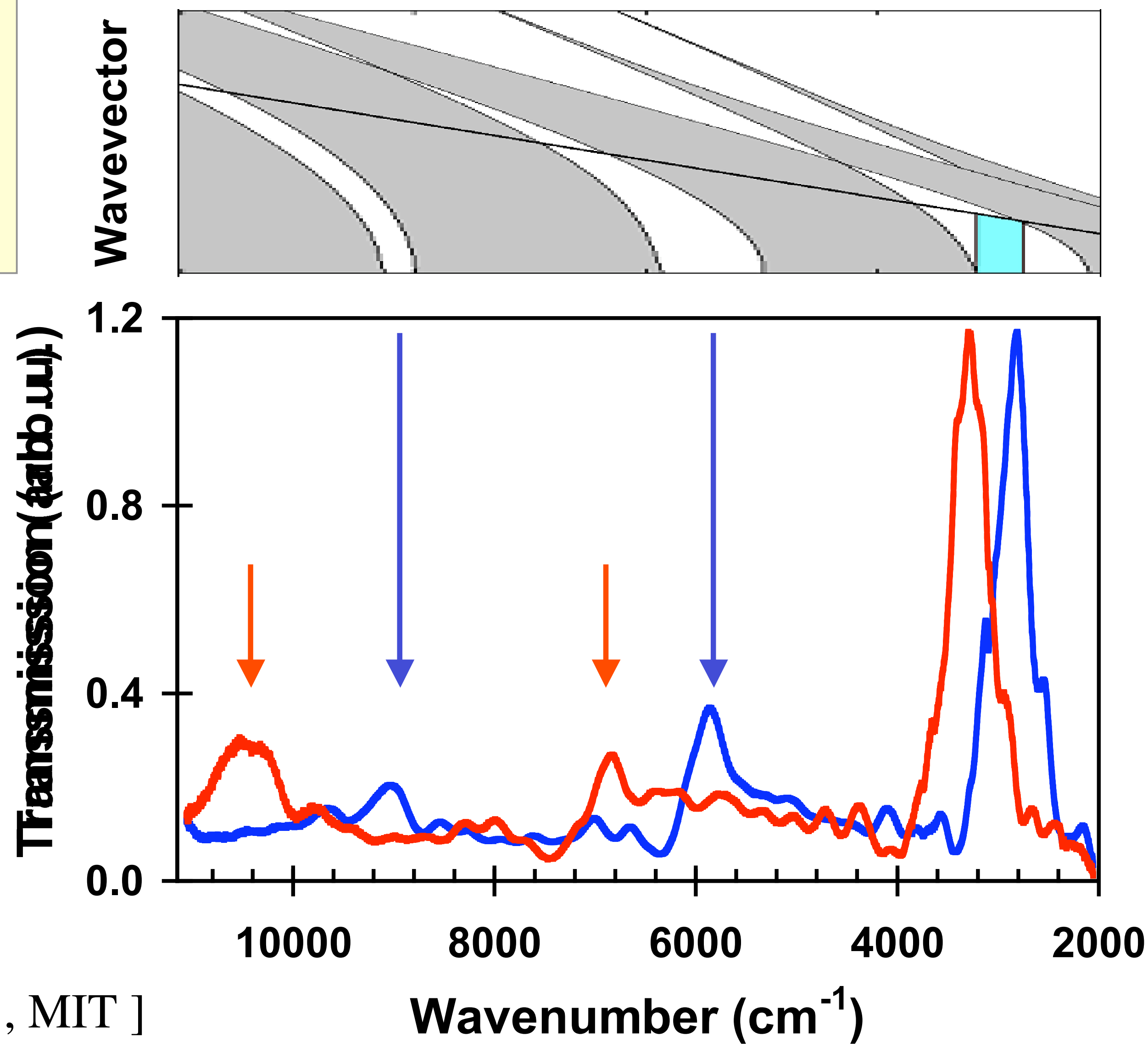
white/grey
= chalco/polymer

Band Gap Guidance



Transmission window can be shifted by scaling (different draw speed)

original (blue) & shifted (red) transmission:



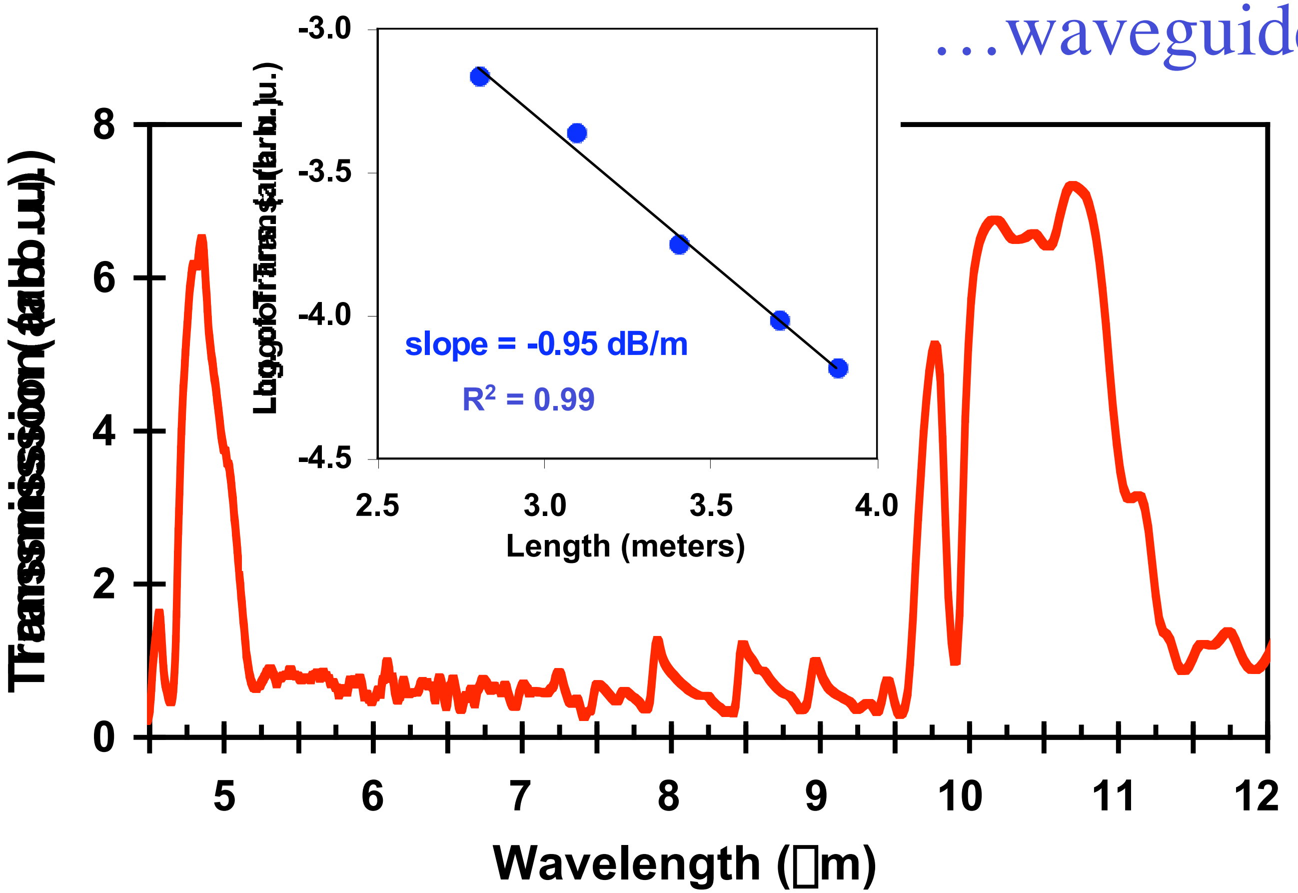
[figs courtesy Y. Fink *et al.*, MIT]

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)]

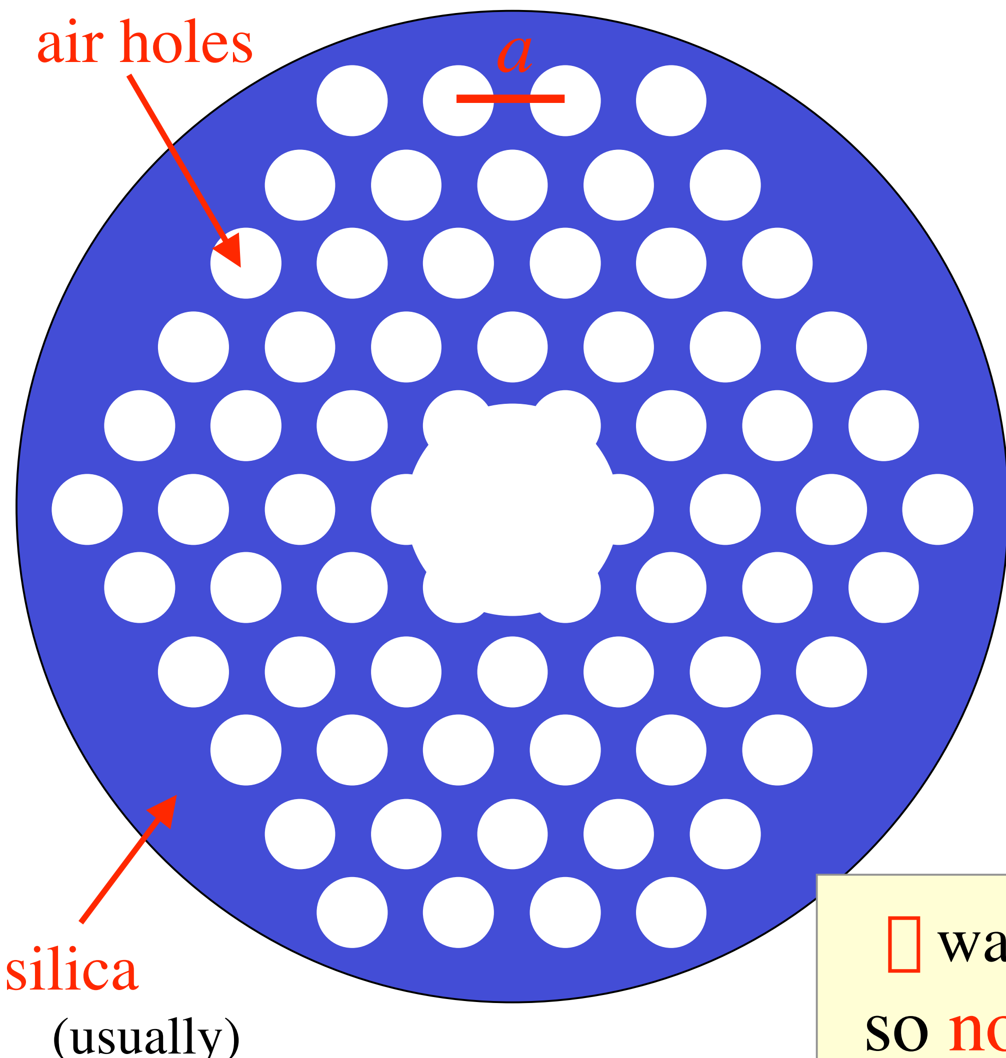
cool movie

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

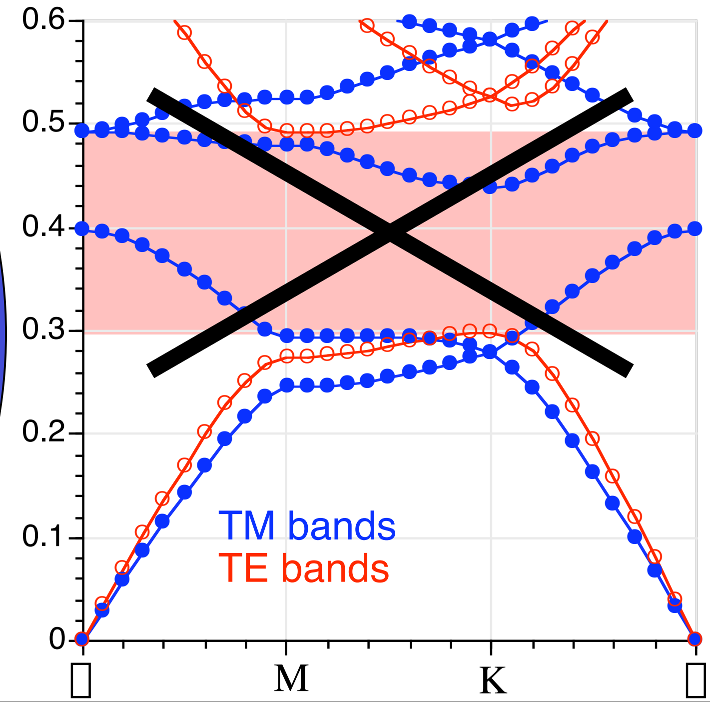
Enough about MIT already…

2d-periodic Photonic-Crystal Fibers

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

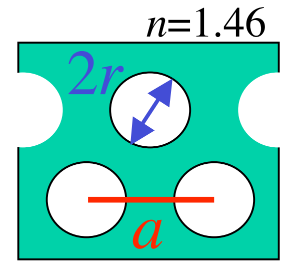


Not guided via
2d TE bandgap:

