Designing Photonic Crystals for Applications

- We want now to examine some in ways in which the described features can be used to build:

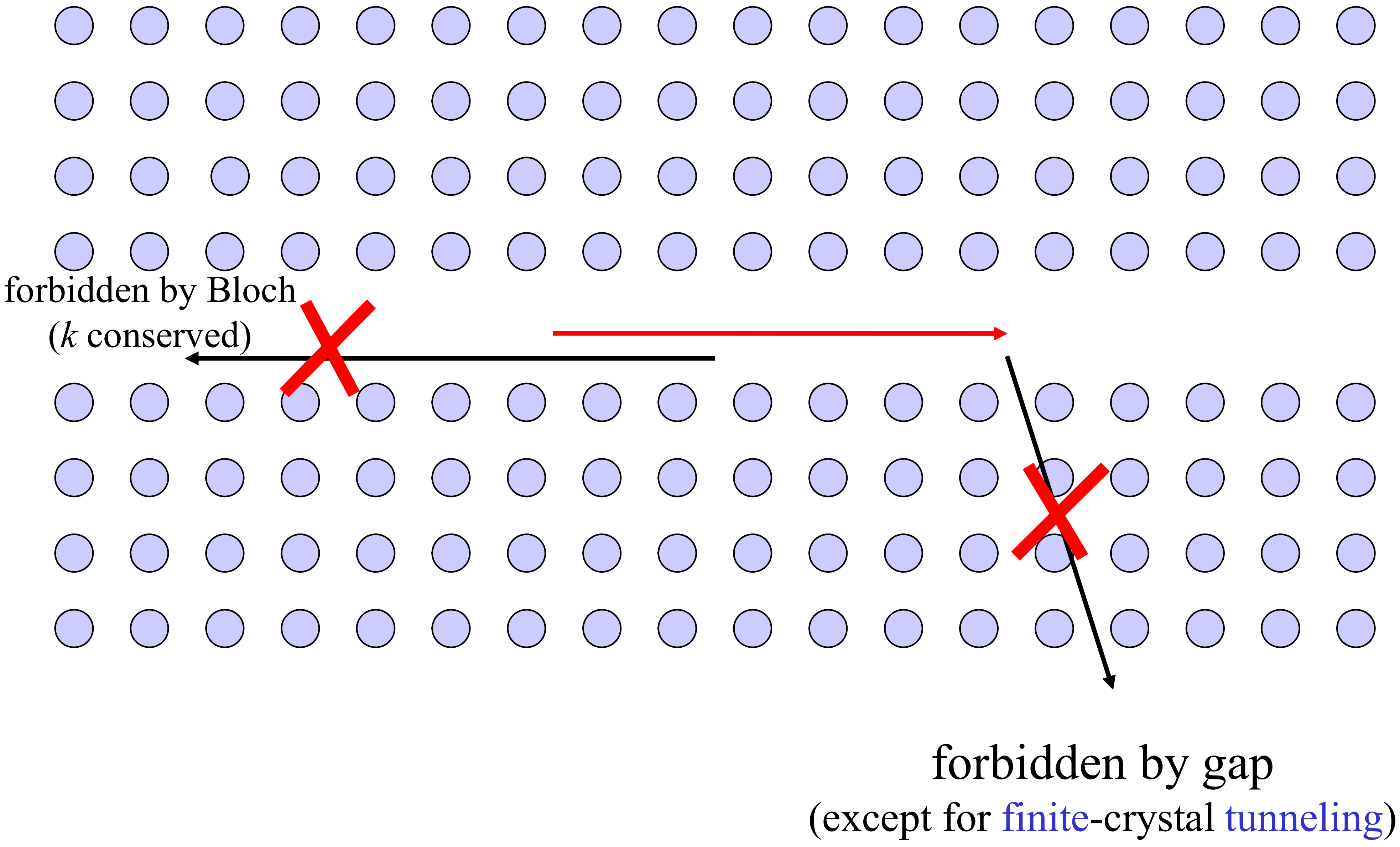
    ✓ filters

    ✓ waveguide bend

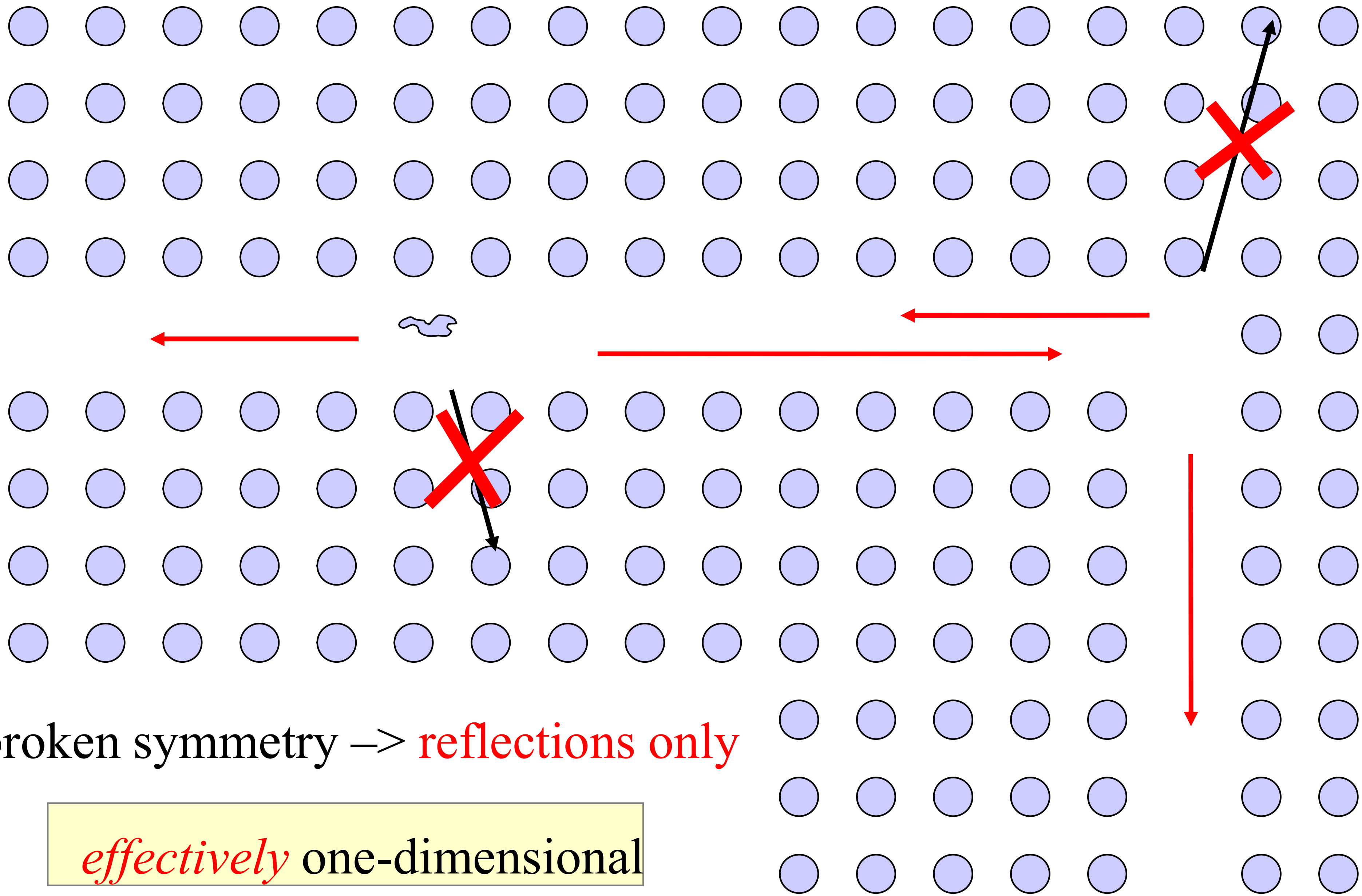
    ✓ splitter

- All these devices can be easily explain with the *temporal coupled-mode theory*

Review: Why no scattering?



Benefits of a complete gap…

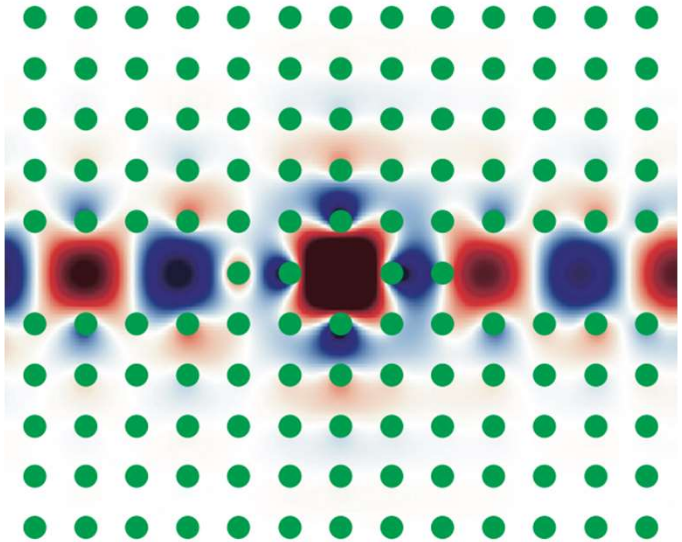


broken symmetry –> reflections only

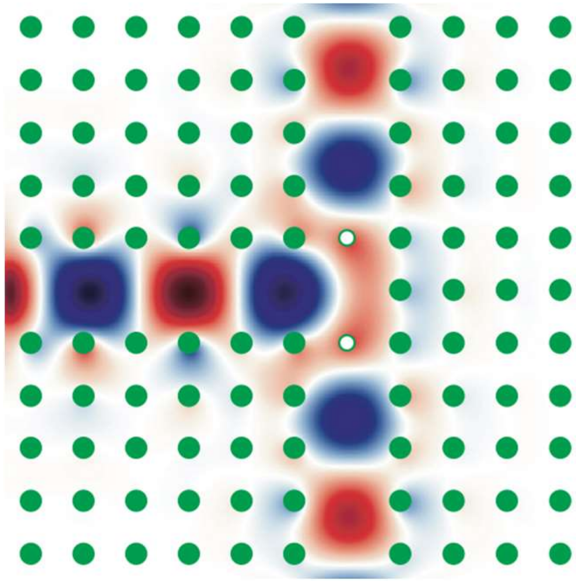
effectively one-dimensional

“1d” Waveguides + Cavities = Devices

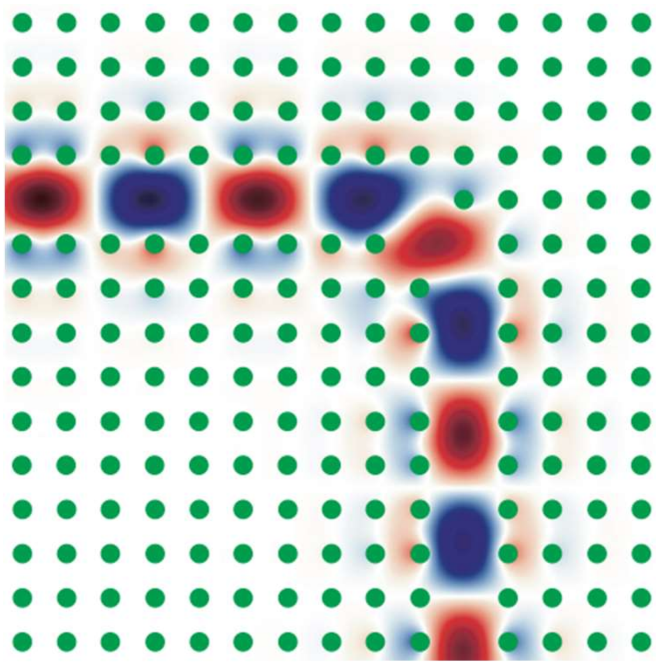
resonant filters



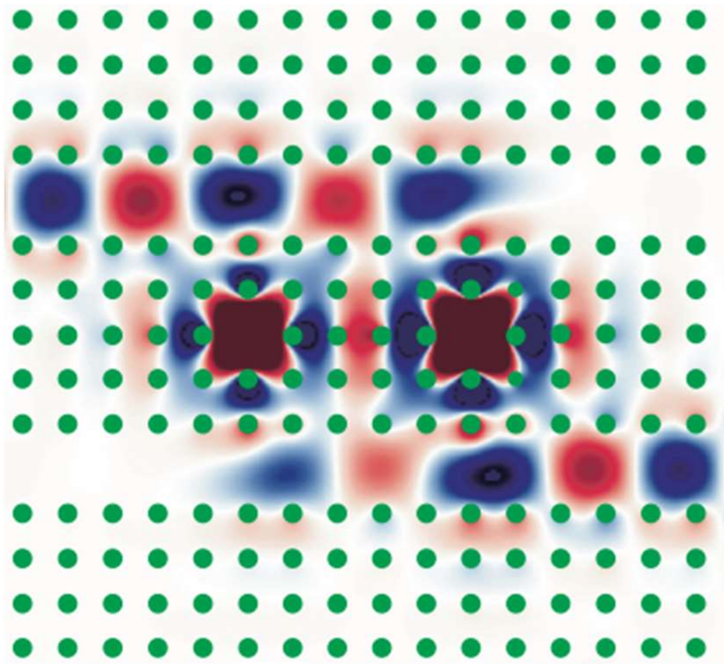
waveguide splitters



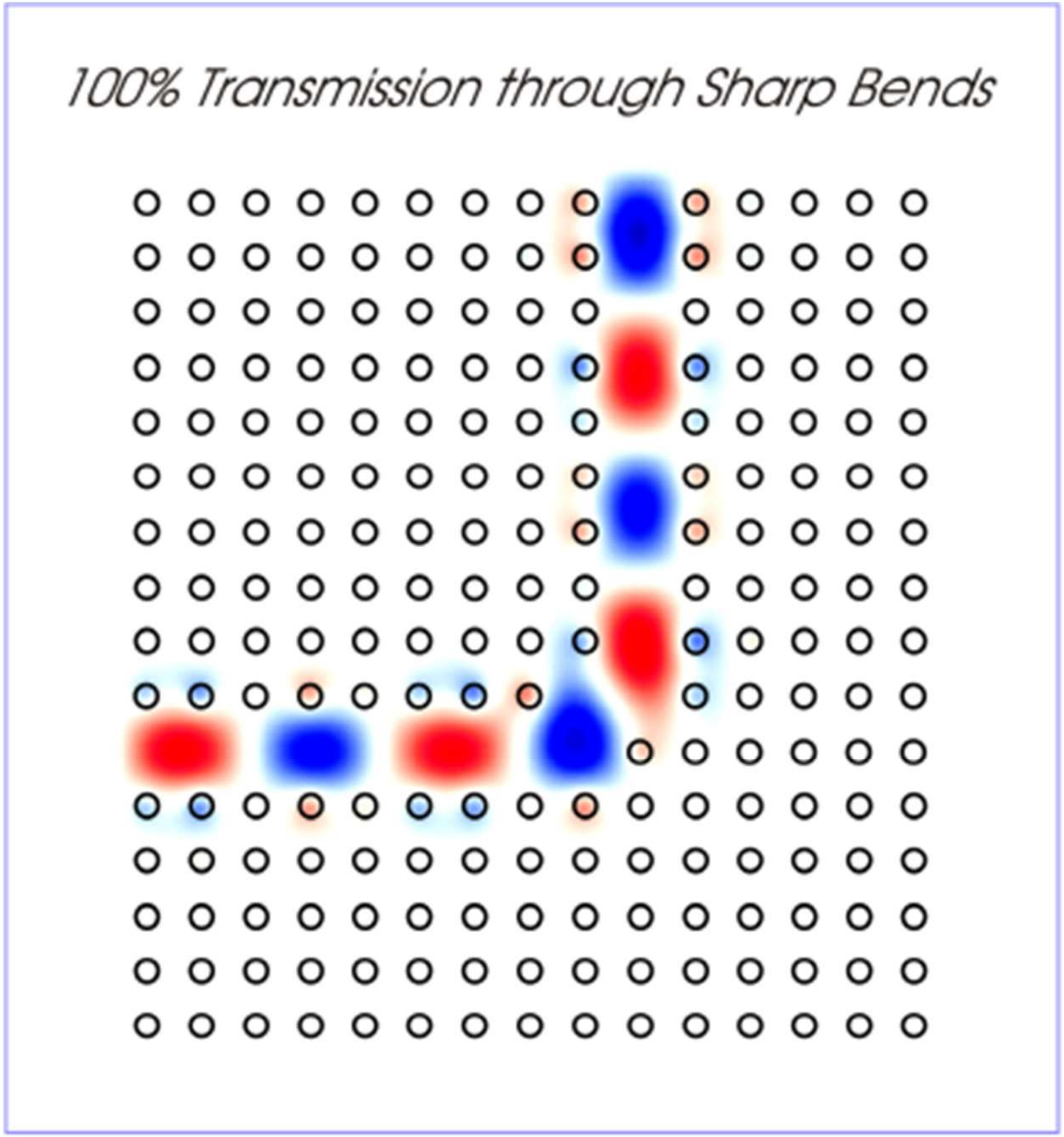
high-transmission sharp bends

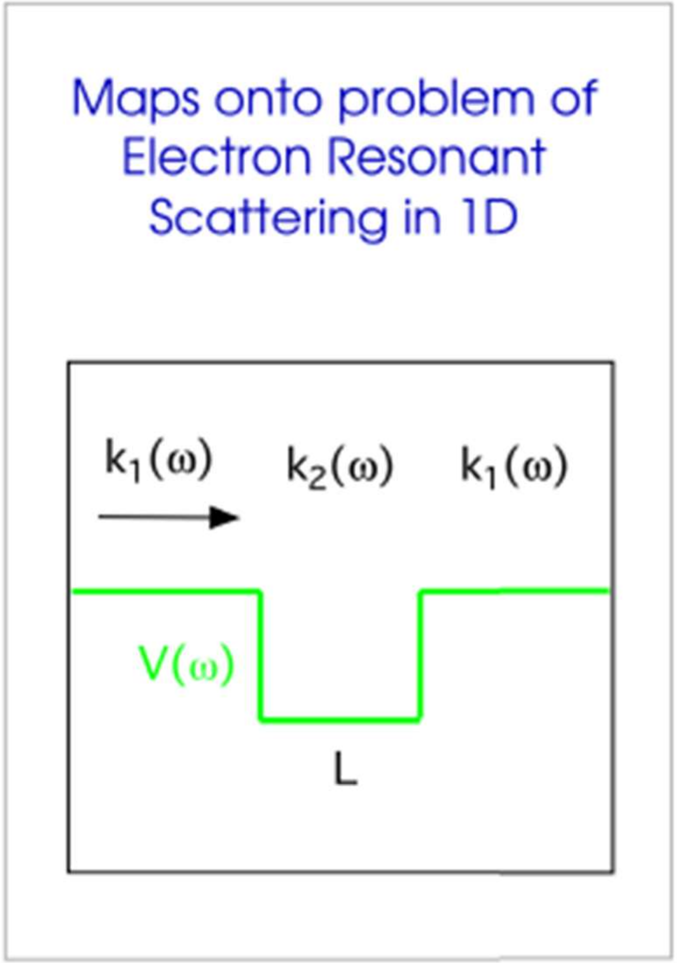


channel-drop filters



Lossless Bends

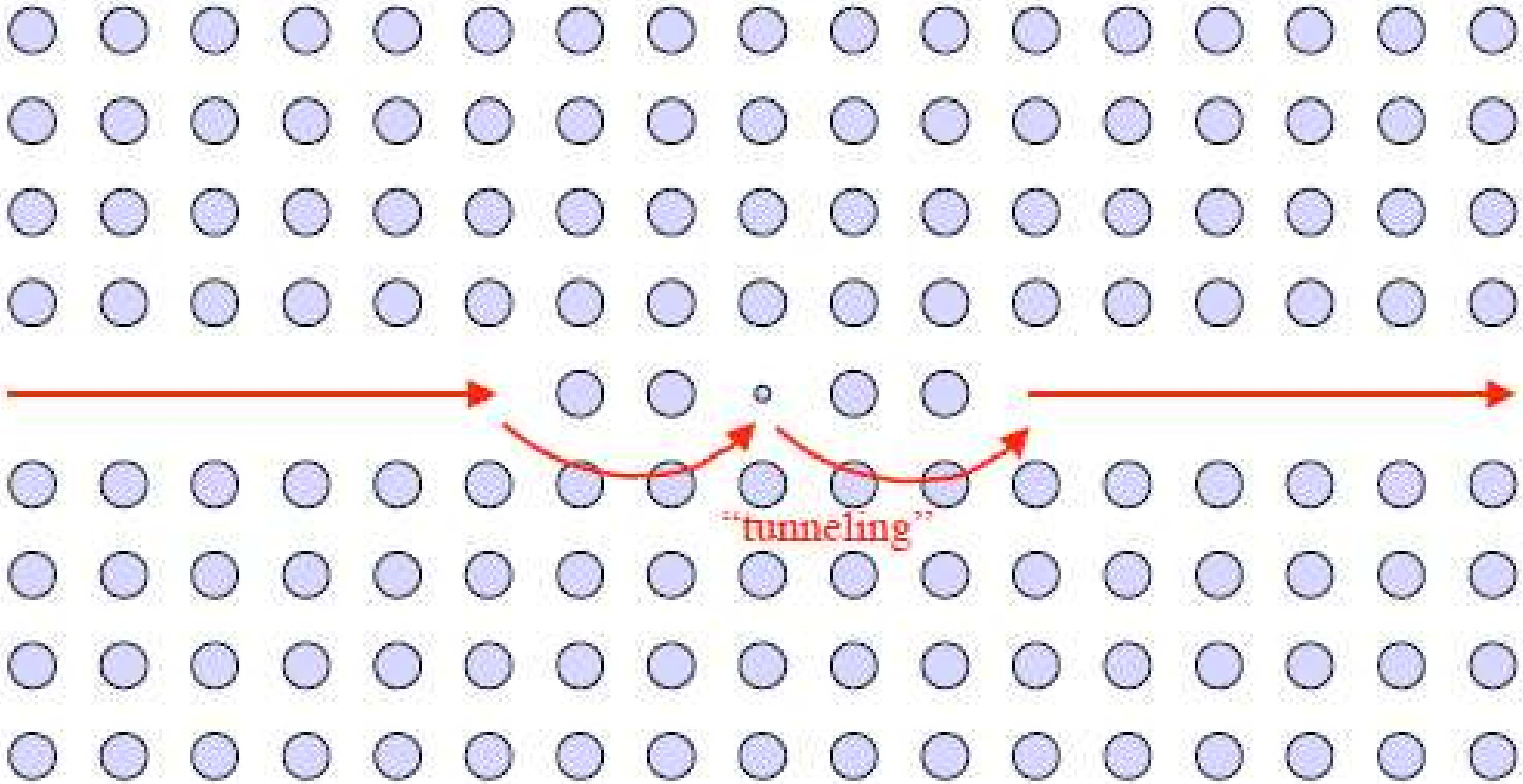




[A. Mekis *et al.*,
Phys. Rev. Lett. **77**, 3787 (1996)]

symmetry + single-mode + “1d” = resonances of 100% transmission

Waveguides + Cavities = Devices



Ugh, must we simulate this to get the basic behavior?

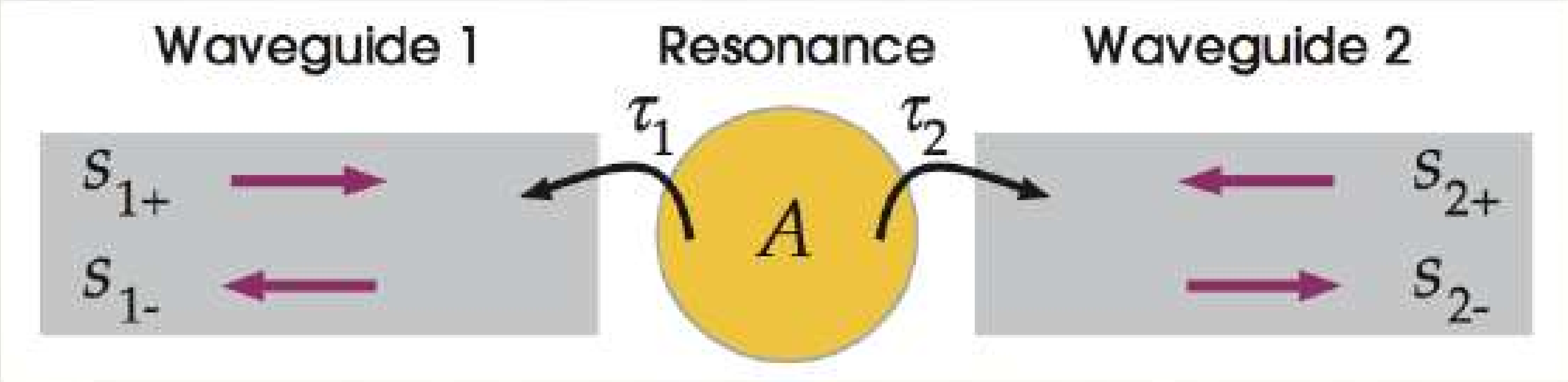
No! Use "coupling-of-modes-in-time" (coupled-mode theory)…

[H. Haus, *Waves and Fields in Optoelectronics*]

Temporal Coupled-Mode Theory

- In order to build a more sophysticated device one needs to describe a system in terms of a set of idealized components that are perturbed, or coupled, in some fashion —> **temporal coupled theory**:

    ✓ key assumption: the coupling among the various elements is *weak*



The temporal coupled-mode equations

- We derive a set of equations describing the coupling of the cavity to the waveguides, in terms of the field amplitudes in those components.
- Assumptions:

  ✓ weak coupling

  ✓ linearity

  ✓ time-invariance

  ✓ conservation of energy

  ✓ time reversal invariance

The temporal coupled-mode equations

- In the cavity the filed is proportional to A. The two loss mechanisms are described by τ_1 and τ_2.
- $s_{l\pm}$ (l=1,2) are the modes in the waveguide.

$$\frac{dA}{dt} = -i\omega_0 A - \frac{A}{\tau_1} - \frac{A}{\tau_2} + \alpha_1 s_1 + \alpha_2 s_2$$

$$s_{l-} = \beta_l s_{l+} + \gamma_l A$$

The temporal coupled-mode equations

- We use the energy conservation to deduce the coefficients γ_l.
- From the time reversal symmetry we compute the coefficients α_l and β_l

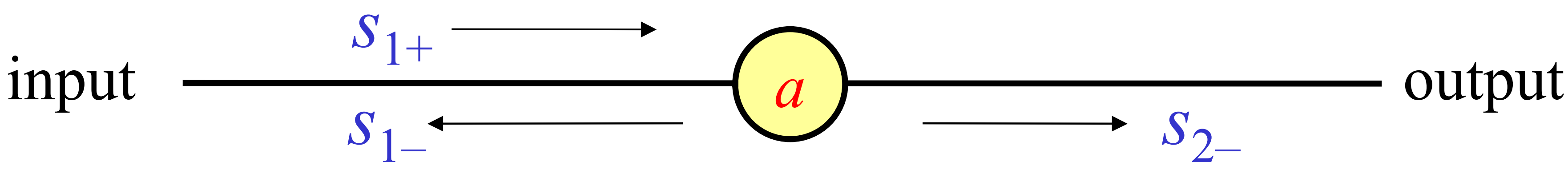
$$\frac{dA}{dt} = -i\omega_0 A - \sum_{l=1}^{2} \frac{A}{\tau_l} + \sum_{l=1}^{2} \sqrt{\frac{2}{\tau_l}} s_{l+}$$

$$s_{l-} = -s_{l+} + \sqrt{\frac{2}{\tau_l}} A$$

Temporal Coupled-Mode Theory

(one of several things called of "coupled-mode theory")

[H. Haus, *Waves and Fields in Optoelectronics*]



resonant cavity
frequency ω_0, lifetime τ

$|s|^2$ = power

$|a|^2$ = energy

$$\frac{da}{dt} = -i\omega_0 a - \frac{2}{\tau} a + \sqrt{\frac{2}{\tau}} s_{1+}$$

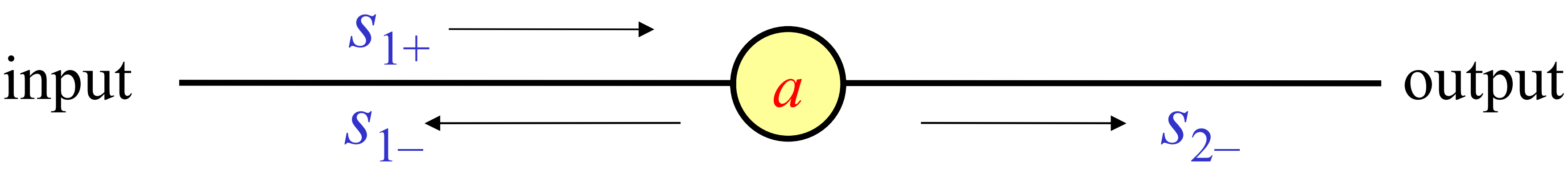
$$s_{1-} = -s_{1+} + \sqrt{\frac{2}{\tau}} a, \quad s_{2-} = \sqrt{\frac{2}{\tau}} a$$

assumes only:
- exponential decay (strong confinement)
- conservation of energy
- time-reversal symmetry

Temporal Coupled-Mode Theory

(one of several things called of "coupled-mode theory")

[H. Haus, *Waves and Fields in Optoelectronics*]



resonant cavity

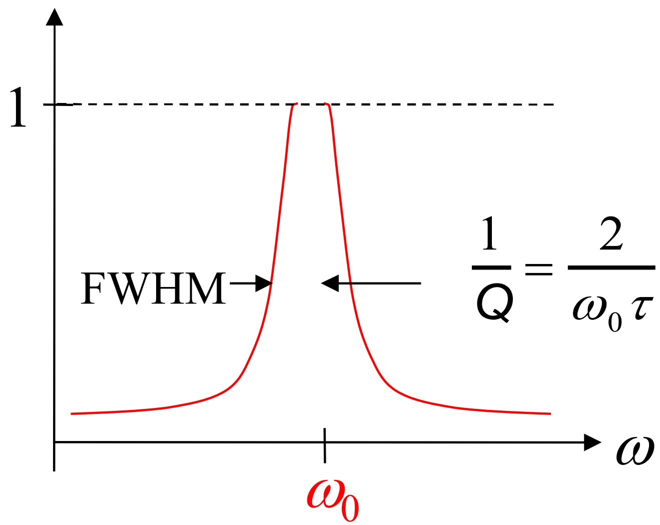
frequency ω_0, lifetime τ

$|s|^2$ = flux

$|a|^2$ = energy

transmission T

$= | s_{2-} |^2 / | s_{1+} |^2$



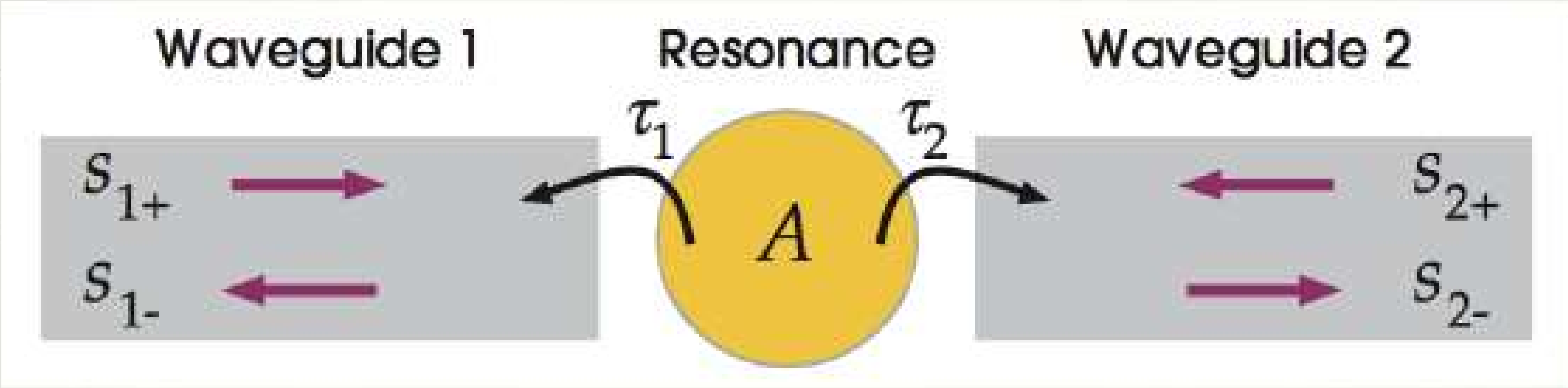
$$\frac{1}{Q} = \frac{2}{\omega_0 \tau}$$

T = Lorentzian filter

$$= \frac{\frac{4}{\tau^2}}{(\omega - \omega_0)^2 + \frac{4}{\tau^2}}$$

…quality factor Q

The filter trasmission



$$\frac{dA}{dt} = -i\omega A$$

$$s_{2+} = 0$$

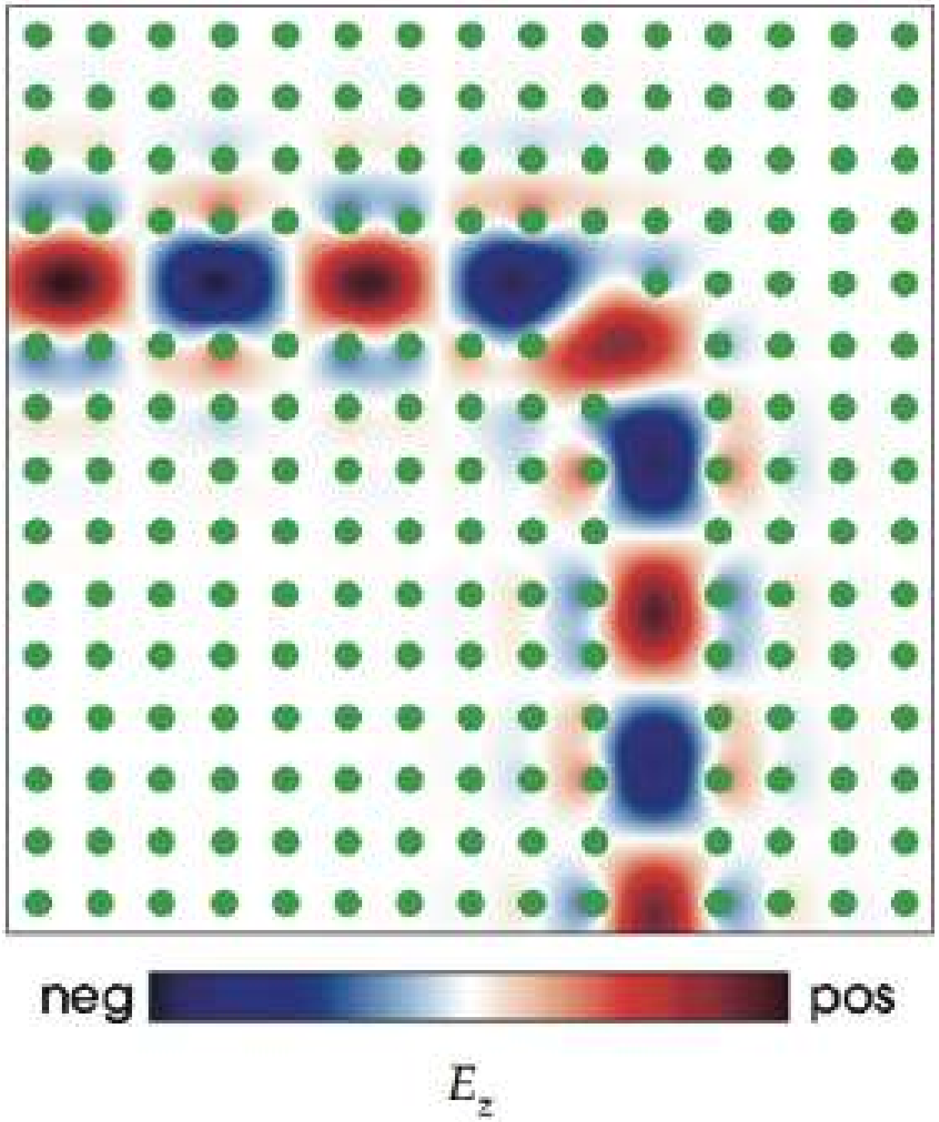
Trasmission spectrum (Lorentzain Peak):

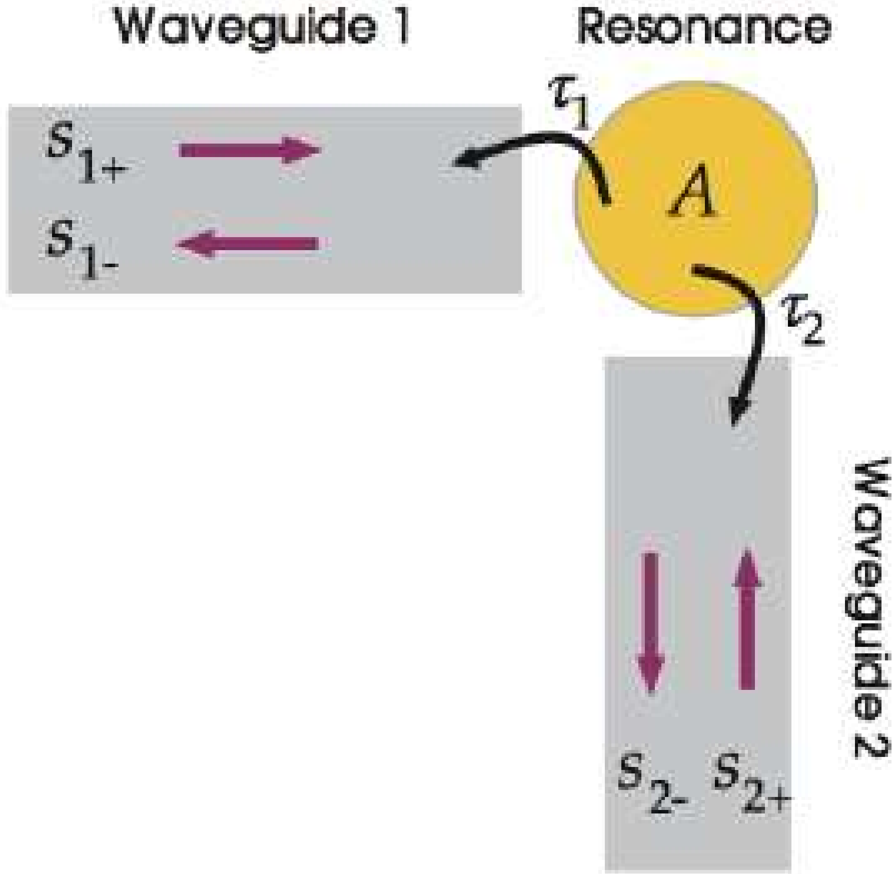
$$T(\omega) = \frac{|s_{2-}|^2}{|s_{1+}|^2} = \frac{\frac{4}{\tau_1 \tau_2}}{(\omega - \omega_0)^2 + \left(\frac{1}{\tau_1} + \frac{1}{\tau_2}\right)^2}$$

Reflection spectrum:

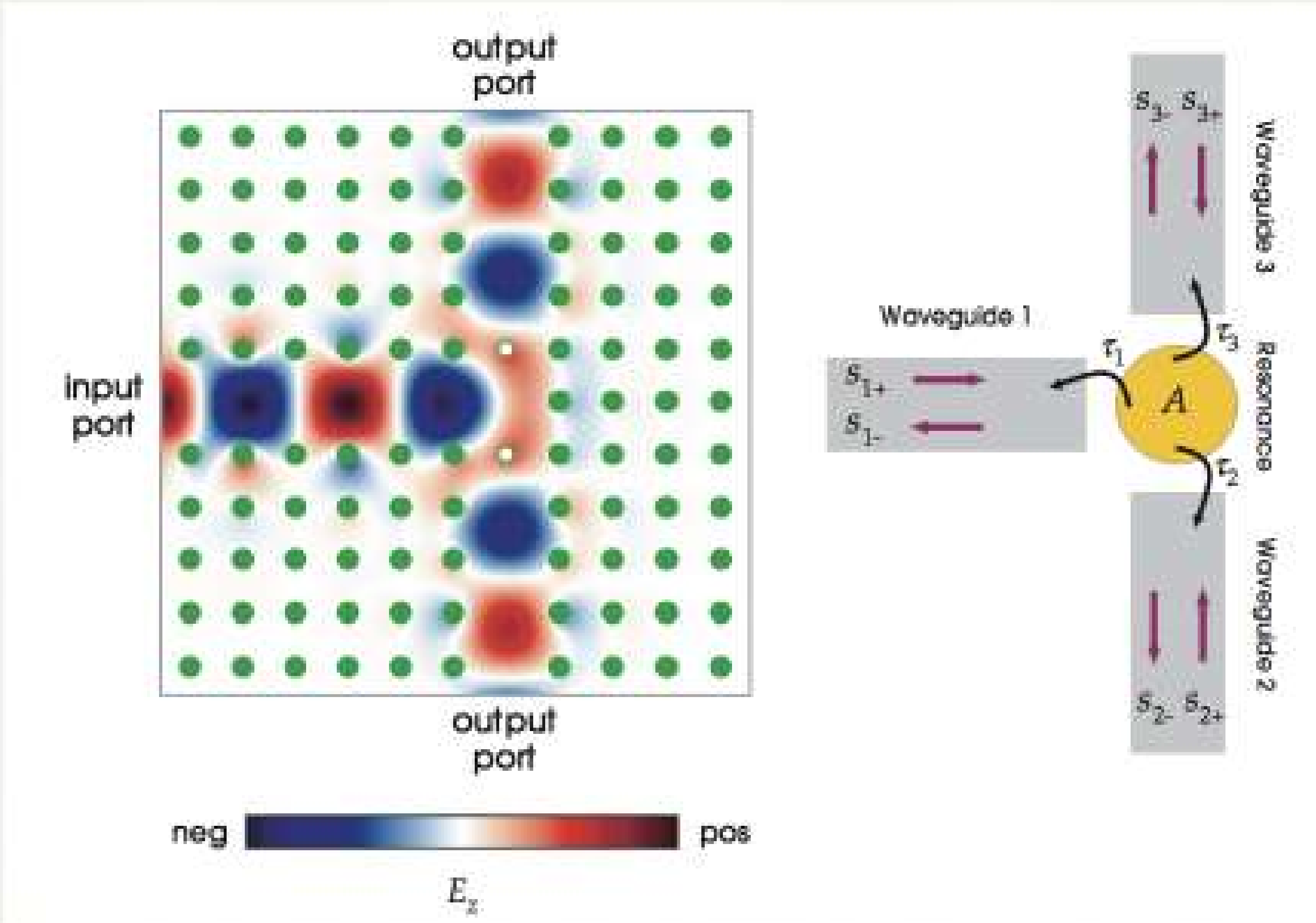
$$R(\omega) = \frac{|s_{1-}|^2}{|s_{1+}|^2} = \frac{(\omega - \omega_0)^2 + \left(\frac{1}{\tau_1} - \frac{1}{\tau_2}\right)^2}{(\omega - \omega_0)^2 + \left(\frac{1}{\tau_1} + \frac{1}{\tau_2}\right)^2}$$