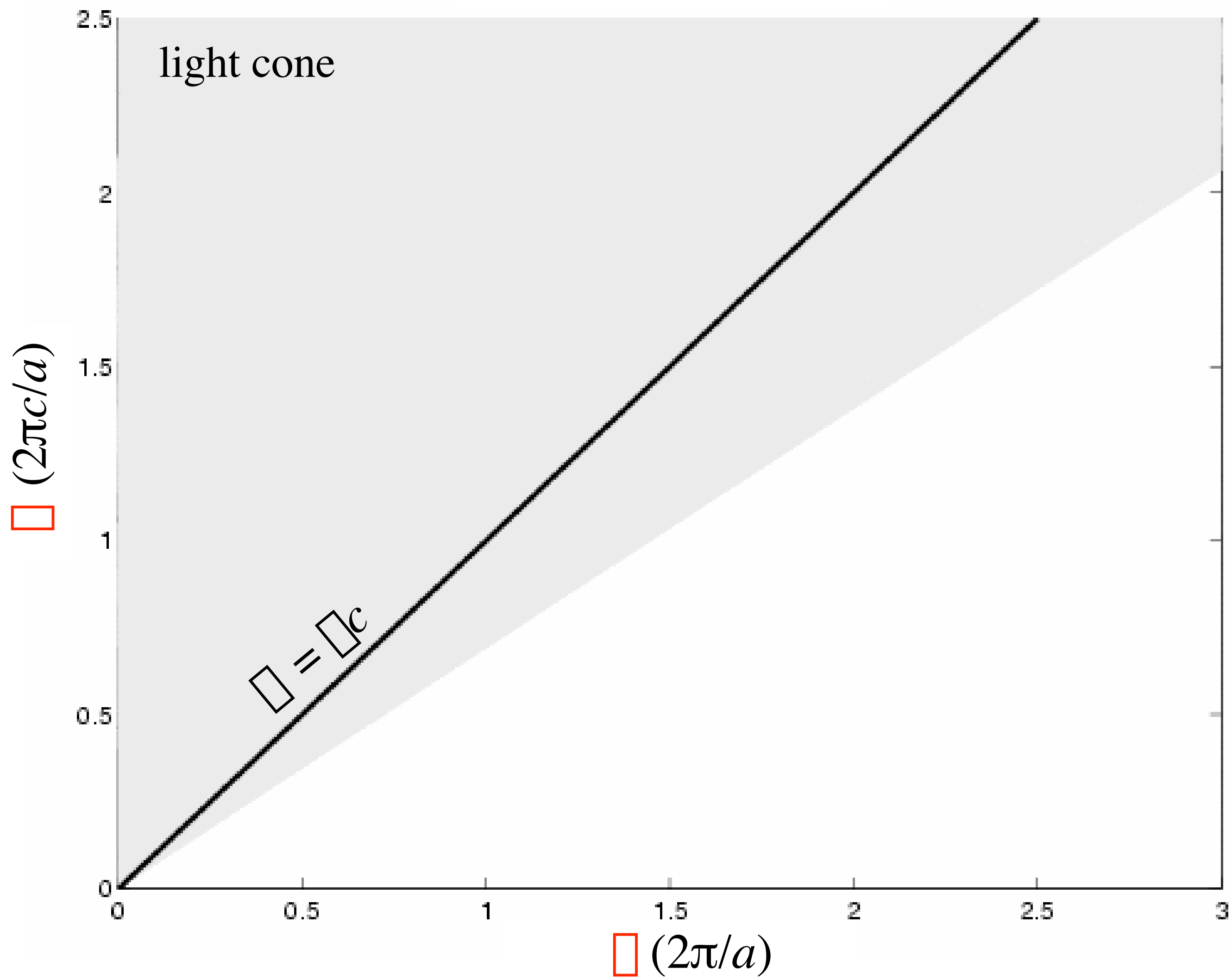


□ wavenumber breaks mirror plane,
so no pure TE/TM polarizations

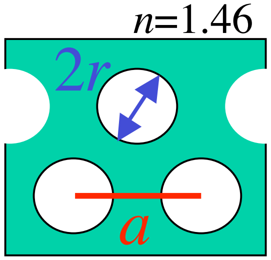
PCF: Holey Silica Cladding



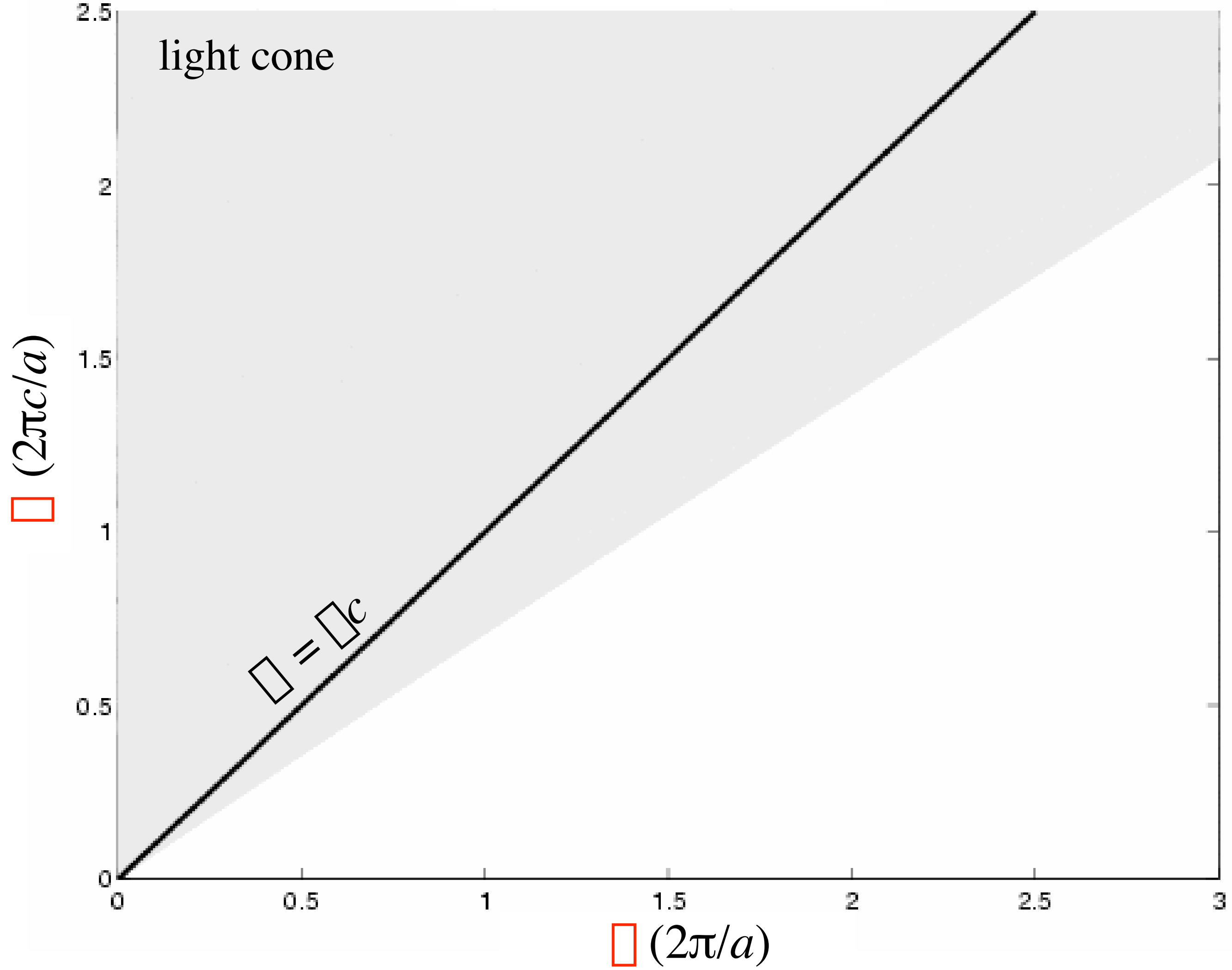
$r = 0.1a$



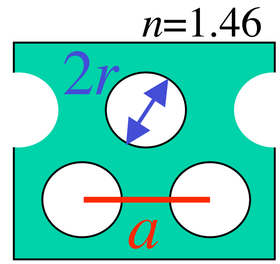
PCF: Holey Silica Cladding



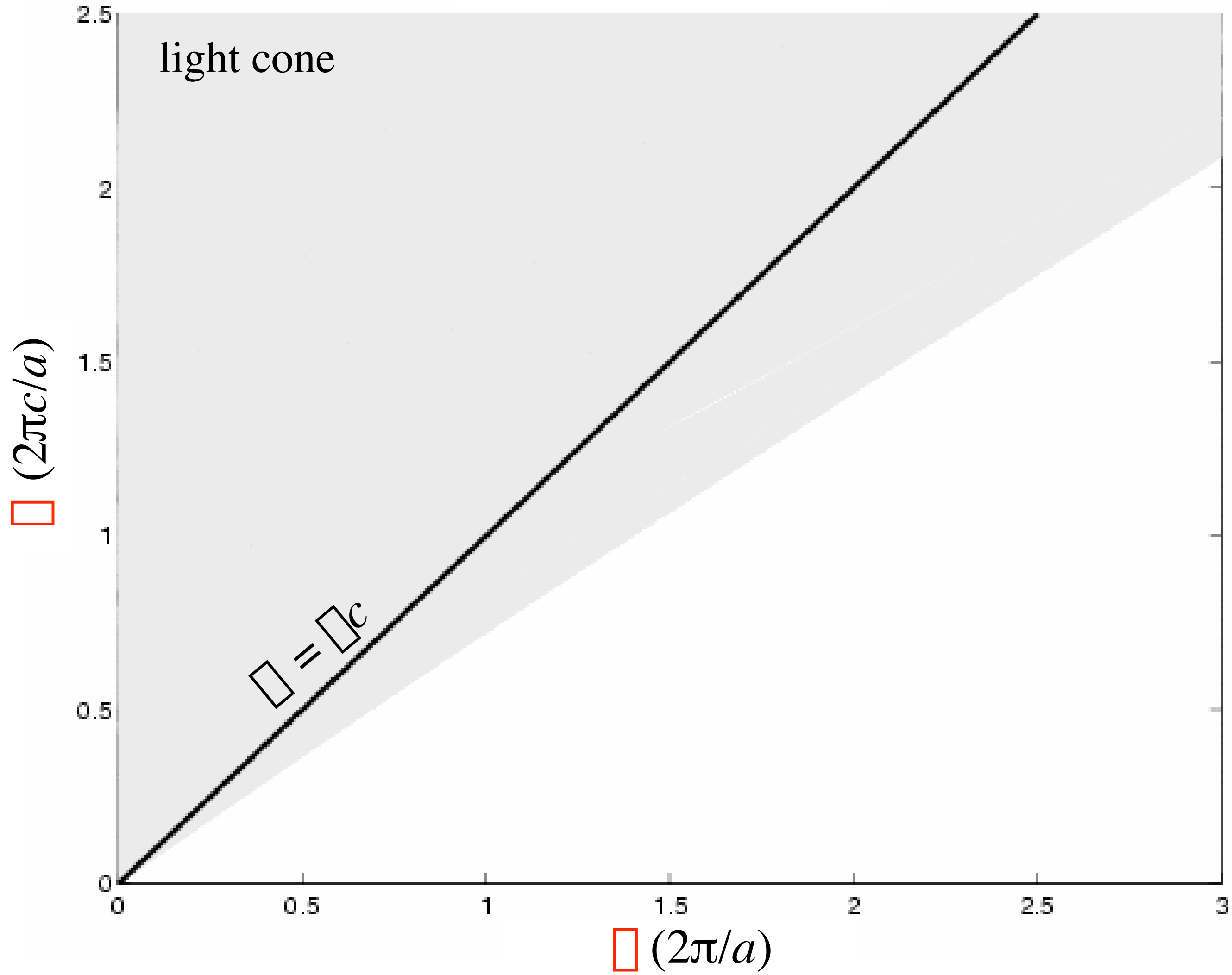
$r = 0.17717a$



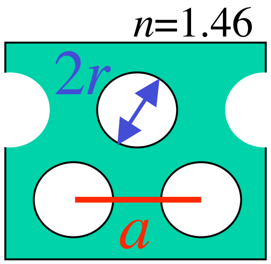
PCF: Holey Silica Cladding



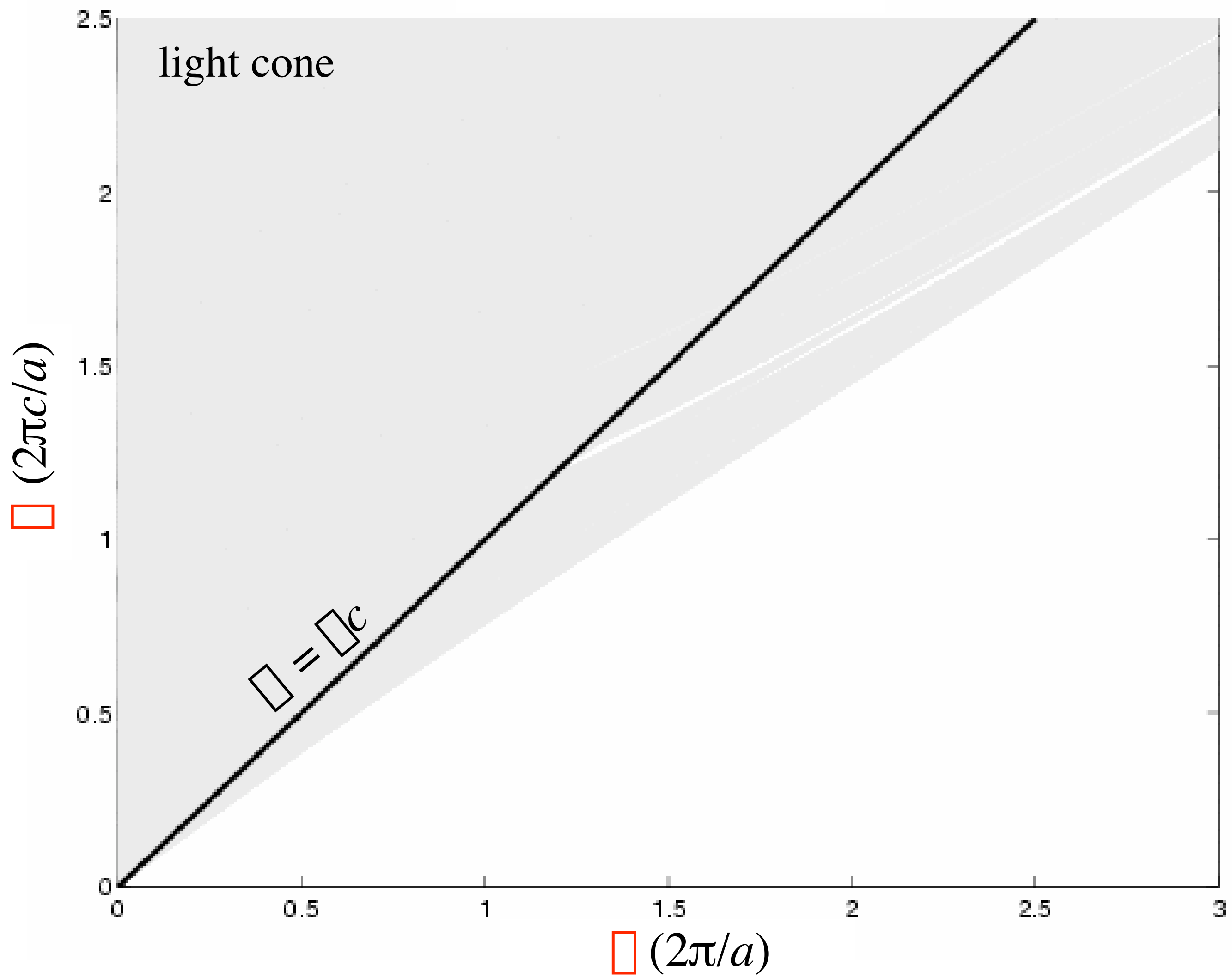
$r = 0.22973a$