A wave guide bend





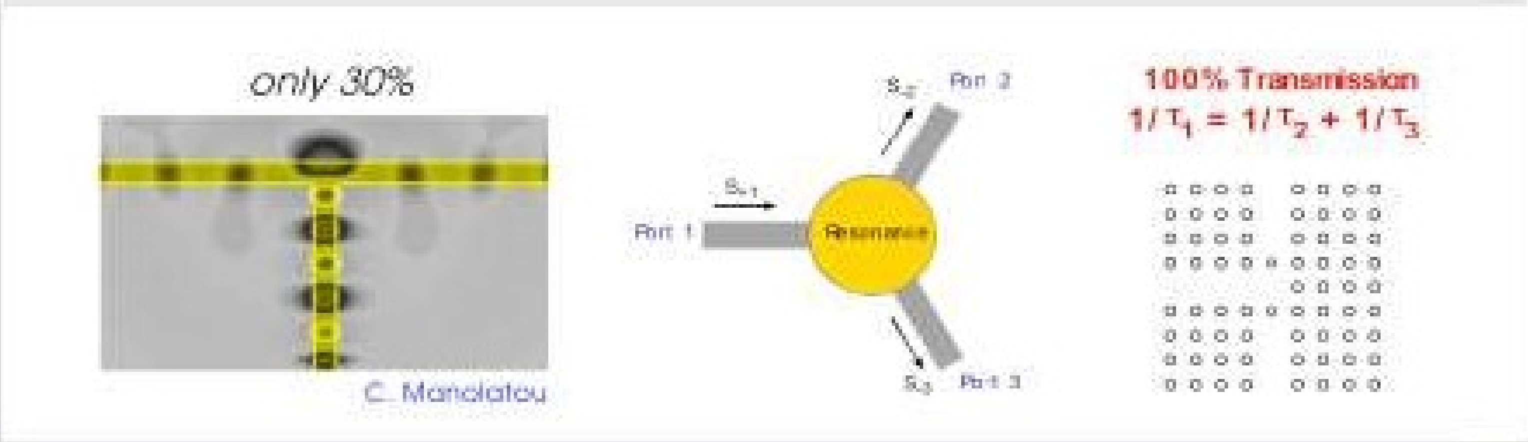
A waveguide splitter

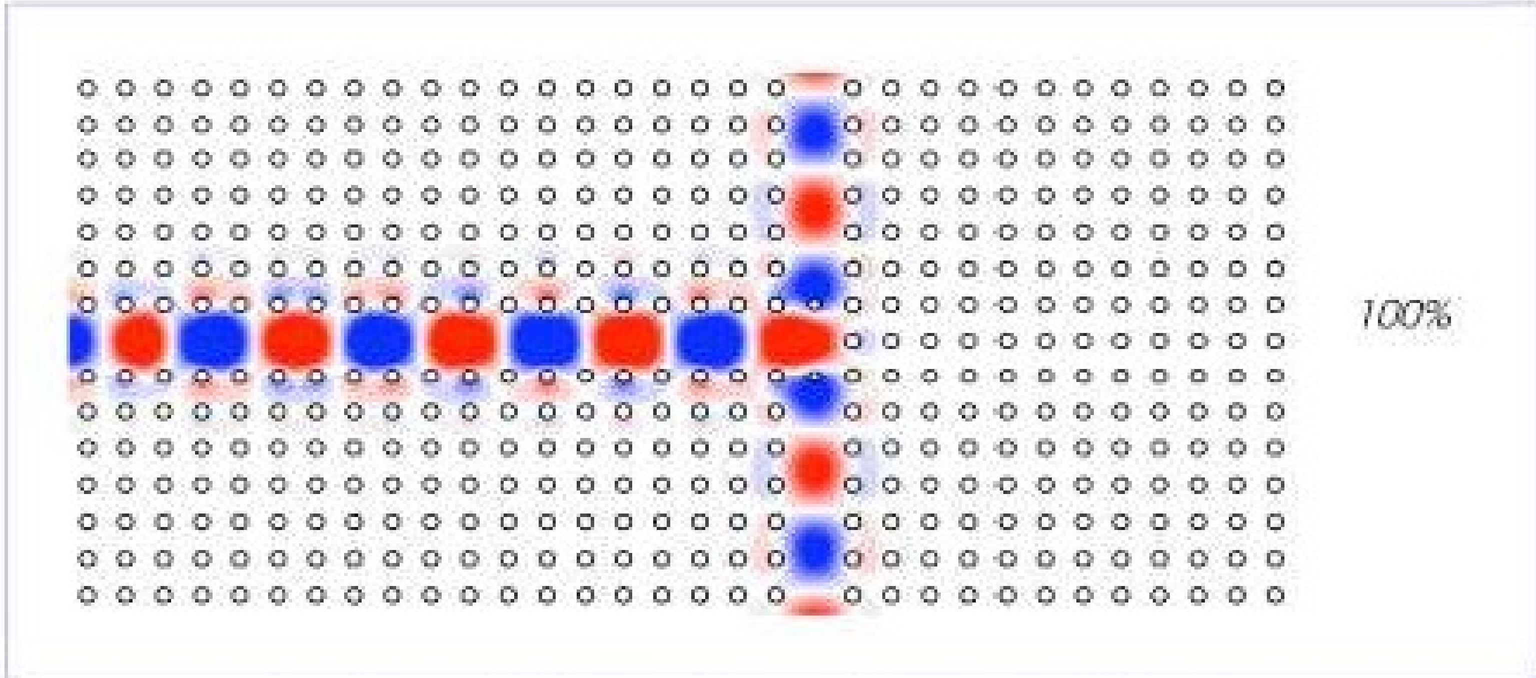


$$\frac{dA}{dt} = -i\omega_0 A - \sum_{l=1}^{3} \frac{A}{\tau_l} + \sum_{l=1}^{3} \sqrt{\frac{2}{\tau_l}} s_{l+}$$

T-shaped splitter

Wide-angle Splitters





[S. Fan *et al.*, *J. Opt. Soc. Am. B* **18**, 162 (2001)]

A waveguide splitter

- Setting $s_{2+}=0$ e $s_{3+}=0$ we get:

$$R(\omega) = \frac{|s_{1-}|^2}{|s_{1+}|^2} = \frac{(\omega-\omega_0)^2 + \left(\frac{1}{\tau_1} - \frac{1}{\tau_2} - \frac{1}{\tau_3}\right)^2}{(\omega-\omega_0)^2 + \left(\frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3}\right)^2}$$

$$T_{1\to2}(\omega) = \frac{|s_{2-}|^2}{|s_{1+}|^2} = \frac{\frac{4}{\tau_1\tau_2}}{(\omega-\omega_0)^2 + \left(\frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3}\right)^2}$$

$$T_{1\to3}(\omega) = \frac{|s_{3-}|^2}{|s_{1+}|^2} = \frac{\frac{4}{\tau_1\tau_3}}{(\omega-\omega_0)^2 + \left(\frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3}\right)^2}$$

At $\omega=\omega_0$ no reflection and 100% trasmission if:

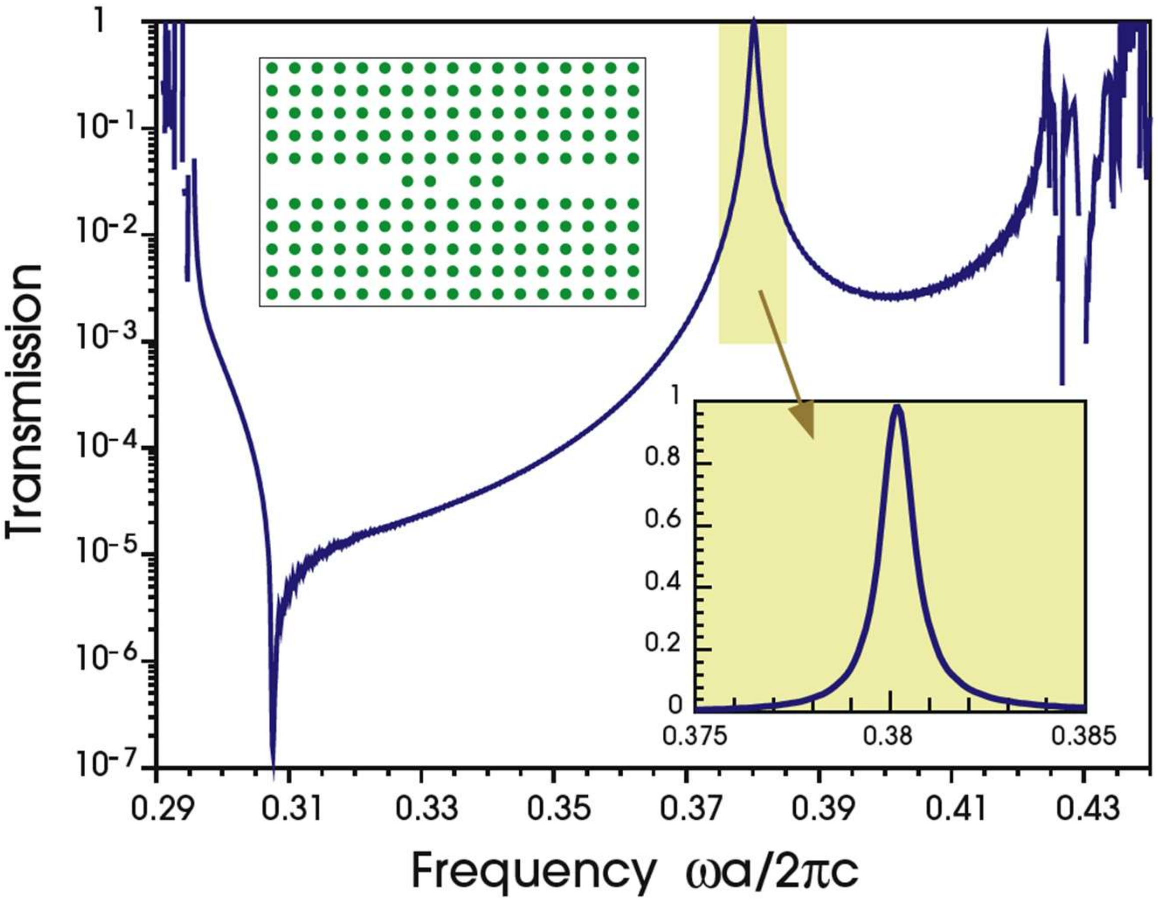
$$\frac{1}{\tau_1} = \frac{1}{\tau_2} + \frac{1}{\tau_3}$$

If:

$$\tau_2 = \tau_3 = \tau \Rightarrow \tau = 2\tau_1$$

we should add obstructions between the junction and the output ports to weaken their coupling!

Resonant Filter Example

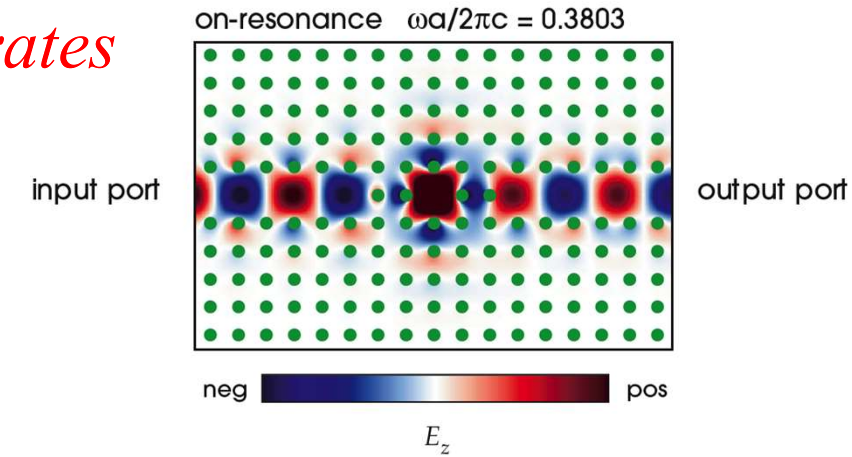


Lorentzian peak, as predicted.

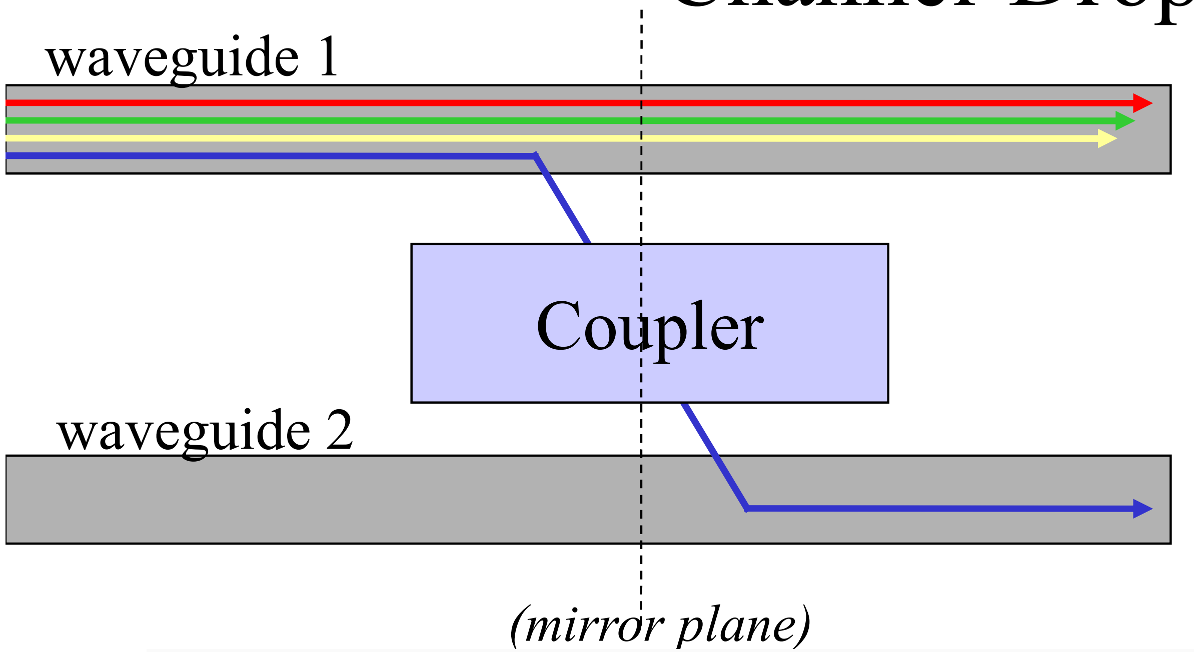
An apparent miracle:

~ 100% transmission
at the resonant frequency

cavity decays to input/output with *equal rates*
⇒ At resonance, reflected wave
destructively interferes
with backwards-decay from cavity
& the two *exactly cancel*.



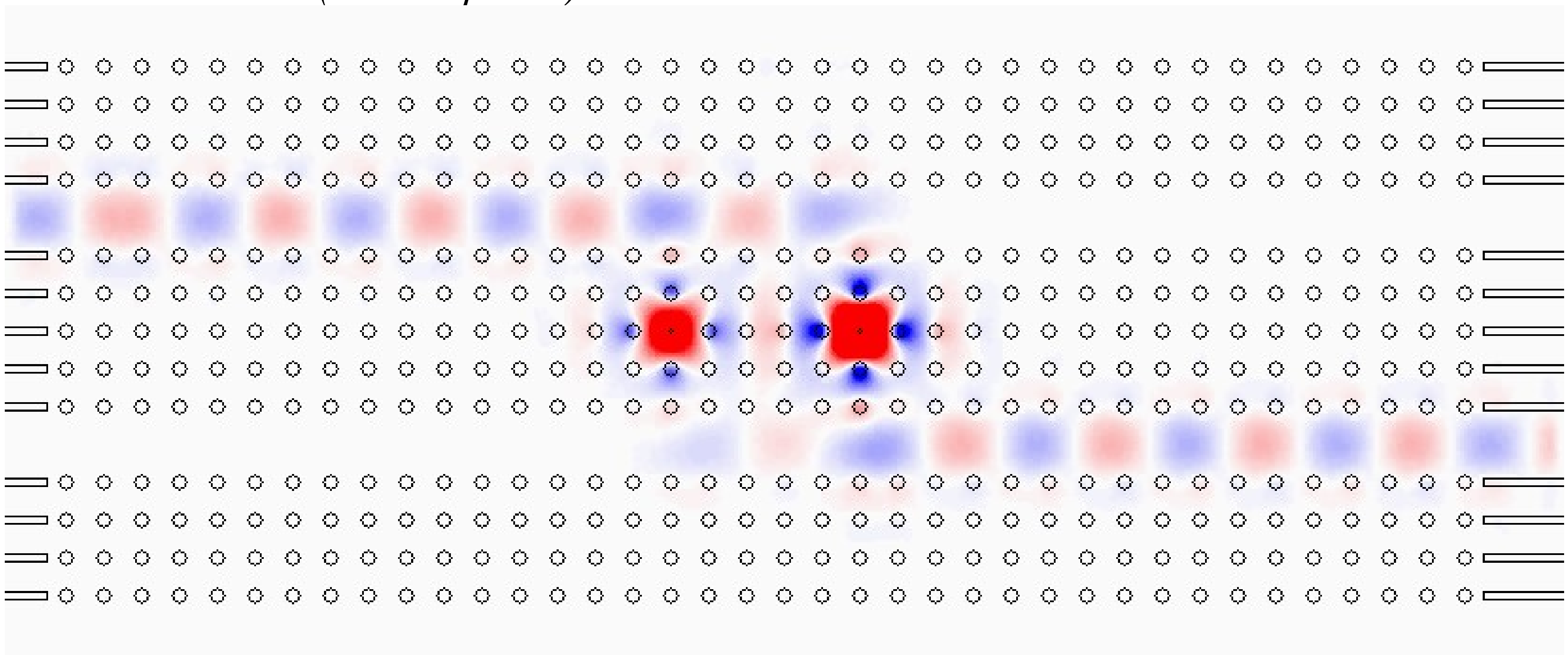
Channel-Drop Filters



Perfect channel-dropping if:

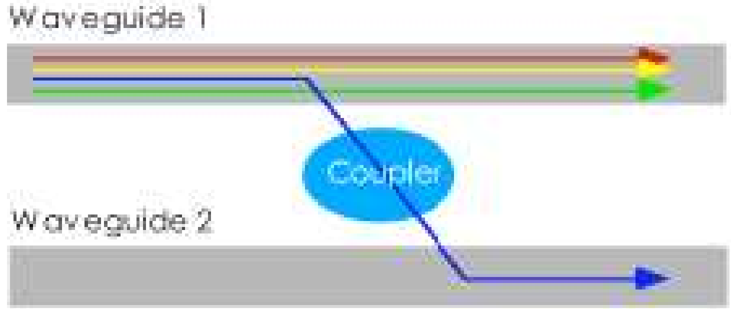
Two resonant modes with:

- even and odd symmetry
- equal frequency (degenerate)
- equal decay rates



[S. Fan *et al.*, *Phys. Rev. Lett.* **80**, 960 (1998)]

Channel-Drop Filters

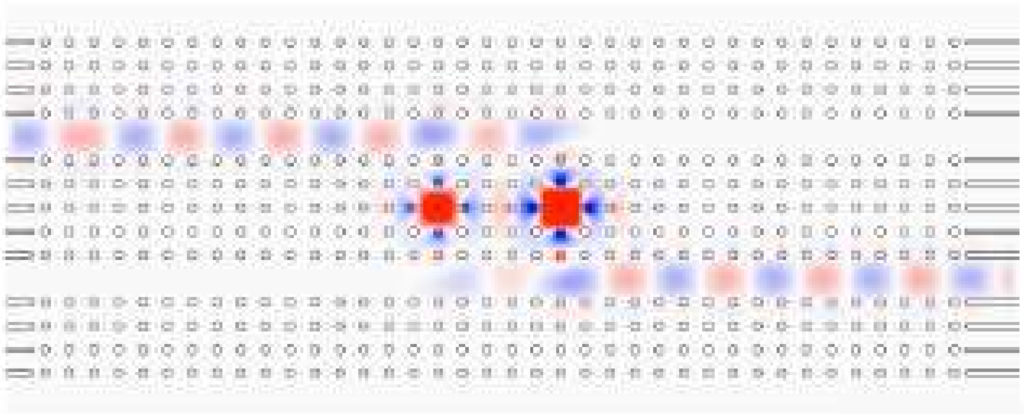


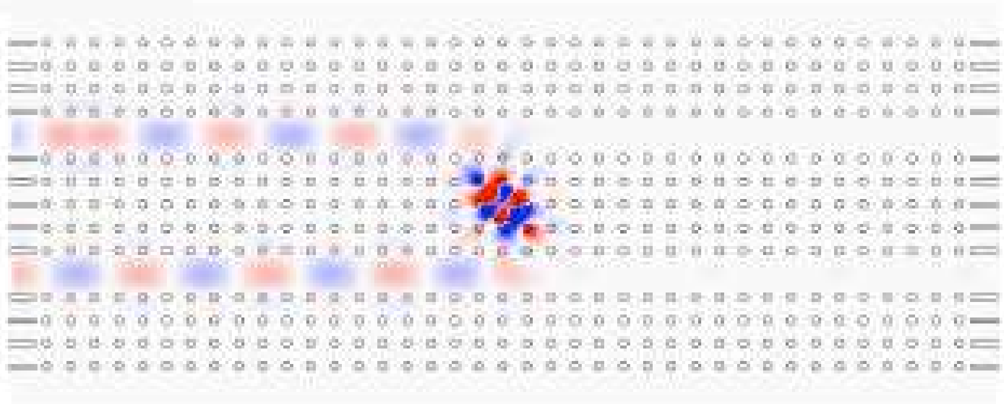
Criteria for Perfect Channel-dropping

Two resonant modes with even and odd symmetry

Modes must be degenerate

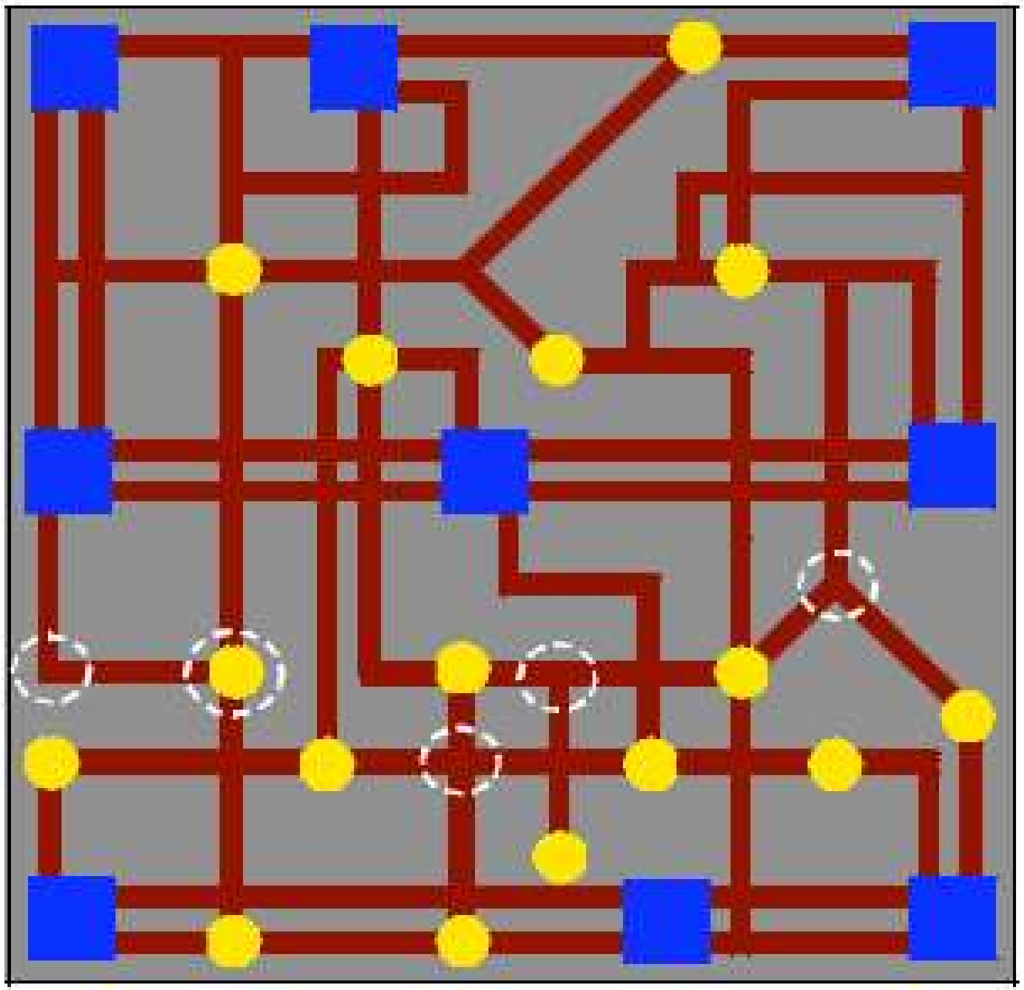
Modes must have equal decay rates





A Menagerie of Devices

λ ⟷ 1.55 microns



Enough passive, linear devices…

Photonic crystal cavities:

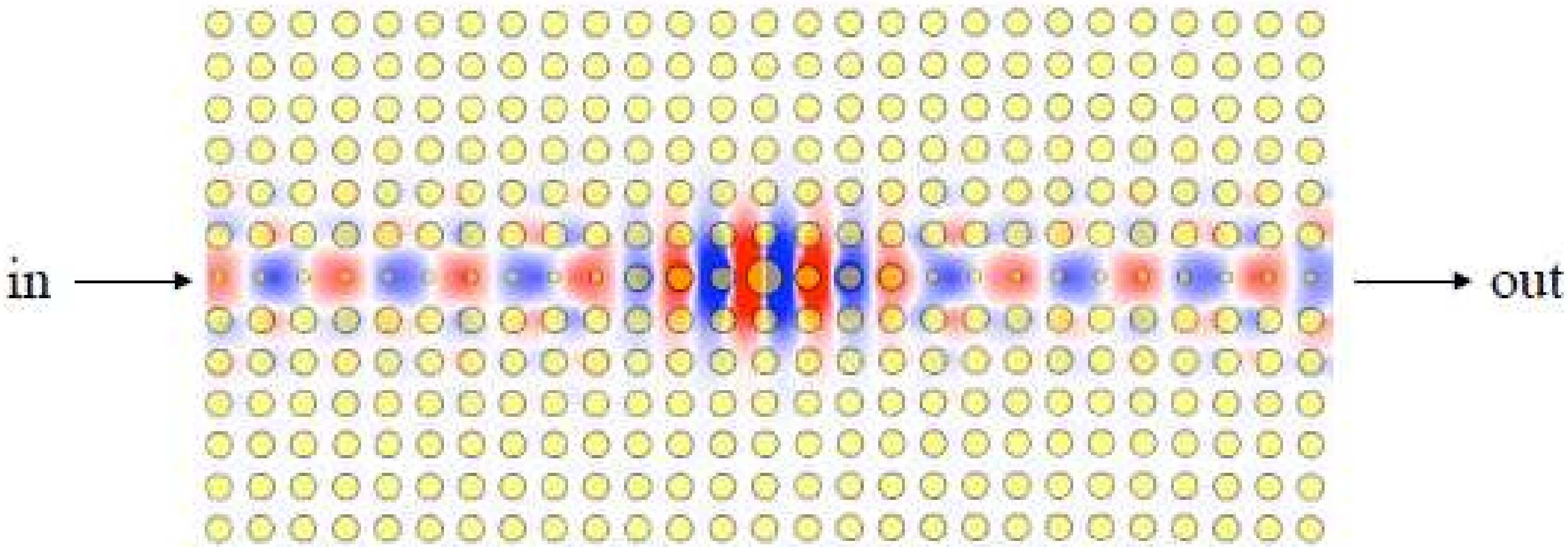
tight confinement (~ $\lambda/2$ diameter)

+ long lifetime (high Q independent of size)

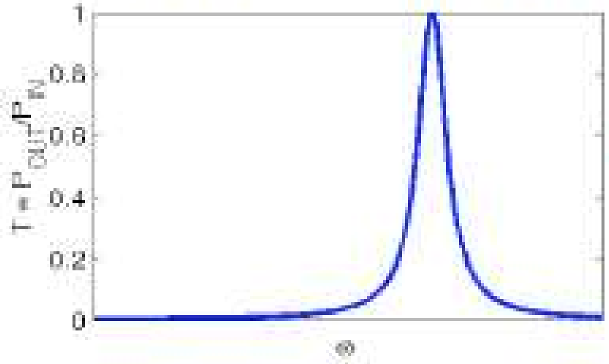
= enhanced nonlinear effects

e.g. Kerr nonlinearity, Δn ~ intensity

A ~~Linear~~ *Nonlinear* Filter

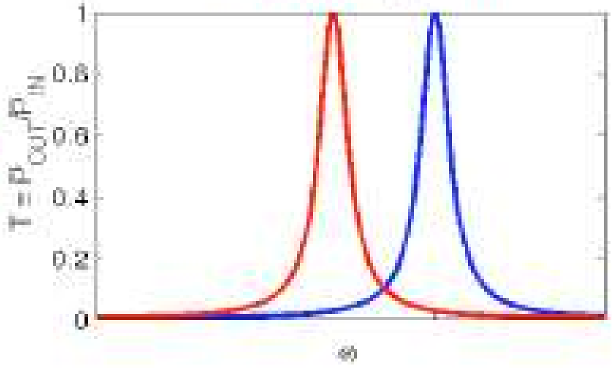


Linear response:
Lorenzian Transmisson



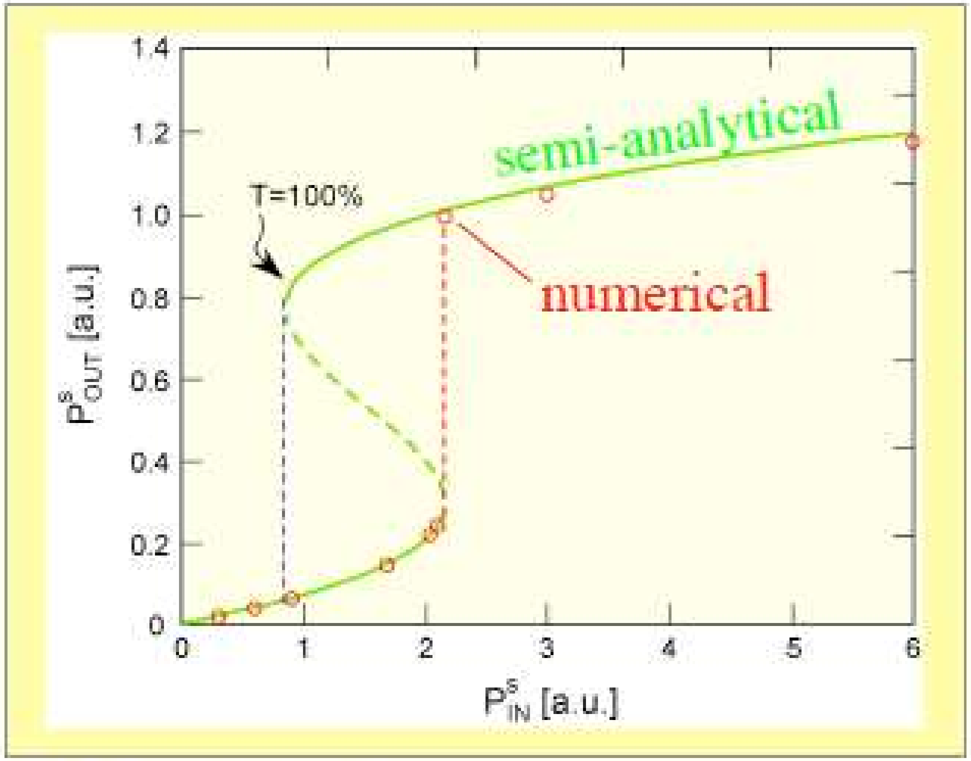
+ nonlinear index shift

shifted peak



PHYSICAL REVIEW E **66**, 055601(R) (2002)

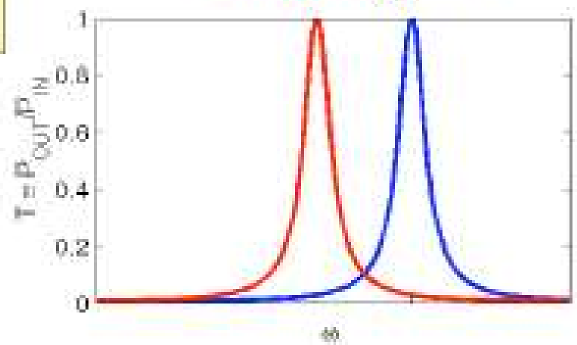
A ~~Linear~~ *Nonlinear* "Transistor"



Logic gates, switching, rectifiers, amplifiers, isolators, …

+ feedback

shifted peak



Bistable (hysteresis) response

Power threshold is near optimal
(~mW for Si and telecom bandwidth)

All-optical transistor action with bistable switching in a photonic crystal cross-waveguide geometry

Mehmet Fatih Yanik and Shanhui Fan

Ginzton Laboratory, Stanford University, Stanford, California 94304

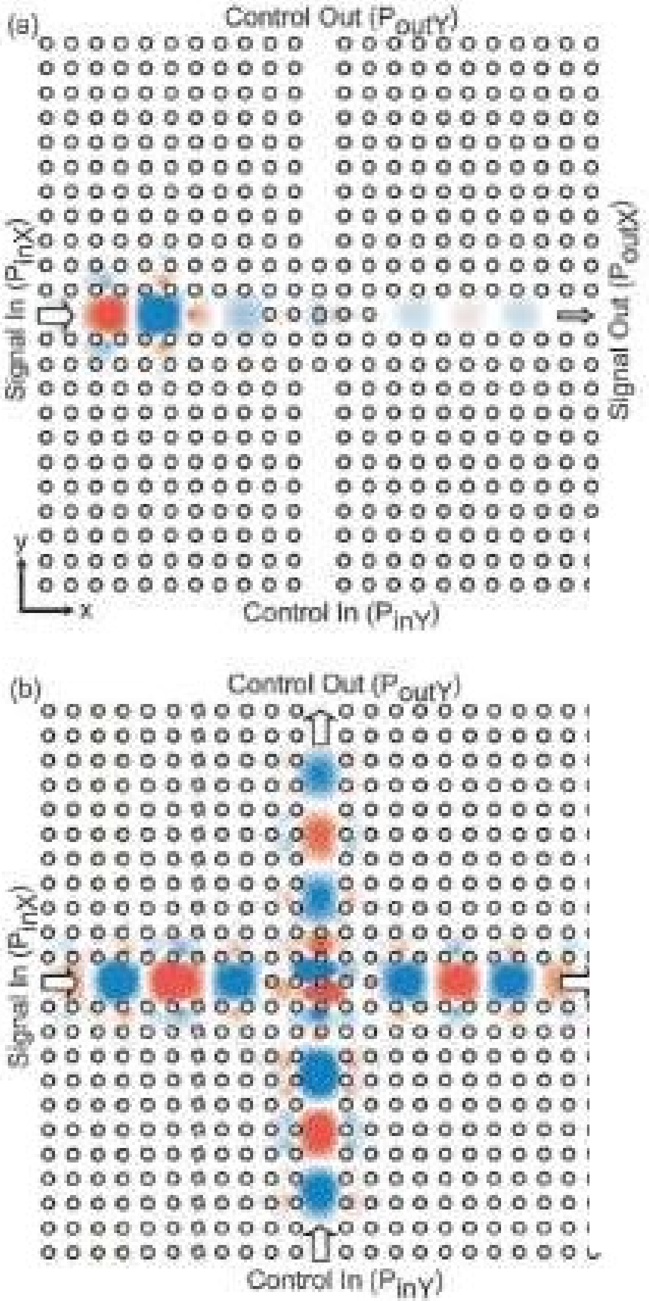
Marin Soljačić and J. D. Joannopoulos

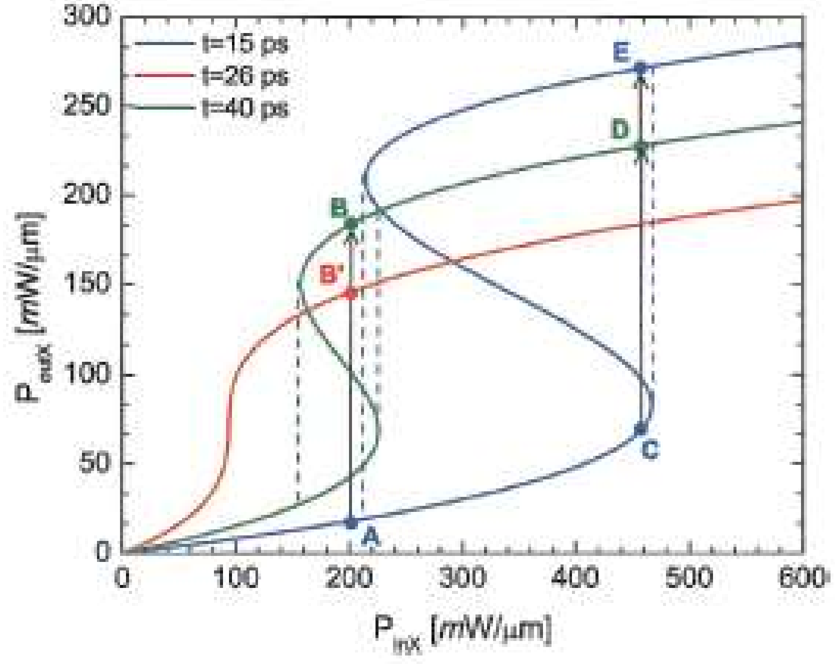
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

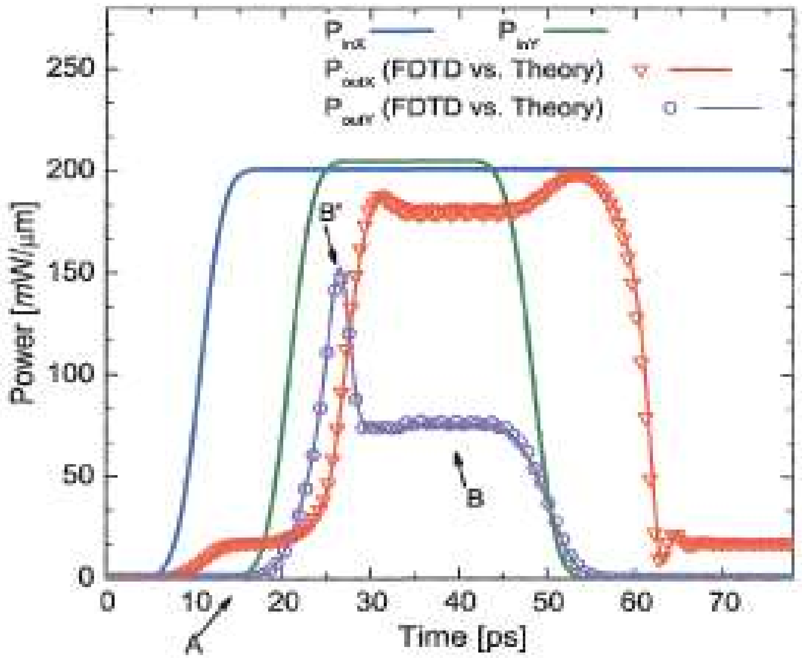
Received July 1, 2003

We demonstrate all-optical switching action in a nonlinear photonic crystal cross-waveguide geometry with instantaneous Kerr nonlinearity, in which the transmission of a signal can be reversibly switched on and off by a control input. Our geometry accomplishes both spatial and spectral separation between the signal and the control in the nonlinear regime. The device occupies a small footprint of a few micrometers squared and requires only a few milliwatts of power at a 10-Gbit/s switching rate by use of Kerr nonlinearity in AlGaAs below half the electronic bandgap. We also show that the switching dynamics, as revealed by both coupled-mode theory and finite-difference time domain simulations, exhibits collective behavior that can be exploited to generate high-contrast logic levels and all-optical memory.

OCIS codes: 130.4310, 190.1450, 230.4110, 230.5750, 130.3750.


(a)
Control Out (P_{outY})
Signal In (P_{inX})
Signal Out (P_{outX})
Control In (P_{inY})
y
x
(b)
Control Out (P_{outY})
Signal In (P_{inX})
Control In (P_{inY})


t=15 ps
t=26 ps
t=40 ps
A
B
B'
C
D
E
P_{outX} [mW/μm]
P_{inX} [mW/μm]
0
50
100
150
200
250
300
0
100
200
300
400
500
600


P_{inX}
P_{inY}
P_{outX} (FDTD vs. Theory)
P_{outY} (FDTD vs. Theory)
B'
B
A
Power [mW/μm]
Time [ps]
0
50
100
150
200
250
0
10
20
30
40
50
60
70

Outline

- Preliminaries: waves in periodic media
- Photonic crystals in theory and practice
- Intentional defects and devices
- Index-guiding and incomplete gaps
- Photonic-crystal fibers
- Perturbations, tuning, and disorder

The advantages of light over electrons in information communicating

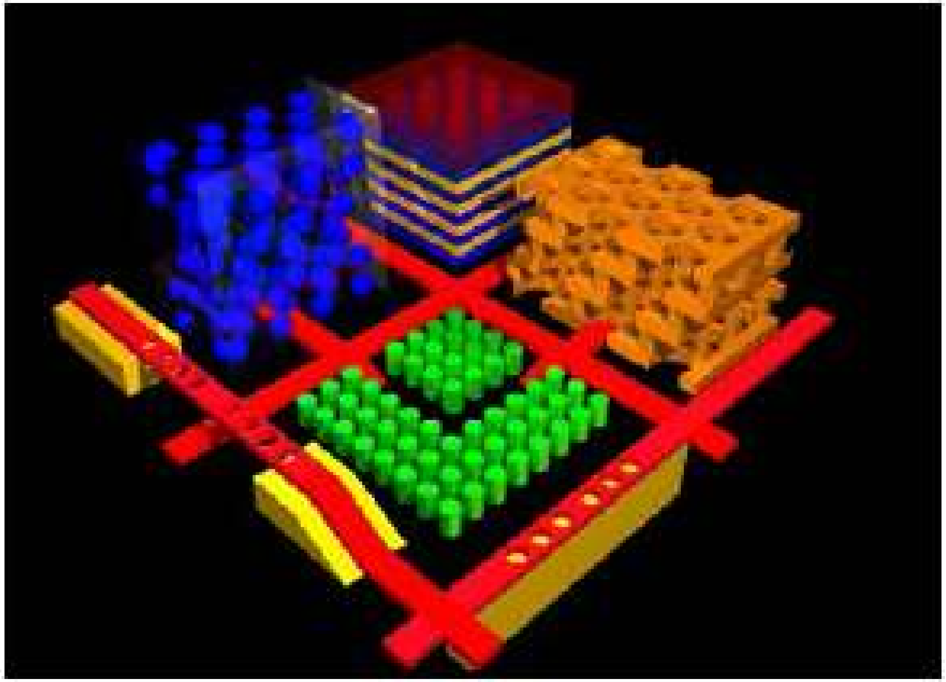
- The speed (travel much faster in dielectric material than electron in metallic wire)

- The frequency each can carry (bandgap) information density(optical fiber– terahertz 10^12, wire- 10^5Hz

- save energy (electrons strongly interact, lose energy) Miniaturization of electron circuits results increased resistance and power dissipation

A bundle of optical fibers

- In order to achieve a better system performance and integration, instead of electrons, researchers are turning to light, or photon as the information carrier, and working on constructing photon circuits.

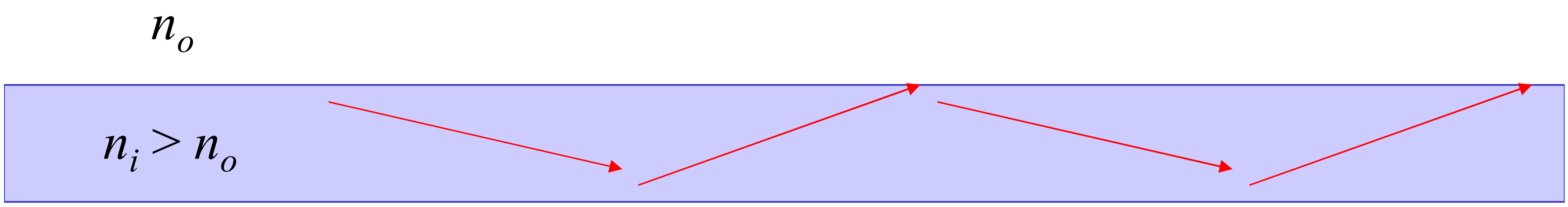


Guide light along narrow channel and around tight corners

J. Joannopoulos, "Photonic crystal: Molding the flow of light", Princeton Univ. 2008

How *else* can we confine light?

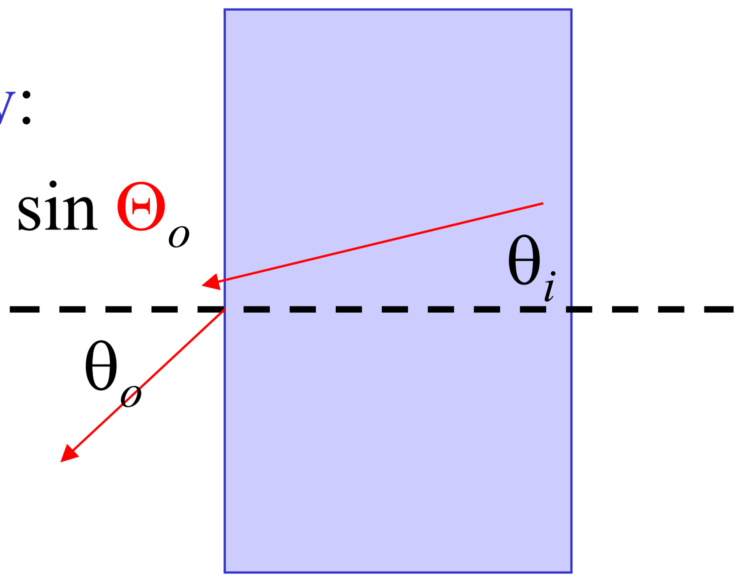
Total Internal Reflection



rays at shallow angles > Θ_c
are totally reflected

Snell's Law:

$$n_i \sin \Theta_i = n_o \sin \Theta_o$$

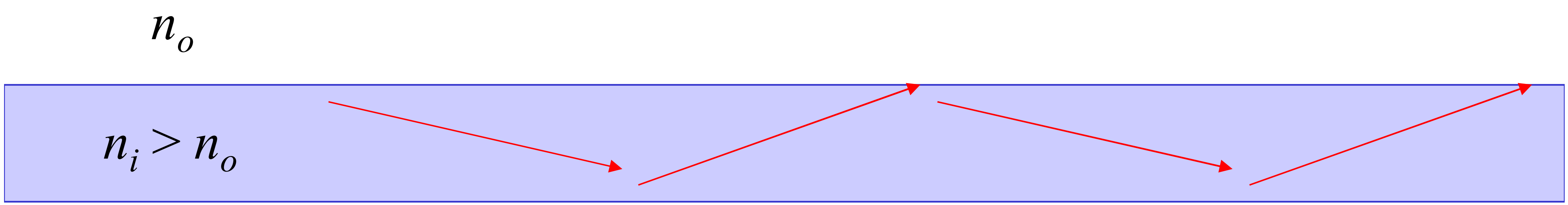


$$\sin \Theta_c = n_o / n_i$$

< 1, so Θ_c is real

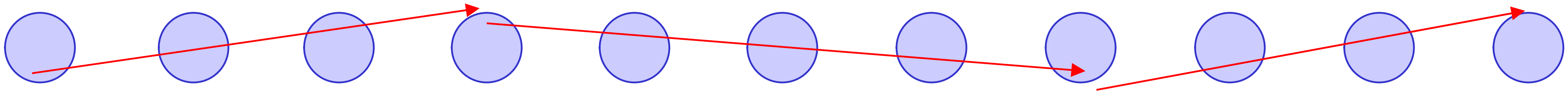
i.e. TIR can only guide
within higher index
unlike a band gap

Total Internal Reflection?



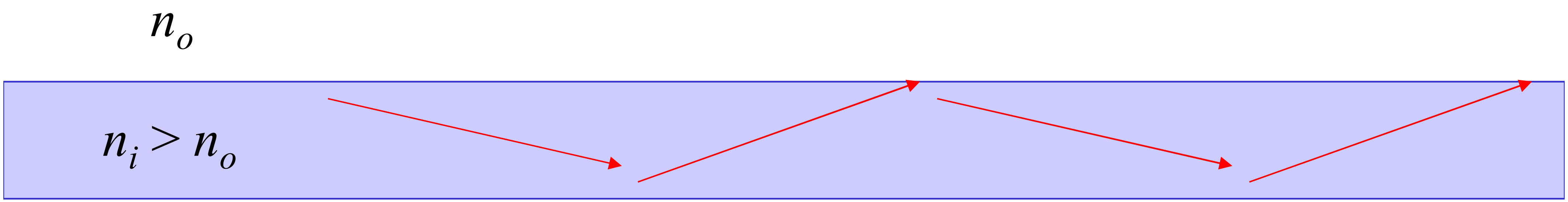
rays at shallow angles > Θ_c
are totally reflected

So, for example,
a discontiguous structure can't possibly guide by TIR…



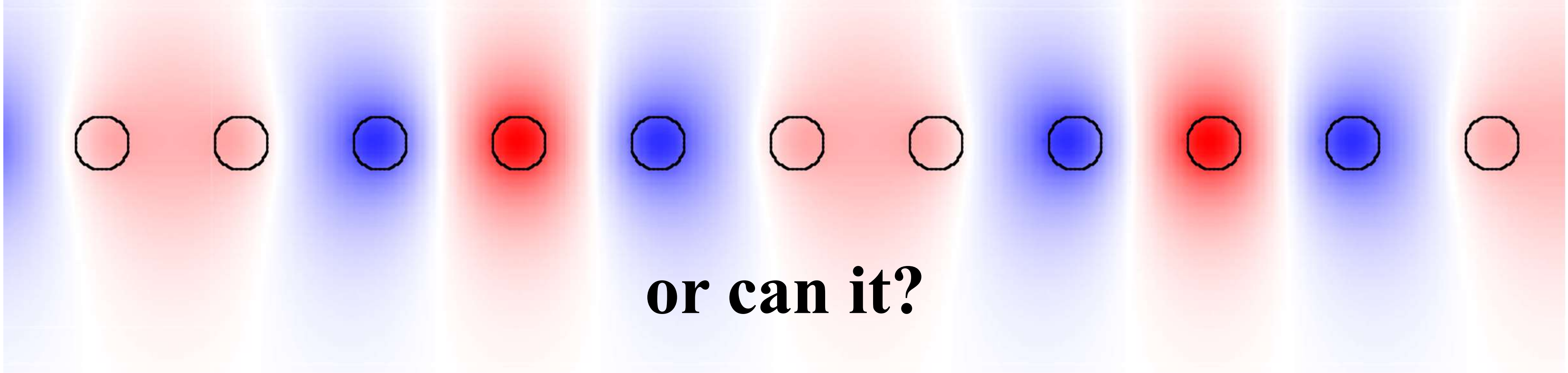
the rays can't stay inside!

Total Internal Reflection?



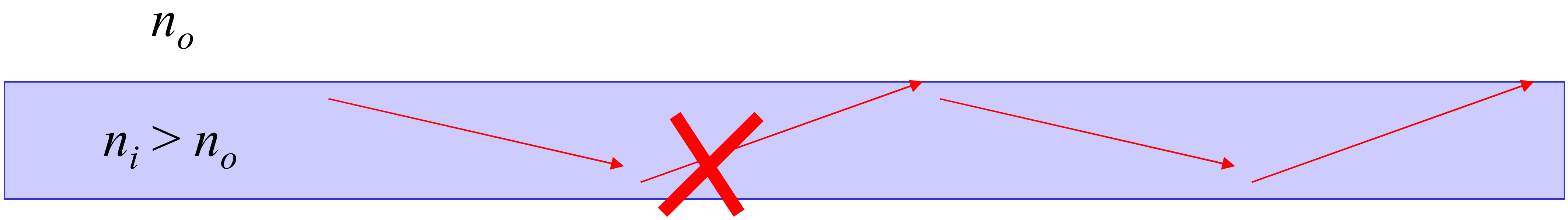
rays at shallow angles > θ_c
are totally reflected

So, for example,
a discontiguous structure can't possibly guide by TIR…



or can it?

Total Internal Reflection Redux



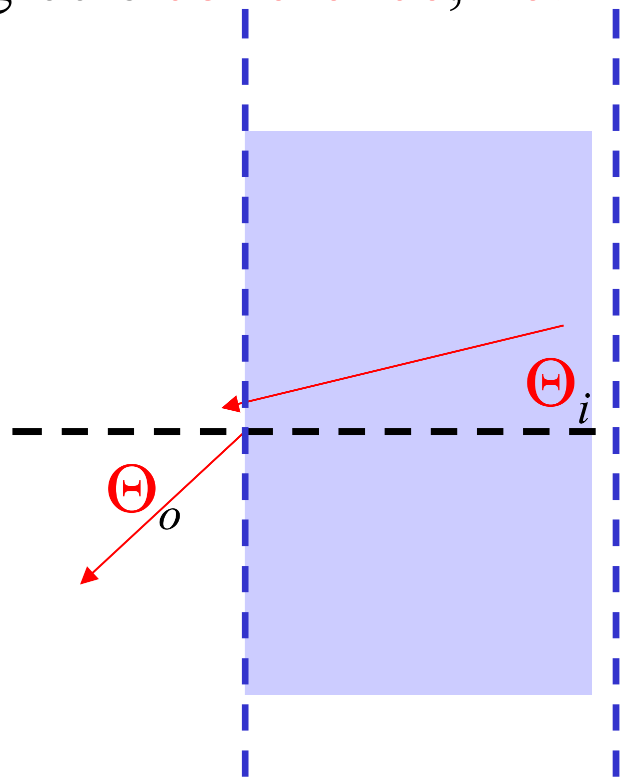
ray-optics picture is invalid on λ scale
(neglects coherence, near field…)

Snell's Law is really
conservation of $k_{||}$ and ω:

$$|k_i| \sin \Theta_i = |k_o| \sin \Theta_o$$

$$|k| = n\omega/c$$

(wavevector) (frequency)



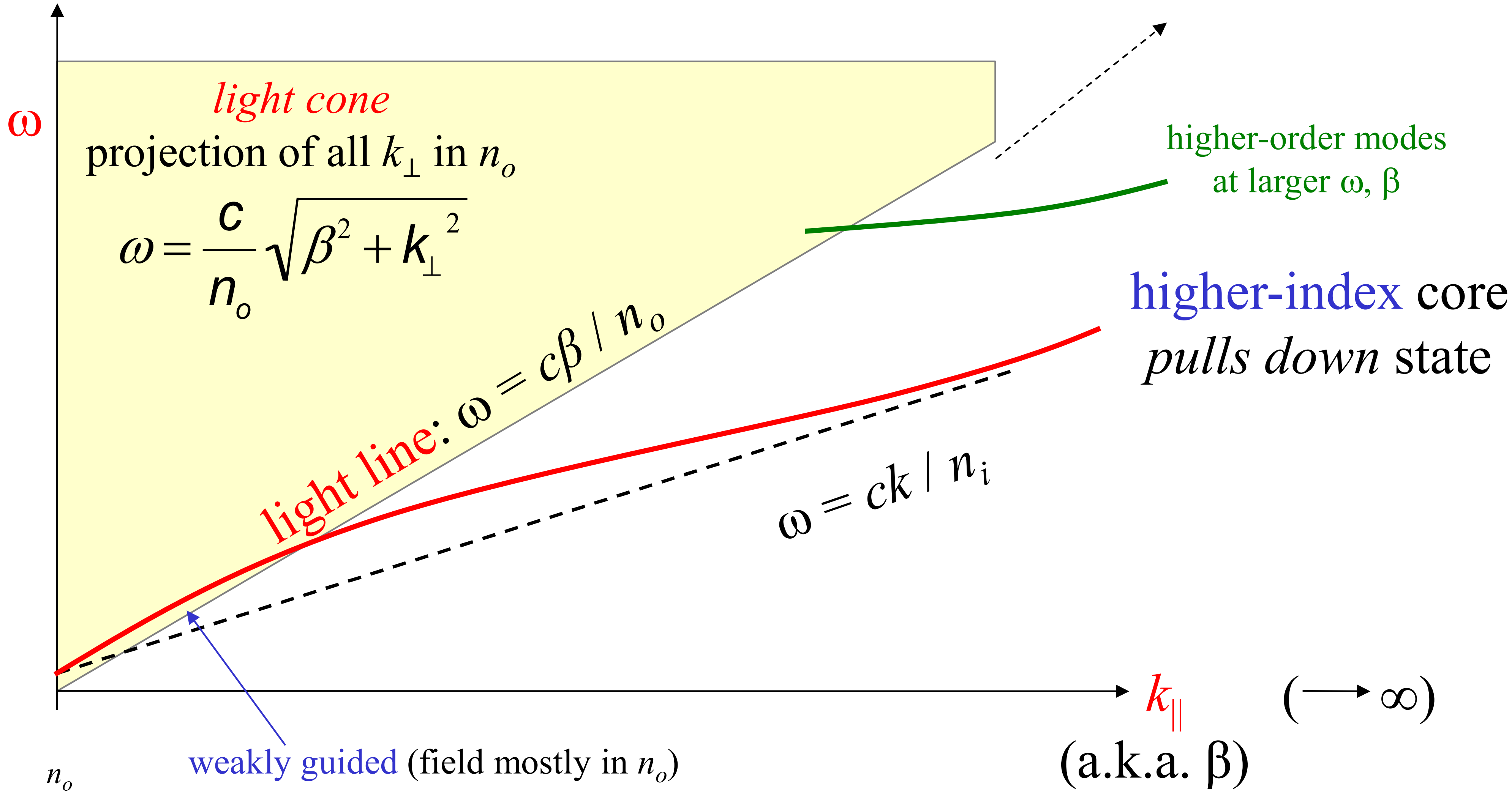
translational symmetry

$k_{||}$ ↓

conserved!

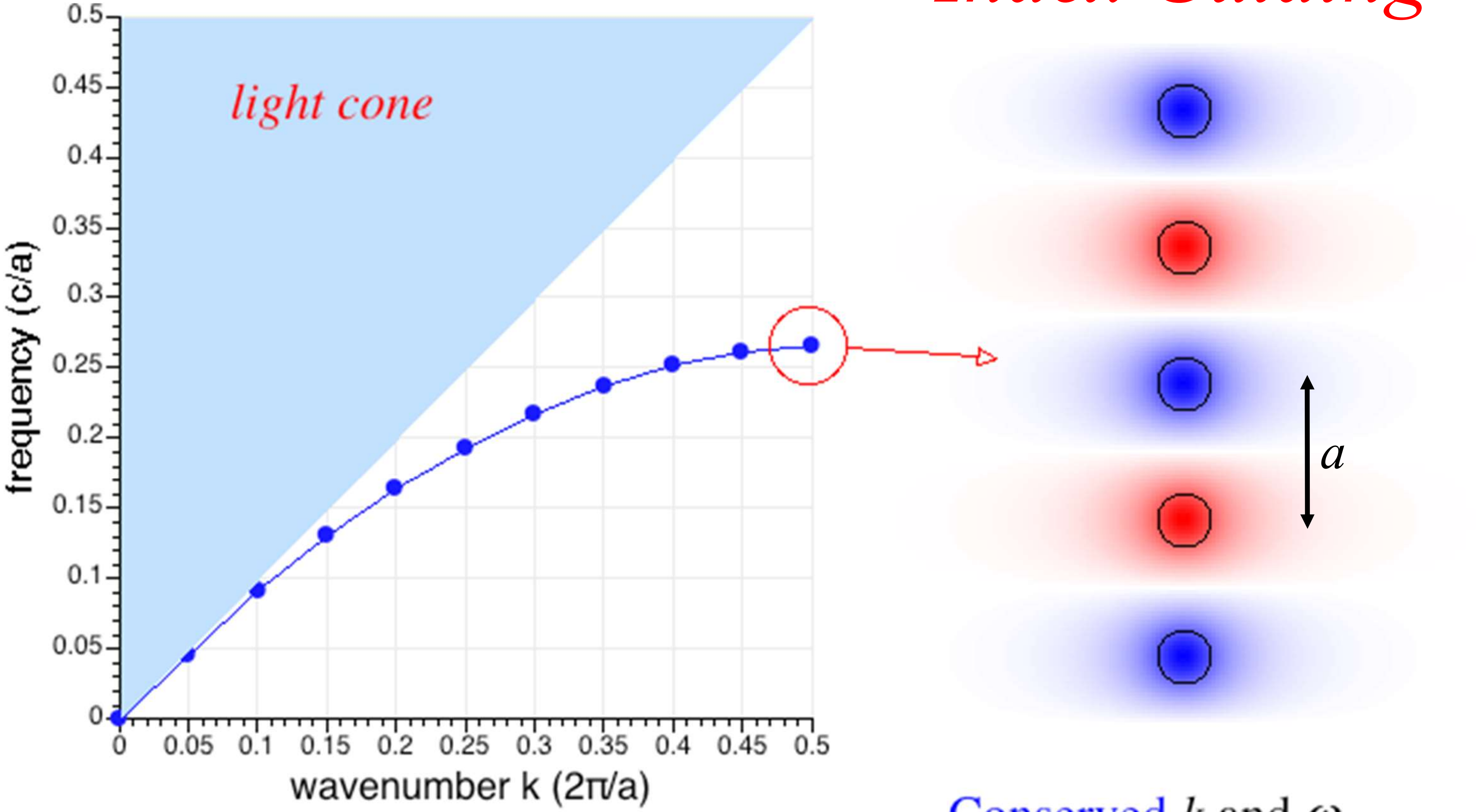
Waveguide Dispersion Relations

i.e. projected band diagrams



$n_i > n_o$

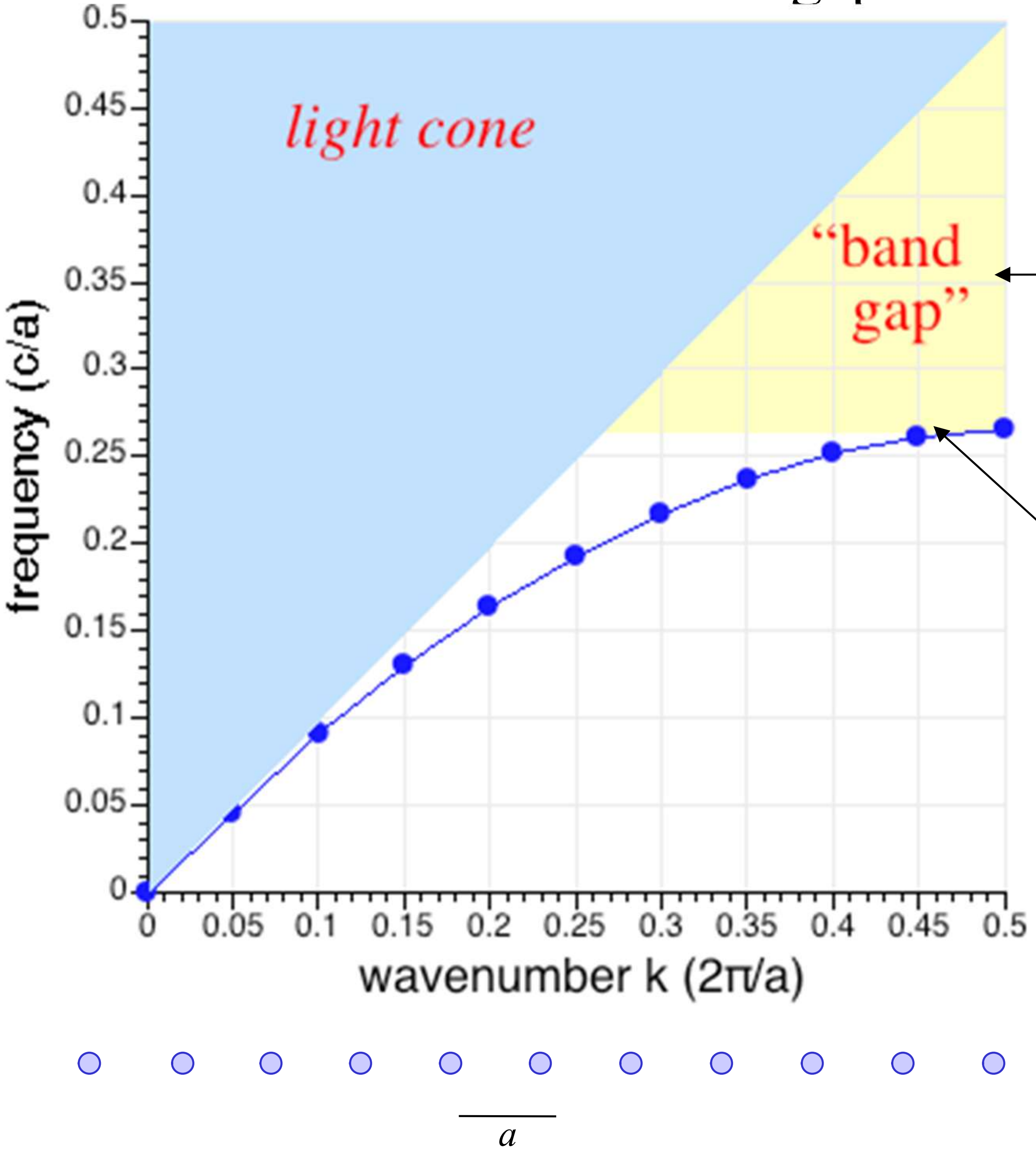
Strange ~~Total Internal Reflection~~ *Index Guiding*



Conserved k and ω
+ higher index to pull down state
= localized/guided mode.

A Hybrid Photonic Crystal:

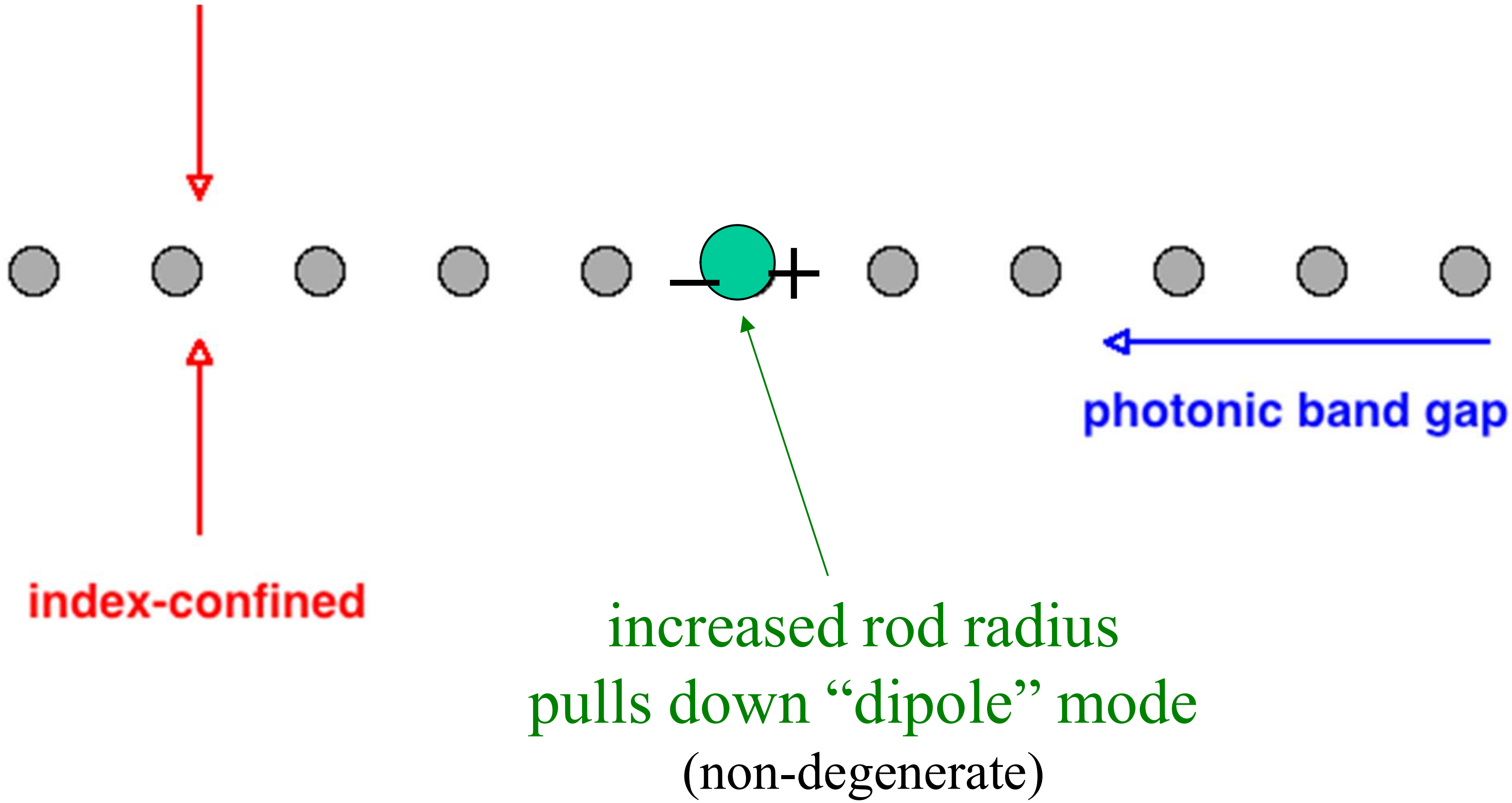
1d band gap + index guiding



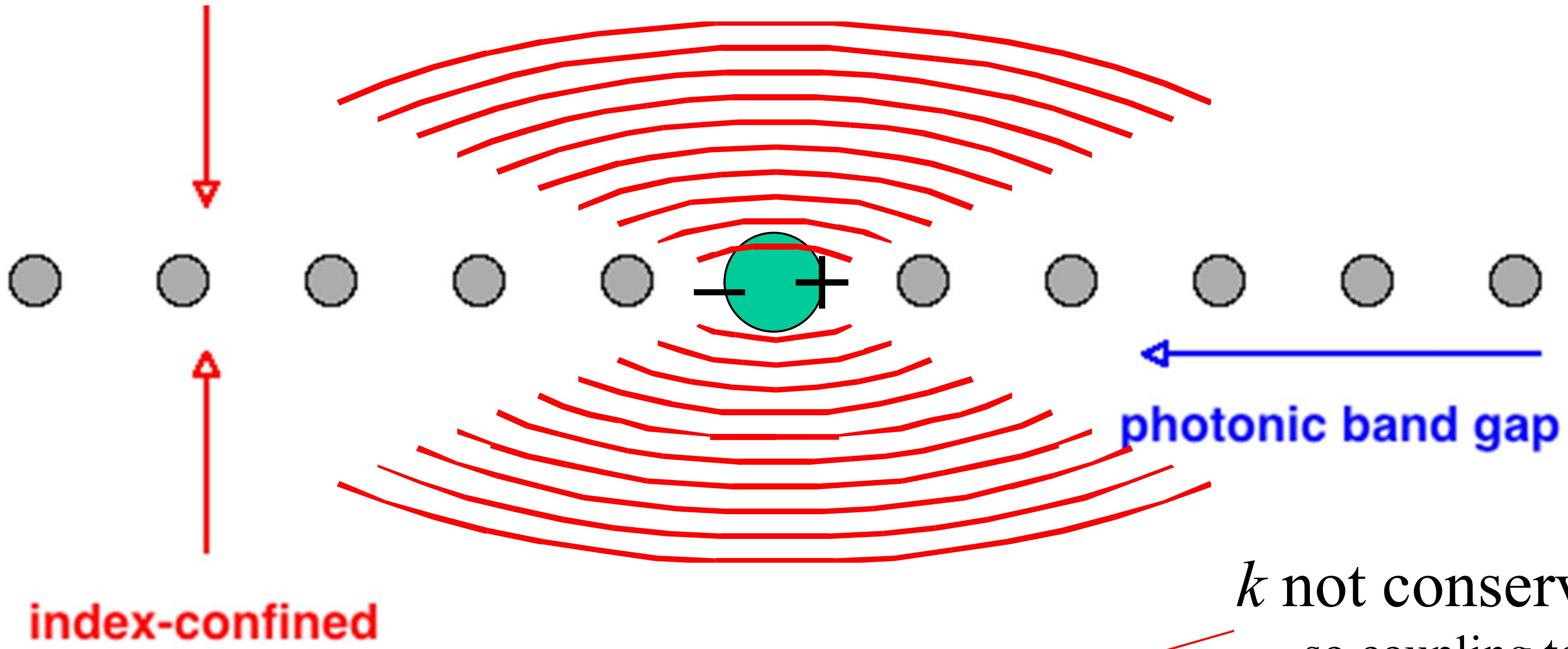
range of frequencies in which there are no guided modes

slow-light band edge

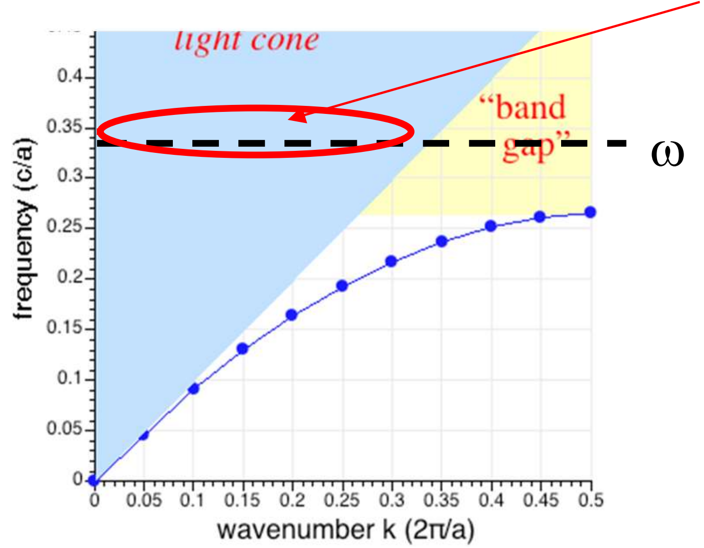
A Resonant Cavity



A Resonant Cavity



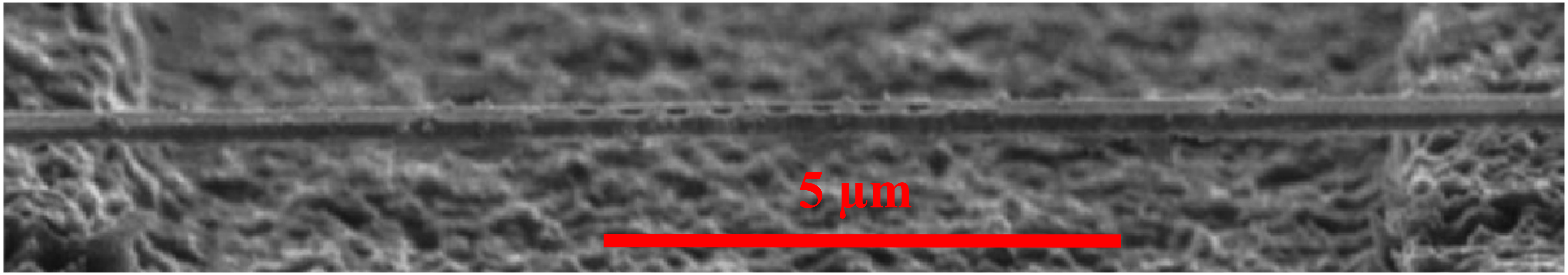
k not conserved
so coupling to
light cone:
radiation

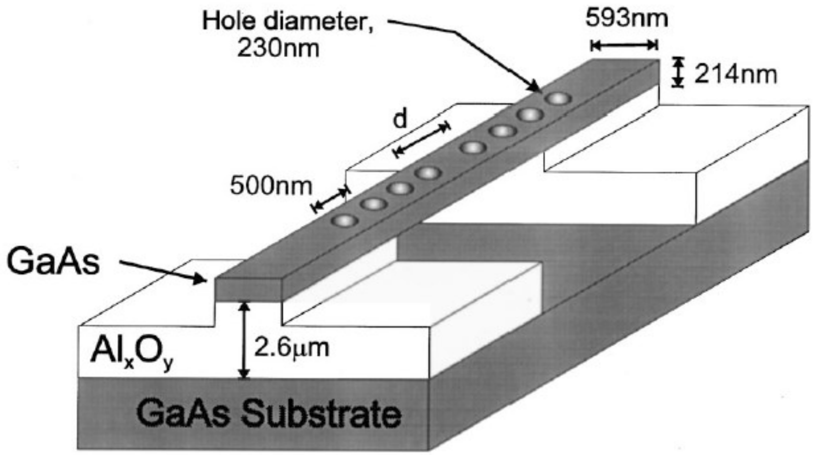


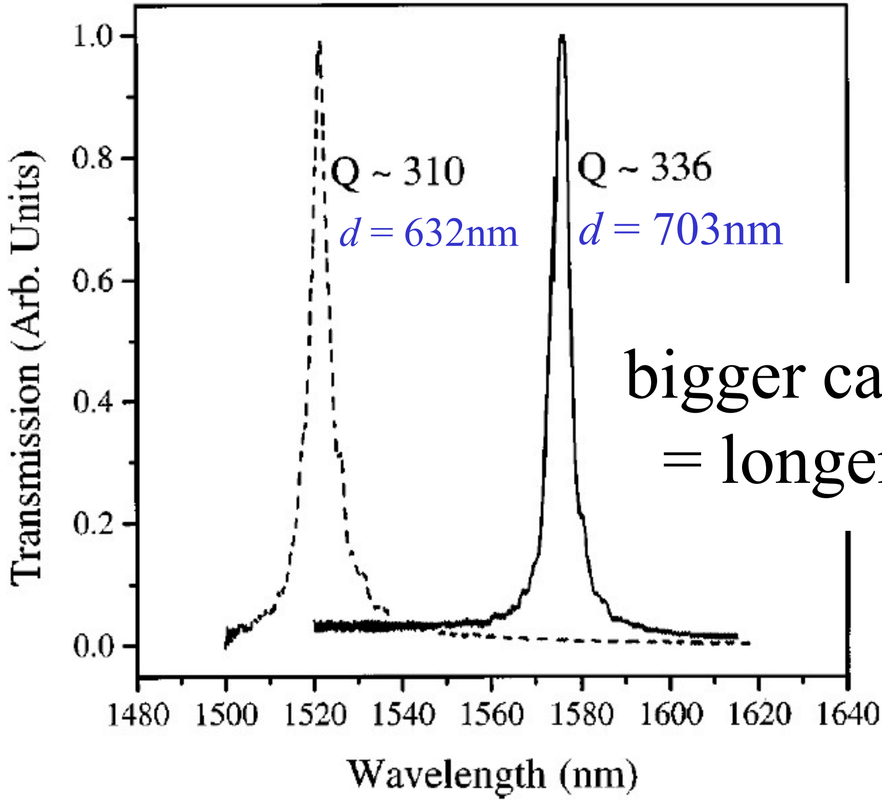
The trick is to
keep the
radiation small…
(more on this later)

Meanwhile, back in reality…

Air-bridge Resonator: 1d gap + 2d index guiding







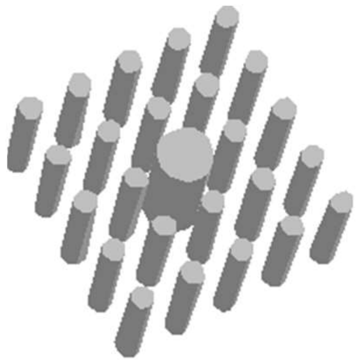
bigger cavity = longer λ

[D. J. Ripin *et al.*, *J. Appl. Phys.* **87**, 1578 (2000)]

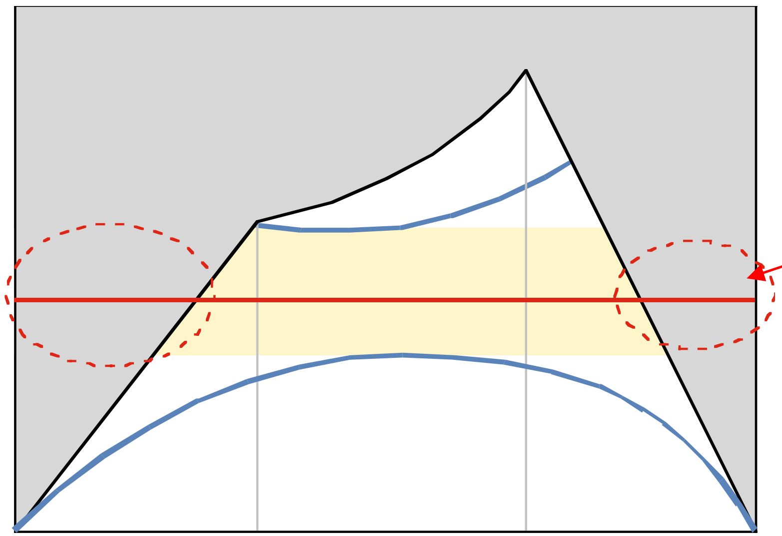
Inevitable Radiation Losses

whenever translational symmetry is broken

e.g. at cavities, waveguide bends, disorder…



ω
(conserved)



coupling to light cone
= radiation losses

k is *no longer* conserved!