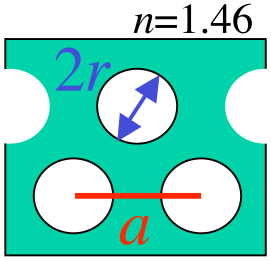
PCF: Holey Silica Cladding



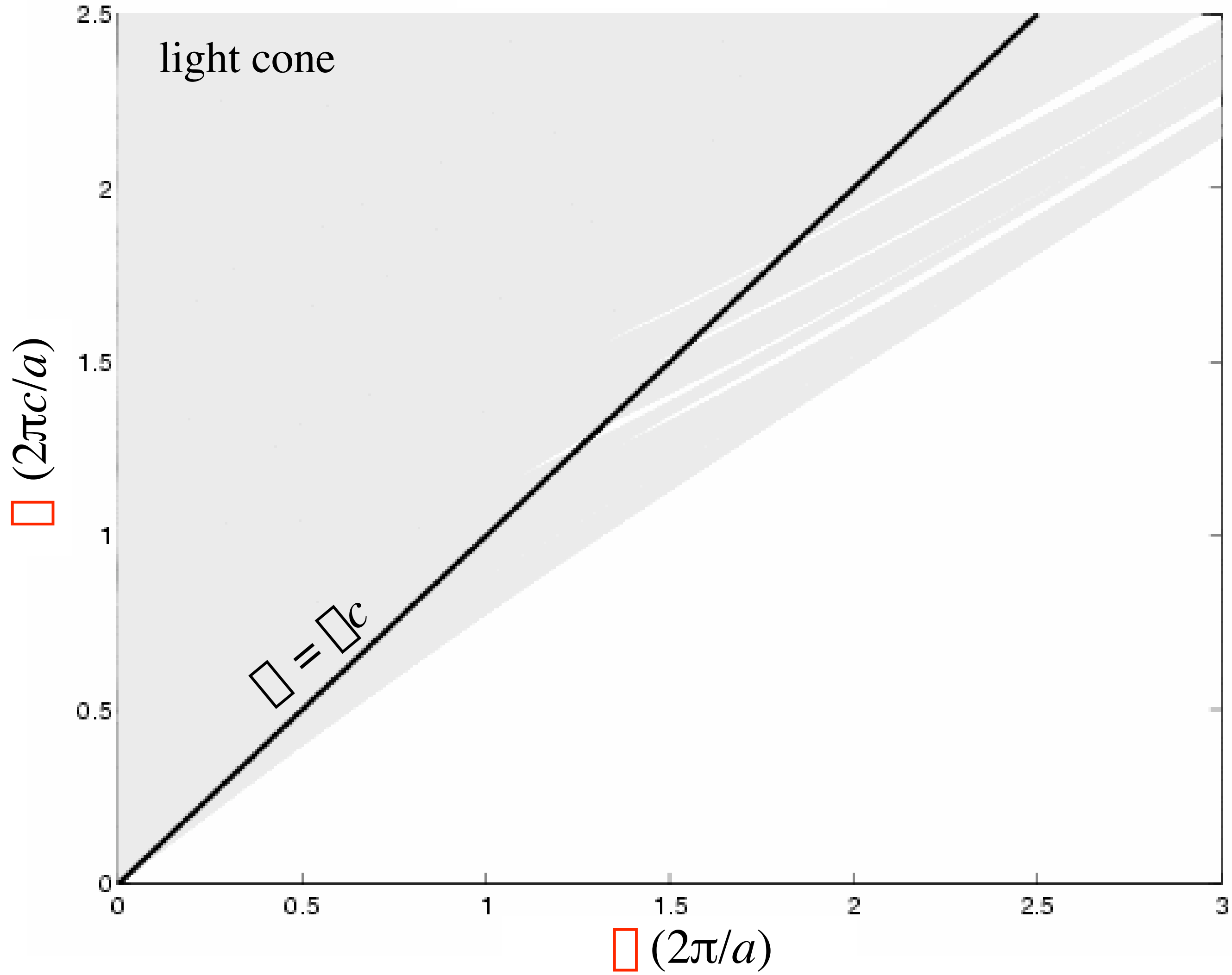
$r = 0.30912a$



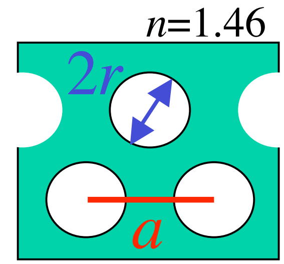
PCF: Holey Silica Cladding



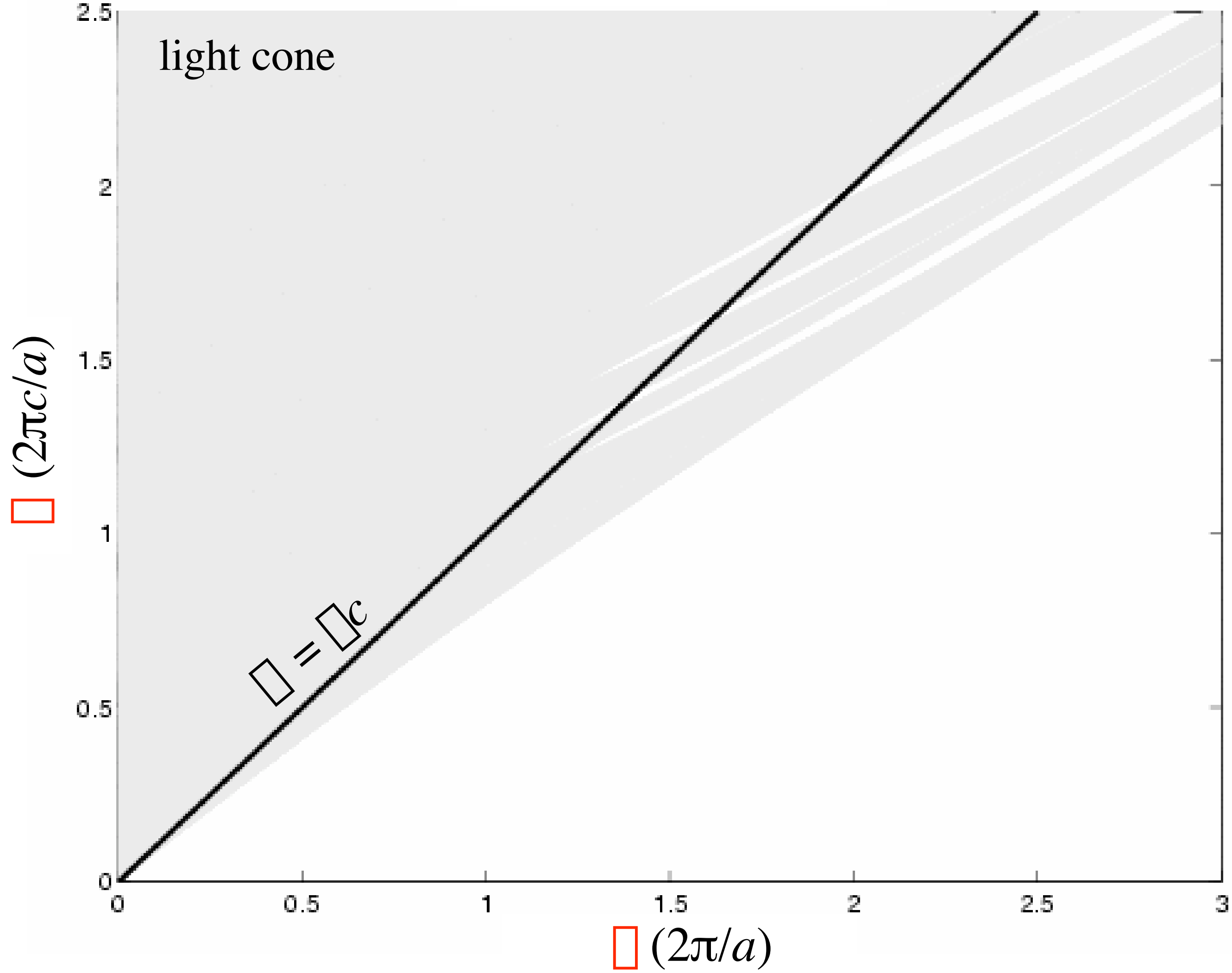
$r = 0.34197a$



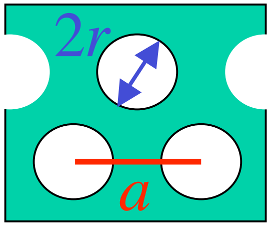
PCF: Holey Silica Cladding



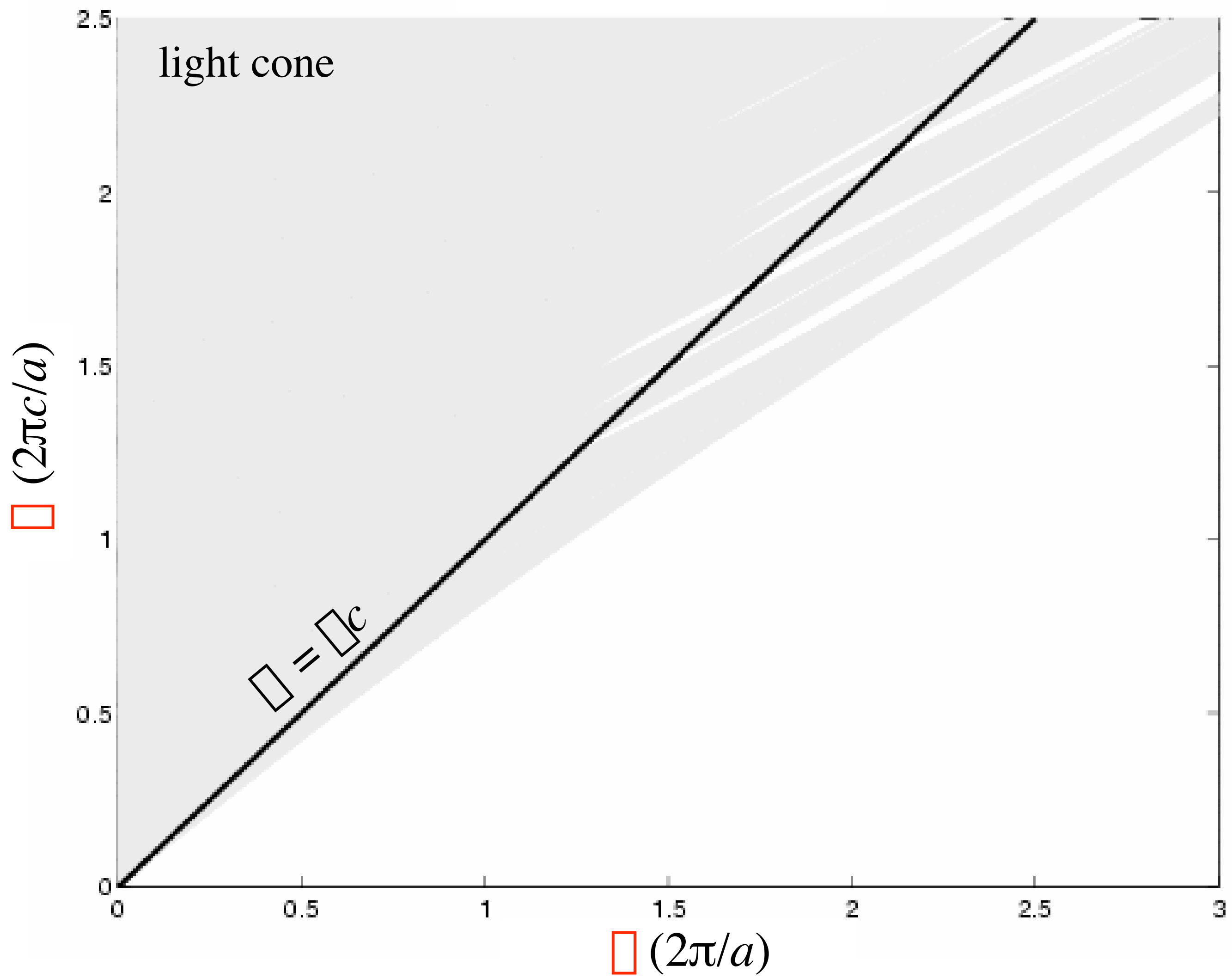
$r = 0.37193a$



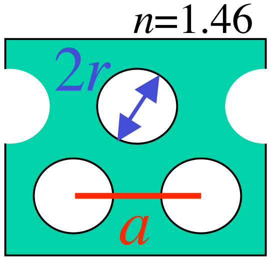
PCF: Holey Silica Cladding



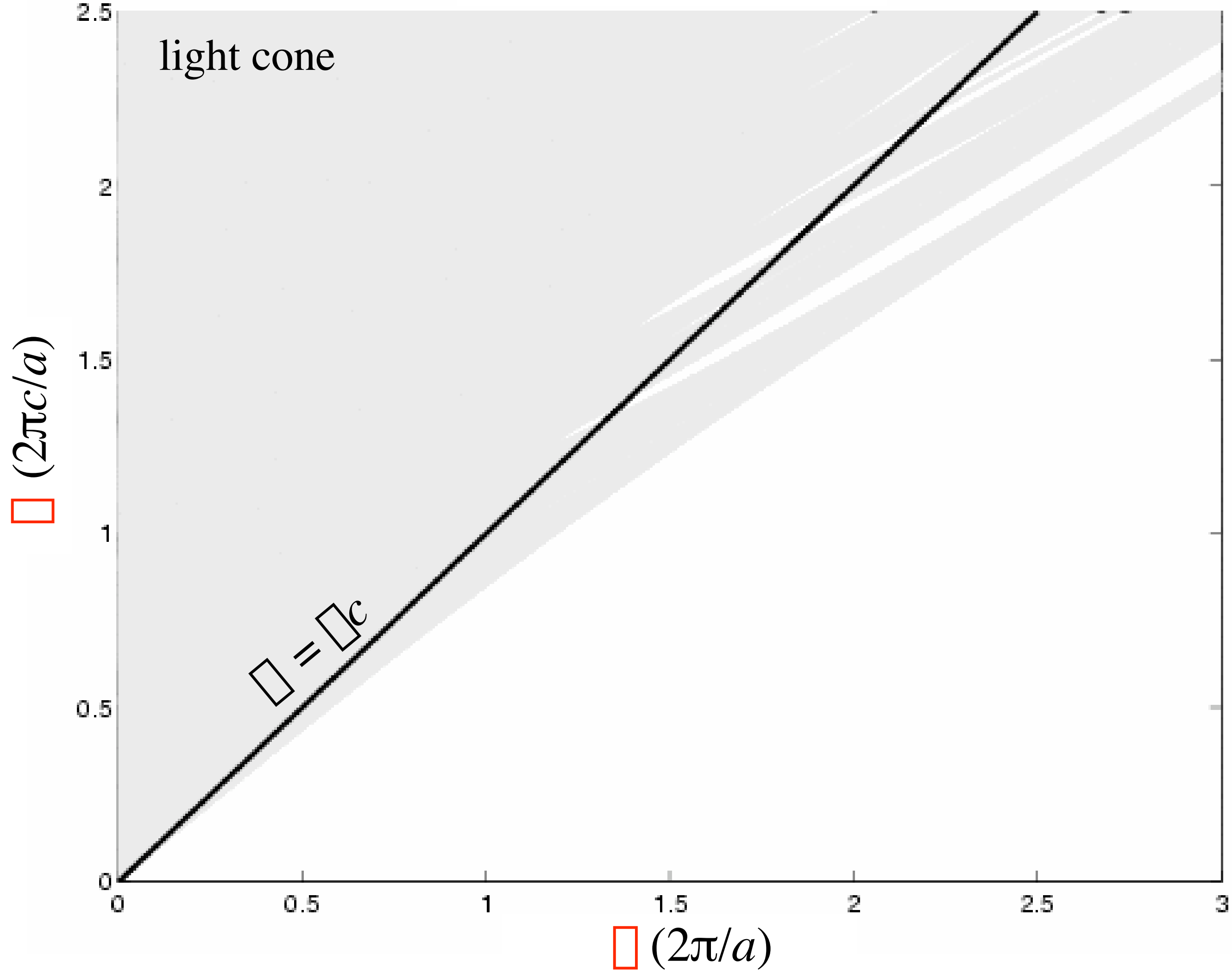
$r = 0.4a$



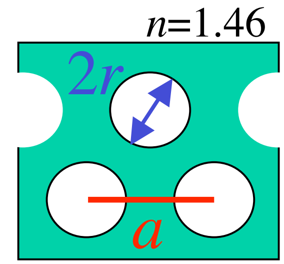
PCF: Holey Silica Cladding



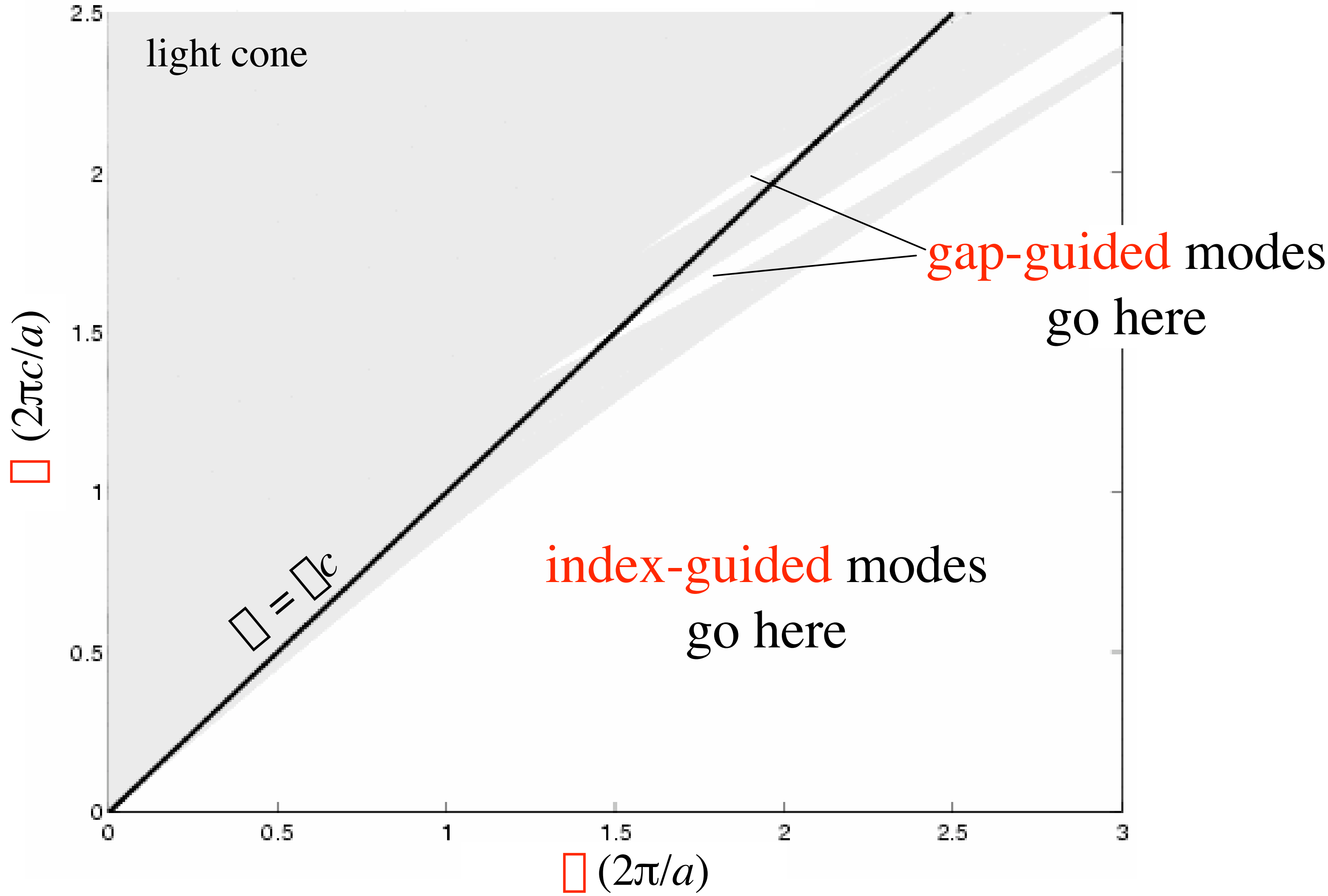
$r = 0.42557a$



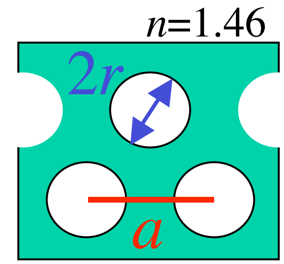
PCF: Holey Silica Cladding



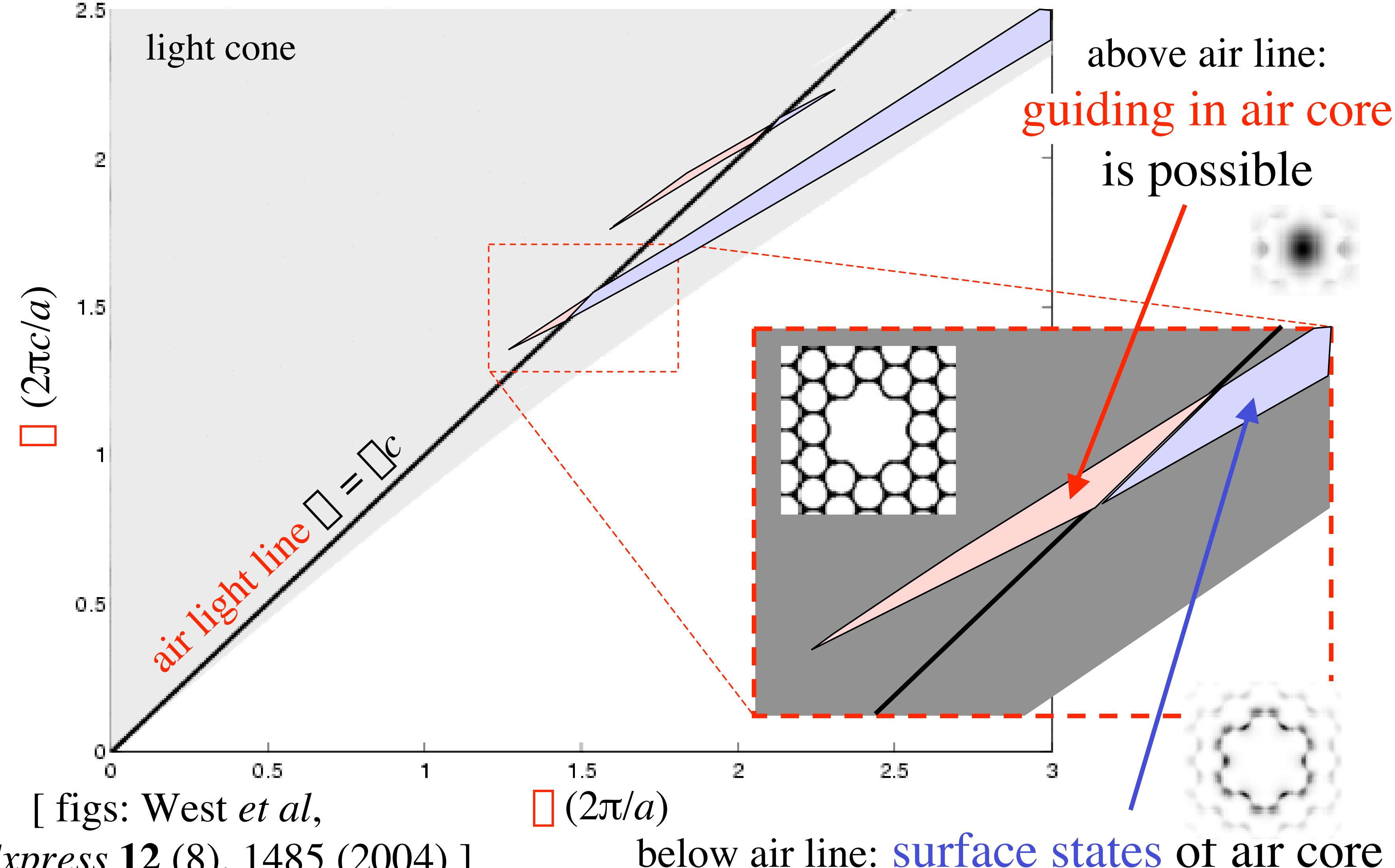
$r = 0.45a$



PCF: Holey Silica Cladding



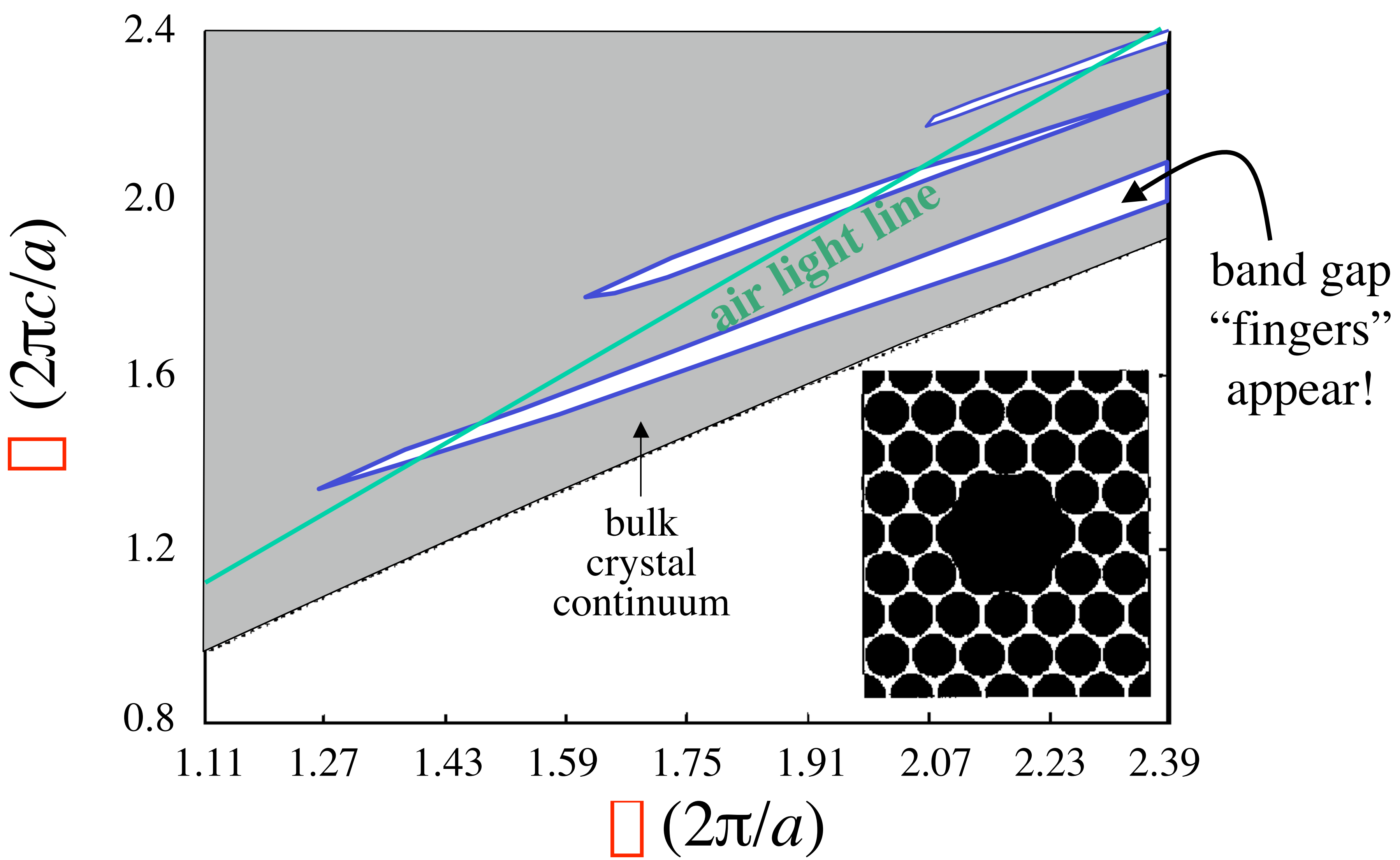
$r = 0.45a$



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

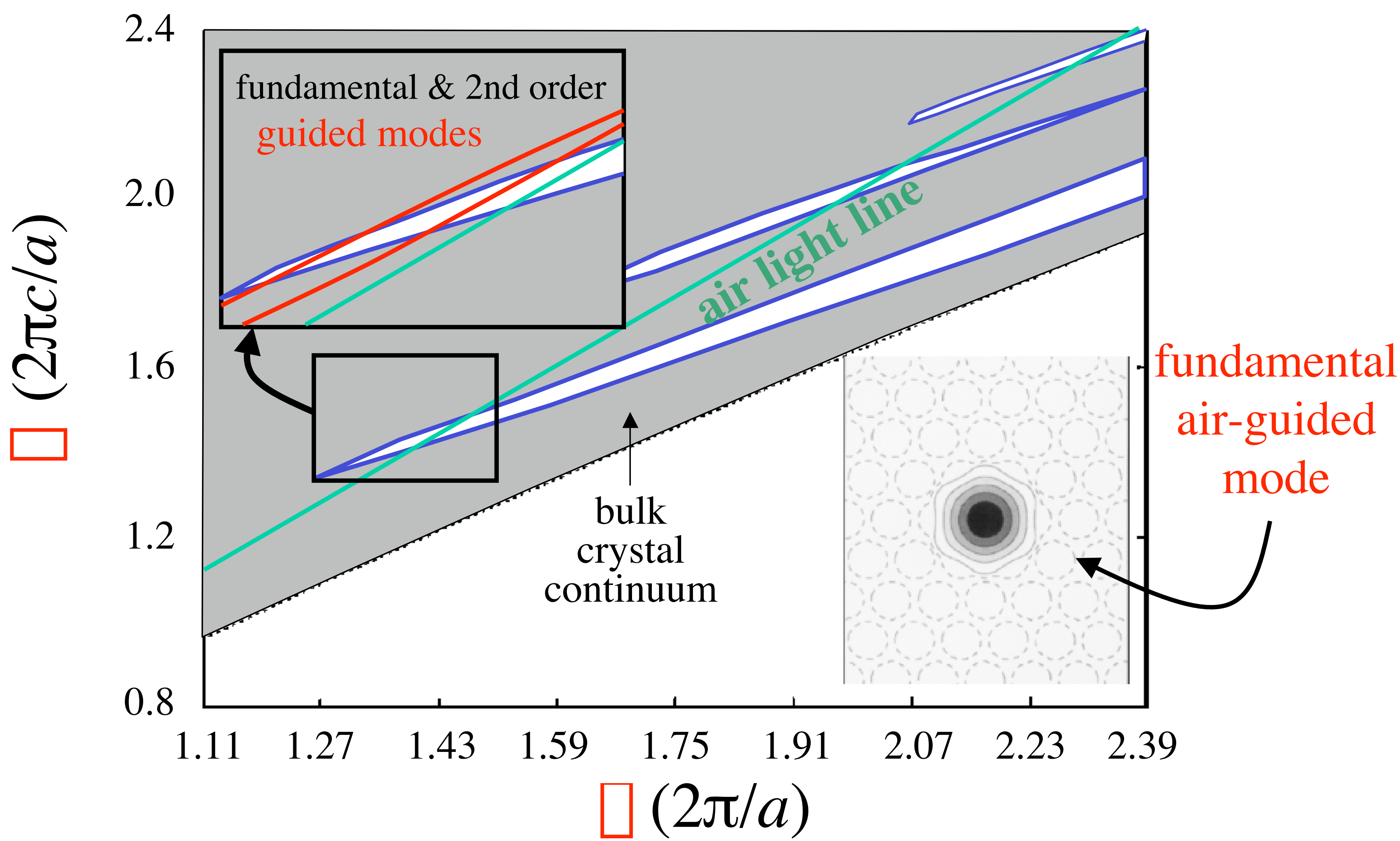
PCF Projected Bands