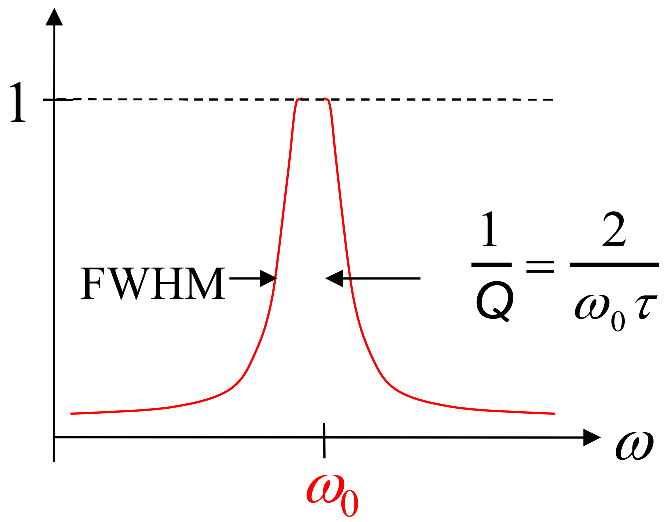
Dimensionless Losses: Q

quality factor Q = # optical periods for energy to decay by exp(–2π)

energy ~ exp(–ω t/Q)

in frequency domain: $1/Q$ = bandwidth

from last time:
(coupling-of-modes-in-time)



$$\frac{1}{Q} = \frac{2}{\omega_0 \tau}$$

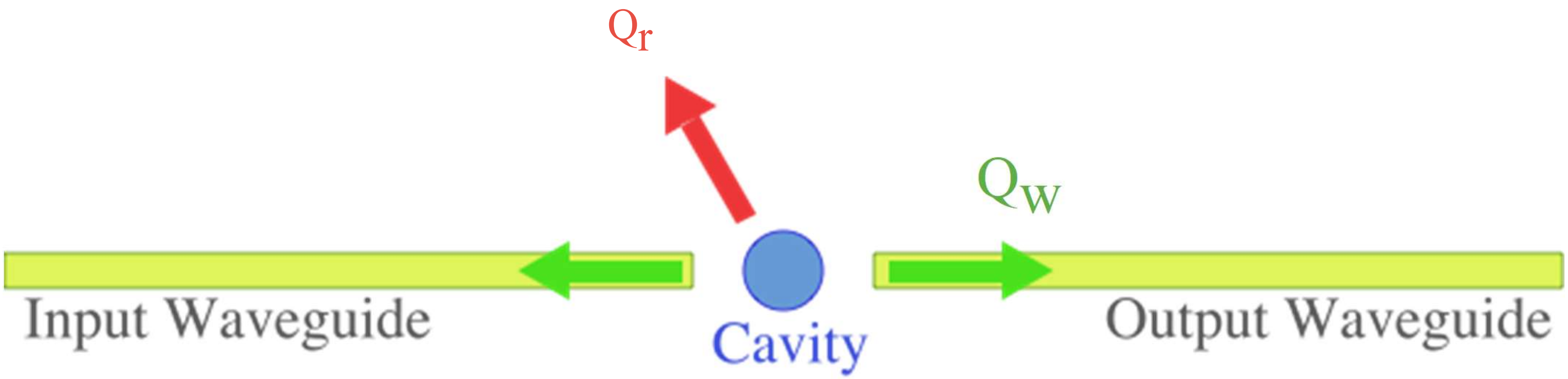
T = Lorentzian filter

$$= \frac{\frac{4}{\tau^2}}{(\omega - \omega_0)^2 + \frac{4}{\tau^2}}$$

…quality factor Q

All Is Not Lost

A simple model device (filters, bends, …):



$$\frac{1}{Q} = \frac{1}{Q_r} + \frac{1}{Q_w}$$

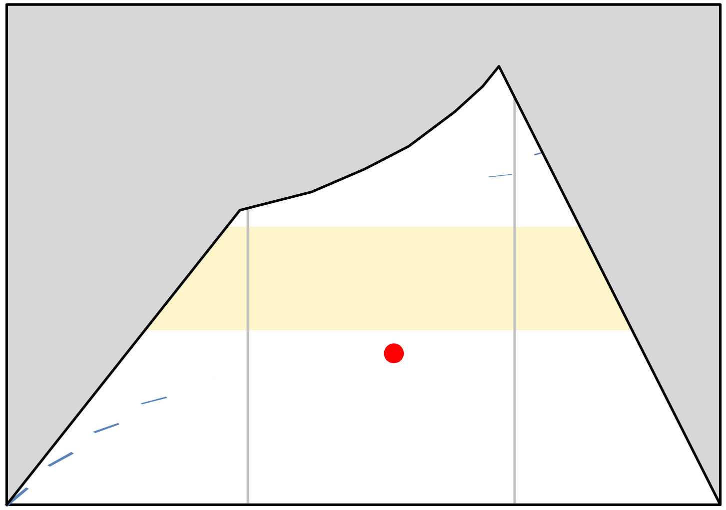
Q = lifetime/period
= frequency/bandwidth

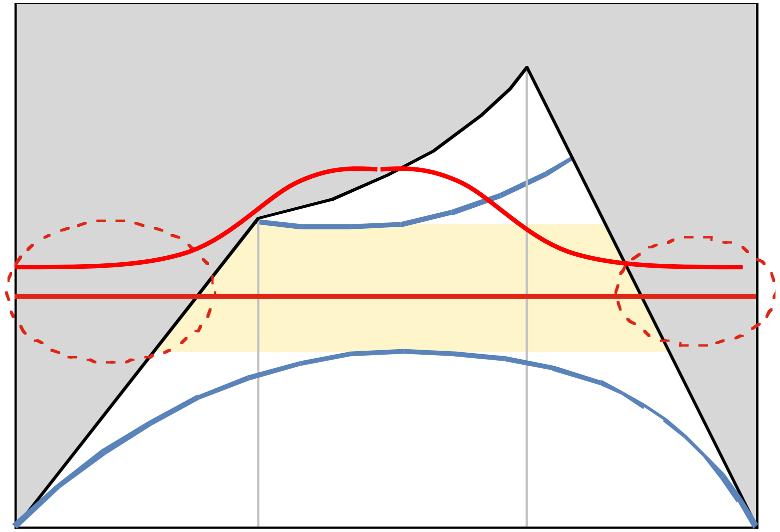
We want: $Q_r >> Q_w$

1 – transmission ~ 2Q / Q_r

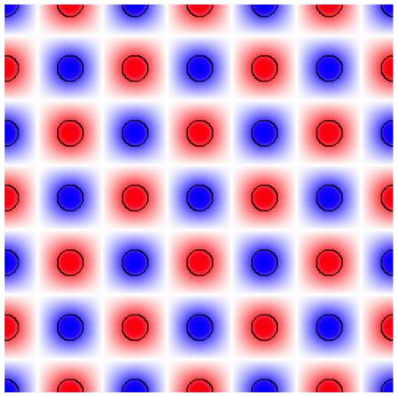
***worst case*:** high-Q (narrow-band) cavities

Radiation loss: A Fourier picture

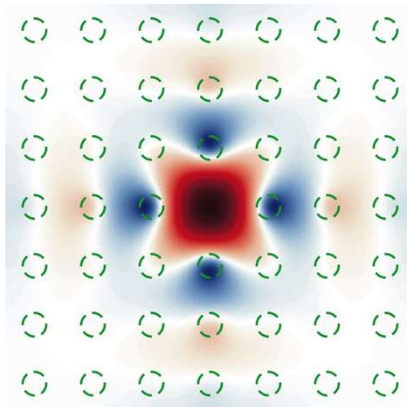




spatial:

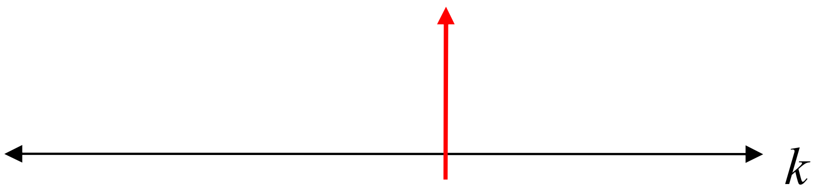


infinitely extended in space

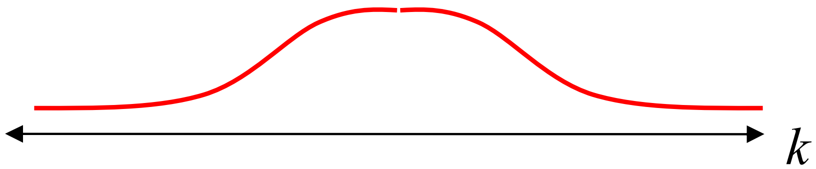


localized in space

Fourier:



delta function(s) [Fourier series]
below light cone = no radiation



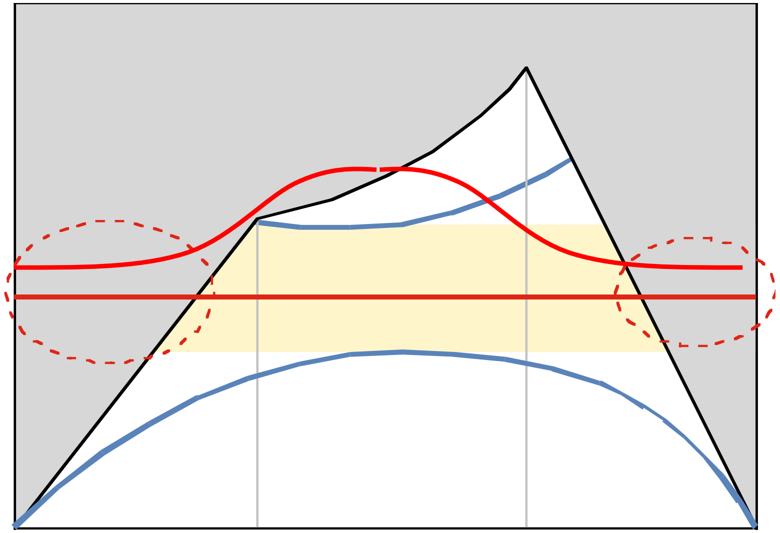
delocalized in Fourier
tails in light cone = radiation

A tradeoff: Localization vs. Loss

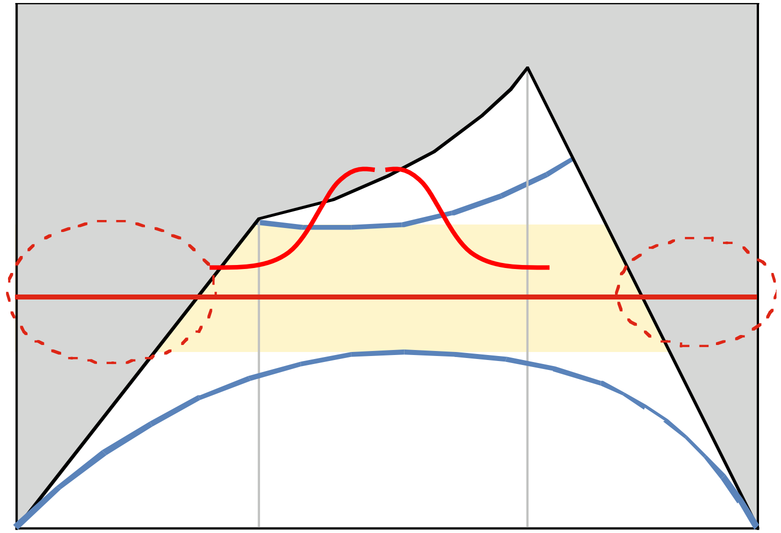
"Uncertainty principle:"

less spatial localization = *more Fourier* localization

= less radiation loss

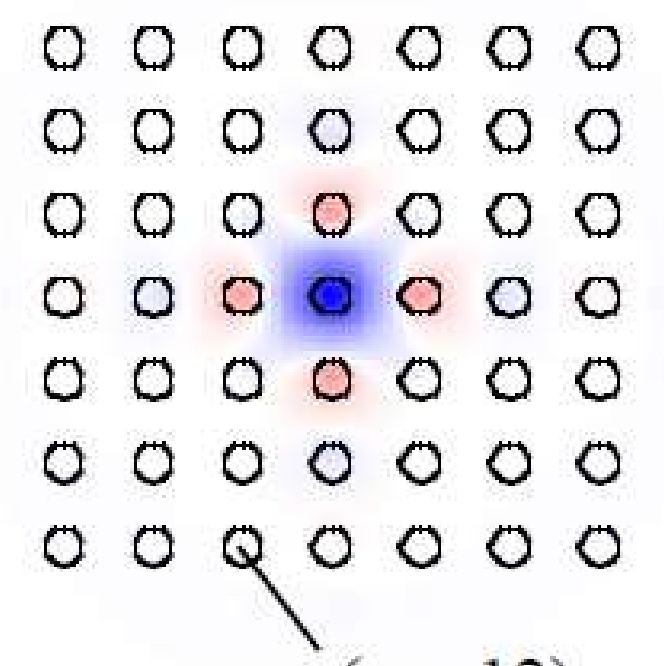


stronger spatial localization

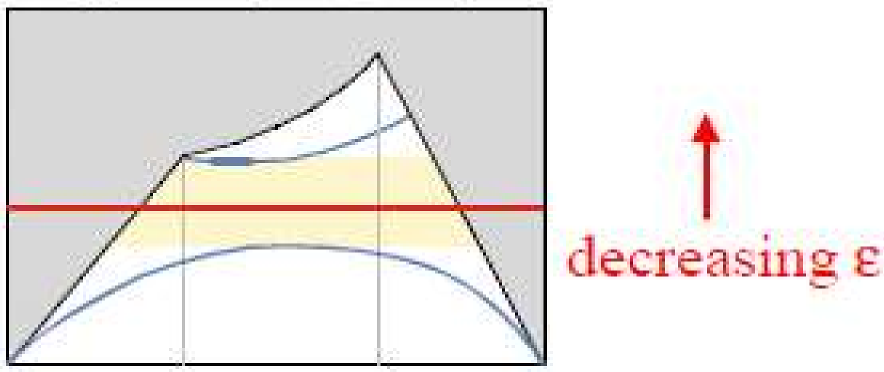


weaker spatial localization

Monopole Cavity in a Slab

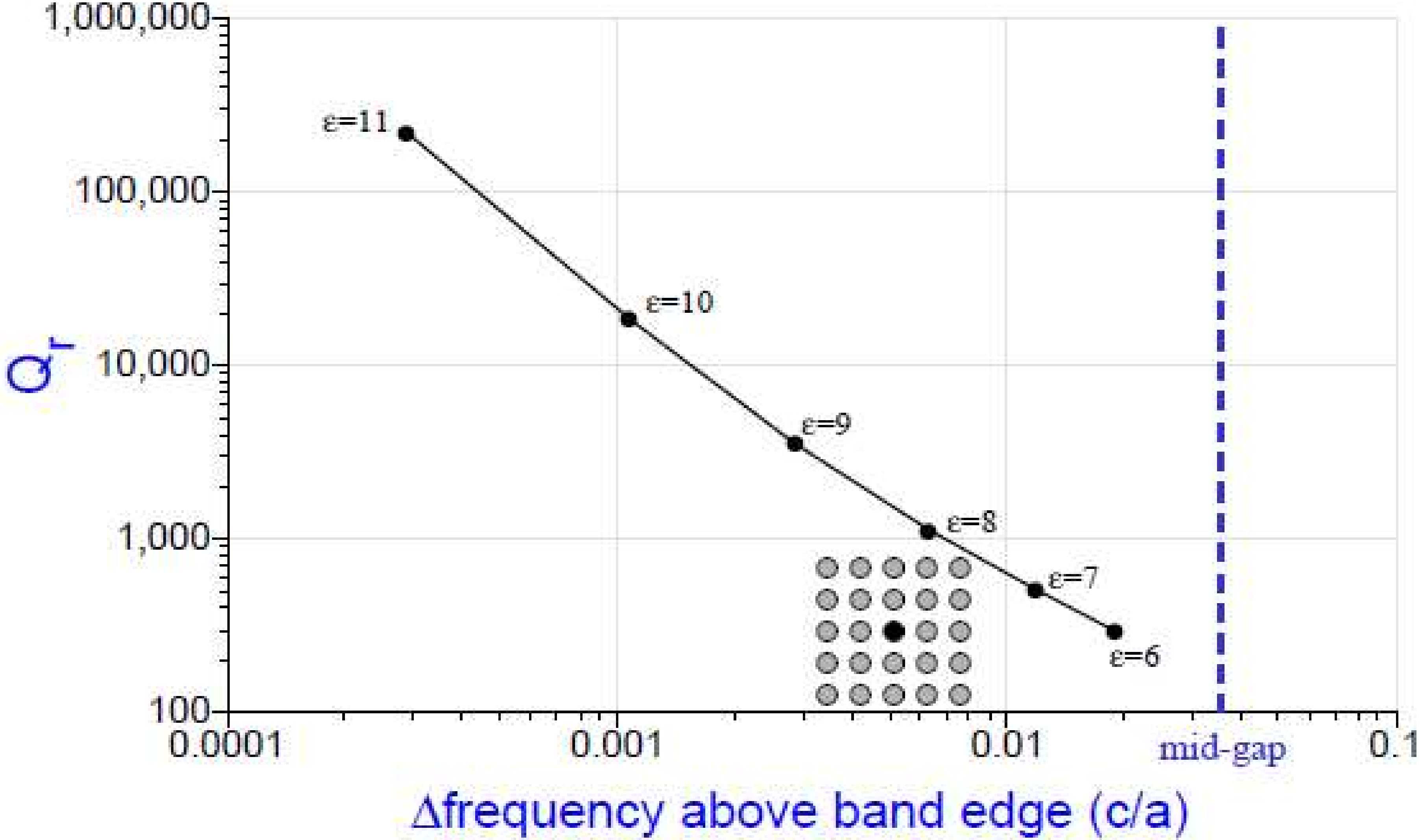


Lower the ε of a single rod: push up a monopole (singlet) state.

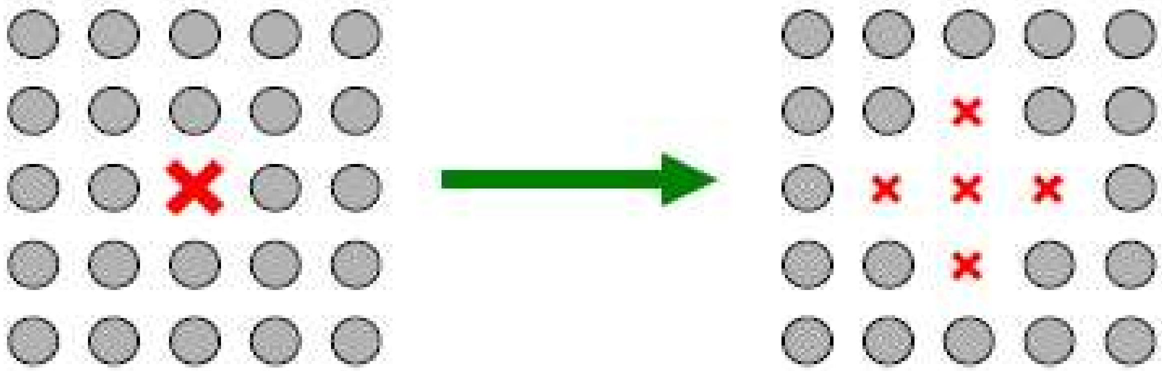


Use small Δε: delocalized in-plane, & high-Q (we hope)

Delocalized Monopole Q



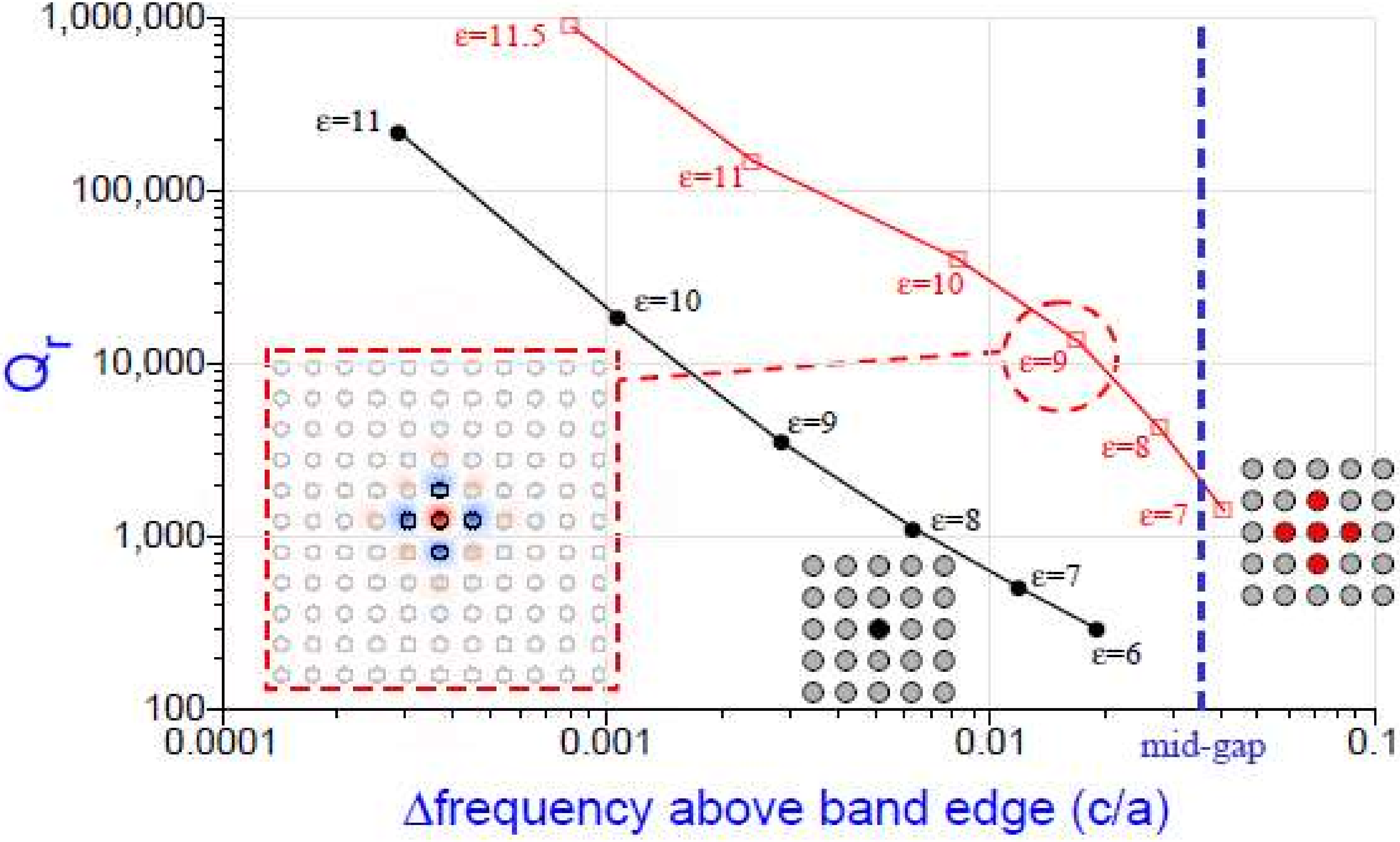
Super-defects



Weaker defect with more unit cells.

More delocalized
at the same point in the gap
(*i.e.* at same bulk decay rate)

Super-Defect vs. Single-Defect Q

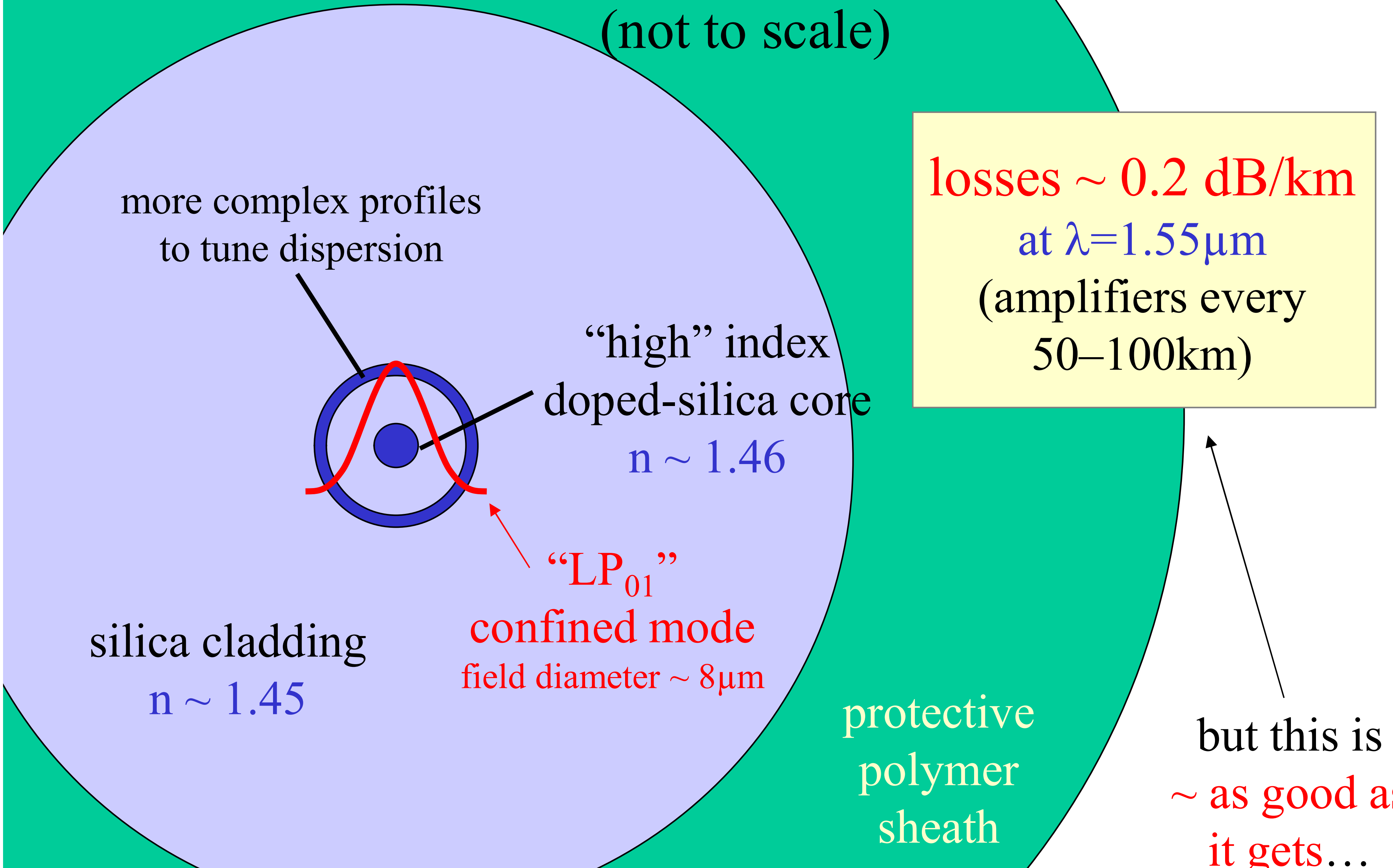


Outline

- Preliminaries: waves in periodic media
- Photonic crystals in theory and practice
- Intentional defects and devices
- Index-guiding and incomplete gaps
- Photonic-crystal fibers
- Perturbations, tuning, and disorder

Optical Fibers Today

(not to scale)

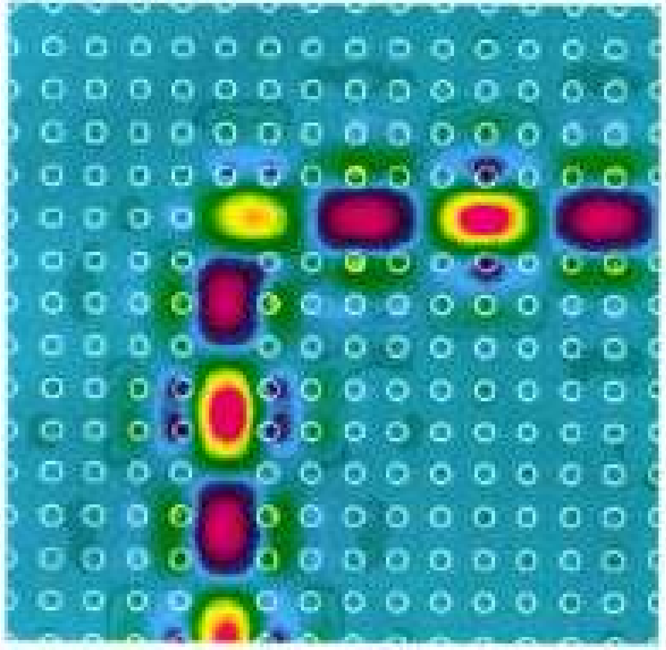


[R. Ramaswami & K. N. Sivarajan, *Optical Networks: A Practical Perspective*]

Advantages over optical fiber

To control light, optical fiber uses total internal reflection

The disadvantage of normal optical fiber is the interface must be smooth respect to the wavelength of light



photonic crystal is totally a different mechanism, based on bandgap

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

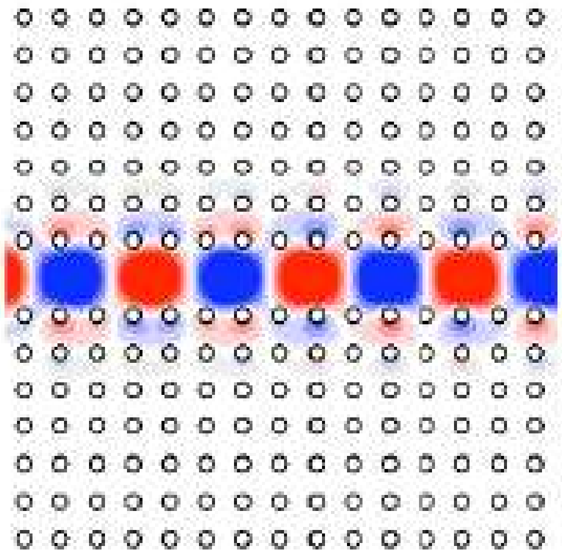
High Bit-Rates

Dense Wavelength Multiplexing (DWDM)

Compact Devices

Advantages over optical fiber

Guiding is NOT possible through air for optical fiber



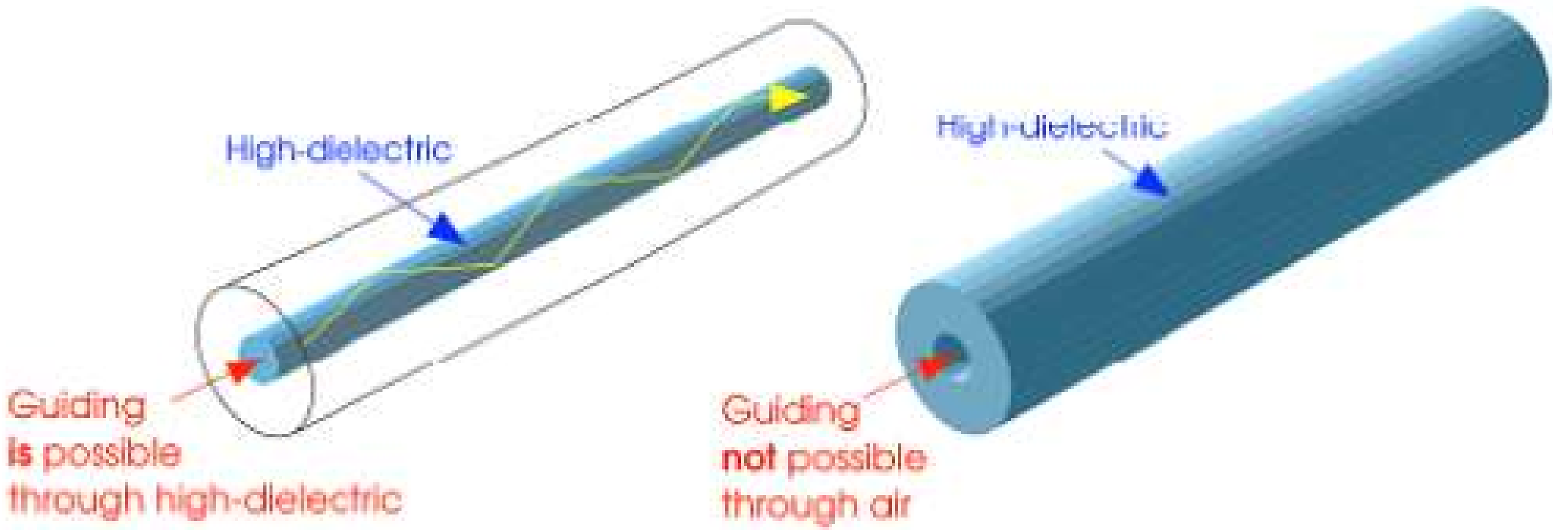
Guiding Optical Light through Air

Reduction of Absorption Losses

Reduction of Non-Linearity Effects

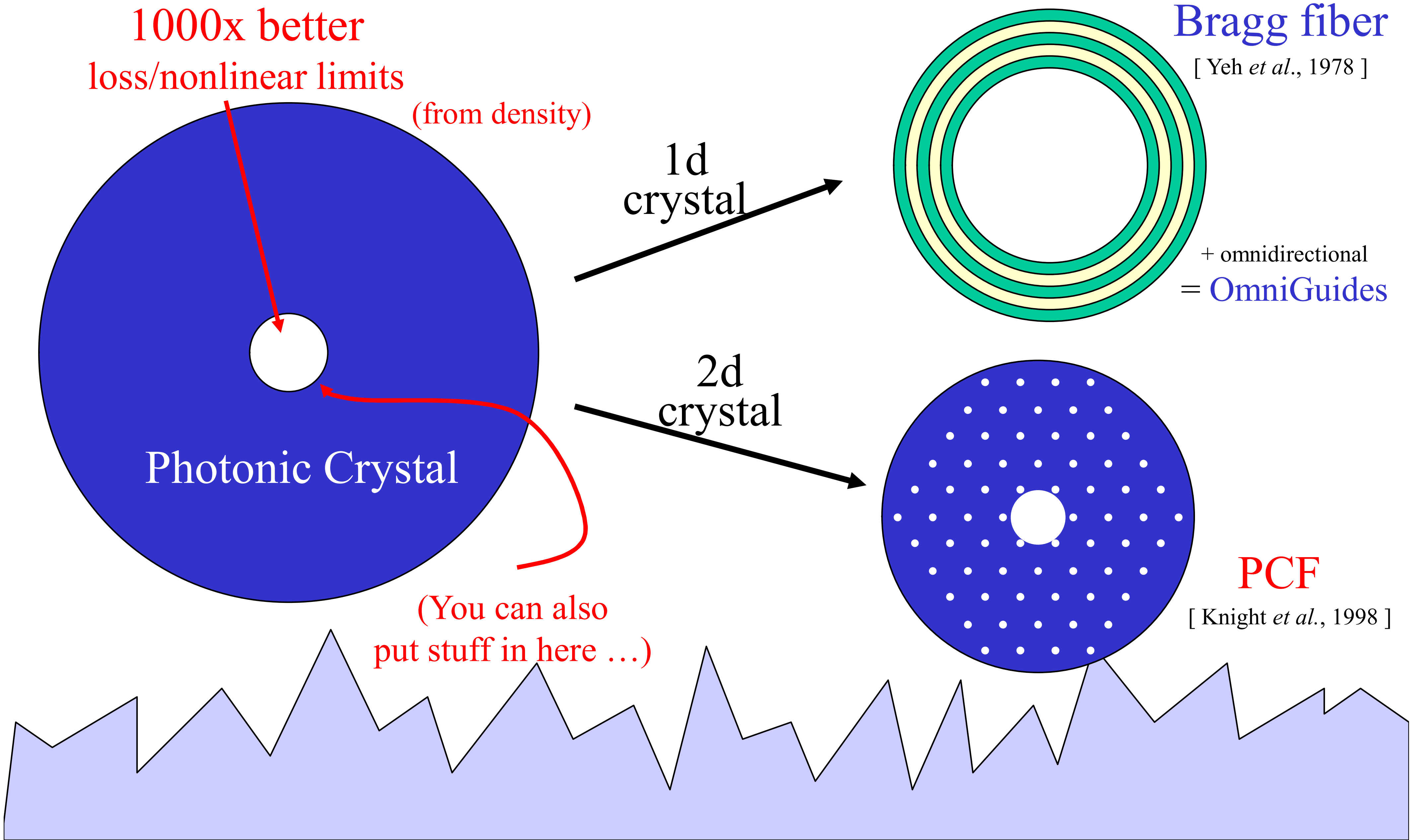
High Power Transmission

Total Internal Reflection



Breaking the Glass Ceiling:

Hollow-core Bandgap Fibers



Hollow fiber core

P. Russel Science 299, 358 (2003) for a review

Fabrication techniques:

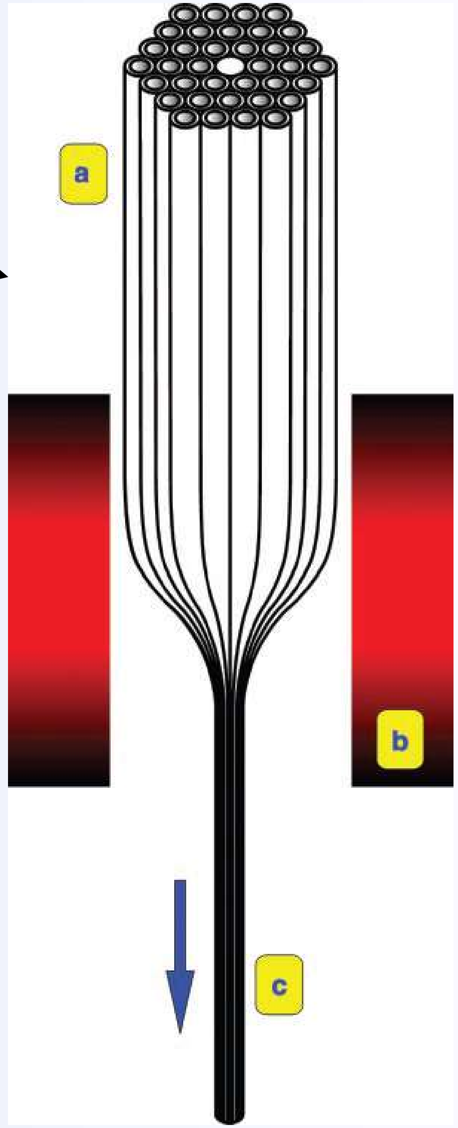
- a stack of glass tube, is constructed as a macroscopic “preform” with the desired PC structure (a)

the silica glass is soften in a fornace 1800-2000° C (b)

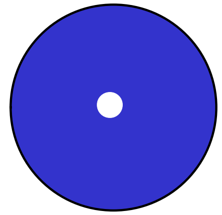
drawn down in fiber (c)

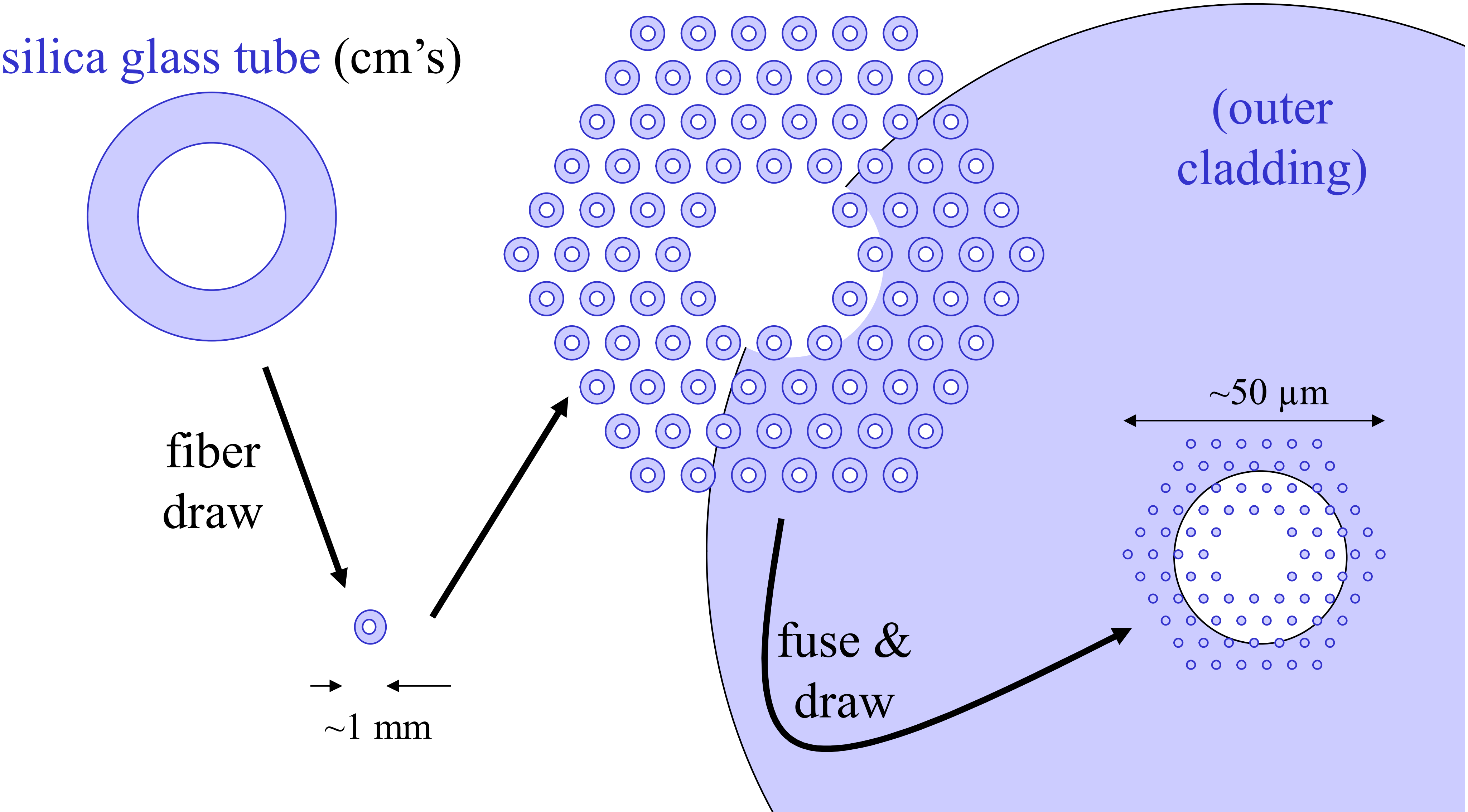
(first used in III century BC by Egyptians to make mosaic glass)

R. J. Tonucci, B. L. Justus, A. J. Campillo, C. E. Ford, Science **258**, 783 (1992).



Experimental Air-guiding PCF

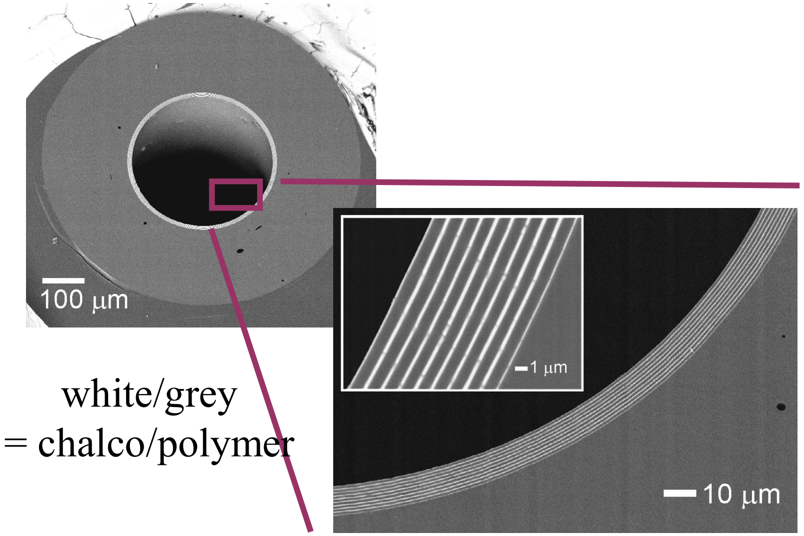

Fabrication (e.g.)