[J. Broeng *et al.*, *Opt. Lett.* **25**, 96 (2000)]

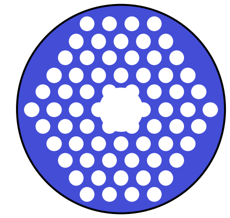


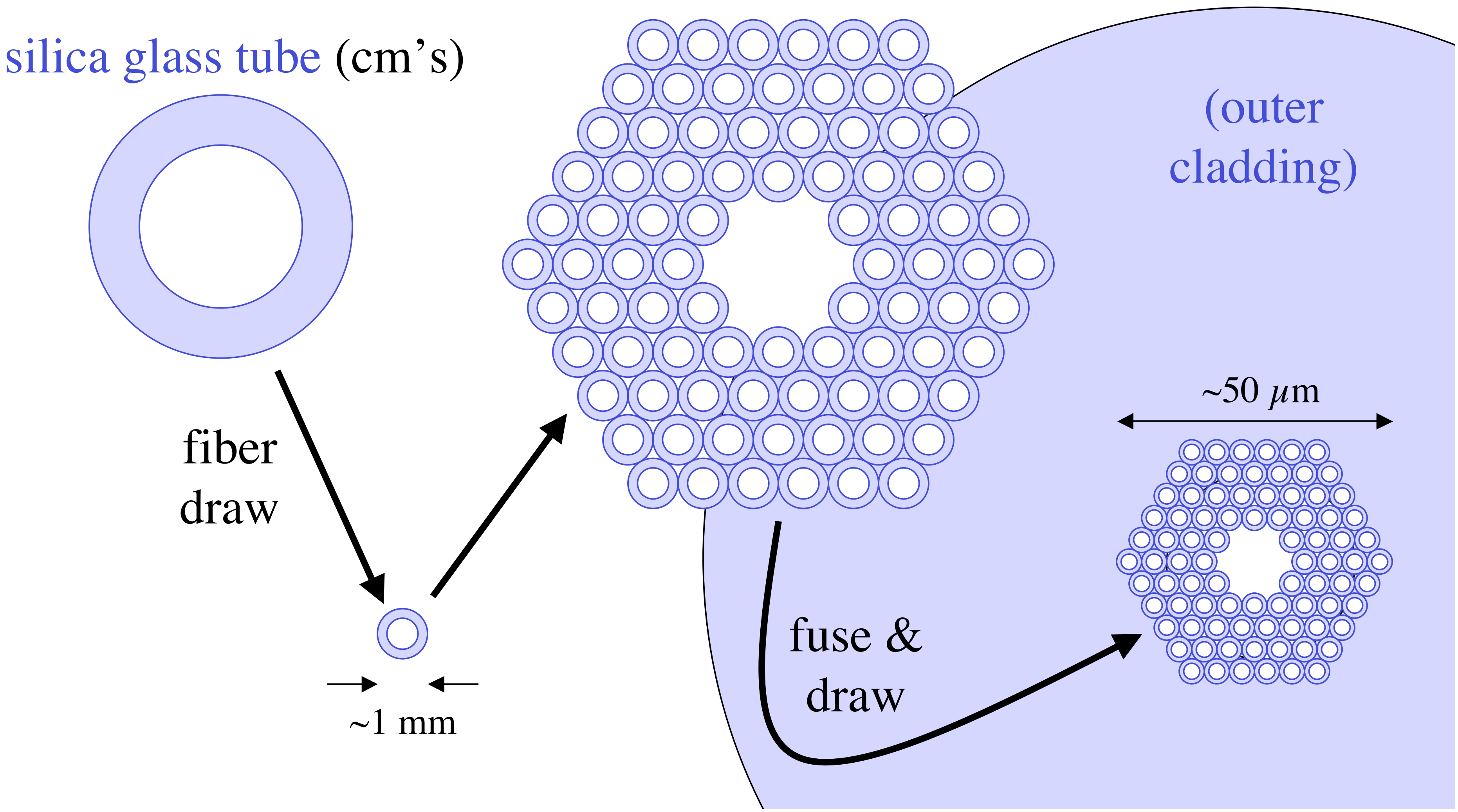
PCF Guided Mode(s)

[J. Broeng *et al.*, *Opt. Lett.* **25**, 96 (2000)]

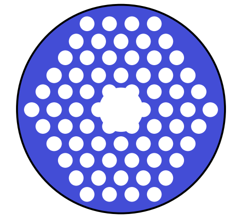


Experimental Air-guiding PCF
Fabrication (e.g.)

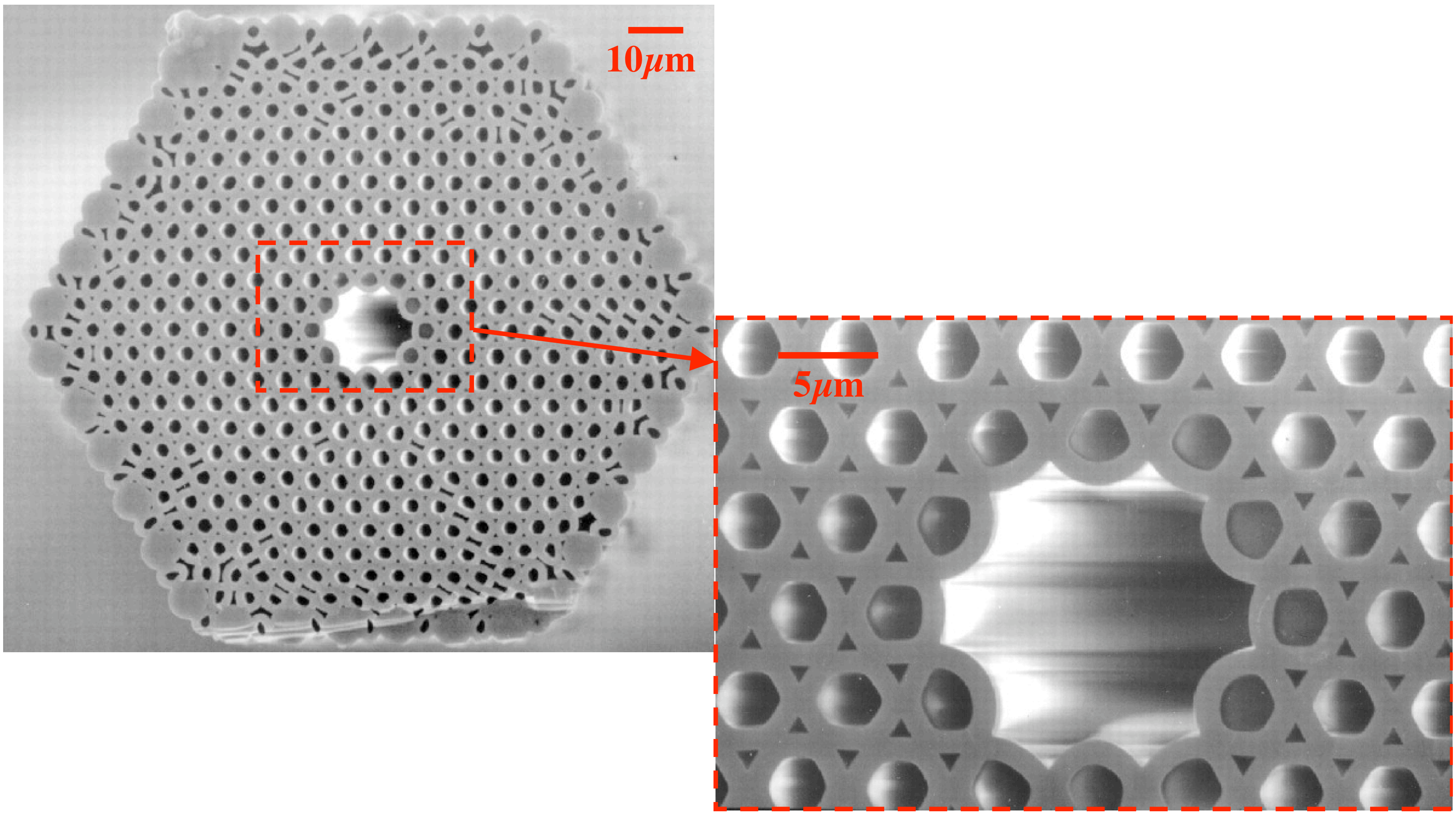




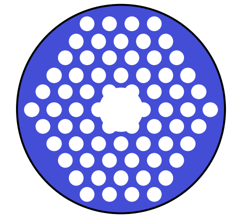
Experimental Air-guiding PCF



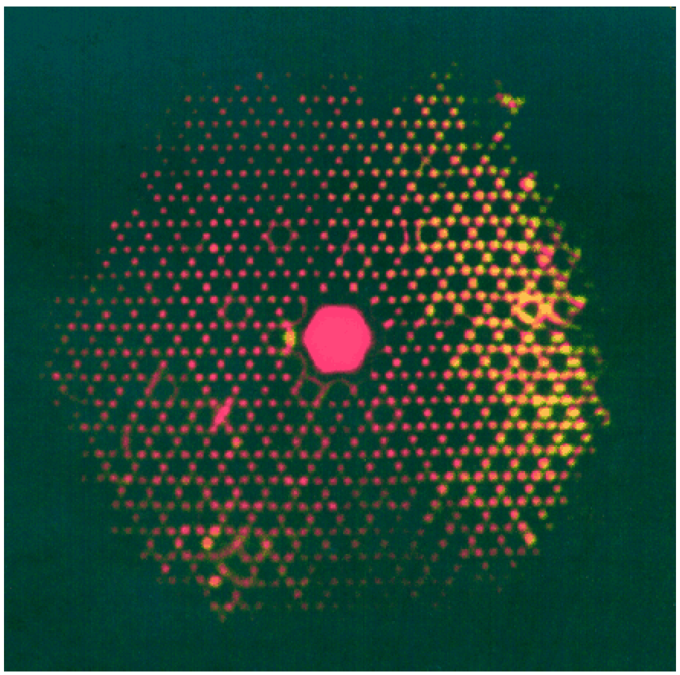
[R. F. Cregan *et al.*, *Science* **285**, 1537 (1999)]