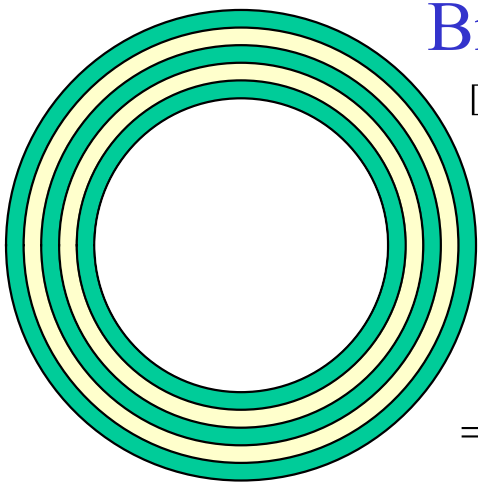
Breaking the Glass Ceiling:

Hollow-core Bandgap Fibers

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



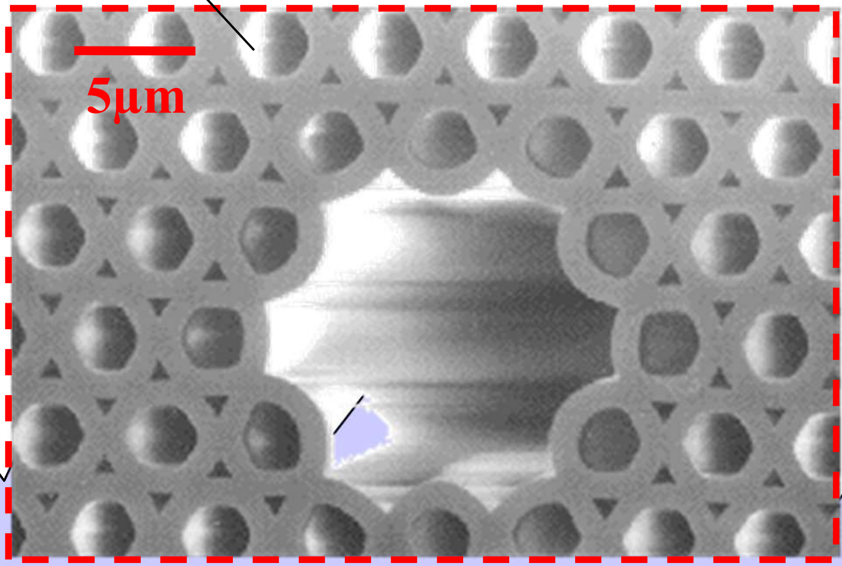
white/grey
= chalco/polymer



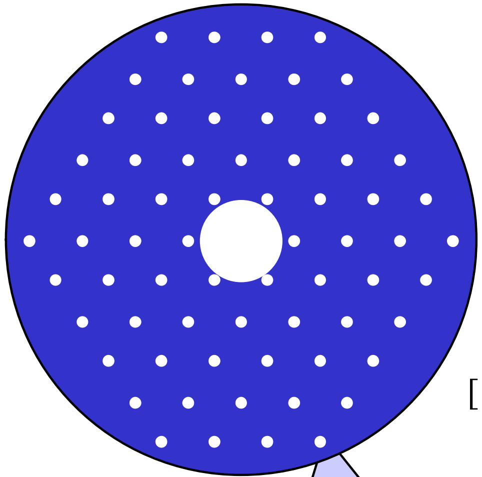
Bragg fiber
[Yeh *et al.*, 1978]

+ omnidirectional
= OmniGuide
fibers

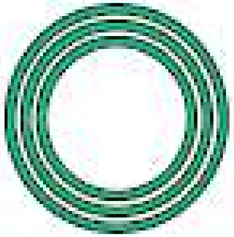
silica



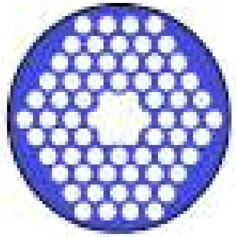
[R. F. Cregan
et al.,
Science **285**,
1537 (1999)]



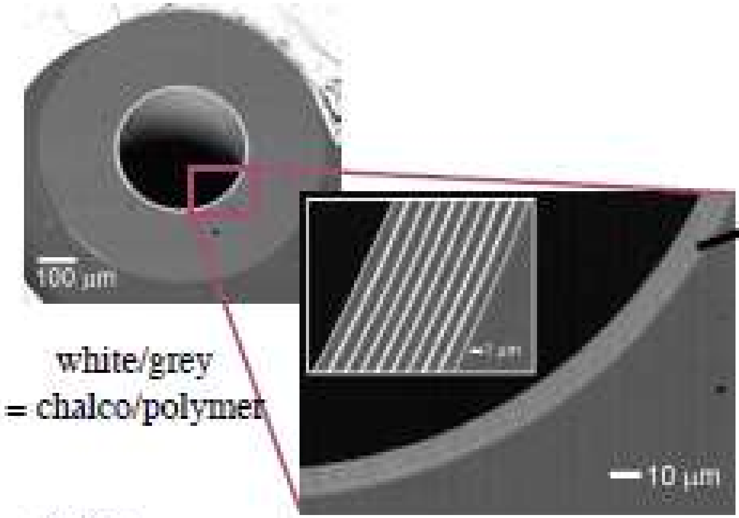
PCF
[Knight *et al.*, 1998]



Breaking the Glass Ceiling: Hollow-core Bandgap Fibers



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

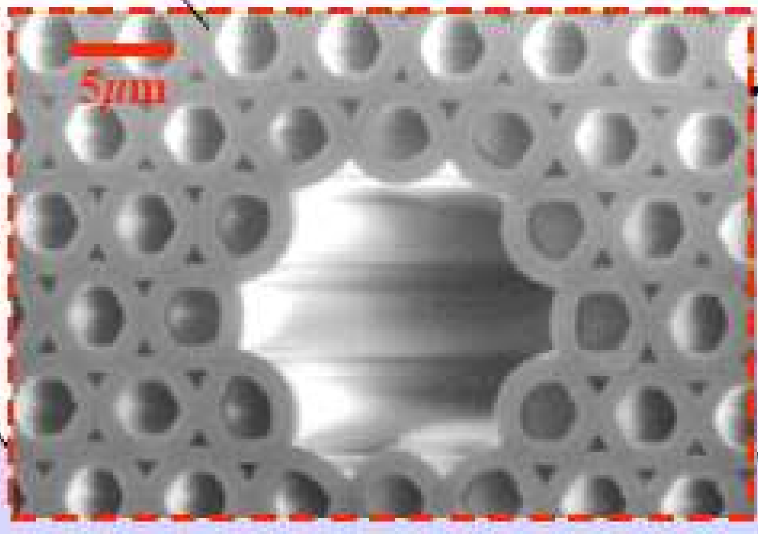


white/grey
= chalco/polymer

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)]

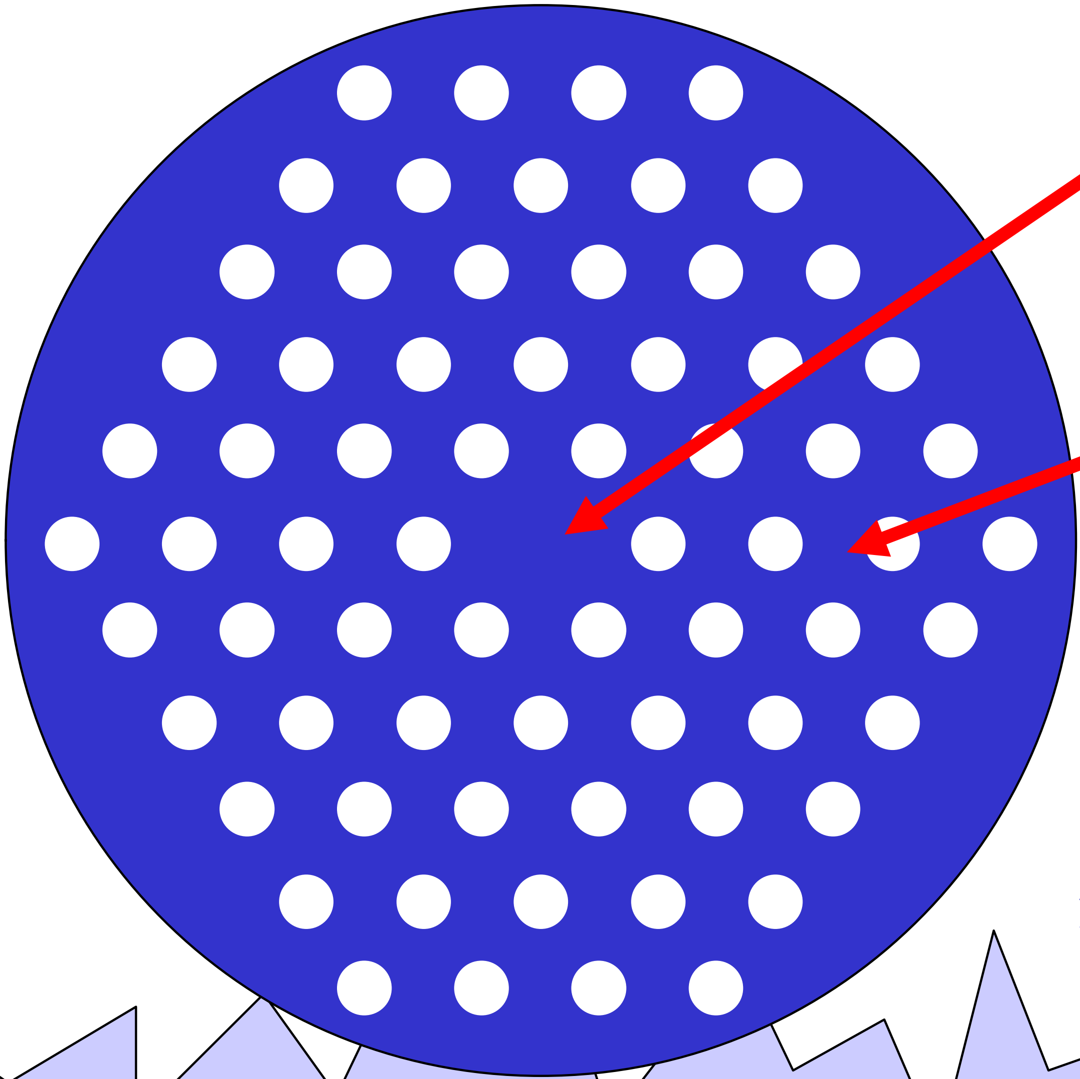
Guiding @ 1.55μm
loss ~ 13dB/km

[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

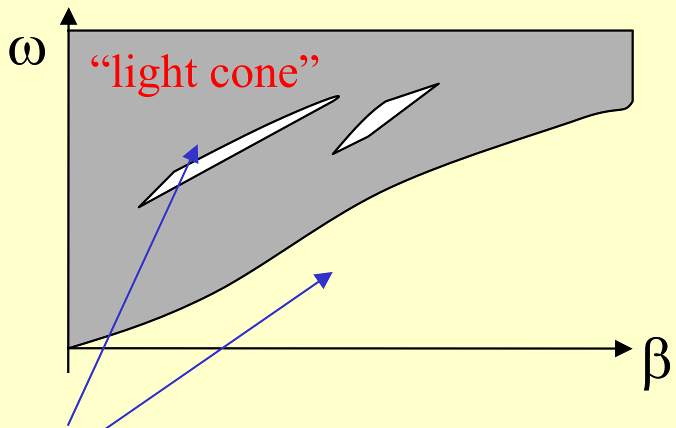
Can have much higher contrast than doped silica…

strong confinement = enhanced nonlinearities, birefringence, …

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

Sequence of Analysis

1 Plot all solutions of infinite cladding as ω vs. β

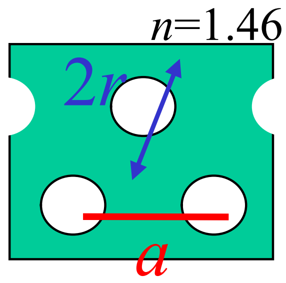


empty spaces (gaps): guiding possibilities

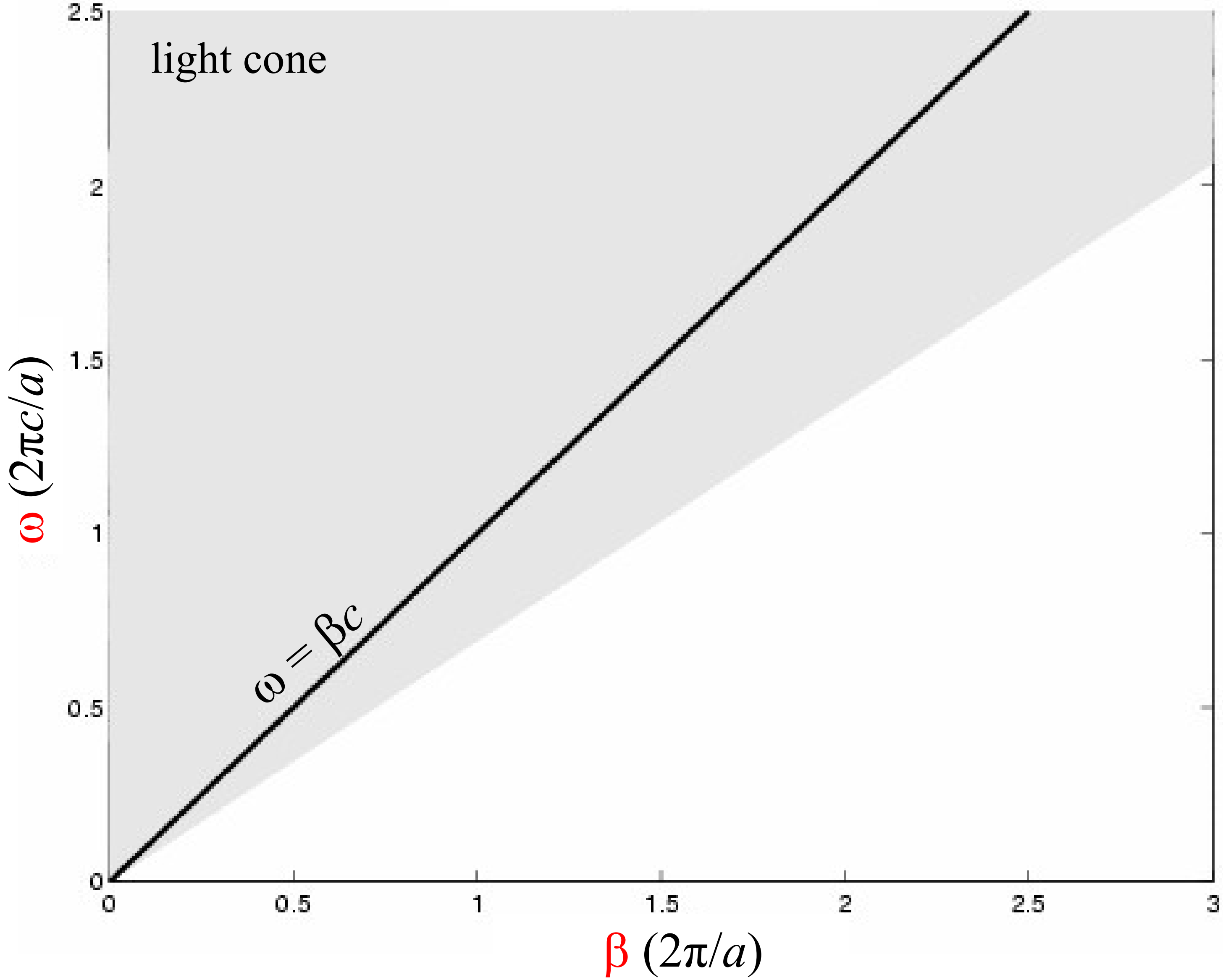
2 Core introduces new states in empty spaces — plot $\omega(\beta)$ dispersion relation

3 Compute other stuff…

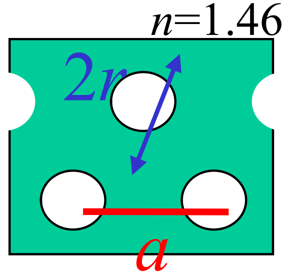
PCF: Holey Silica Cladding



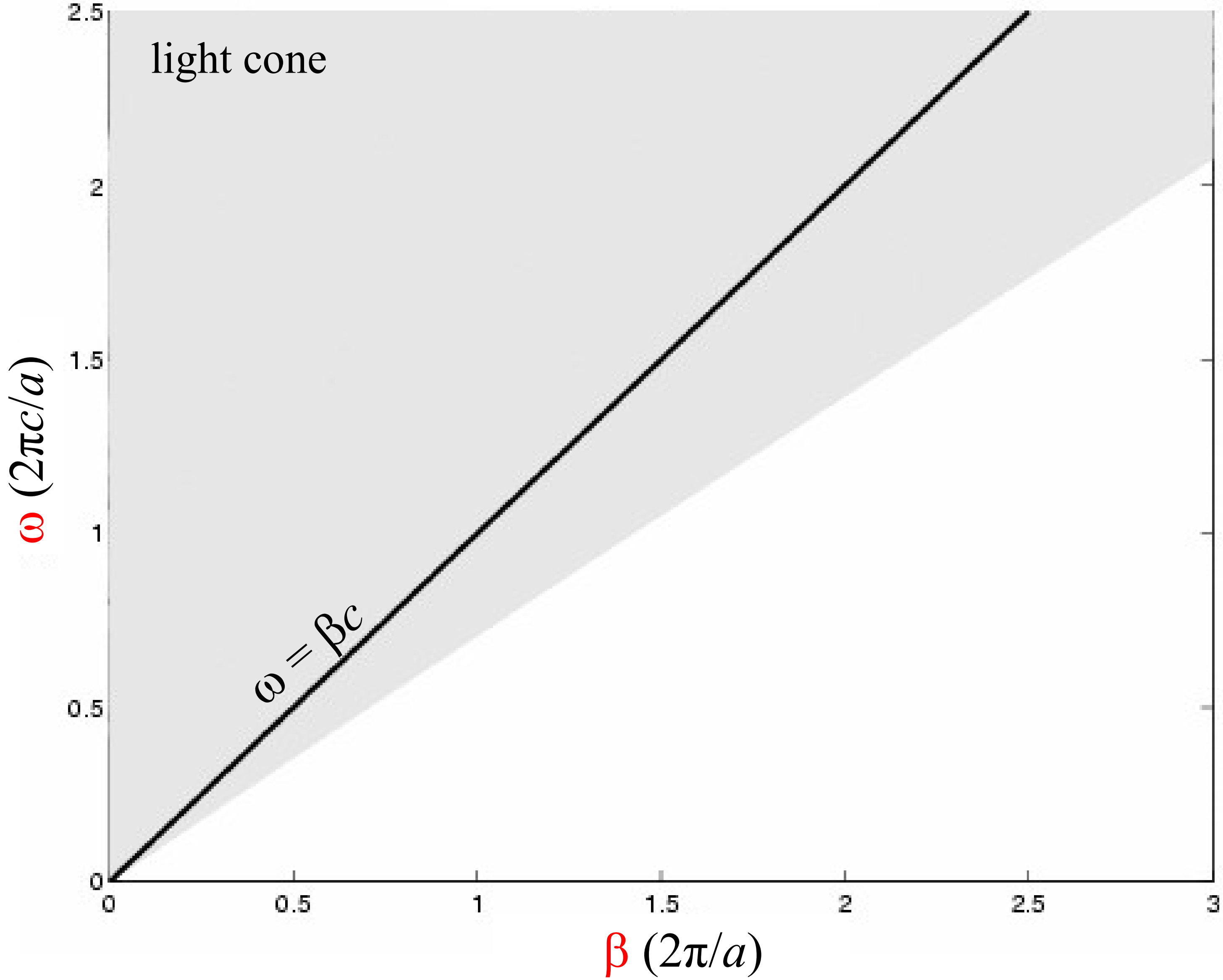
$r = 0.1a$



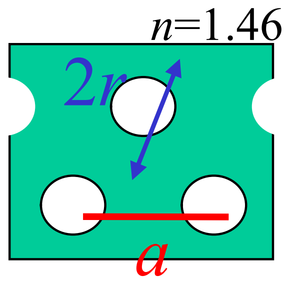
PCF: Holey Silica Cladding



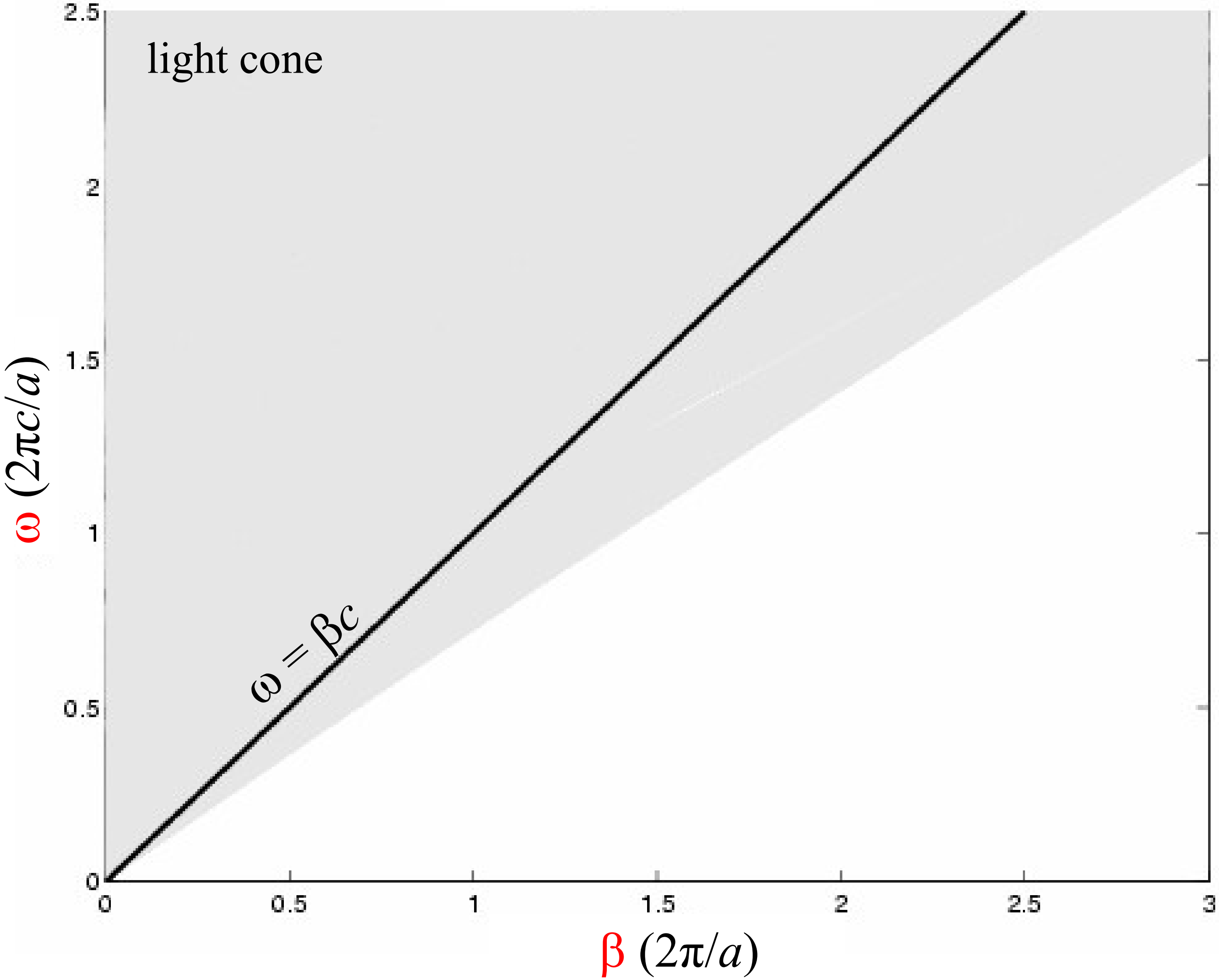
$r = 0.17717a$



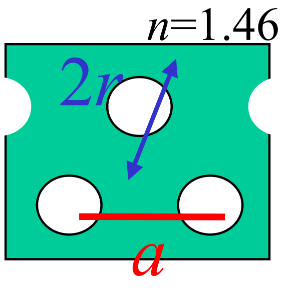
PCF: Holey Silica Cladding



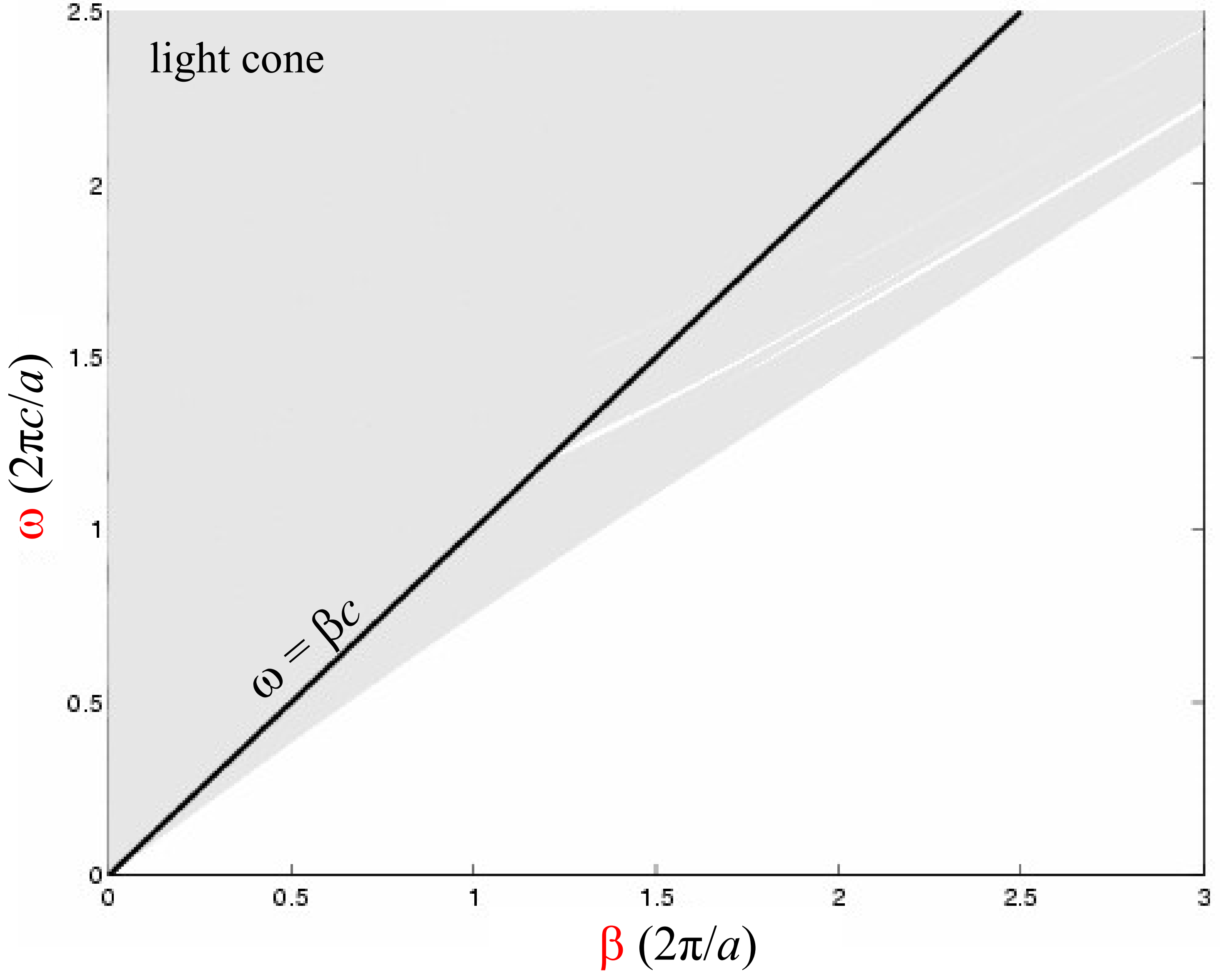
$r = 0.22973a$



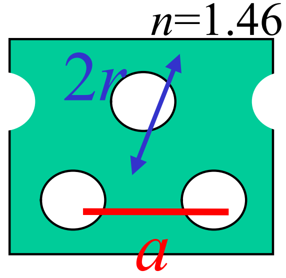
PCF: Holey Silica Cladding



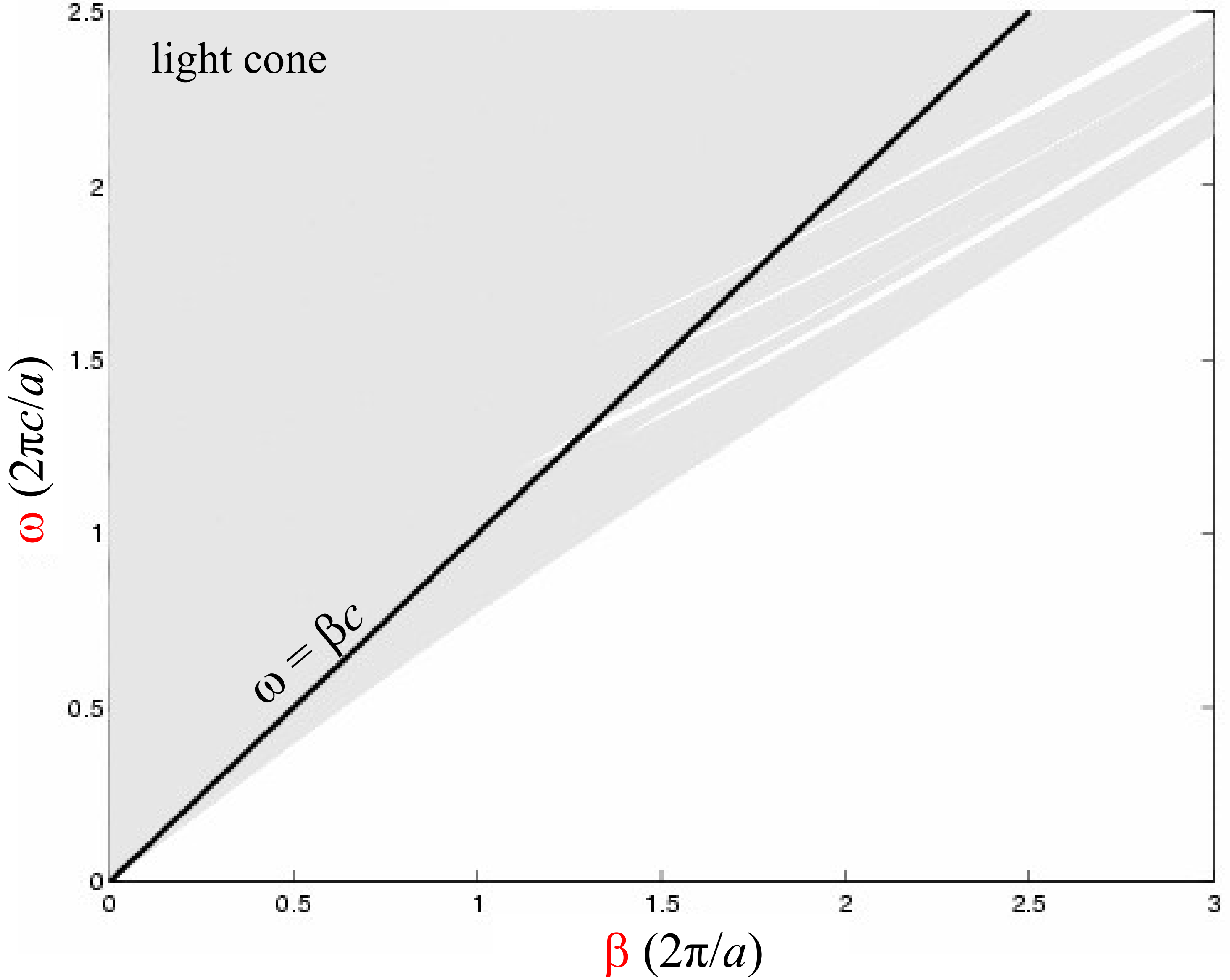
$r = 0.30912a$



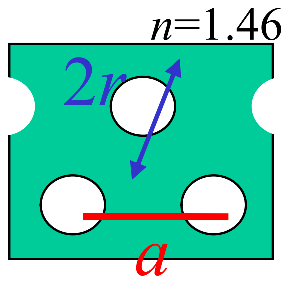
PCF: Holey Silica Cladding



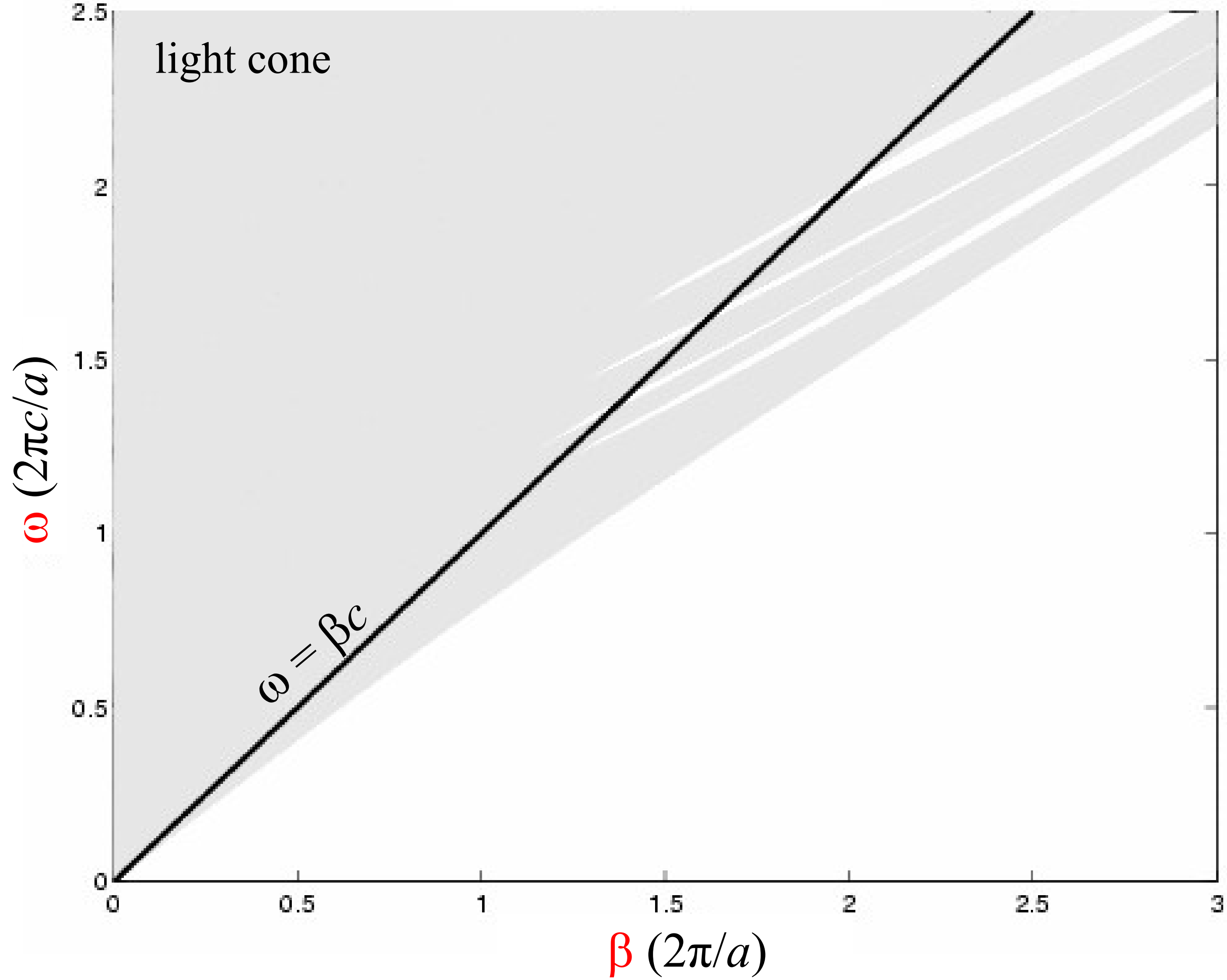
$r = 0.34197a$



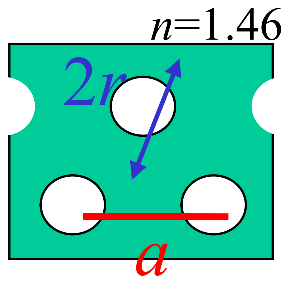
PCF: Holey Silica Cladding

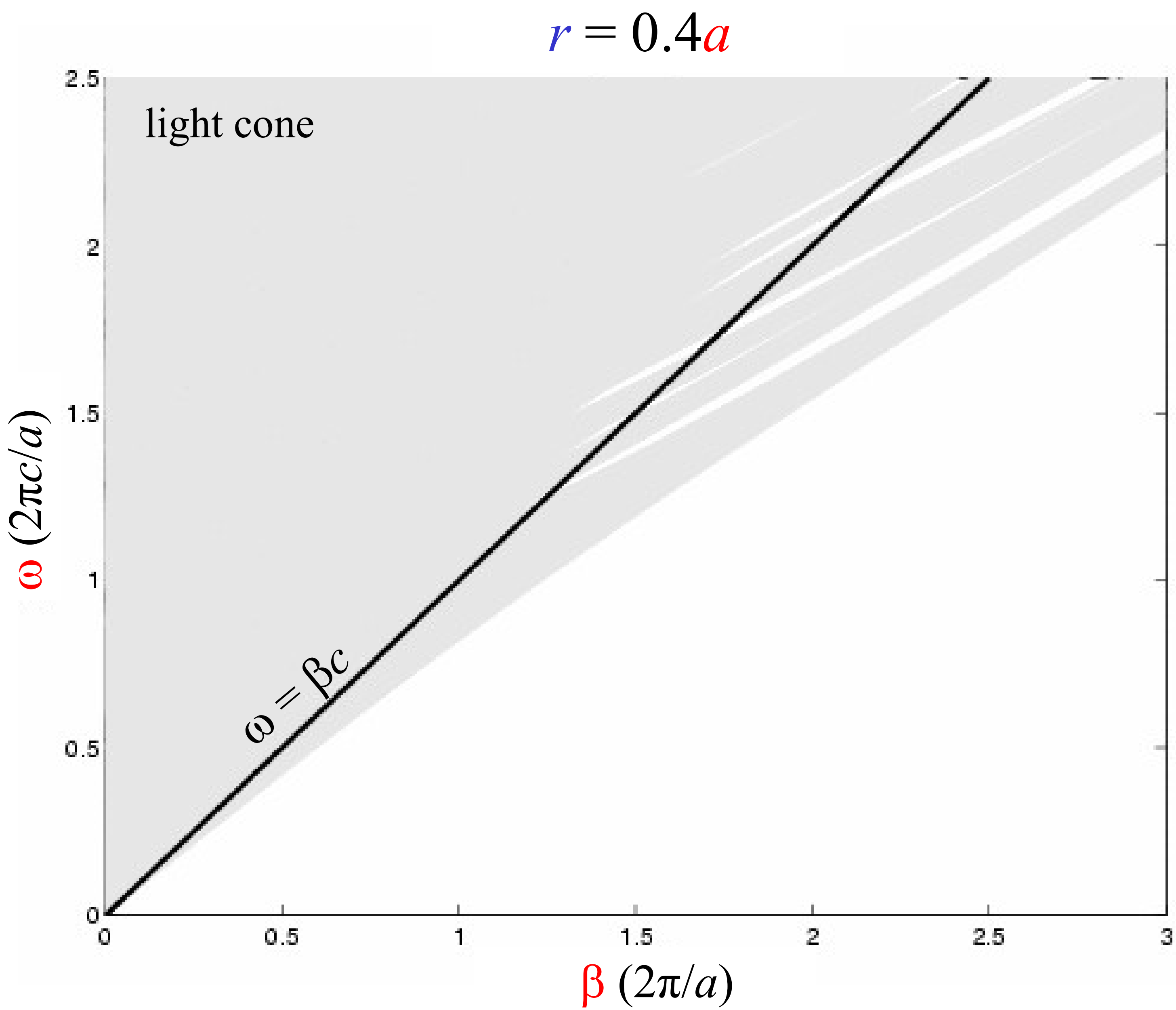


$r = 0.37193a$

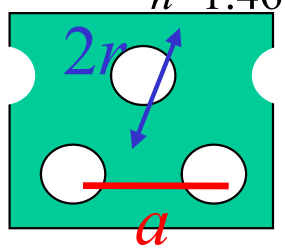


PCF: Holey Silica Cladding

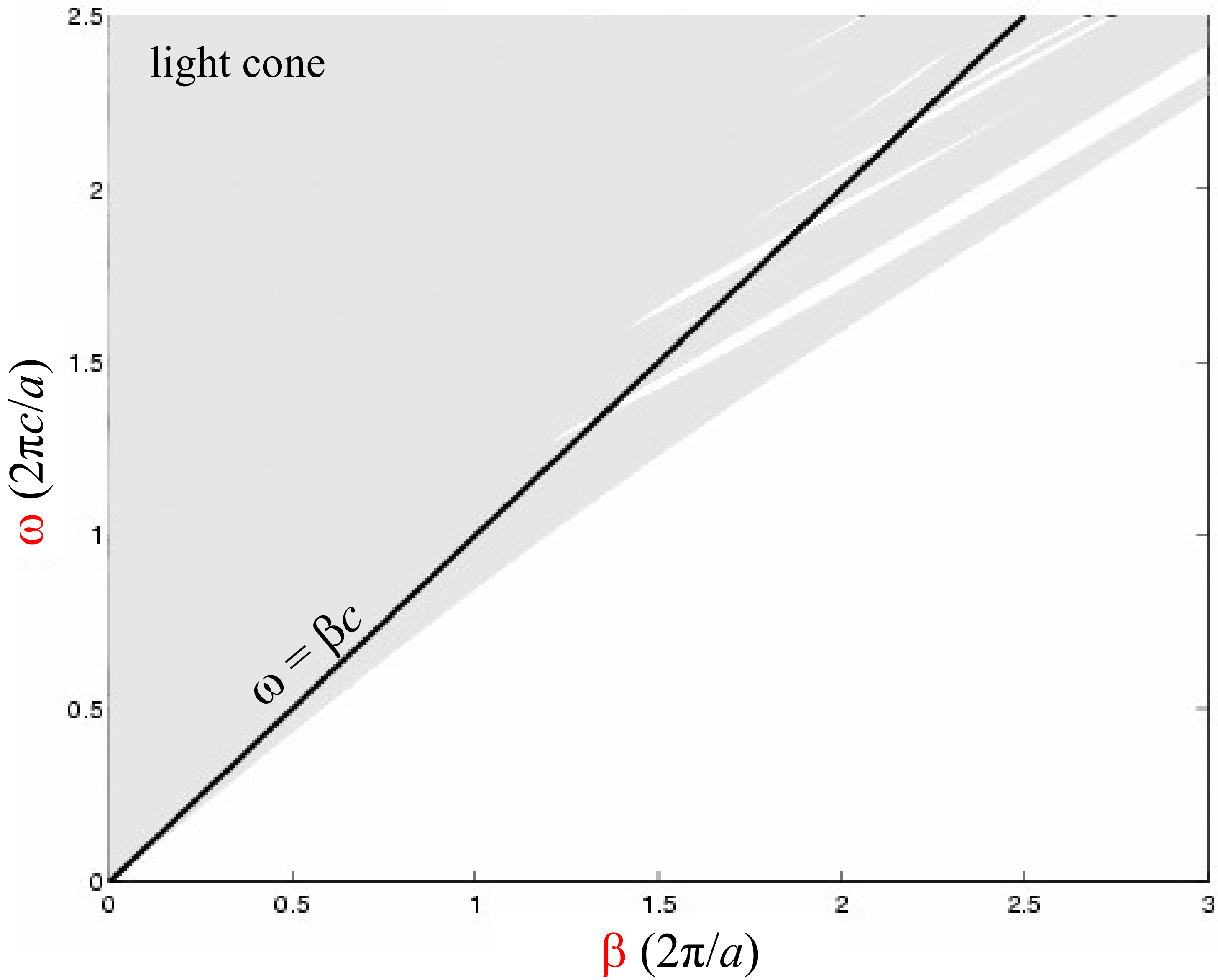




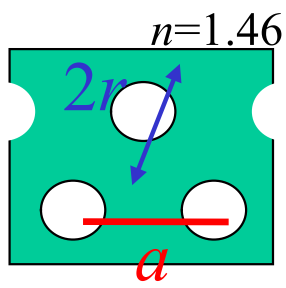
PCF: Holey Silica Cladding



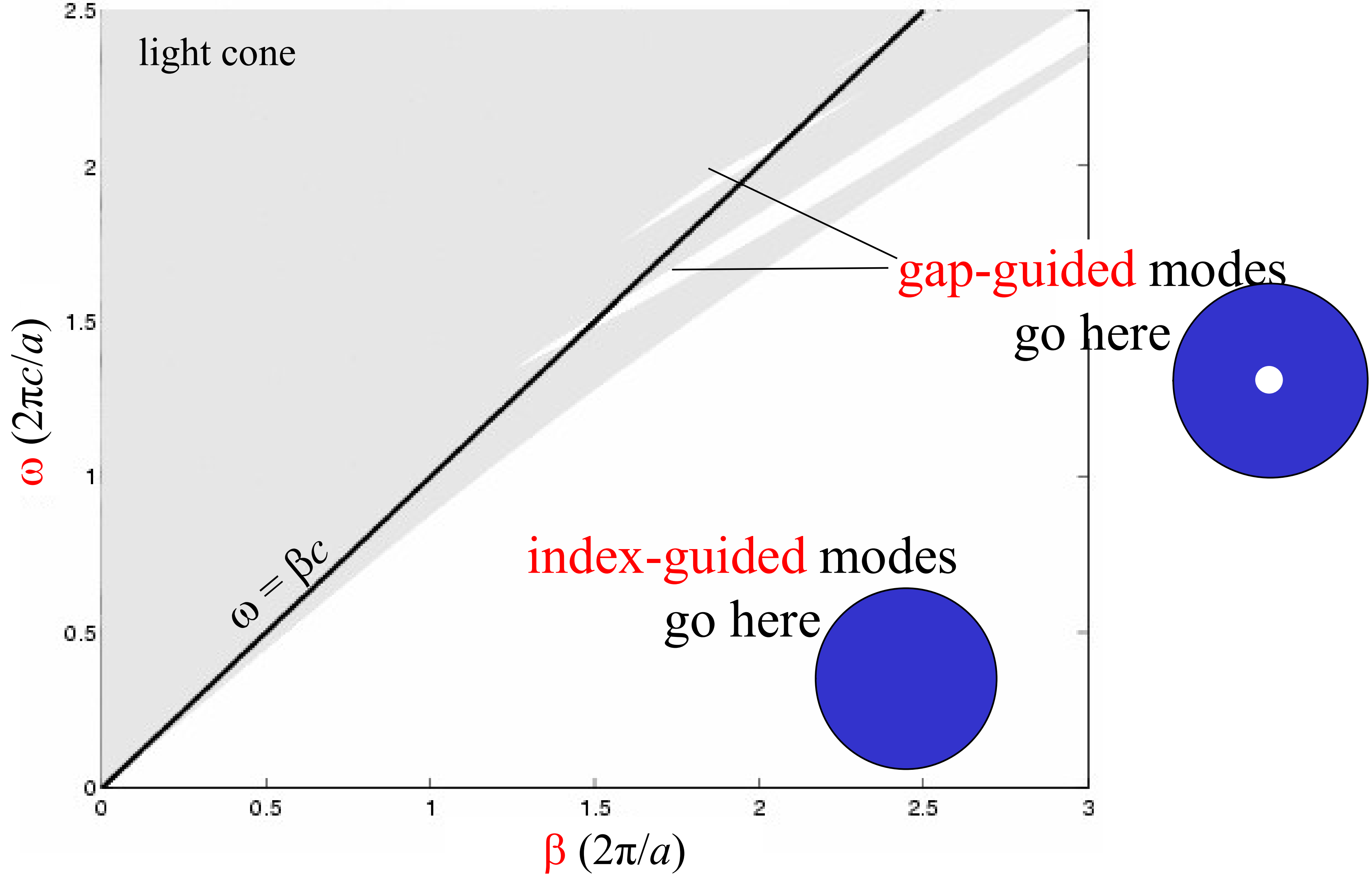
$r = 0.42557a$



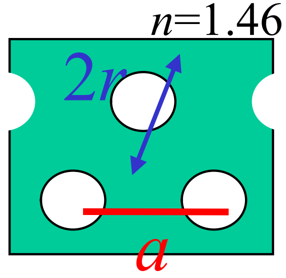
PCF: Holey Silica Cladding



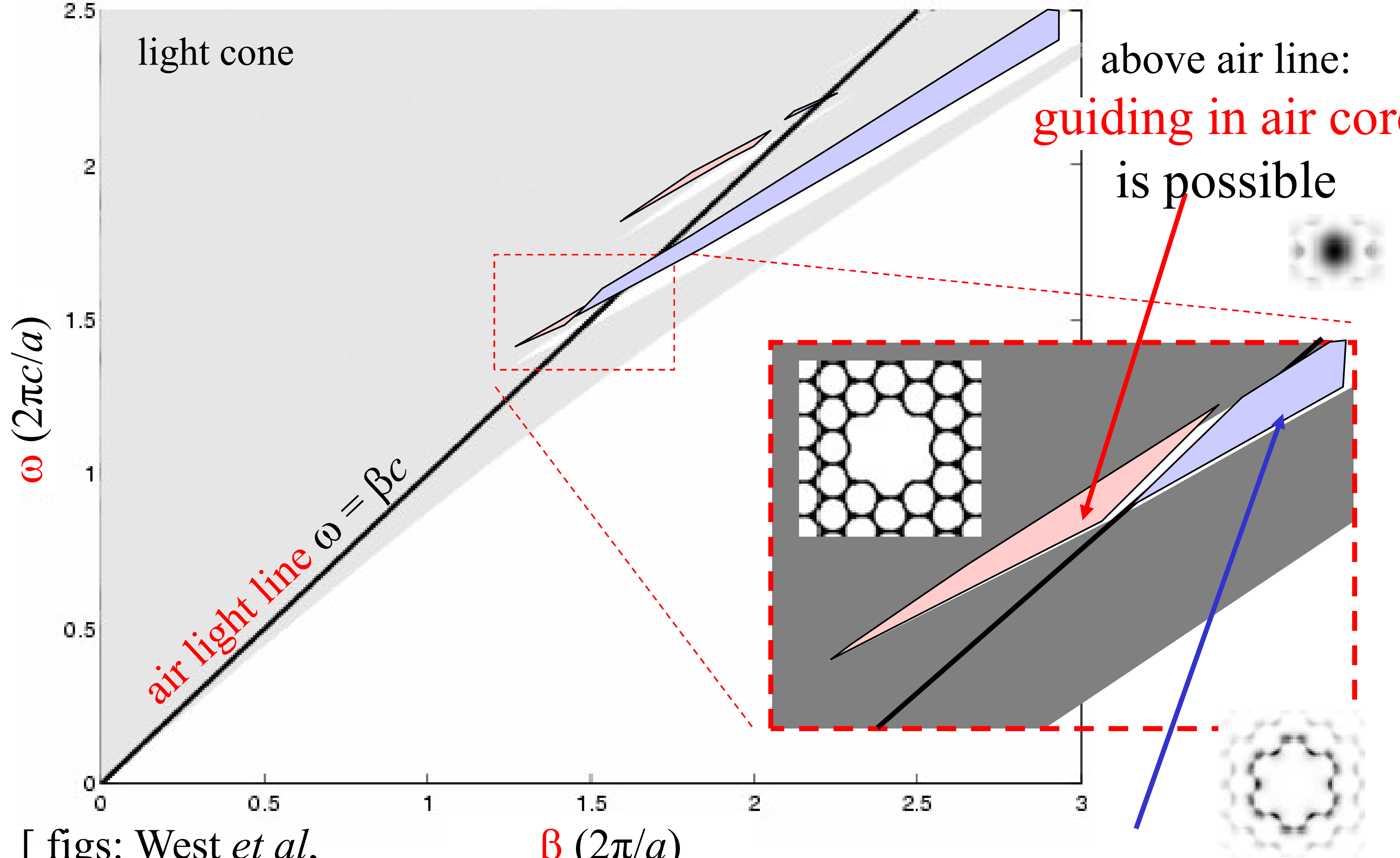
$r = 0.45a$



PCF: Holey Silica Cladding



$r = 0.45a$

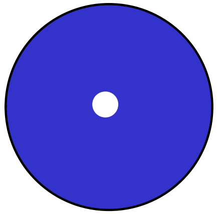


above air line: guiding in air core is possible

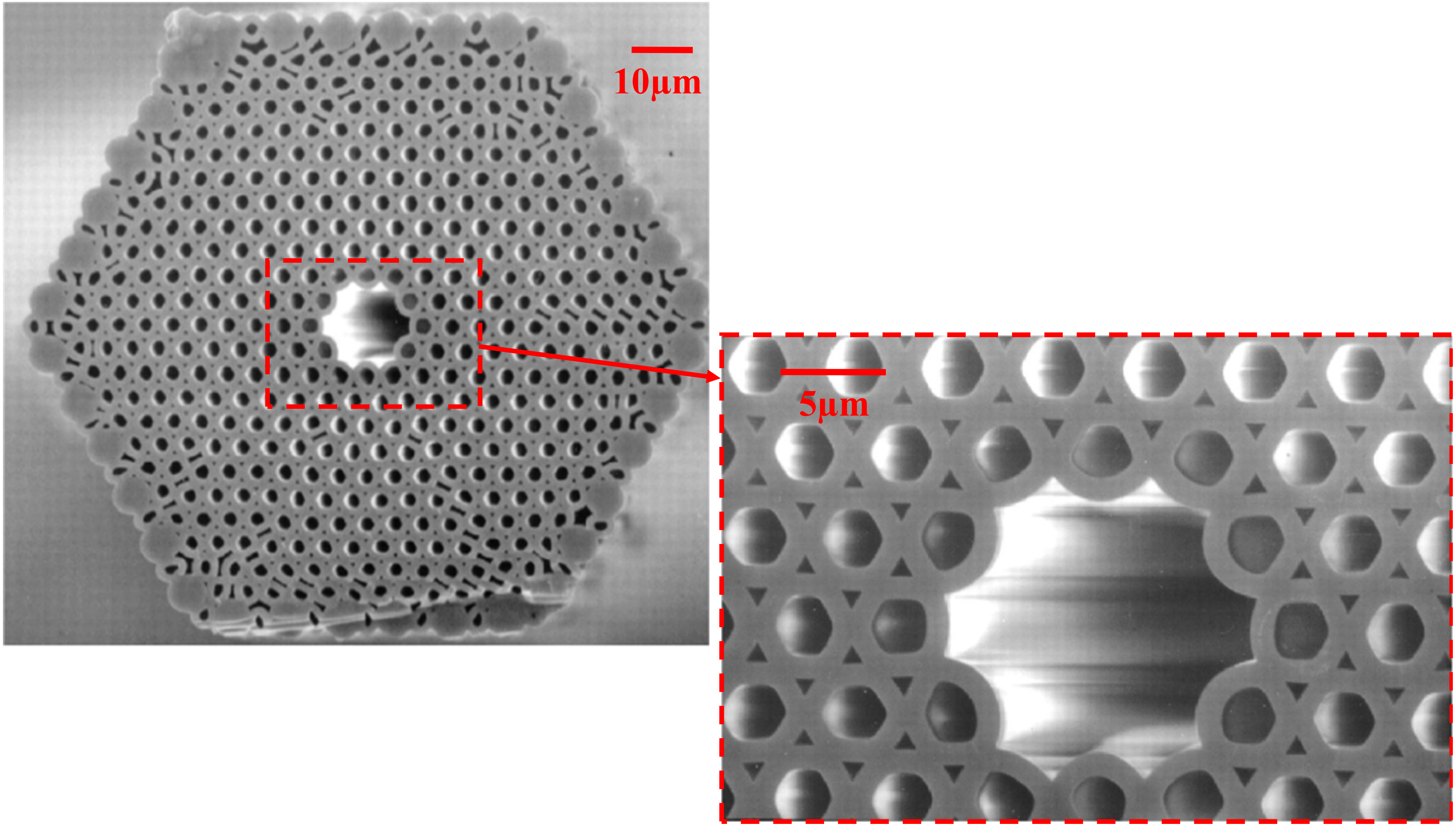
below air line: surface states of air core

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

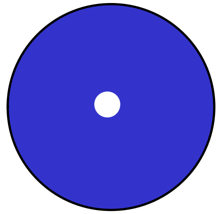
Experimental Air-guiding PCF



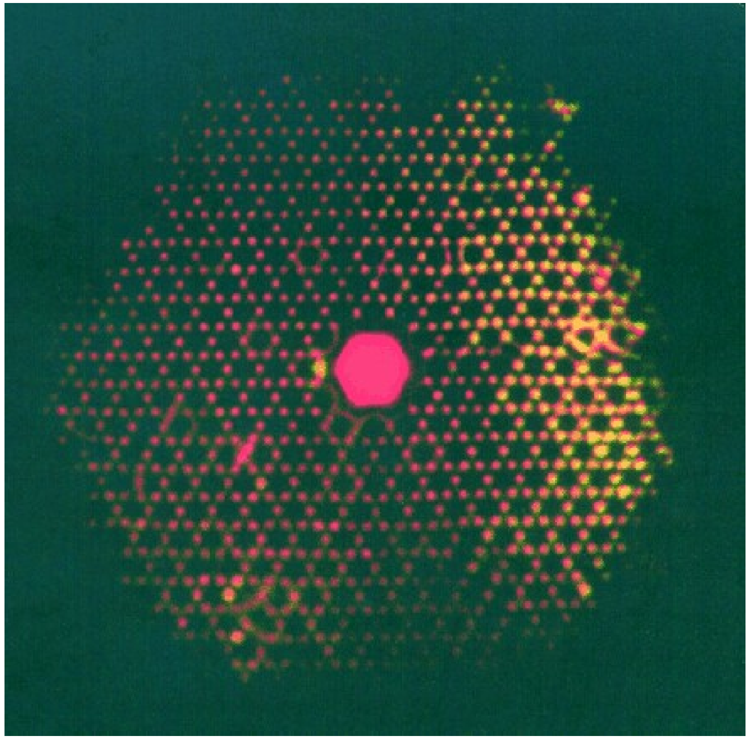
[R. F. Cregan *et al.*, *Science* **285**, 1537 (1999)]



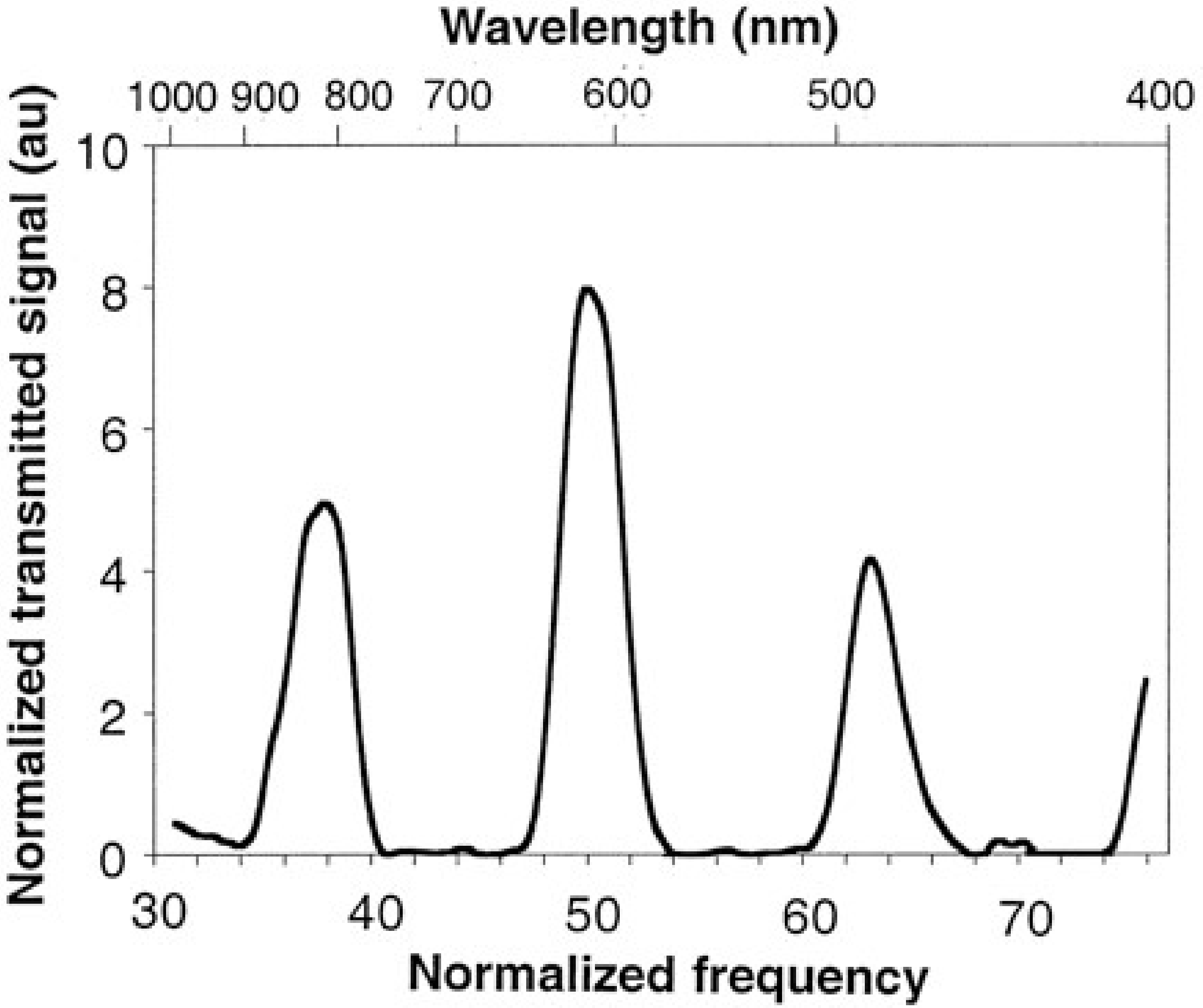
Experimental Air-guiding PCF



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



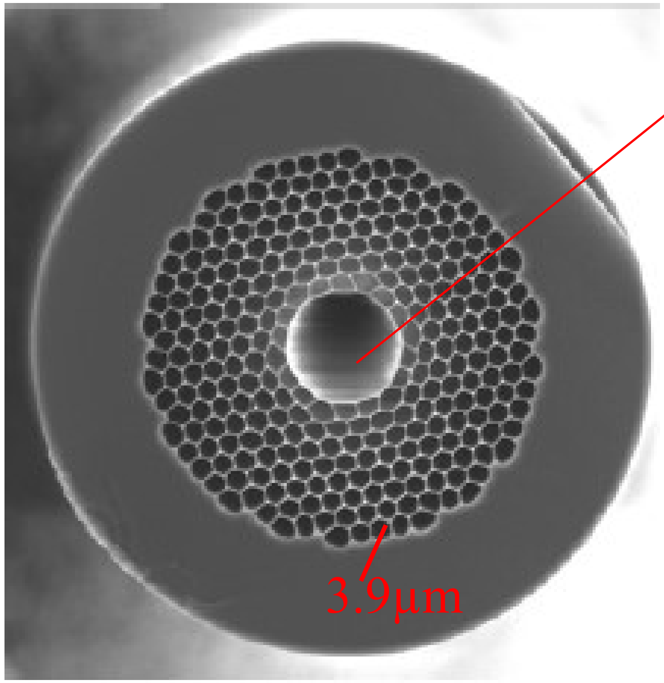
transmitted intensity
after ~ 3cm



ω (c/a) (**not** $2\pi c/a$)

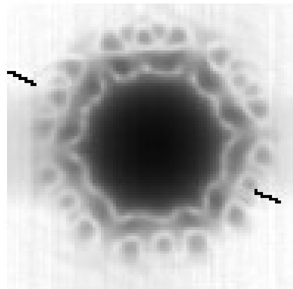
A more recent (lower-loss) example

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



hollow (air) core (covers 19 holes)

guided field profile:
(flux density)

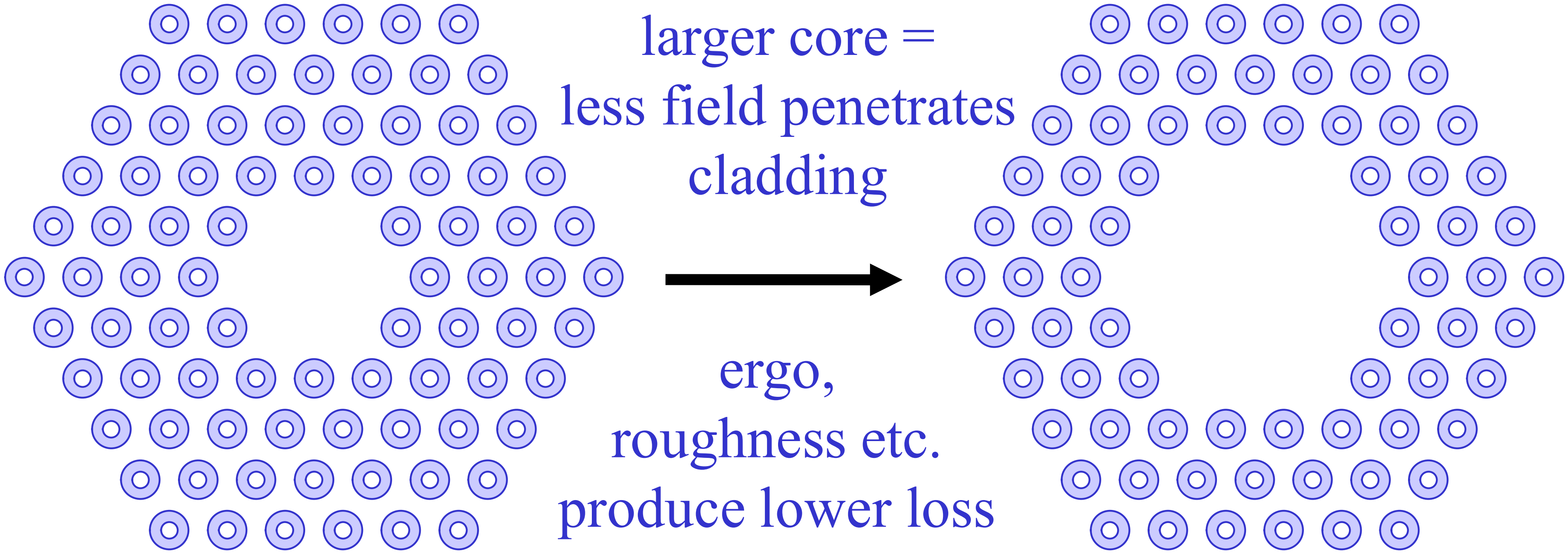


1.7dB/km

BlazePhotonics

over ~ 800m @1.57μm

Improving air-guiding losses



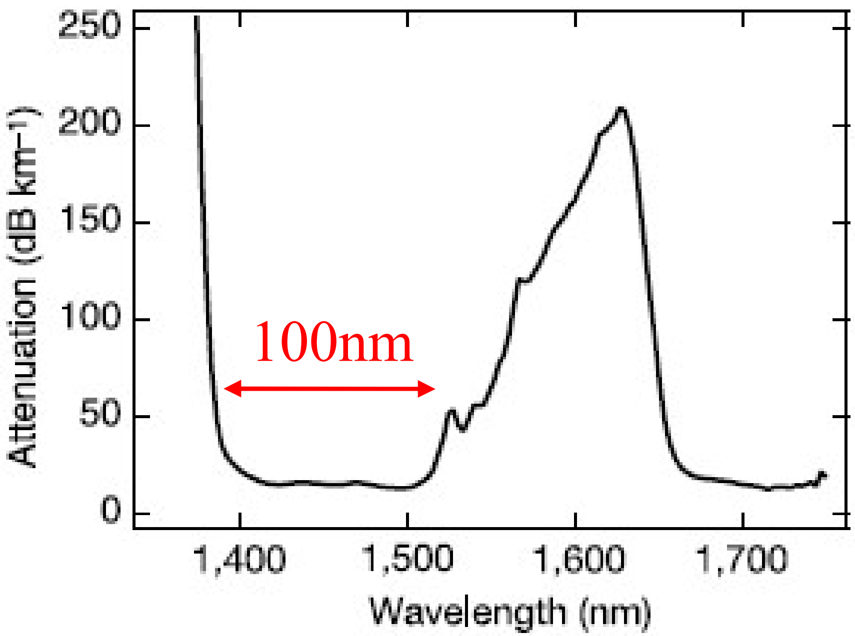
13dB/km	1.7dB/km
Corning	BlazePhotonics
over ~ 100m @1.5μm	over ~ 800m @1.57μm
[Smith, *et al.*, *Nature* **424**, 657 (2003)]	[Mangan, *et al.*, *OFC 2004* PDP24]

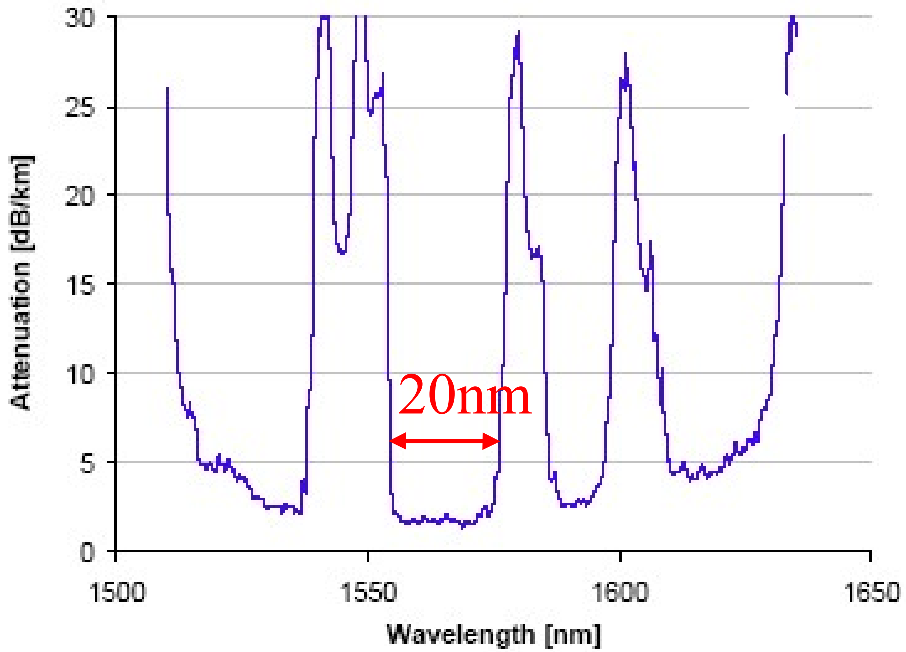
State-of-the-art air-guiding losses

larger core = more surface states crossing guided mode

… 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)]

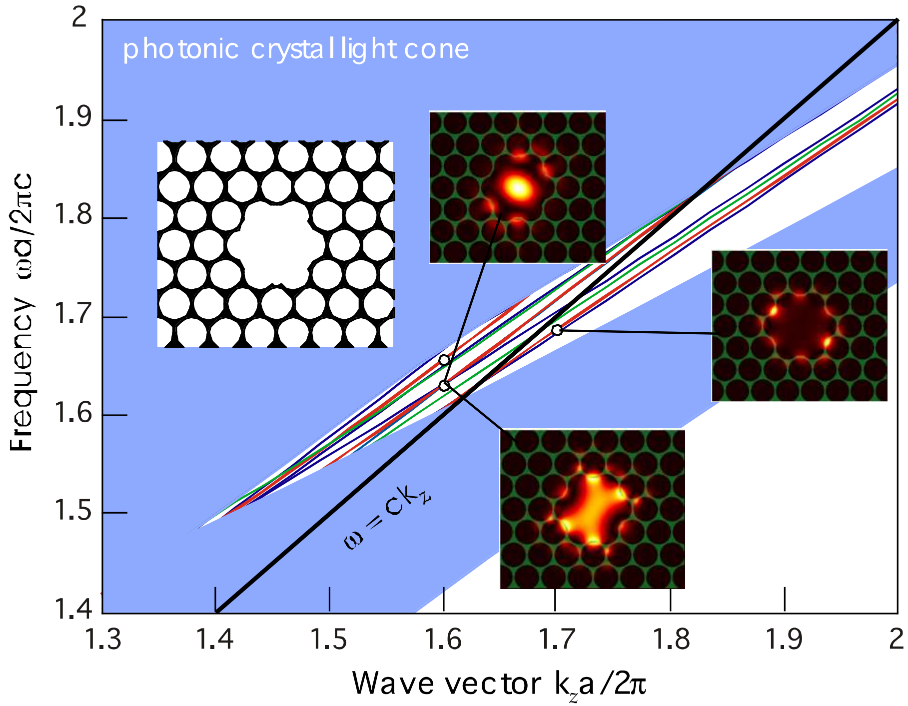
1.7dB/km

BlazePhotonics

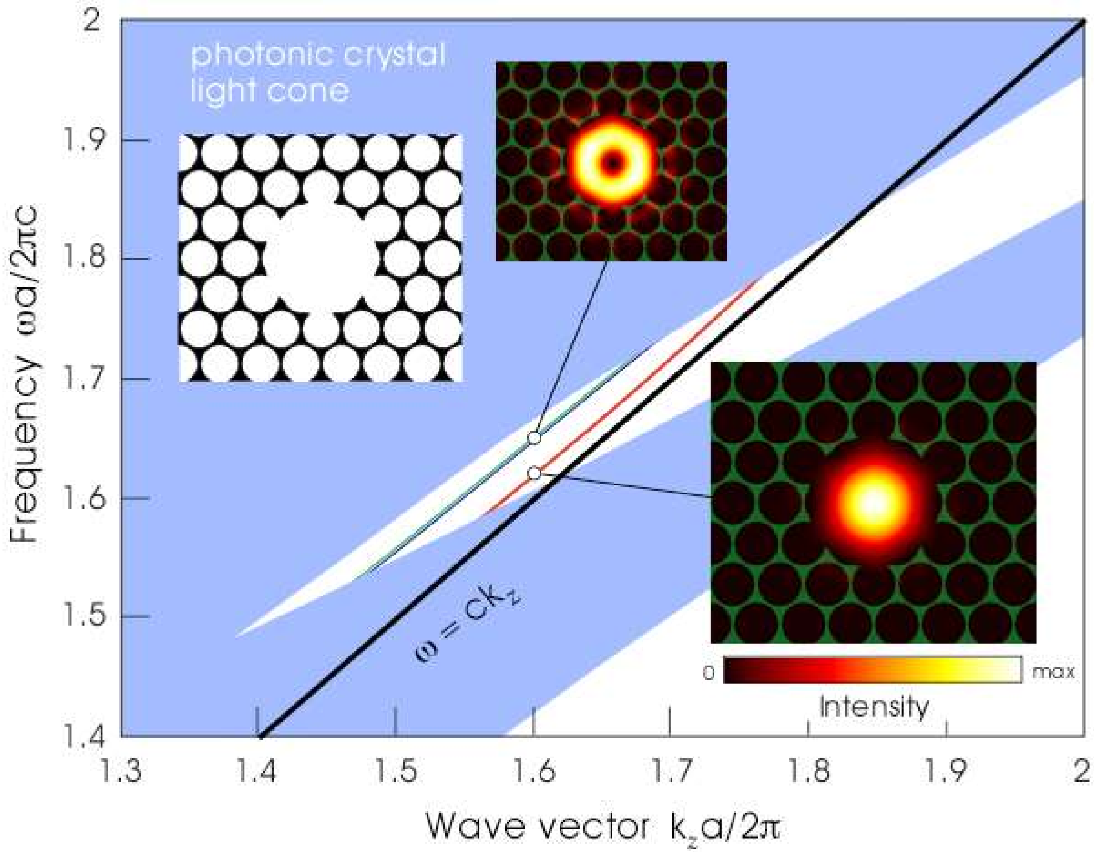
over ~ 800m @1.57µm

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

Surface States vs. Termination



changing the crystal termination
can eliminate surface states

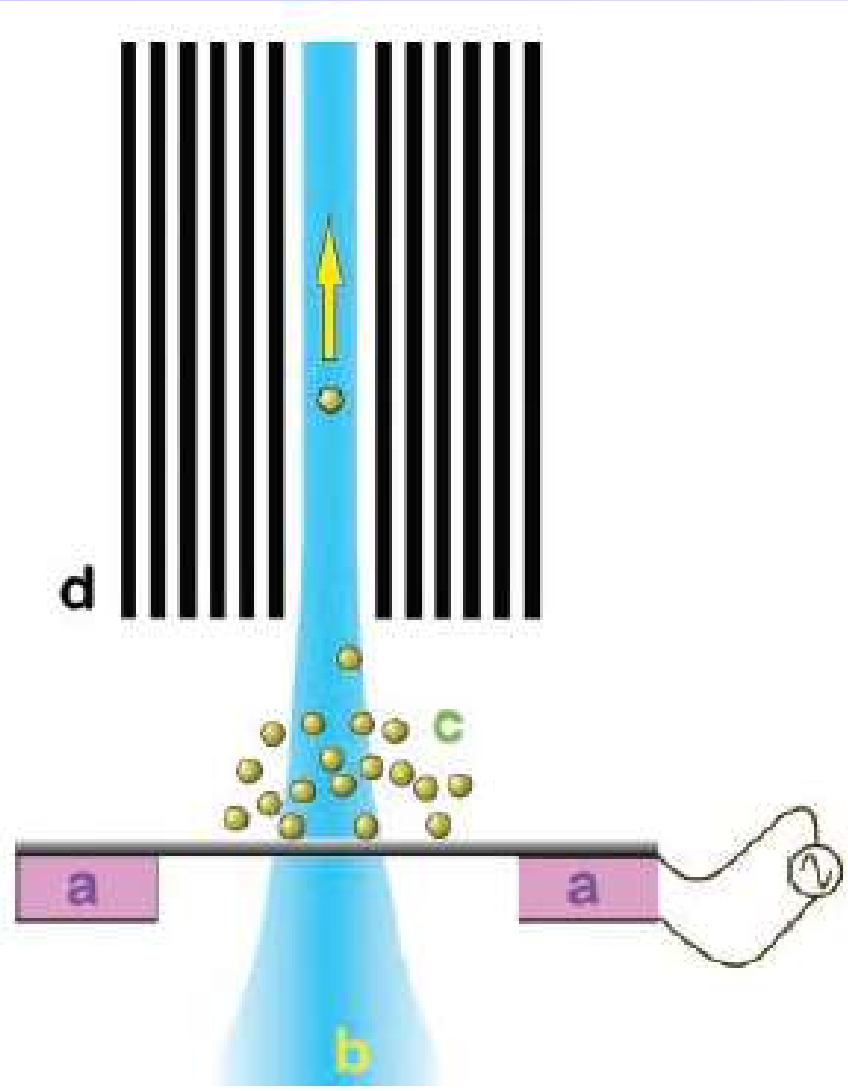


[West, *Opt. Express* **12** (8), 1485 (2004)]

[Saitoh, *Opt. Express* **12** (3), 394 (2004)]

[Kim, *Opt. Express* **12** (15), 3436 (2004)]

Particle levitation and guidance in hollow- core photonic crystal fiber.



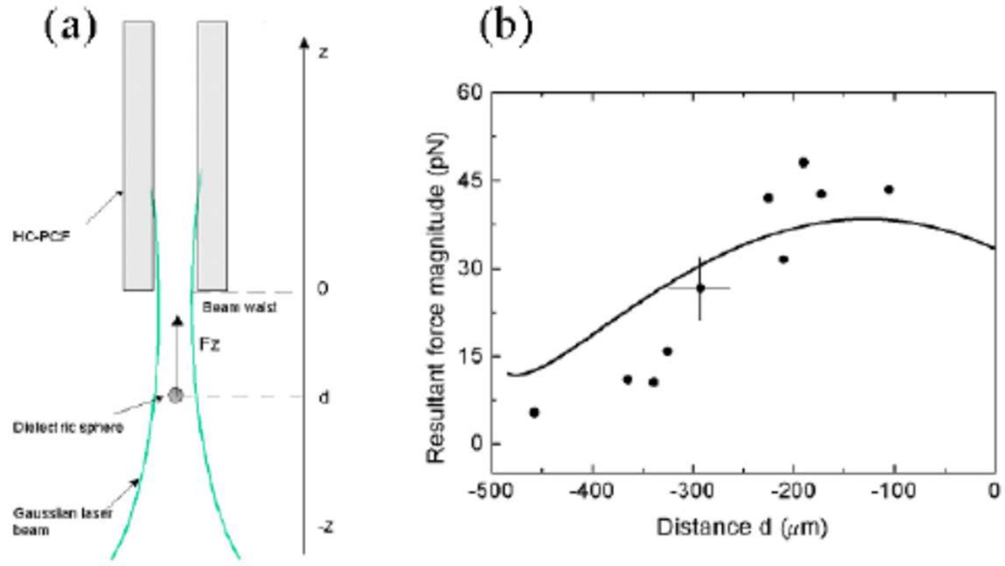


Fig. 3. (a) The schematic of the particle levitation (b) The axial force as a function of the distance waist-particle. The power is 80 mW, the solid circle represent the experimental data.

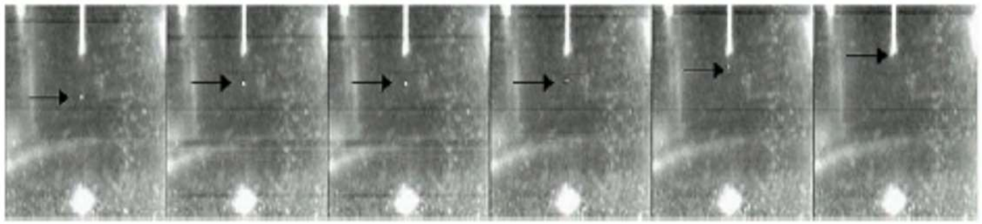
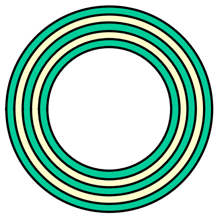


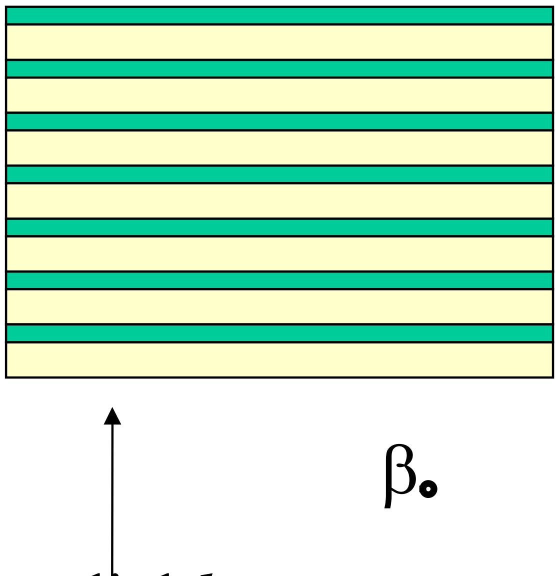
Fig. 4. A sequence of a polystyrene particle (pointed out by an arrow) being levitated. The time spacing between consecutive frames is 67 ms, and each frame corresponds to a captured scene size of 2.5x2.5 mm^2. The sequence is extracted from the movie (2.24 MB) (see fig. 5) of levitated particles and coupled to the fiber.

F. Benabid *et al.*, *Opt. Express* **10**, 1195 (2002).



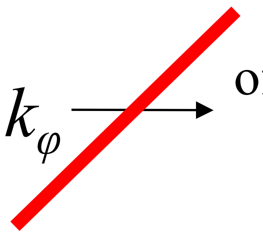
Bragg Fiber Cladding

at large radius,
becomes ~ planar



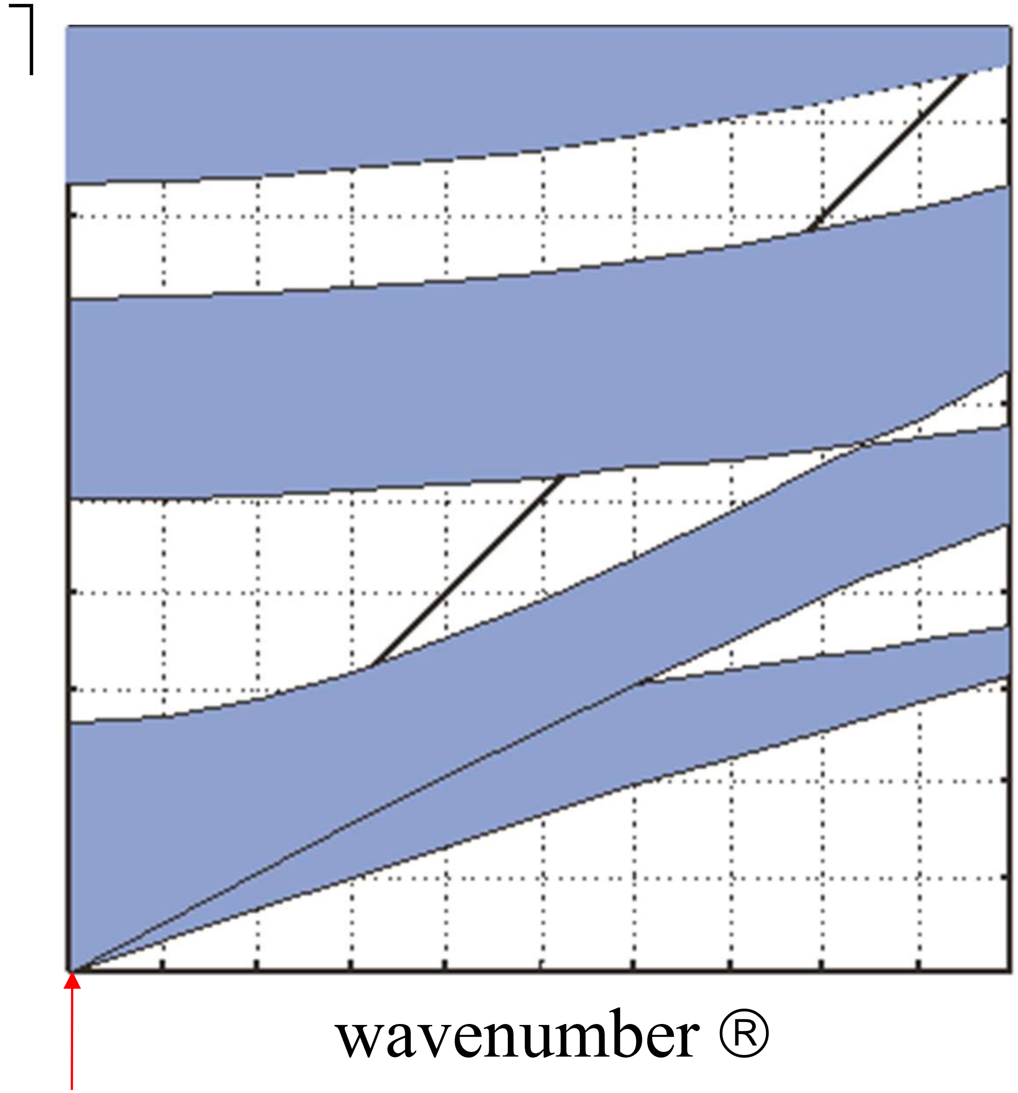
β•

radial k_r
(Bloch wavevector)