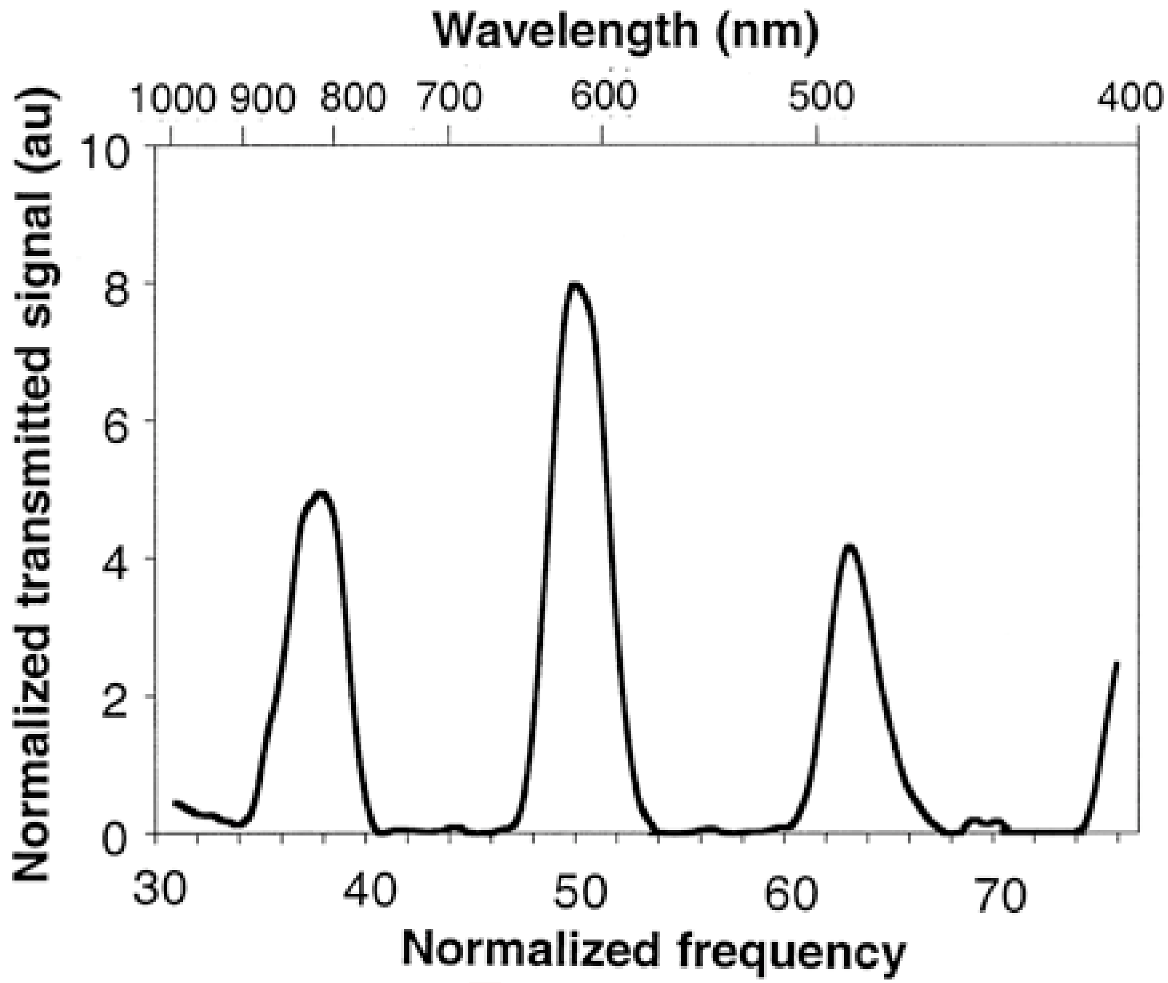
Experimental Air-guiding PCF



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



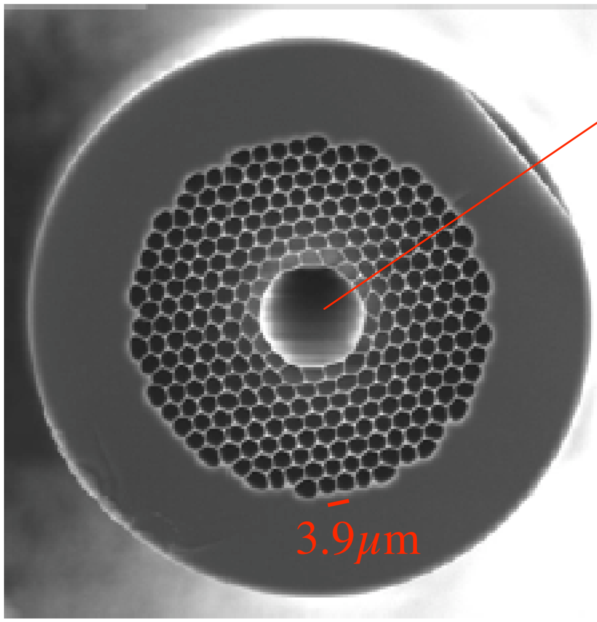
transmitted intensity
after ~ 3cm



(c/a) (**not** $2\pi c/a$)

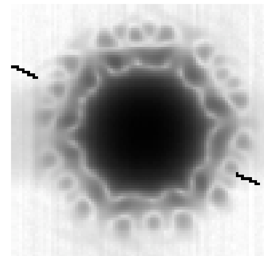
State-of-the-art air-guiding losses

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



hollow (air) core (covers 19 holes)

guided field profile:
(flux density)

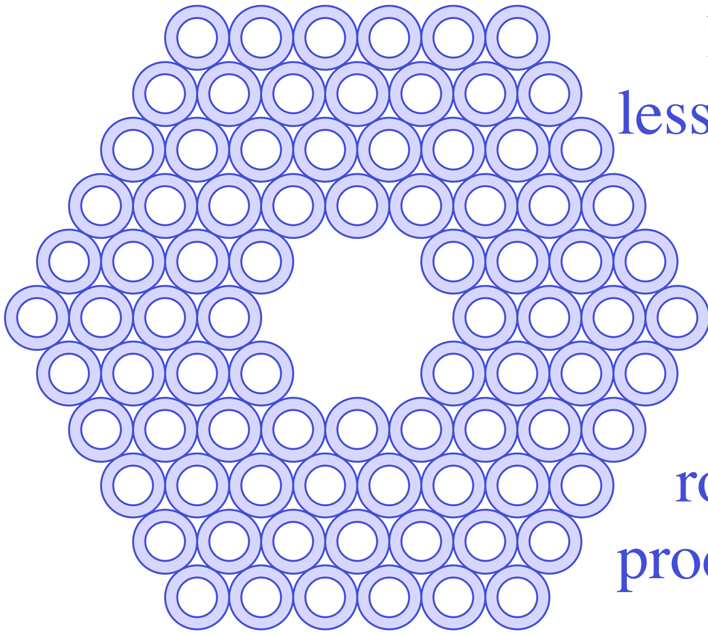


1.7dB/km

BlazePhotonics

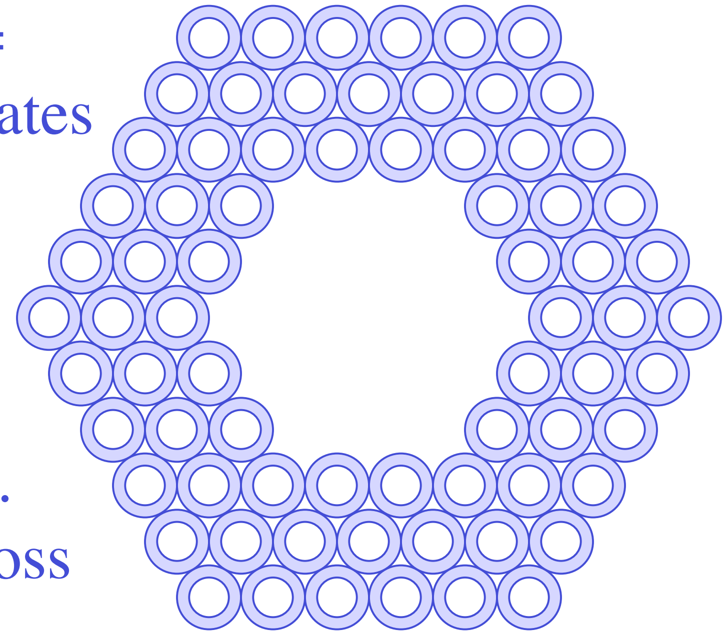
over ~ 800m @1.57μm

State-of-the-art air-guiding losses



larger core =
less field penetrates
cladding

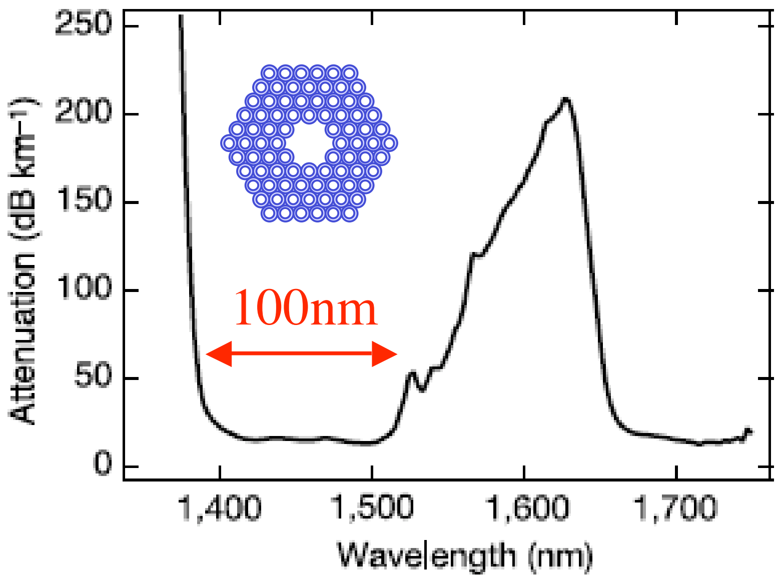
ergo,
roughness etc.
produce lower loss

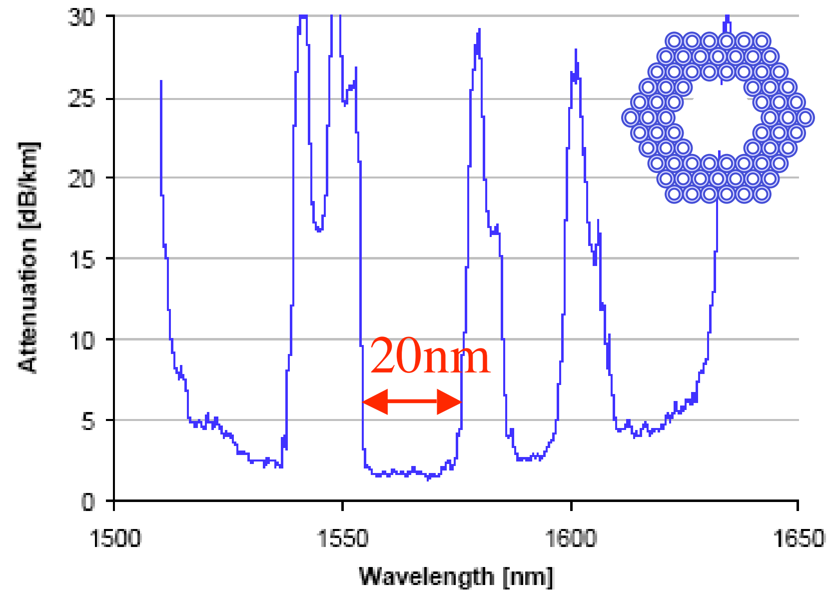


13dB/km	1.7dB/km
Corning	BlazePhotonics
over ~ 100m @1.5μm	over ~ 800m @1.57μm
[Smith, *et al.*, *Nature* **424**, 657 (2003)]	[Mangan, *et al.*, *OFC 2004* PDP24]

State-of-the-art air-guiding losses

larger core = more surface states crossing guided mode





13dB/km

Corning

over ~ 100m @1.5μm

[Smith, *et al.*, *Nature* **424**, 657 (2003)]