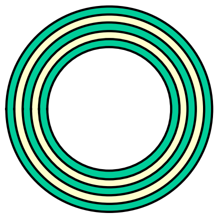
0 by conservation
of angular momentum

Bragg fiber gaps (1d eigenproblem)



wavenumber ®

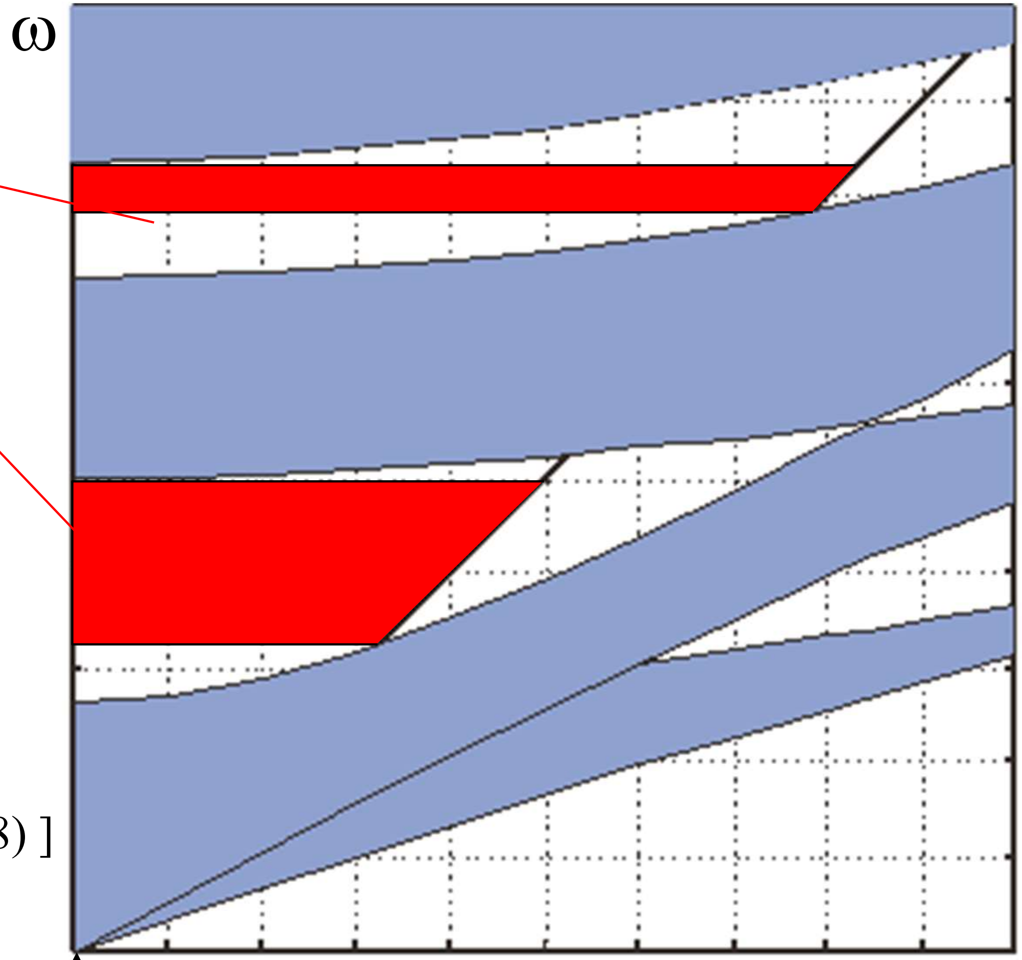
β = 0: normal incidence



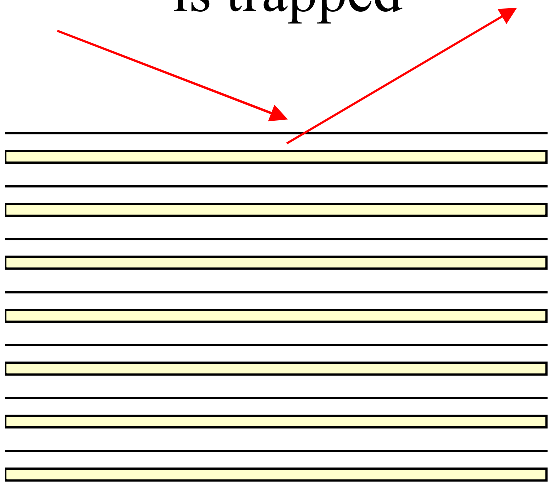
Omnidirectional Cladding

Bragg fiber gaps (1d eigenproblem)

omnidirectional
(planar) reflection



e.g. light from fluorescent sources is trapped



for n_{hi} / n_{lo} big enough and $n_{lo} > 1$

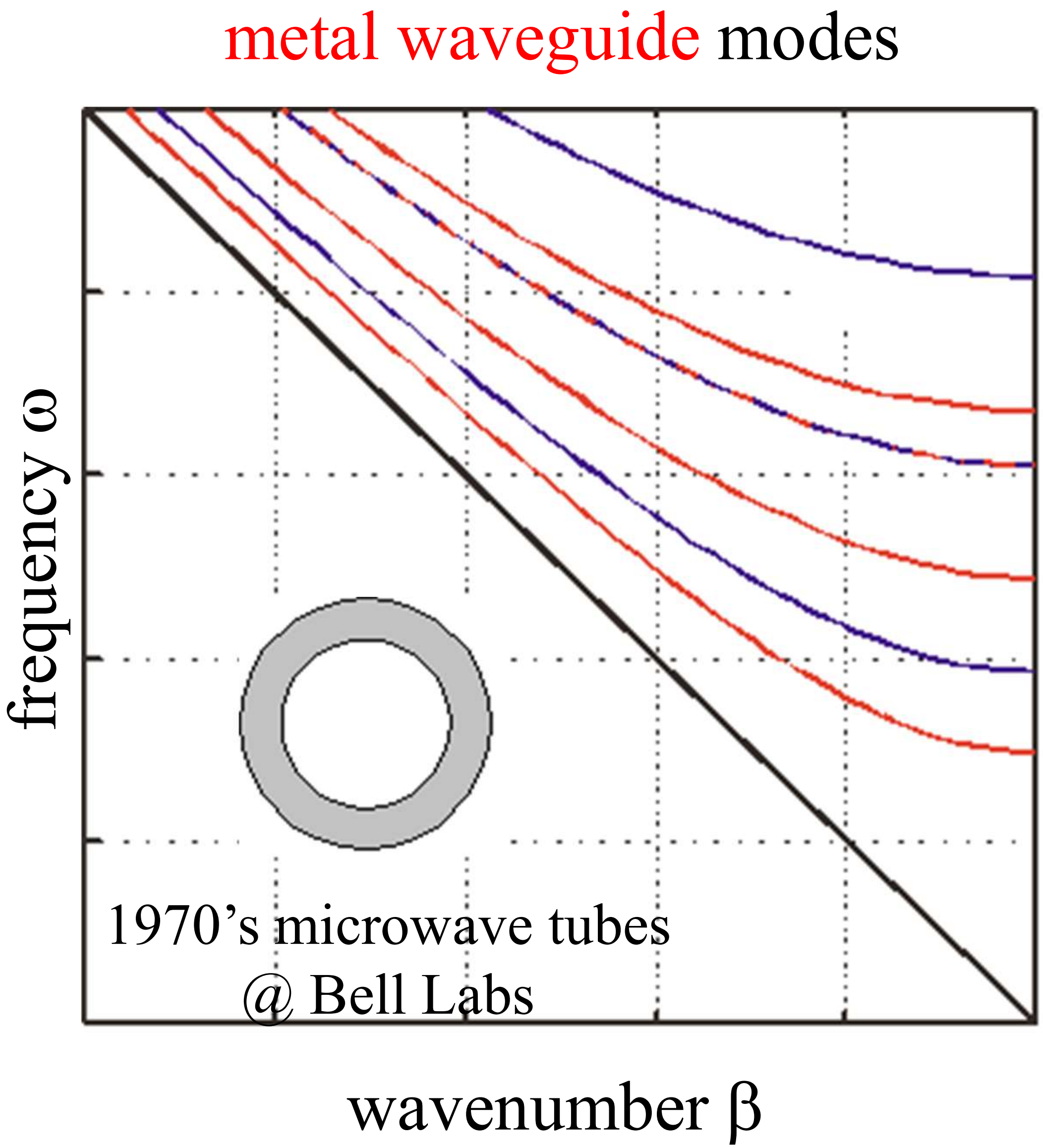
[J. N. Winn *et al*, *Opt. Lett.* **23**, 1573 (1998)]

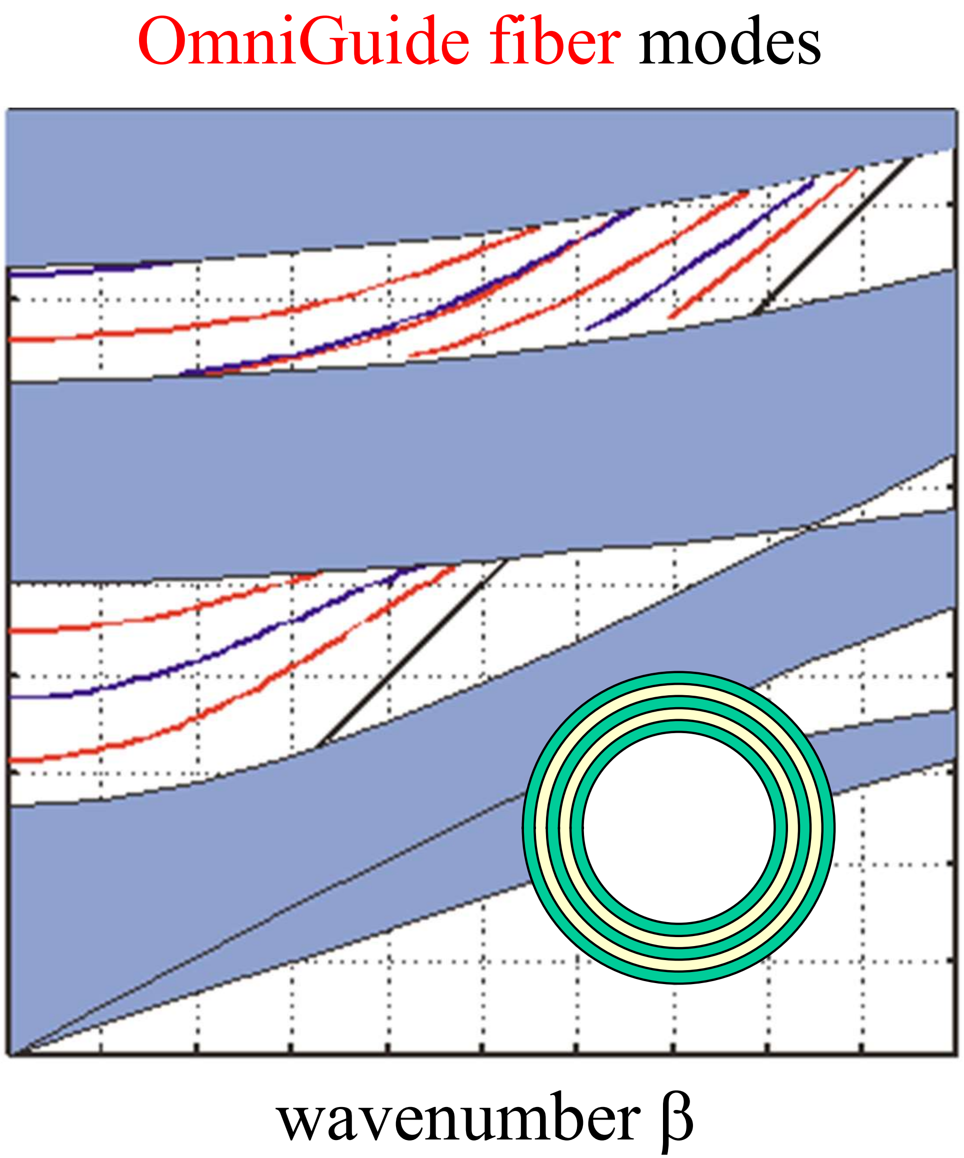
wavenumber ®

β°

β = 0: normal incidence

Hollow Metal Waveguides, Reborn





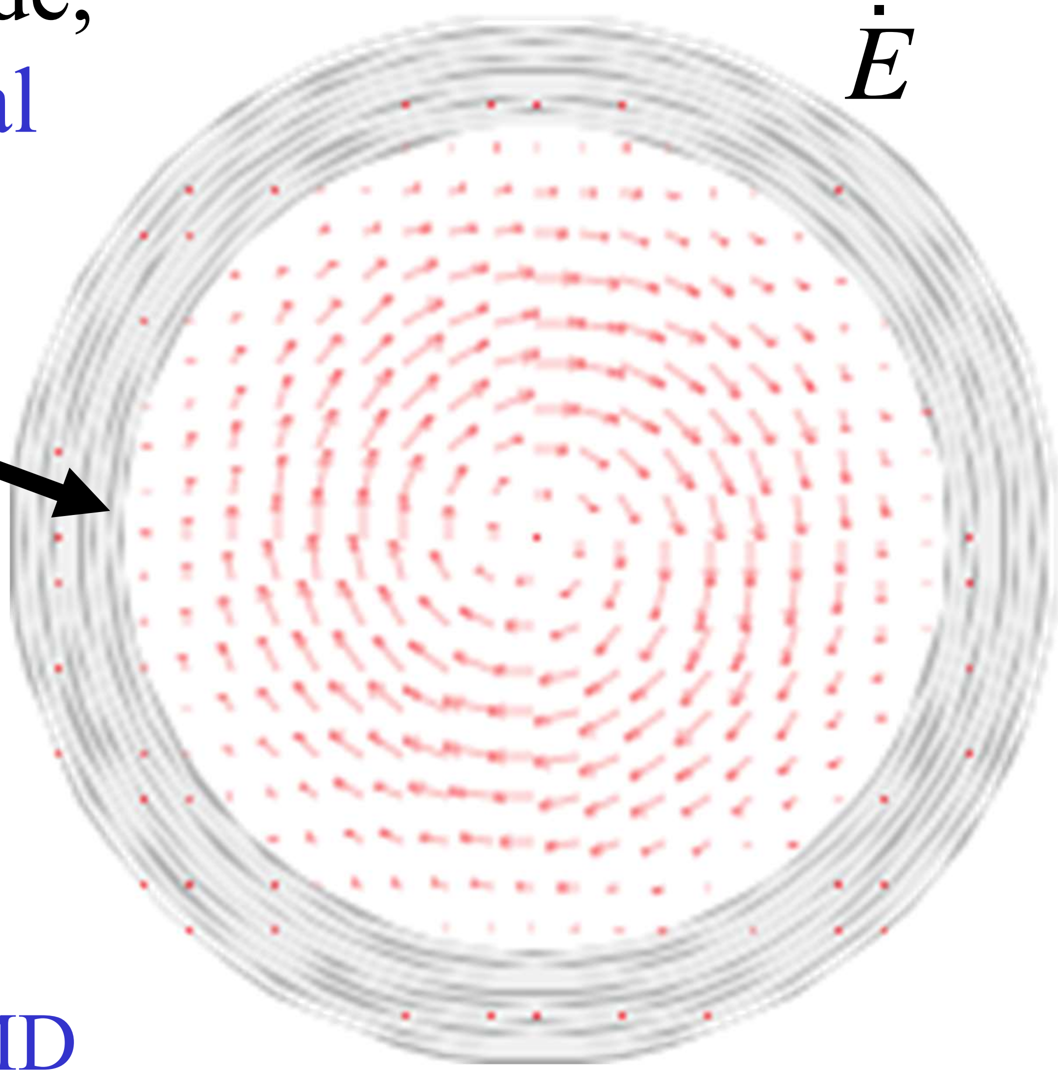
modes are directly analogous to those in hollow metal waveguide

An Old Friend: the TE_{01} mode

lowest-loss mode,
just as in metal

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

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



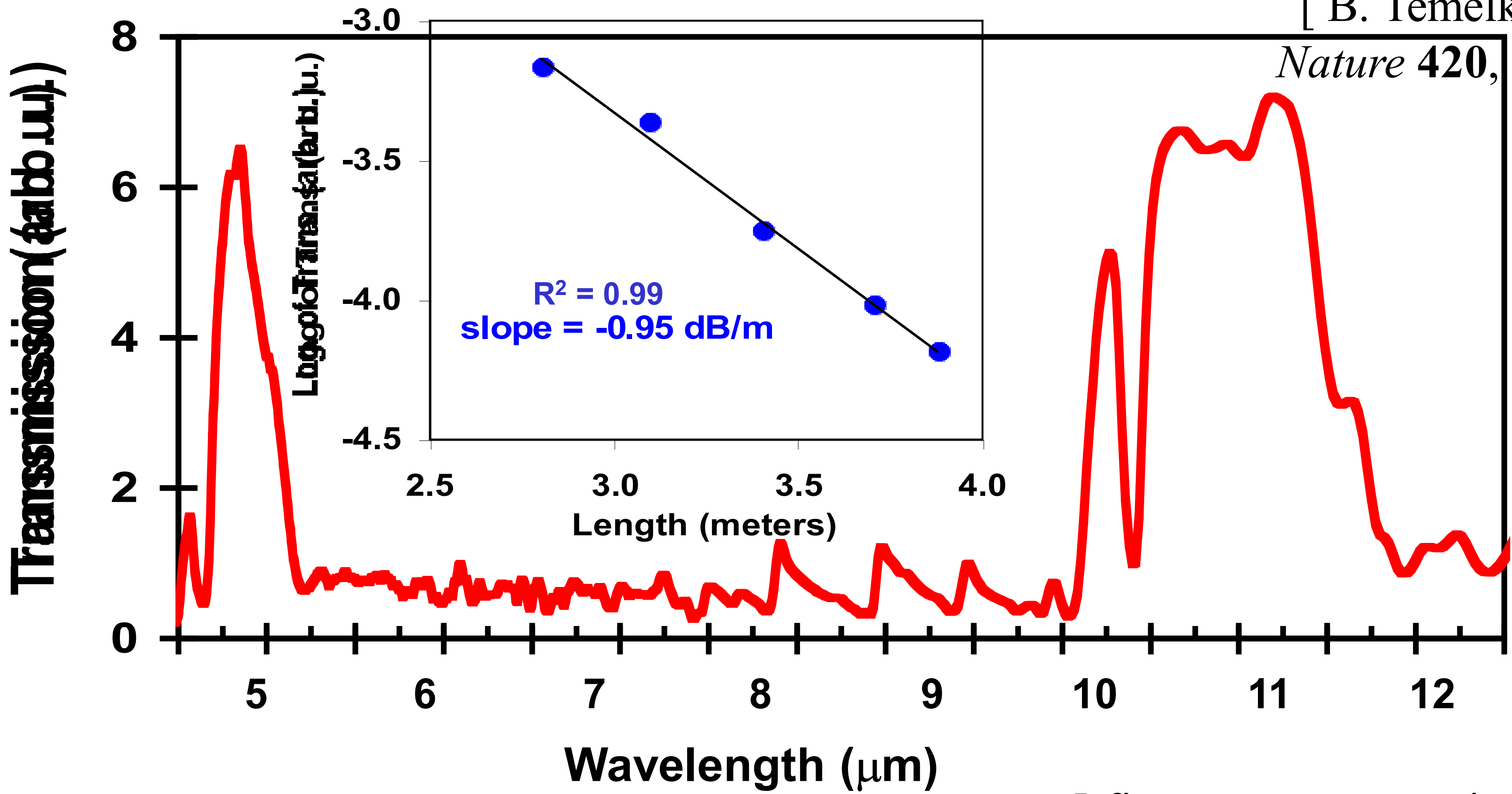
High-Power Transmission

at 10.6μm (no previous dielectric waveguide)

Polymer losses @10.6μm ~ 50,000dB/m…

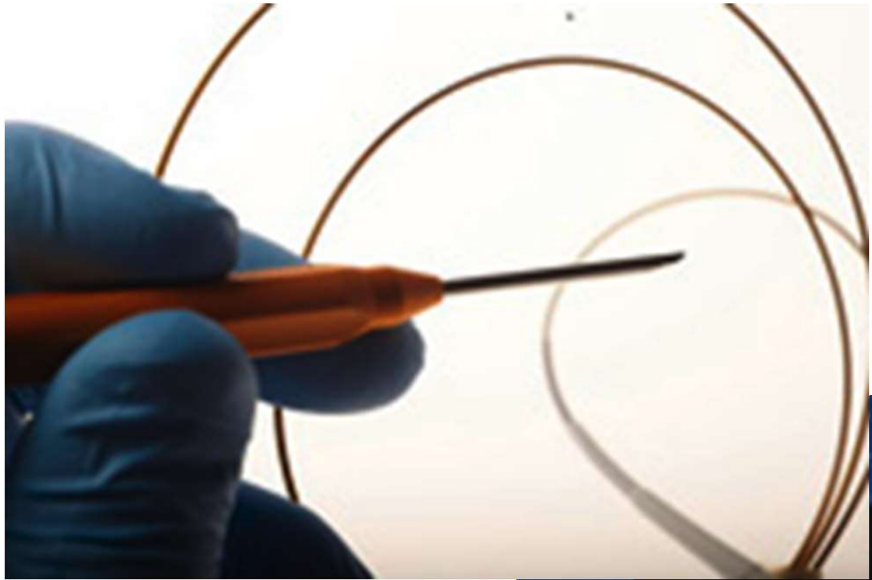
…waveguide losses < 1dB/m

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

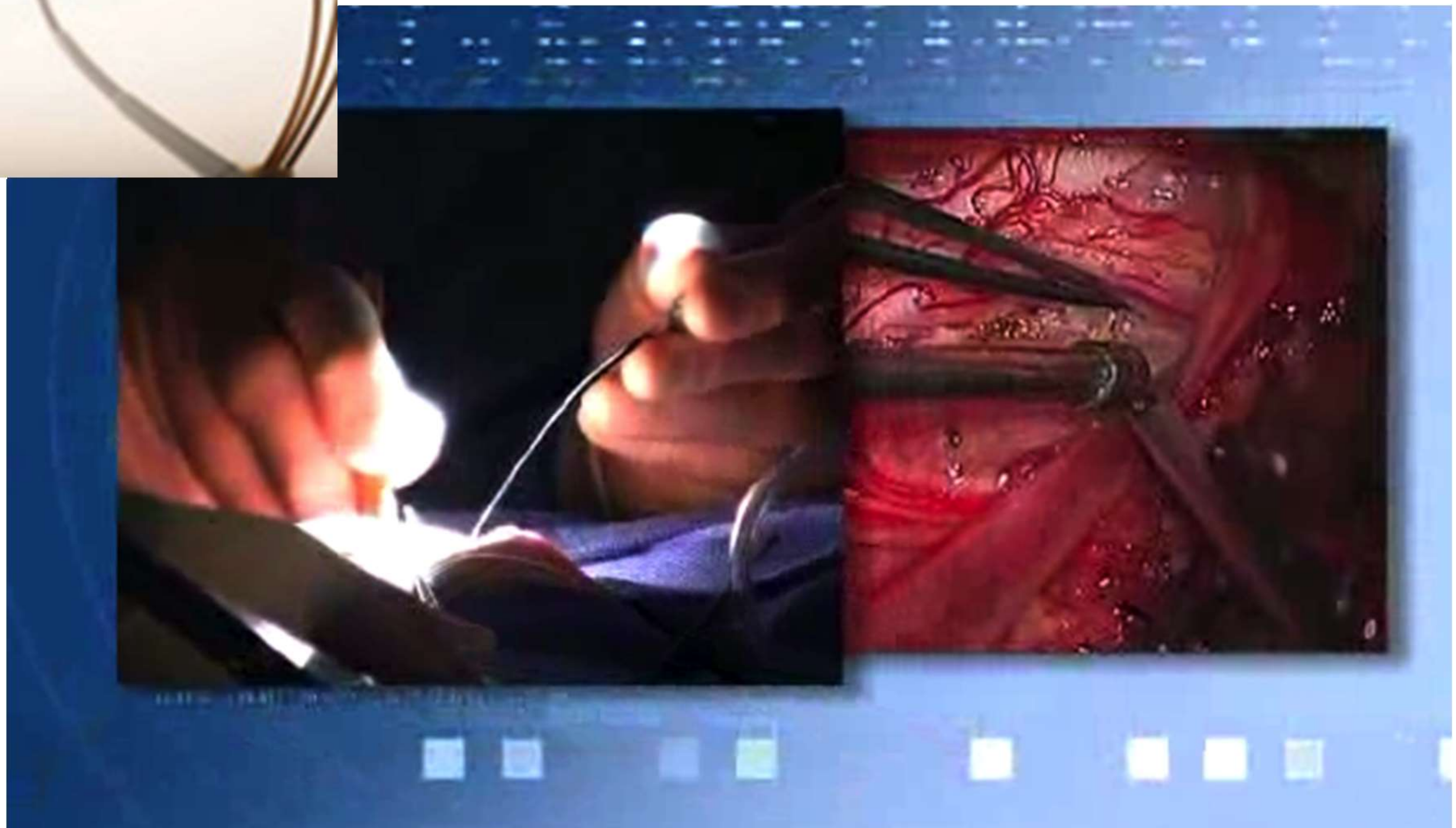


[figs courtesy Y. Fink *et al.*, MIT]

Application: Laser Surgery

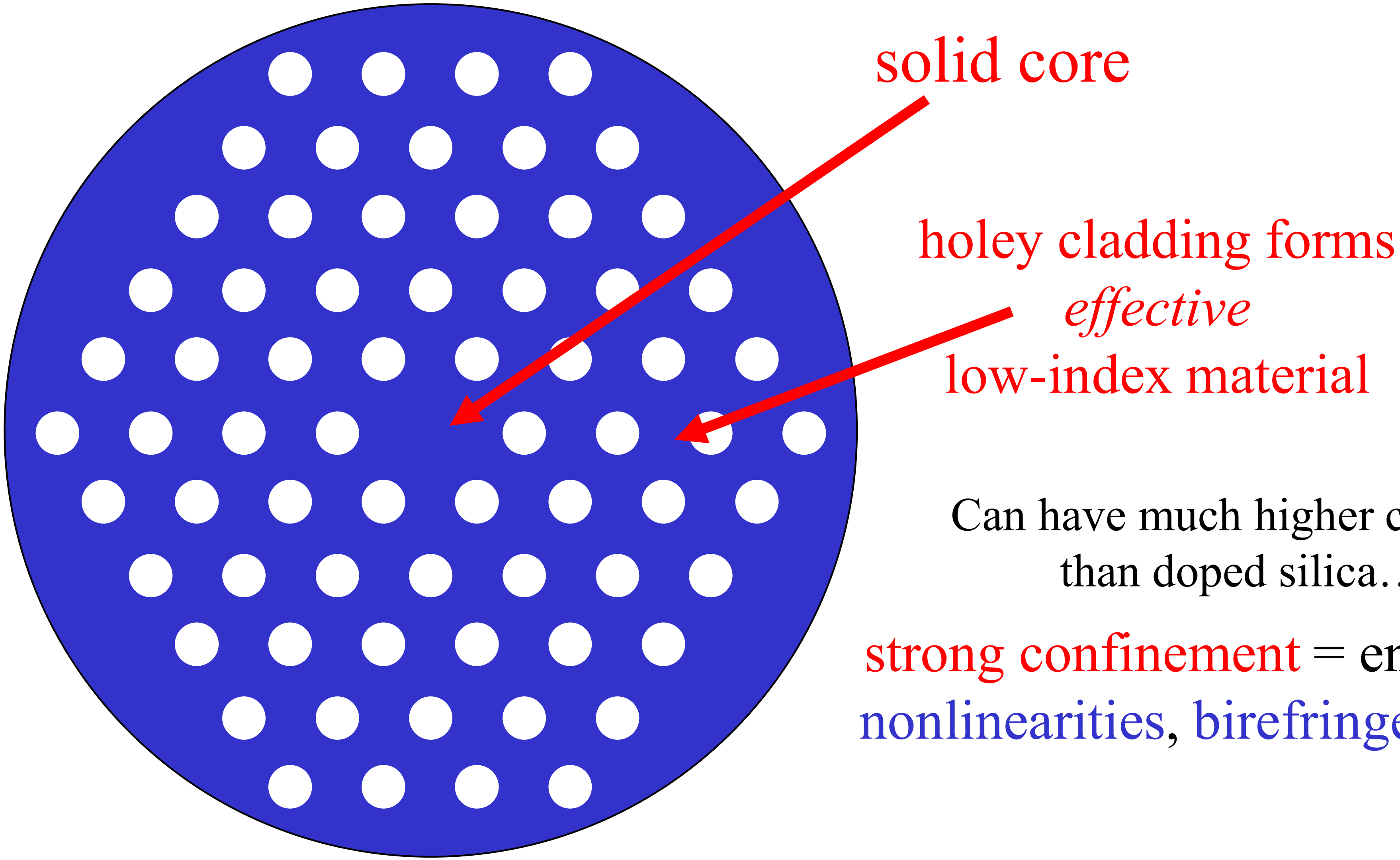


[www.omni-guide.com]



Index-Guiding PCF & microstructured fiber:

Holey Fibers



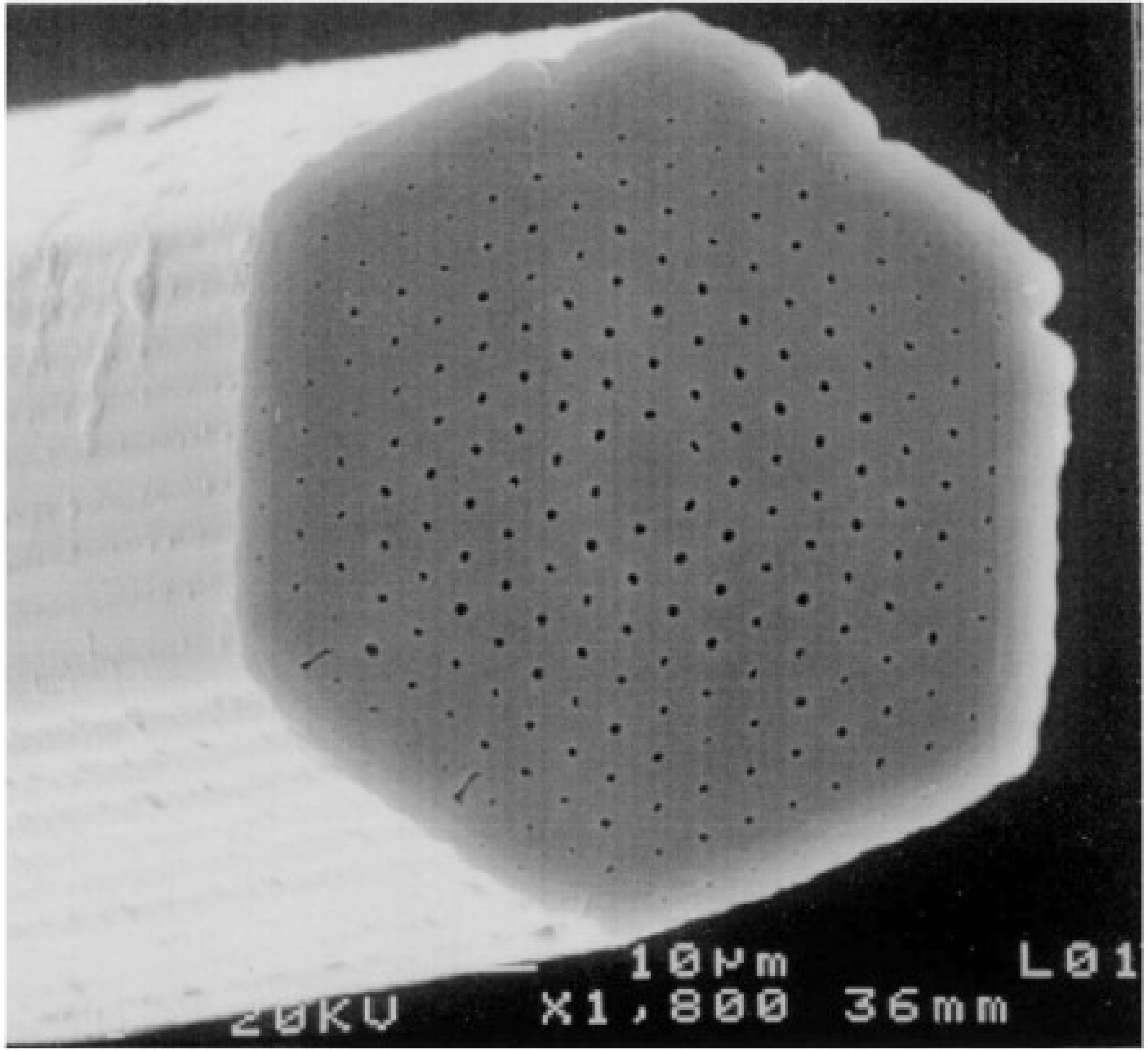
Can have much higher contrast than doped silica…

strong confinement = enhanced nonlinearities, birefringence, …

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

Endlessly Single-Mode

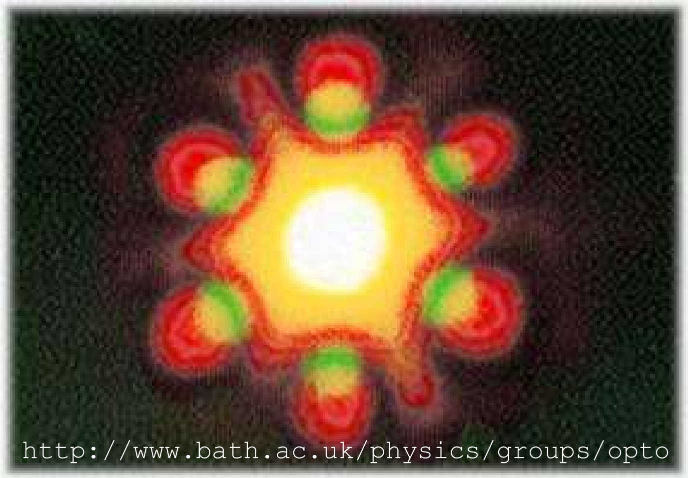
[T. A. Birks *et al.*, *Opt. Lett.* **22**, 961 (1997)]



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

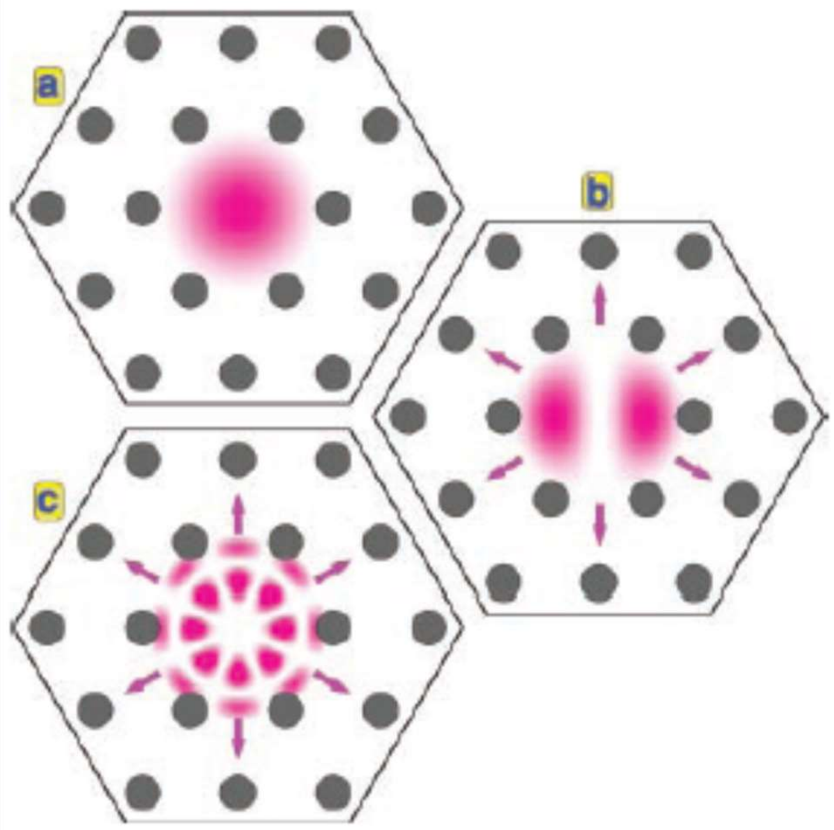
…so the effective
index contrast is less

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



Mode selection

Fig. 4. In a solid-core PCF, the pattern of air holes acts like a modal sieve. In (a), the fundamental mode is unable to escape because it cannot fit in the gaps between the air holes—its effective wavelength in the transverse plane is too large. In (b) and (c), the higher order modes are able to leak away because their transverse effective wavelength is smaller. If the diameter of the air holes is increased, the gaps between them shrink and more and more higher order modes become trapped in the "sieve."



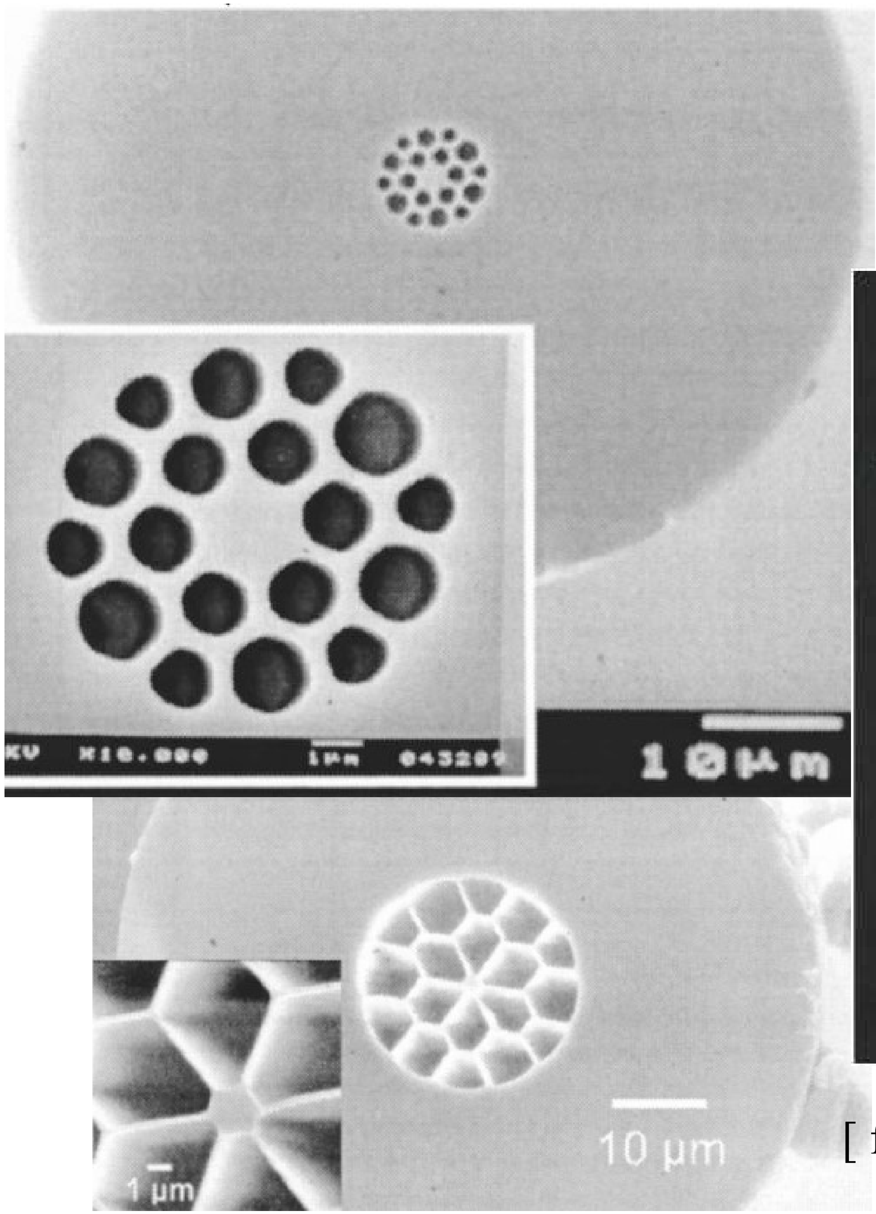
P. Russel Science 299, 358 (2003)

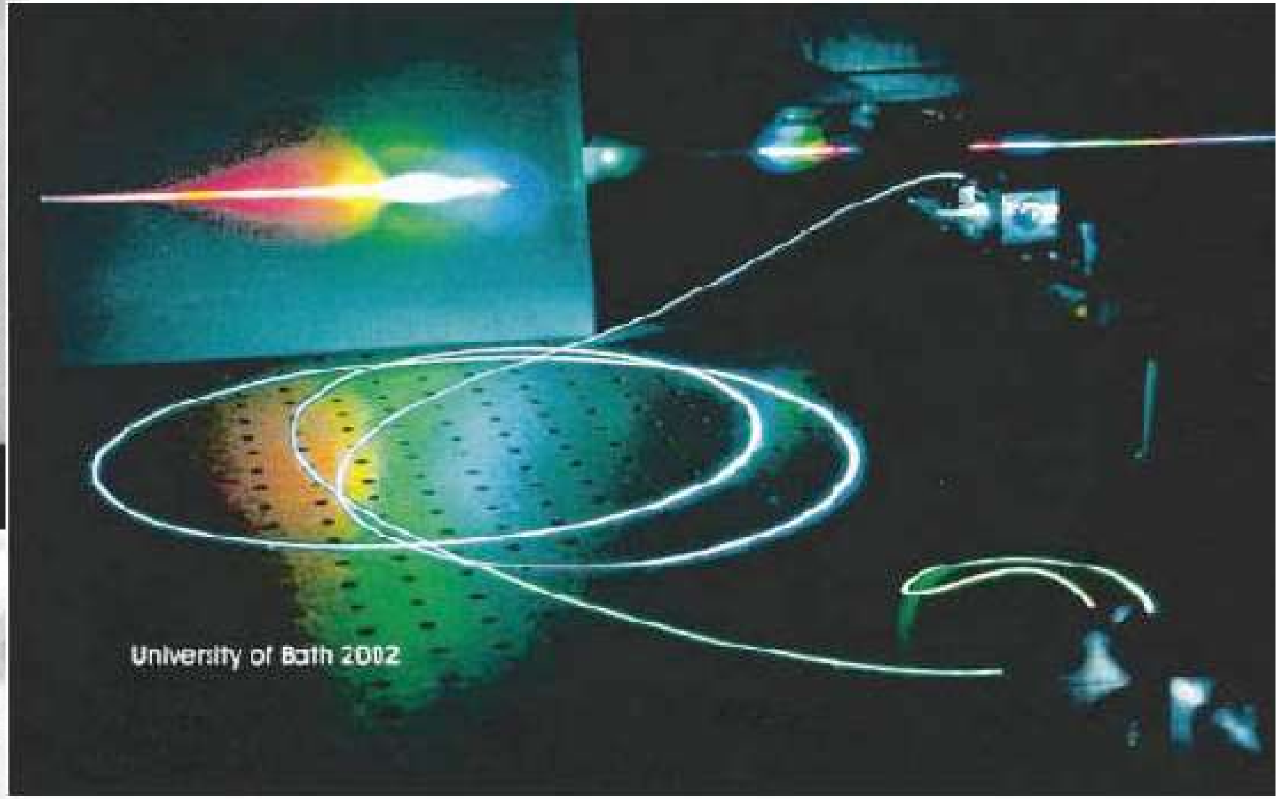
Nonlinear Holey Fibers:

Supercontinuum Generation

(enhanced by strong confinement + unusual dispersion)

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





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

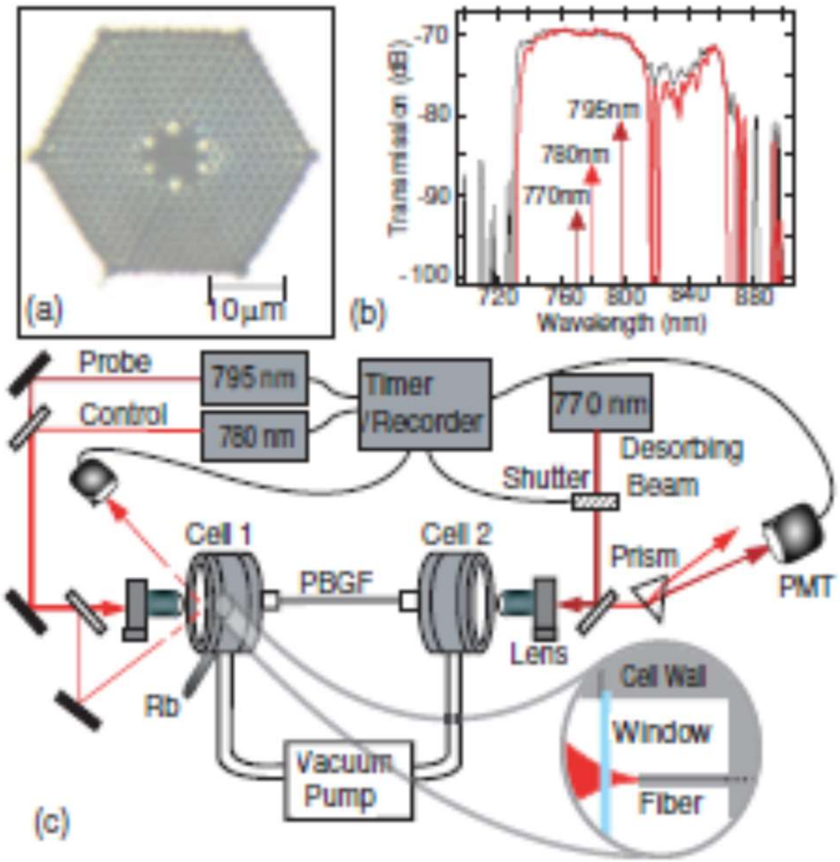
[earlier work: J. K. Ranka *et al.*, *Opt. Lett.* **25**, 25 (2000)]

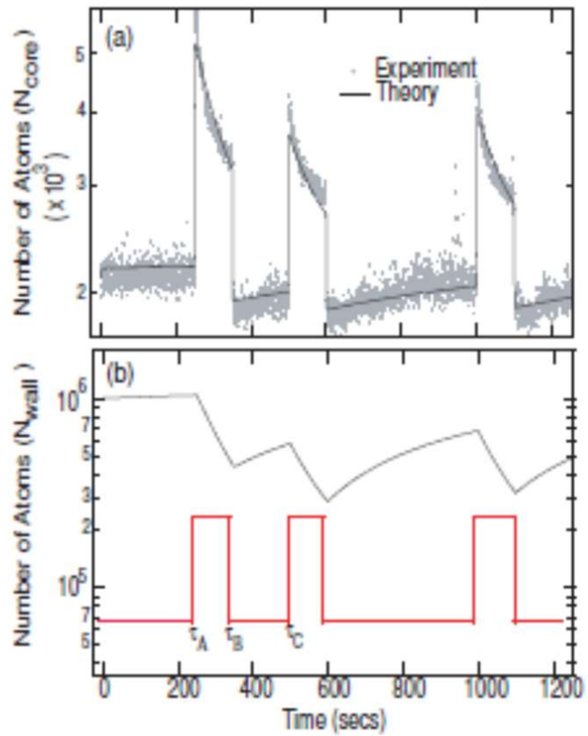
PRL 97, 023603 (2006) PHYSICAL REVIEW LETTERS week ending 14 JULY 2006

Low-Light-Level Optical Interactions with Rubidium Vapor in a Photonic Band-Gap Fiber

Saikat Ghosh, Amar R. Bhagwat, C. Kyle Renshaw, Shireen Goh, and Alexander L. Gaeta*
School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853, USA

Brian J. Kirby





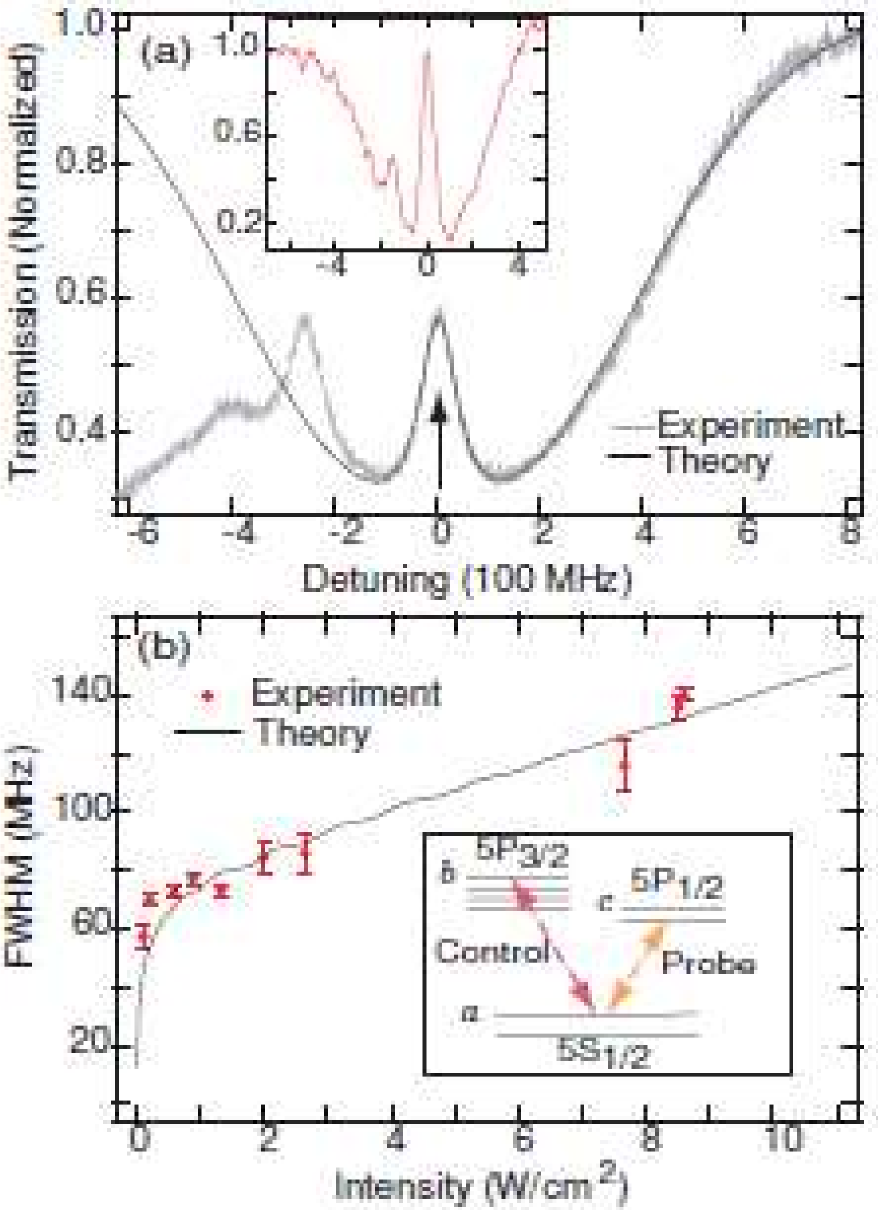
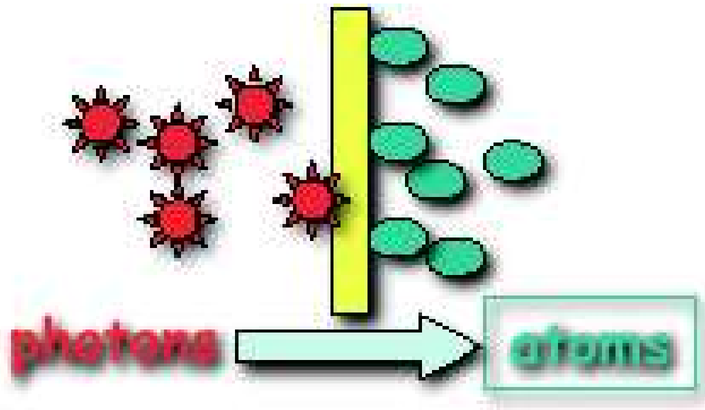


FIG. 4 (color online). (a) Transmission spectra of the probe field in the presence of a 361-nW control field. The arrow shows the transparency window due to EIT. The inset shows transparency larger than 90% for a probe scanned over $5S_{1/2}$, $F = 1 \rightarrow 5P_{1/2}$, $F' = 1$ with a 2.65 μW control field tuned to $5S_{1/2}$, $F = 1 \rightarrow 5P_{3/2}$, $F' = 1$ transition. (b) Experimental and theoretical variation of the EIT linewidth as a function of control intensity.