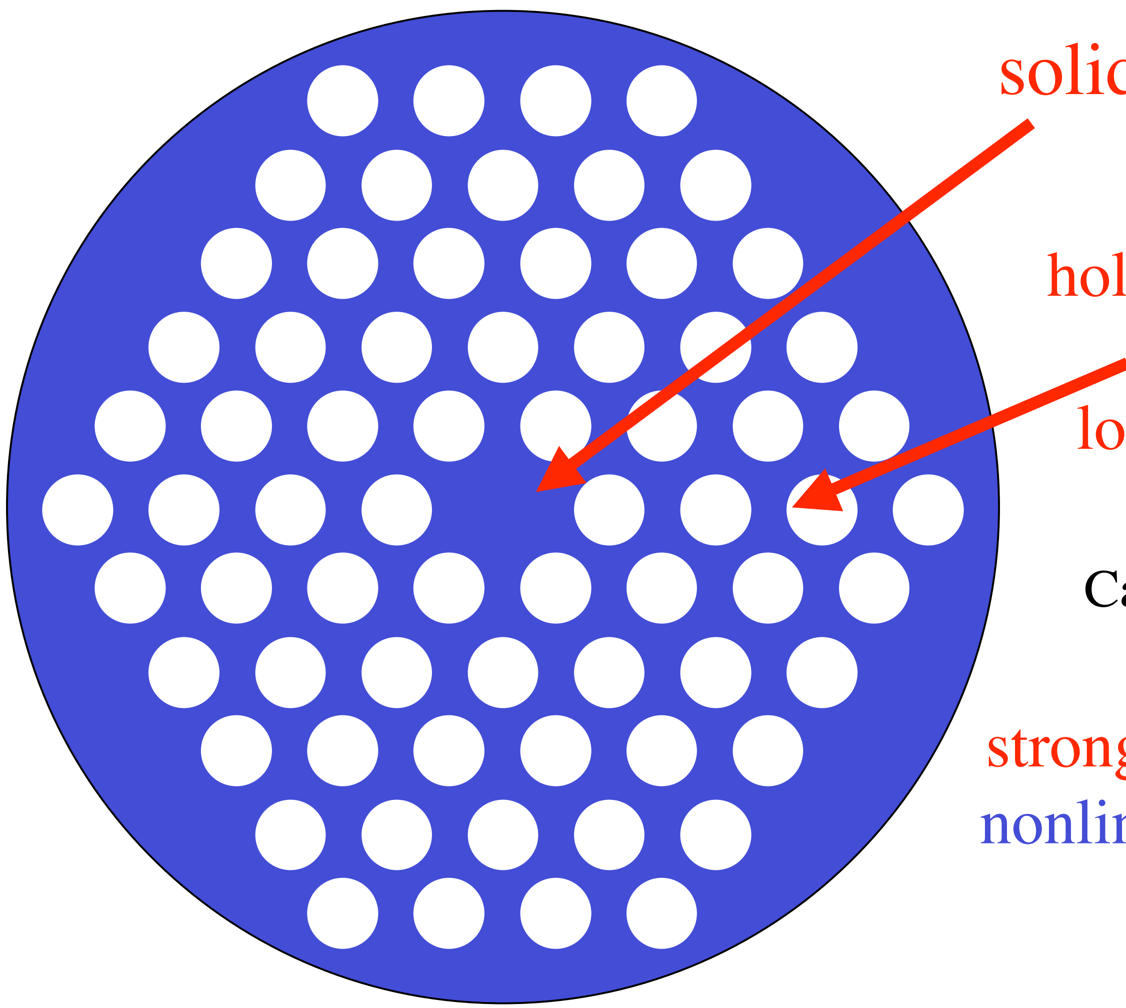
1.7dB/km

BlazePhotonics

over ~ 800m @1.57μm

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

Index-Guiding PCF & microstructured fiber:
Holey Fibers



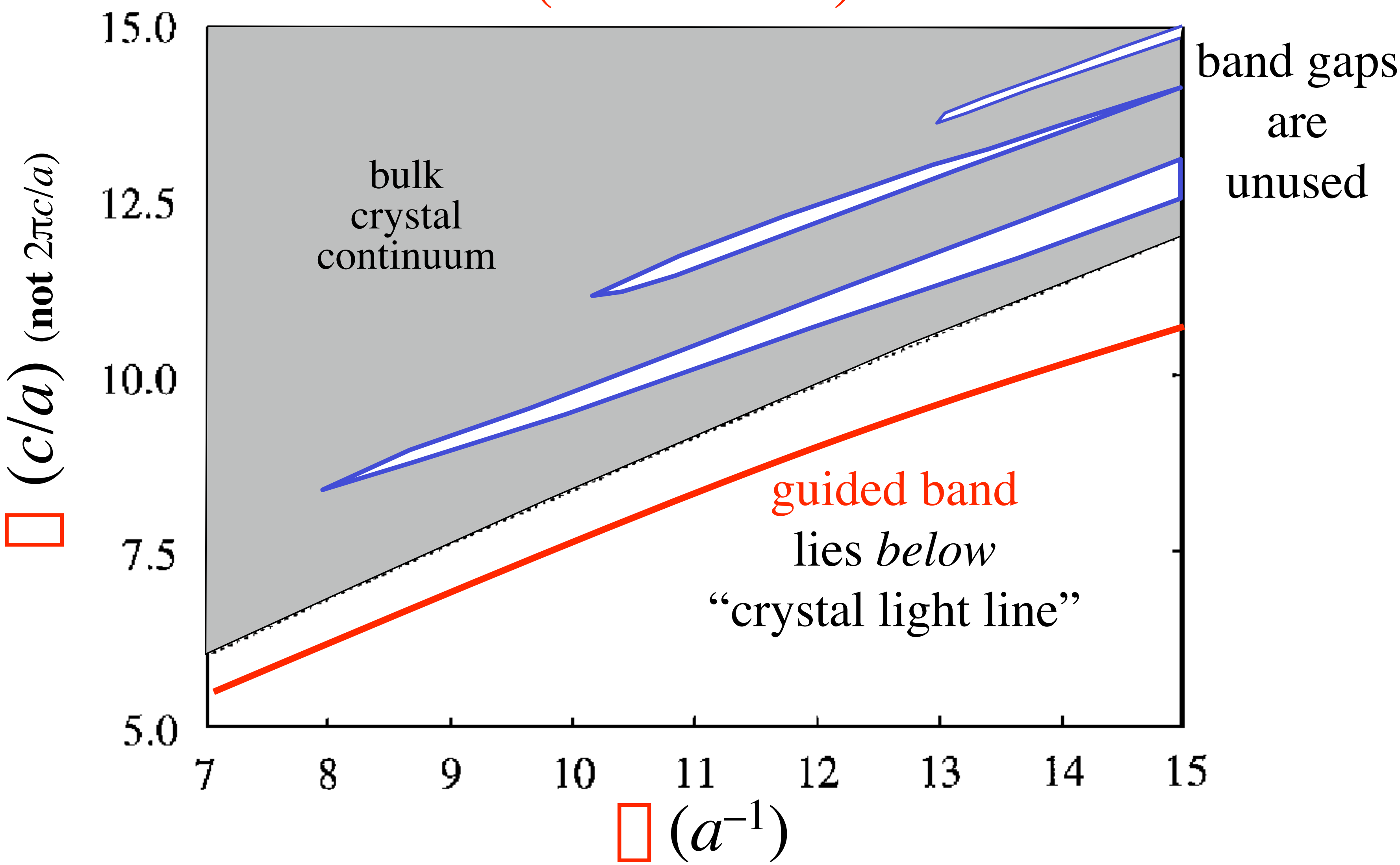
Can have much higher contrast
than doped silica…

strong confinement = enhanced
nonlinearities, birefringence, …

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

Holey Projected Bands, Batman!

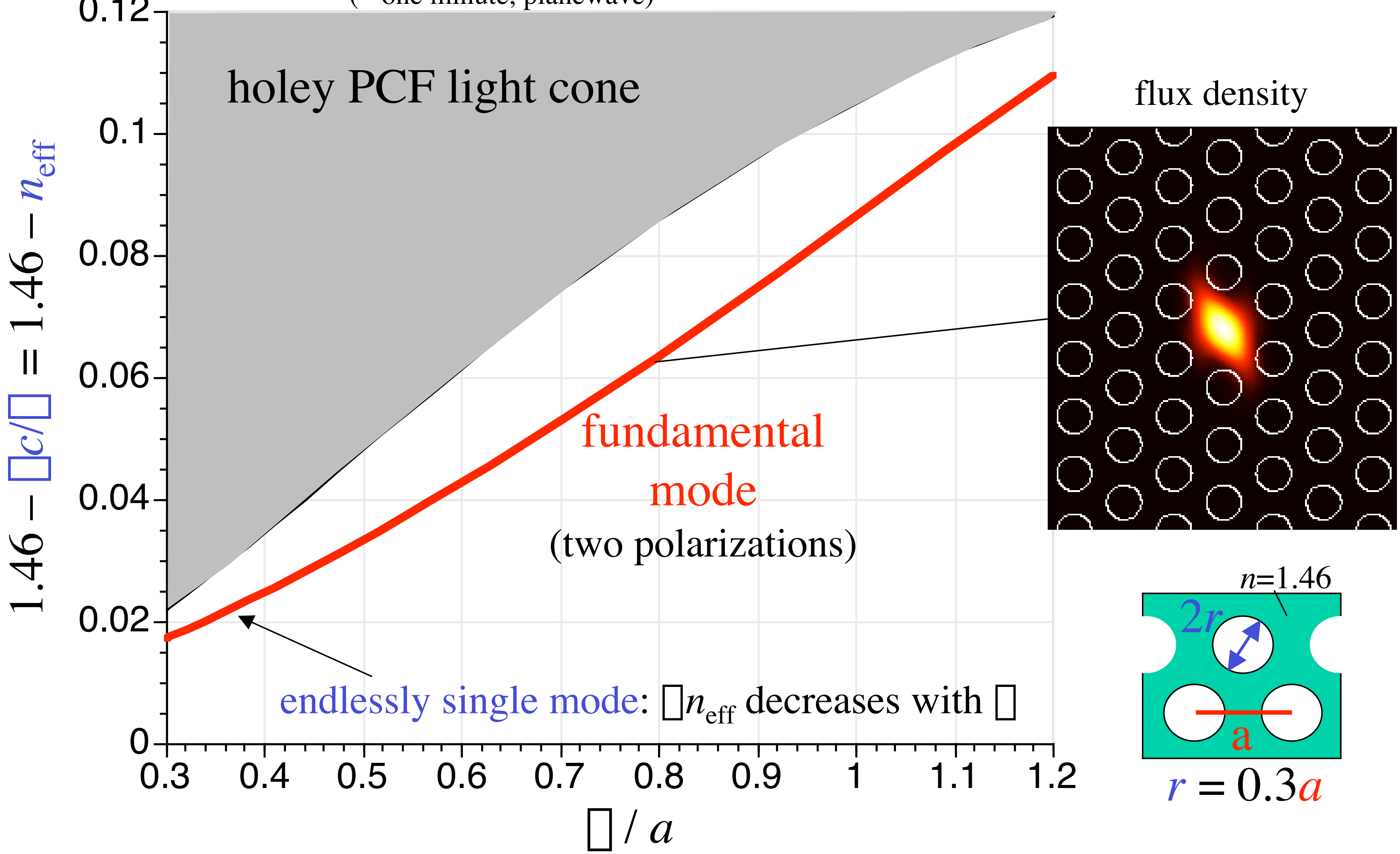
(Schematic)



Guided Mode in a Solid Core

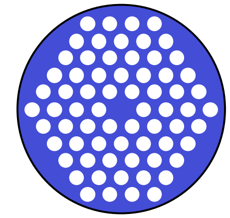
small computation: only lowest-□ band!

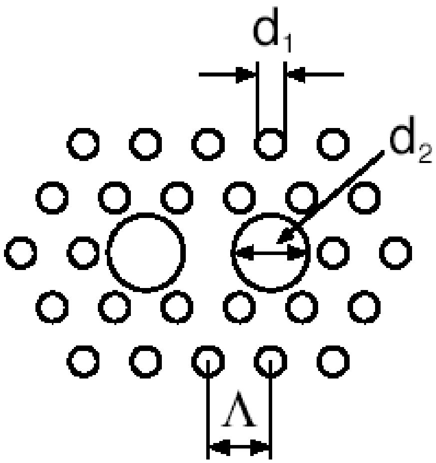
(~ one minute, planewave)

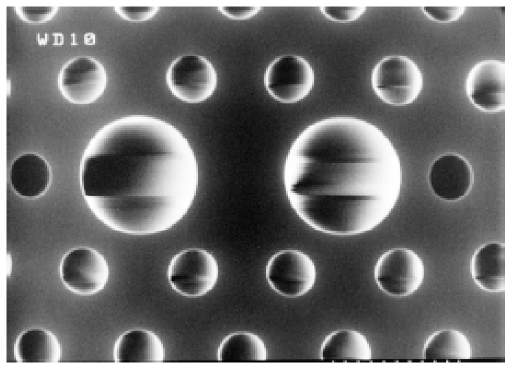


Holey Fiber PMF

(Polarization-Maintaining Fiber)

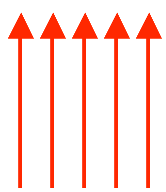
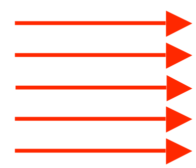






birefringence B = □□c/□
= 0.0014
(10 times B of silica PMF)

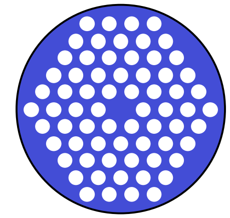
Loss = 1.3 dB/km @ 1.55μm
over 1.5km

 no longer degenerate with 

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

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

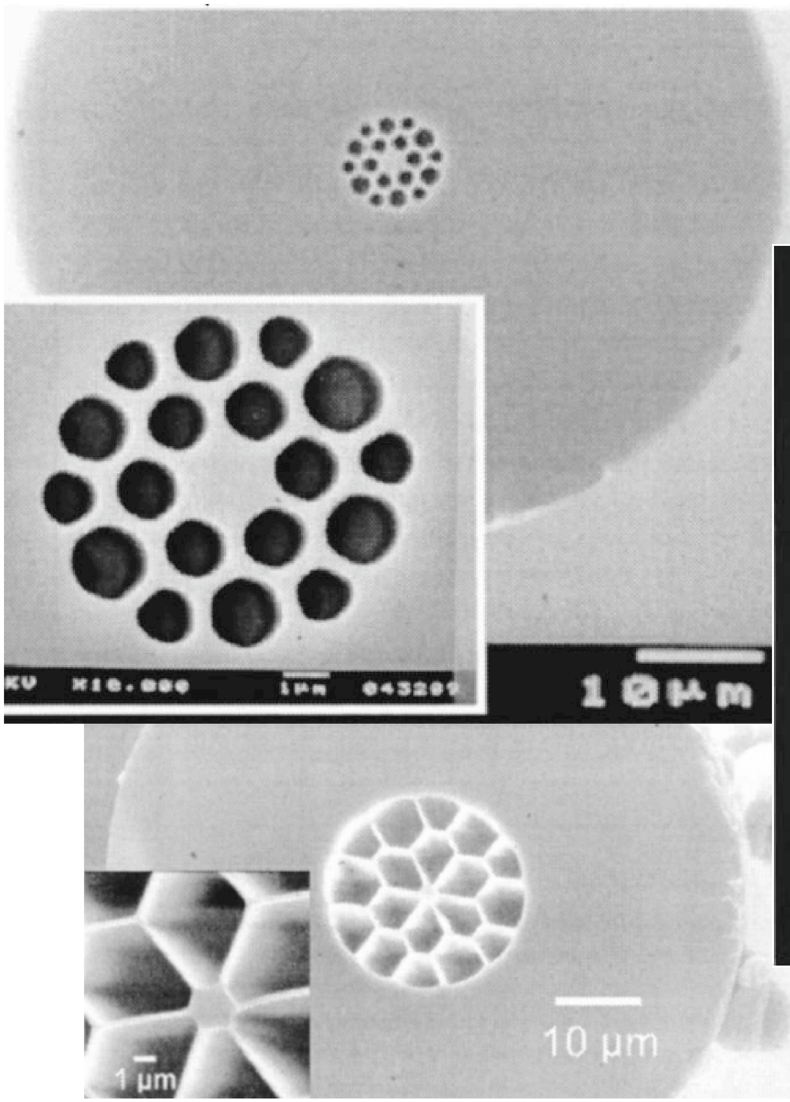
Nonlinear Holey Fibers:

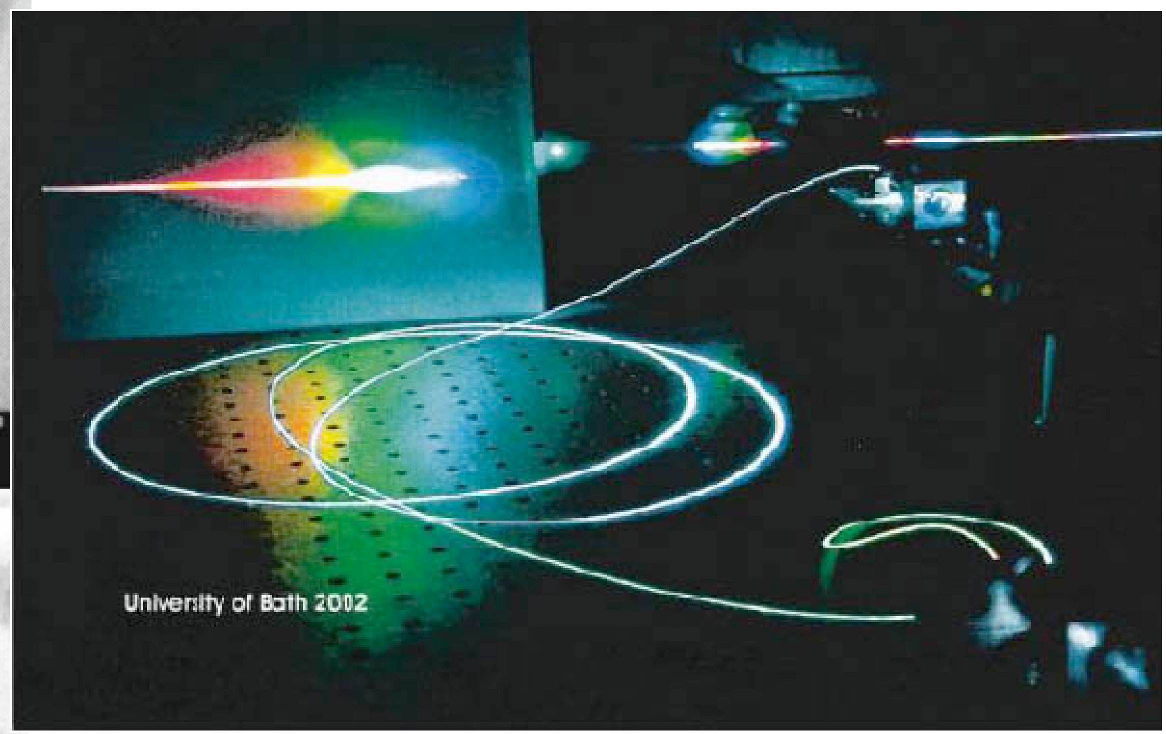


Supercontinuum Generation

(enhanced by strong confinement + unusual dispersion)

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

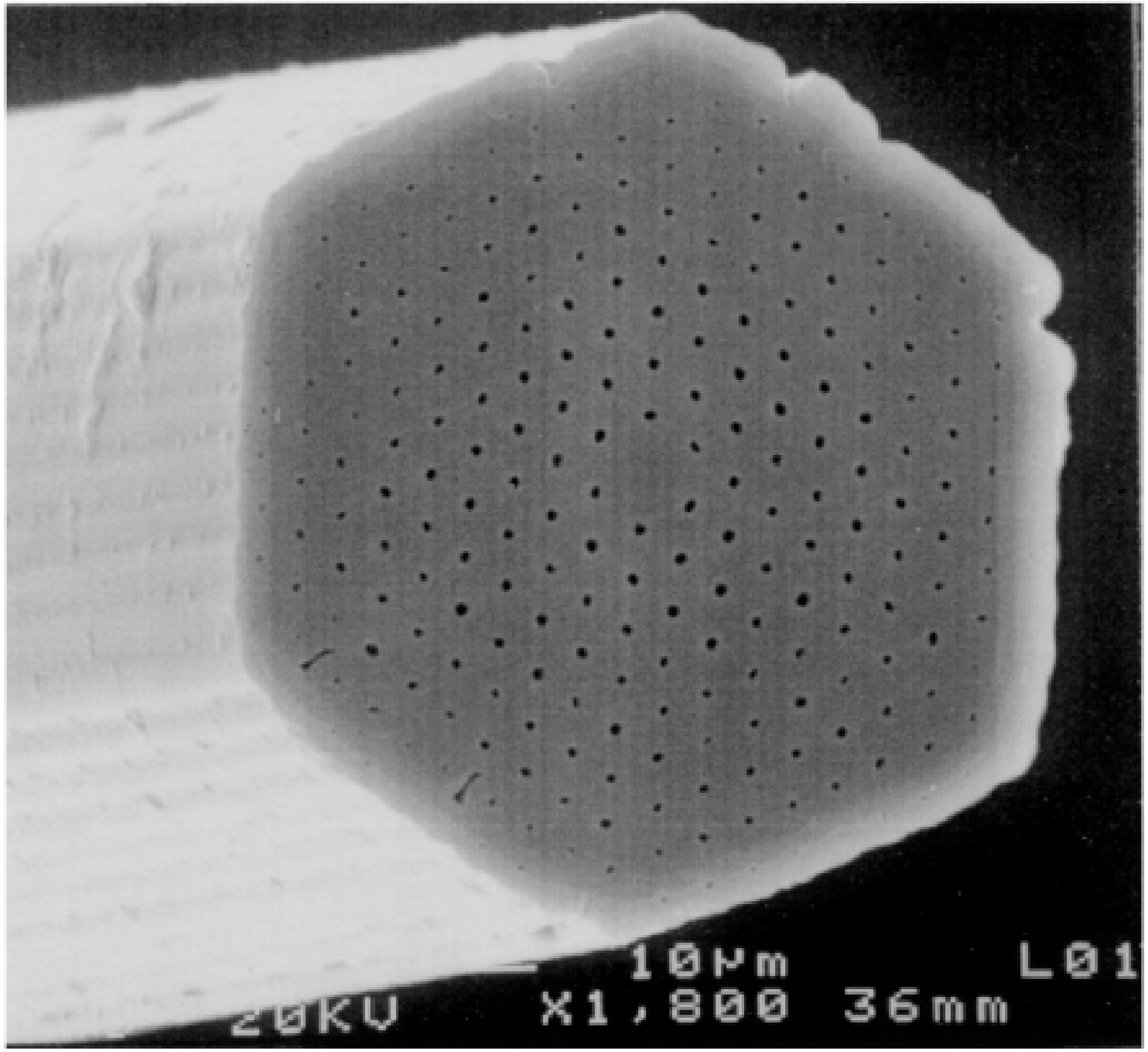




[W. J. Wadsworth *et al*., *J. Opt. Soc. Am. B* **19**, 2148 (2002)]

Endlessly Single-Mode

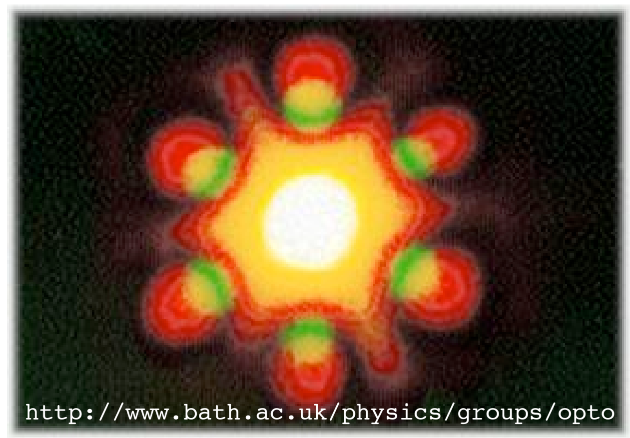
[T. A. Birks *et al.*, *Opt. Lett.* **22**, 961 (1997)]



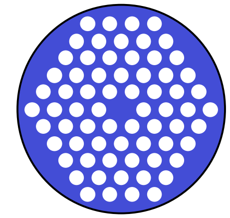
at higher ω
(smaller λ),
the light is more
concentrated in silica

…so the effective
index contrast is less

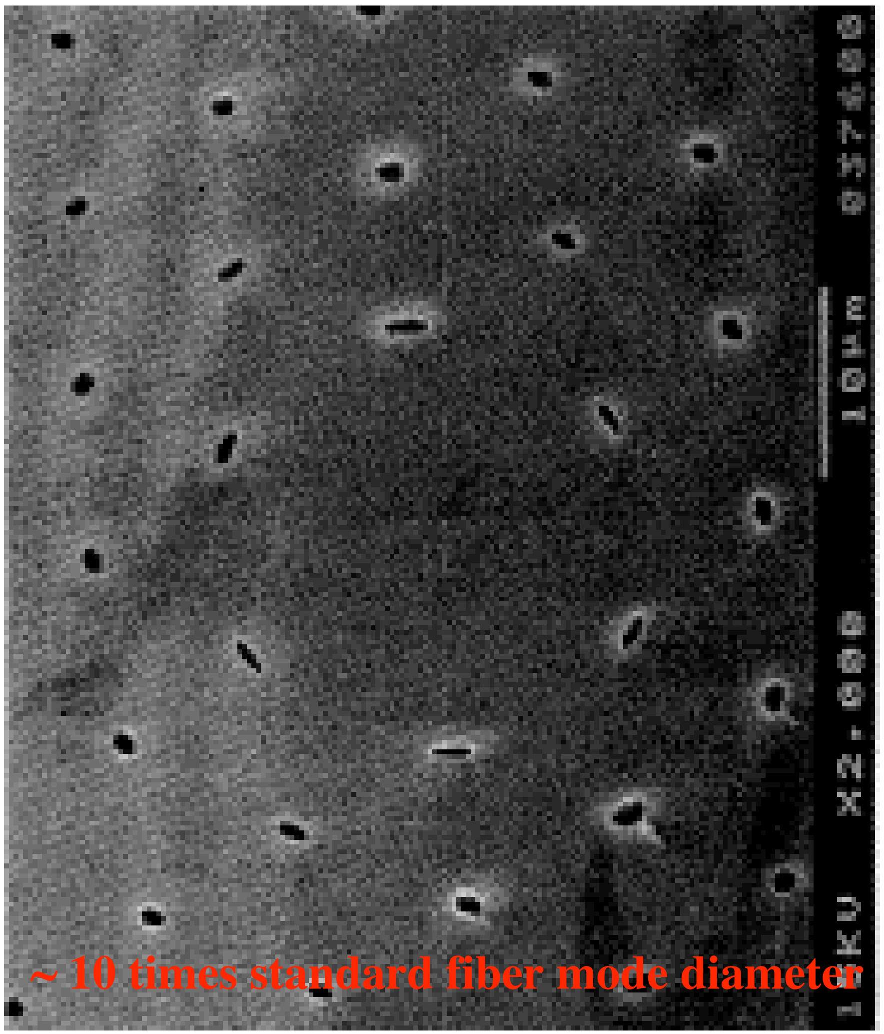
…and the fiber can stay
single mode for all λ!



Low Contrast Holey Fibers



[J. C. Knight *et al.*, *Elec. Lett.* **34**, 1347 (1998)]

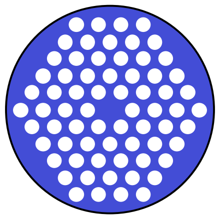


The holes can also form an
effective low-contrast medium

i.e. light is only affected slightly
by small, widely-spaced holes

This yields
large-area, single-mode
fibers (low nonlinearities)

…but bending loss is worse



Holey Fiber Losses

Best reported results:

0.28 dB/km @1.55μm

[Tajima, ECOC 2003]

The Upshot

Potential new regimes for fiber operation,

even using very poor materials.

The Story of Photonic Crystals

Finding Materials –> Finding Structures