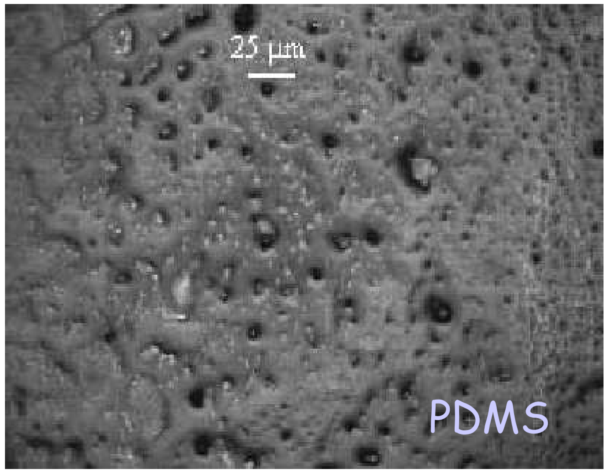
The LIAD effect



Light even nonresonant, weak and incoherent

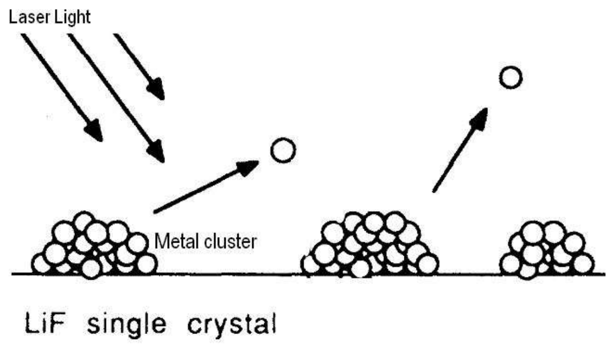
Alkali-metal atoms: Na, Rb, Cs, K (Na_2, Ca)

Adsorbing surfaces: organic coatings, glass, quartz, Vycor, porous glass, porous alumina, stainless steel, sapphire



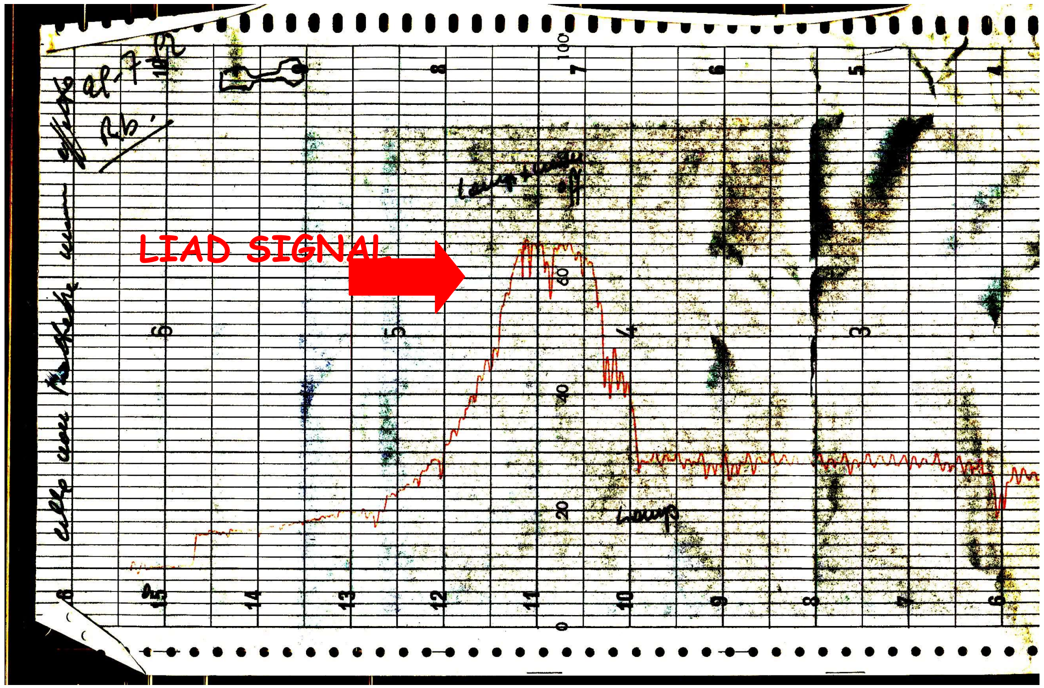
First experiments on LIAD

1988 - Photodesorption from metal nanoparticles, Hoheisel et al.



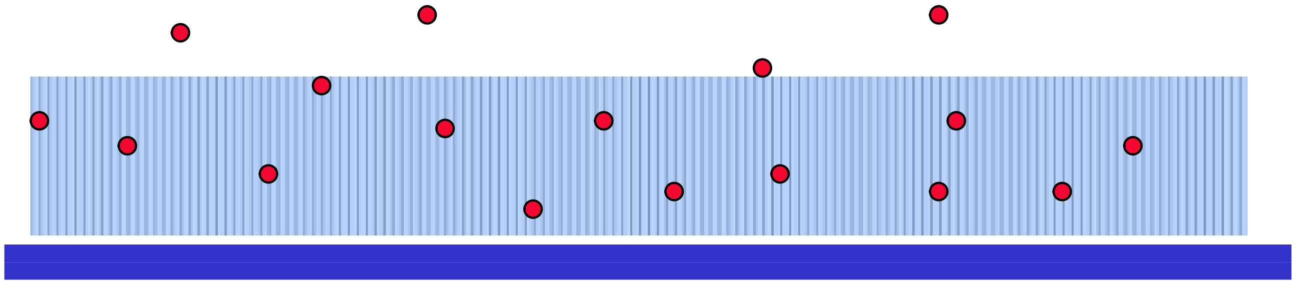
1993 - Na photodesorption from PDMS, Gozzini et al.

1994 - Rb photodesorption from PDMS, Meucci et al.



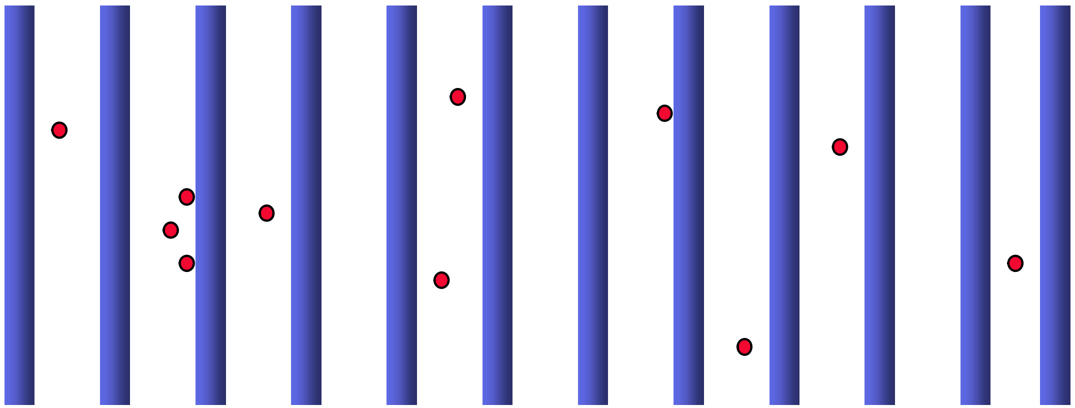
1999 - Na photodesorption from SiO_2 Yakshinskiy and Madey

Surface-Atom Interaction



PDMS

$$E_{Ads} \approx 0.1eV$$



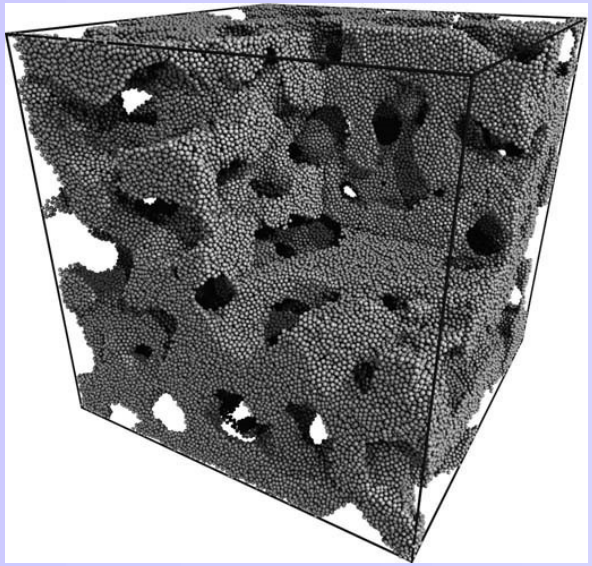
POROUS GLASS

$$E_{Ads} \approx 1eV$$

Surface Atomic Density

$$\sigma = \frac{n}{4} v_T \tau_0 e^{\frac{E_{Ads}}{kT}}$$

Porous glass

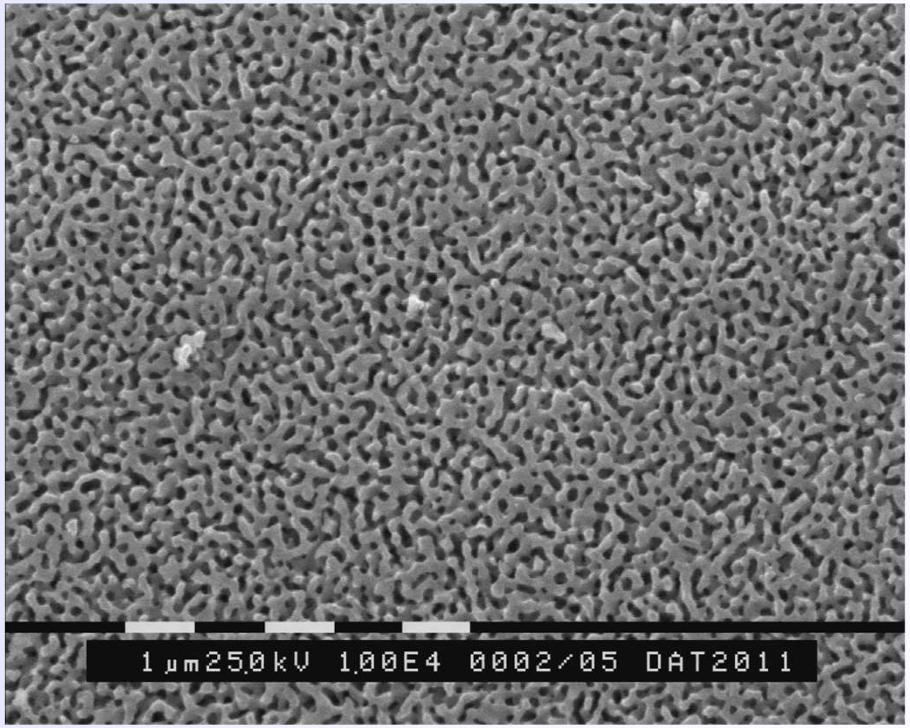


www.npaci.edu website

We use as host matrix for atoms and nanoparticles porous silica with a mean pore diameter of **17 nm** and a free volume of about **50%** of the whole silica mass.

Pore volume: 500mm^3/g
Pore surface: 100m^2/g
Mean pore diameter: 17nm
SiO_2>96%

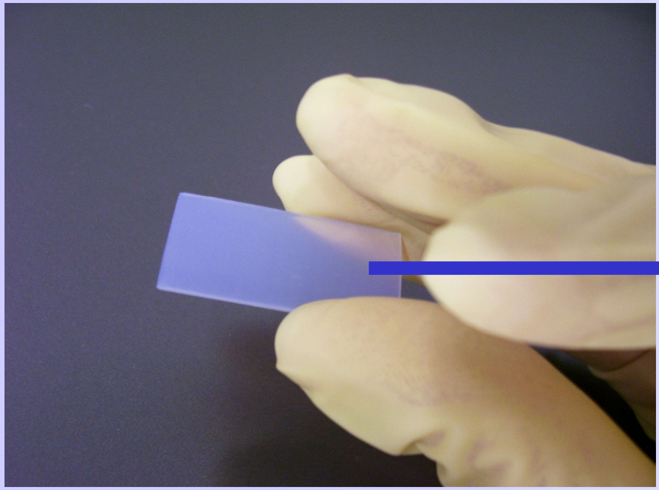
~17nm



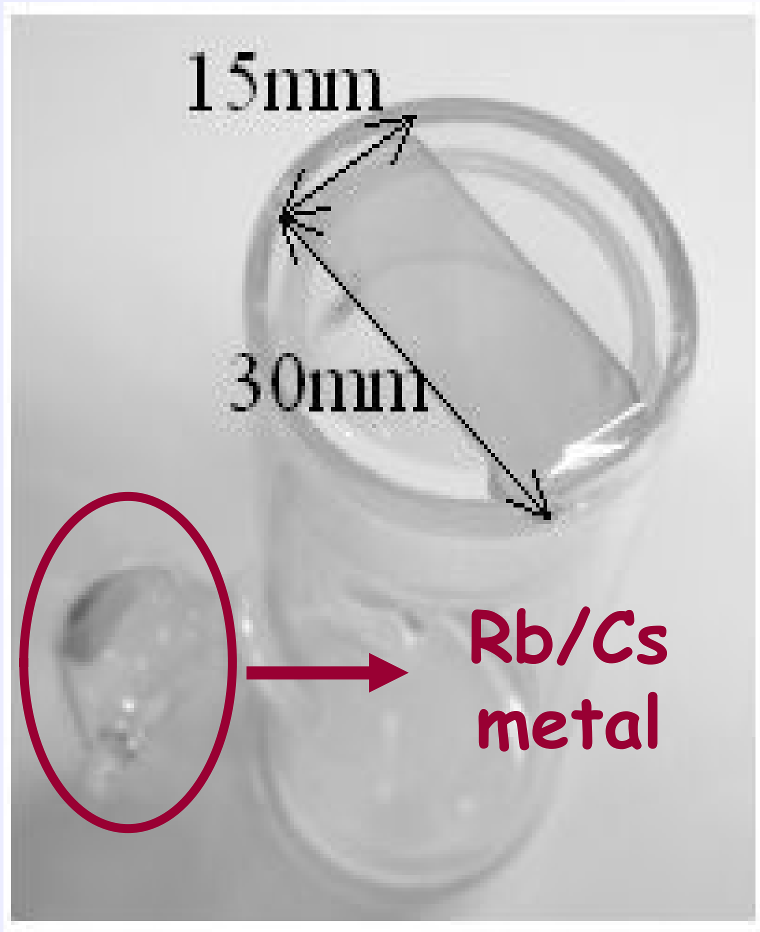
REM picture - VitraBio

The porous glass sample used is a rectangular plate **30x15x1mm³** in size. It is placed inside a Pyrex resonance cell, kept at room temperature, and filled with rubidium.

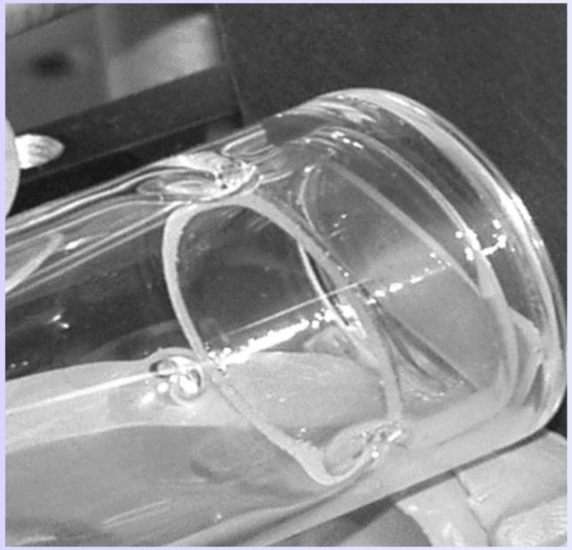
Sample and alkali vapor cell

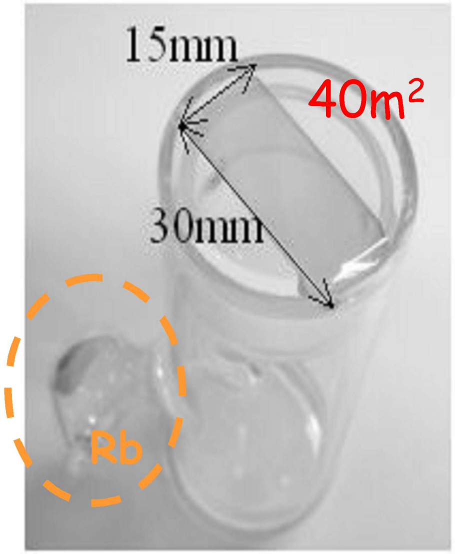


0.4g=40m²

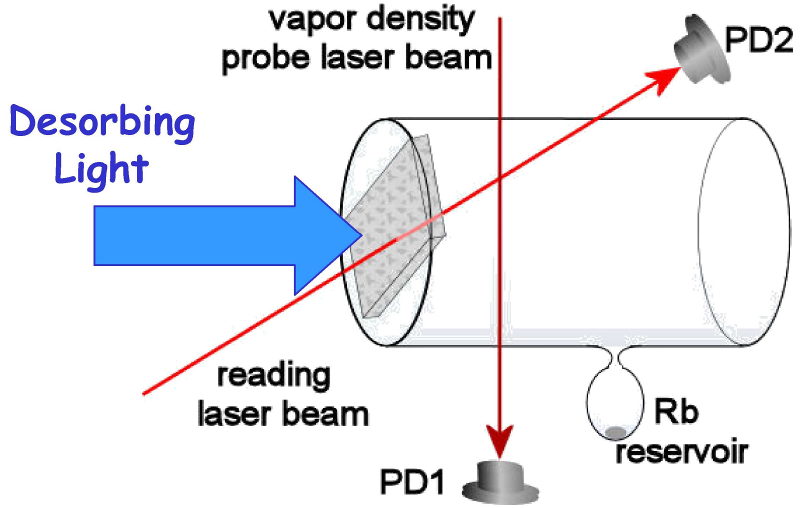


The sample is fixed close to one of the cell windows by a Pyrex Ring sealed to the cell body

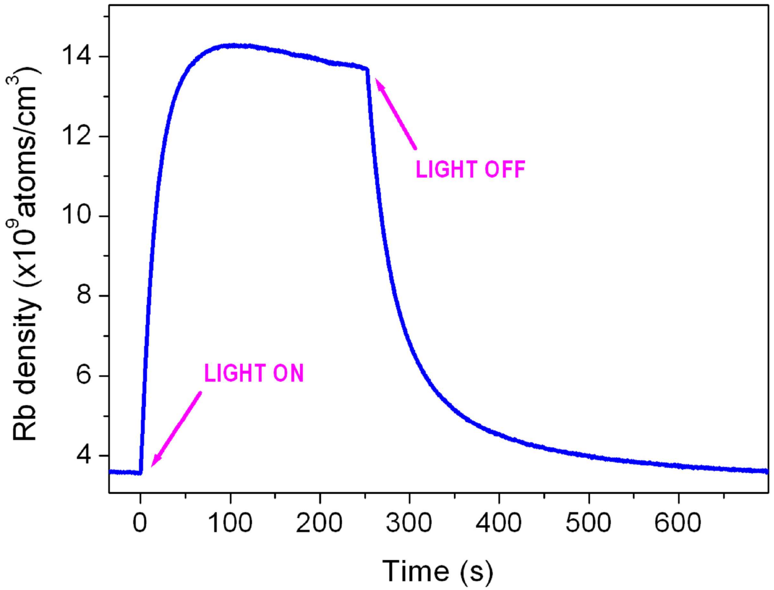


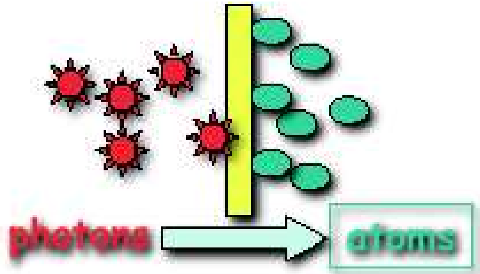


LIAD set-up

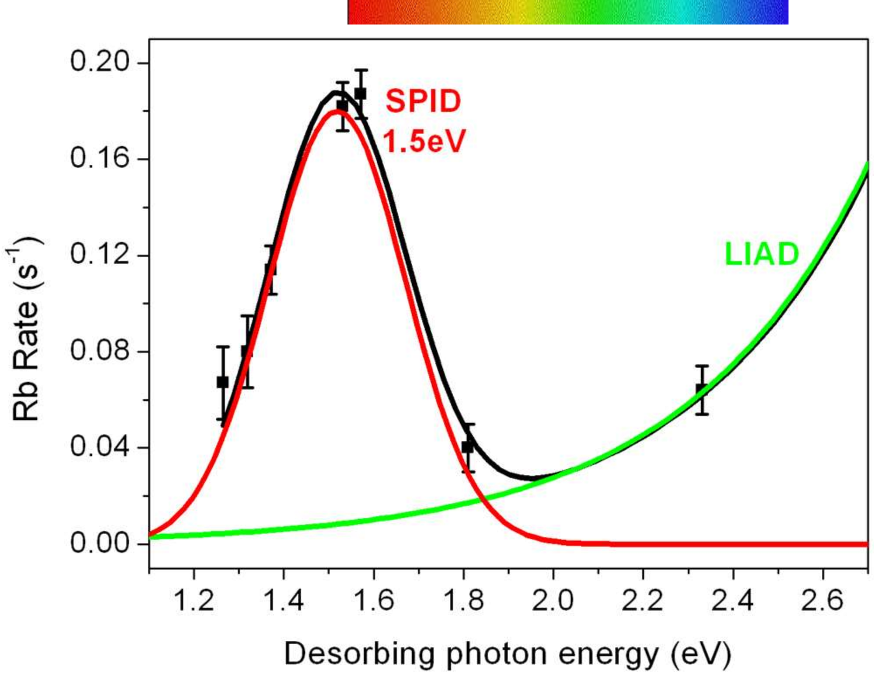


LIAD SIGNAL

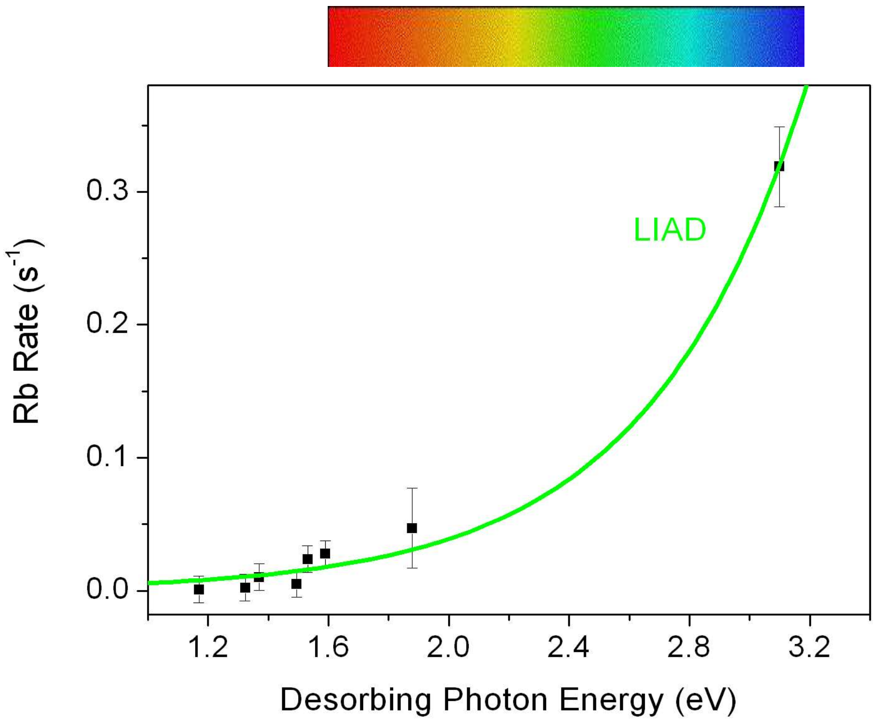


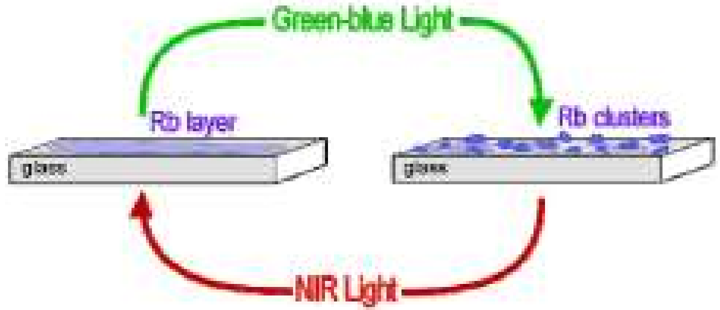


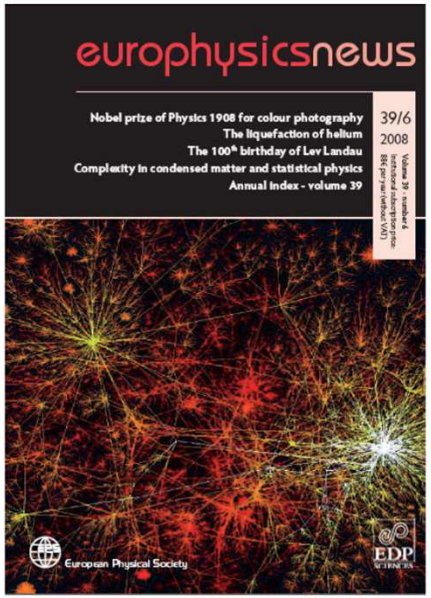
Rb + POROUS GLASS



Rb + PDMS







Optical response of Rb and Cs nano-particles in porous silica

Adsorption, desorption and nanoparticle formation processes are of great importance in the study of surface interactions. The possibility to understand and to modify the underlying mechanisms has a remarkable impact on fundamental physics as well as on technological applications. Indeed, the ability to control the adsorption/desorption and nucleation rates opens the way for the fabrication of nano-structured surface layers and nano-particle arrays.

We studied the influence of optical radiation on adsorption/desorption and cluster growth of Rb and Cs alkali metals confined at the nano-scale. Atomic layers and quasi-spherical nano-particles are formed in a nano-porous glass template by vapour diffusion in the dark. As light hits the porous matrix, the equilibrium inside the nano-pores between nano-particles, atomic layers and vapor phase, is suddenly shifted. In fact light, depending on its frequency and intensity, detaches atoms either from clusters or atomic layers. A small part of the desorbed atoms diffuses out of the porous sample, while the others, trapped in the glass matrix, re-condense on the pore walls, forming either nano-particles or layers. Therefore light moves atoms from layers to clusters and vice versa. The shift direction is clearly visible as particle formation induces a deep bluish coloration of the porous sample (Fig.).

▲ **Dragon's picture recorded on porous glass loaded with Rb. The sample region exposed to light becomes blue due to the increase of the number of Rb nano-particles with respect to the equilibrium condition in the dark.**

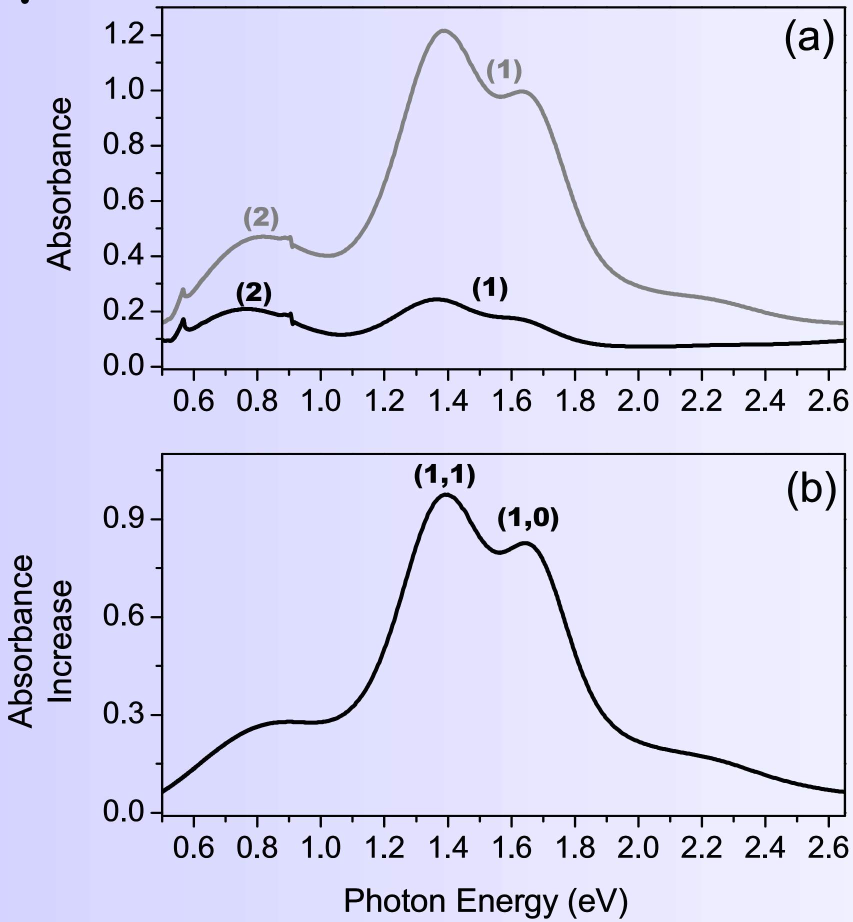
Furthermore, we found that the nanoparticles formed in the dark, as well as the ones grown by light, are almost identical in size and shape. Therefore light increases or decreases the number of nano-particles dispersed in the porous sample without substantially affecting their structural properties. This result provides clear evidence that the confinement geometry imposes tight conditions on the equilibrium configuration of the existing clusters. ■

A. Burchianti, A. Bogi, C. Marinelli, C. Maibohm, E. Mariotti, S. Sanguinetti and **L. Moi**, 'Optical characterization and manipulation of alkali metal nanoparticles in porous silica', *Eur. Phys. J. D* **49**, 201 (2008)

Phase transformations induced by UV-visible light:

Cluster growth

Rb/PG



Hg Lamp

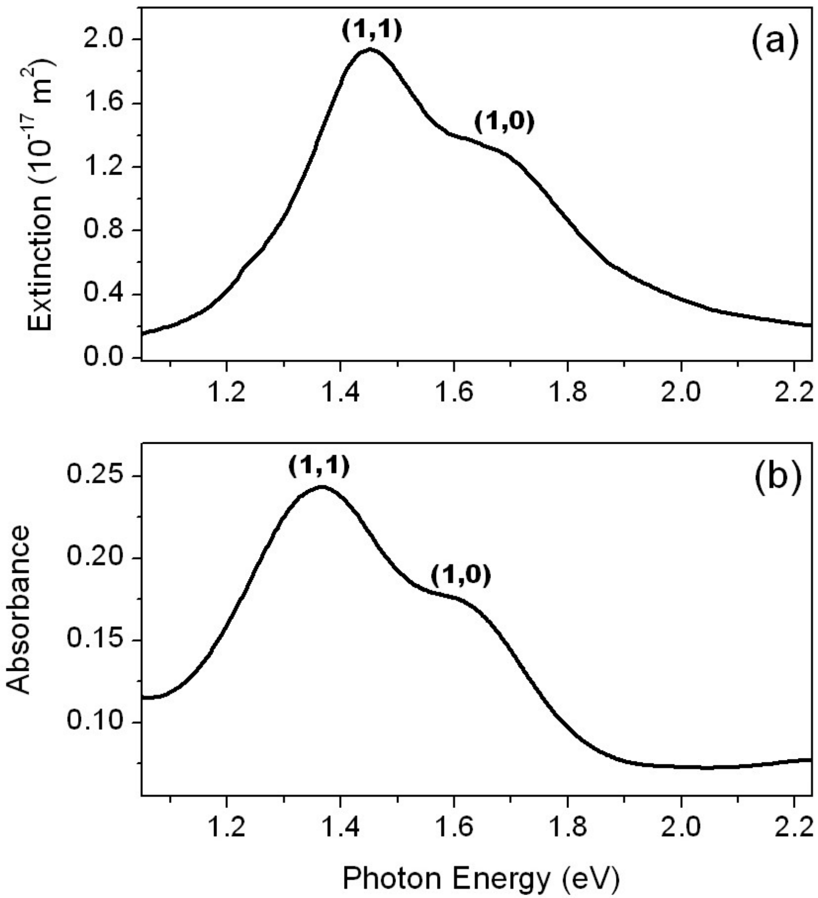
10 mW/cm^2; 2 min

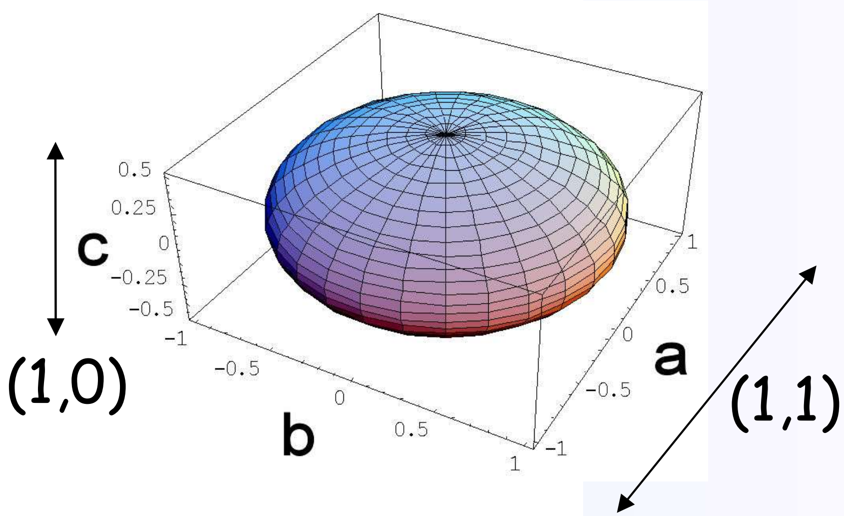
Light decreases the sample transmission in the red-NIR region. **The sample turns blue**

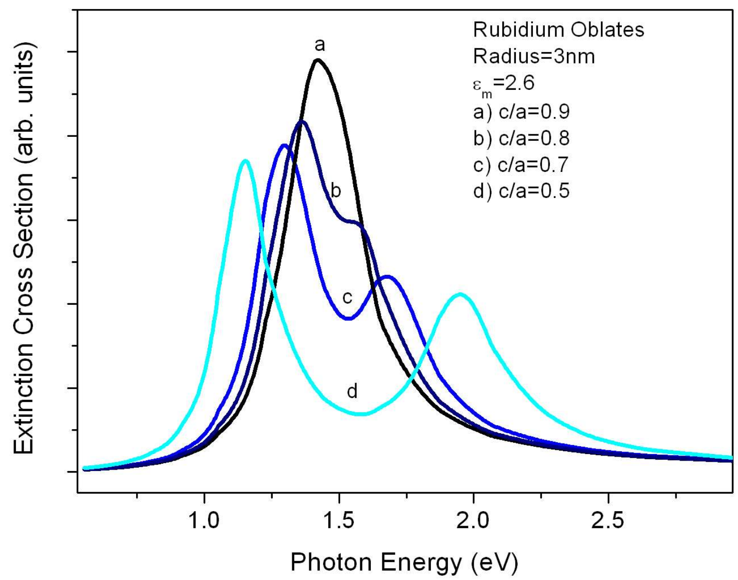
Optics Express 16, 1377 (2008)

Phys. Rev.Lett. 97 157404 (2006)

Rb/PG





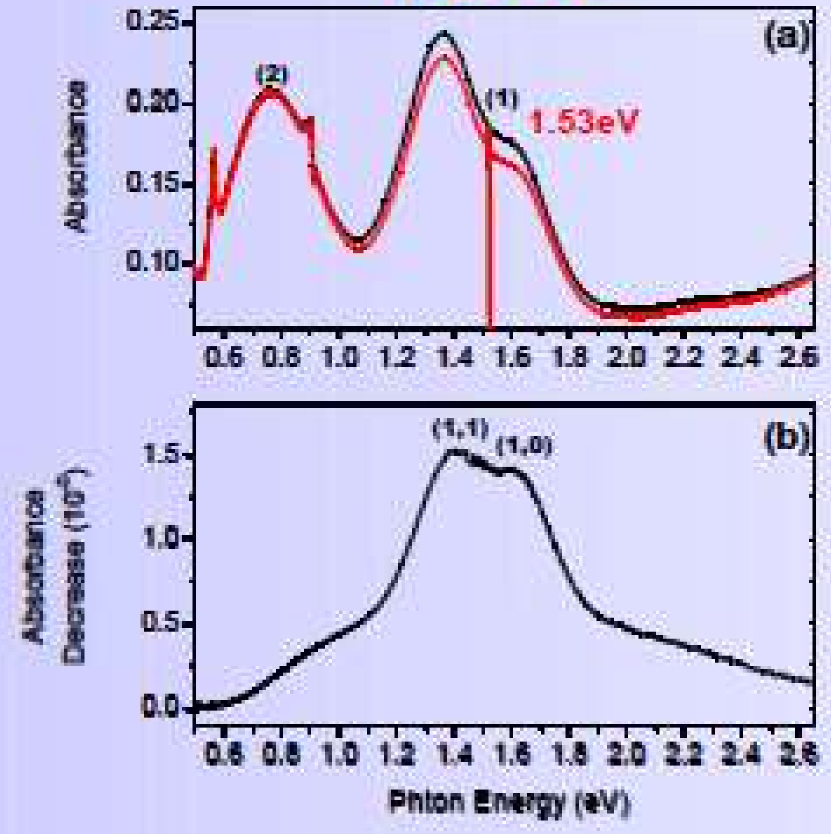


R=3nm; c/a=0.8

Phase transformations induced by NIR light:

Competition between cluster evaporation and growth

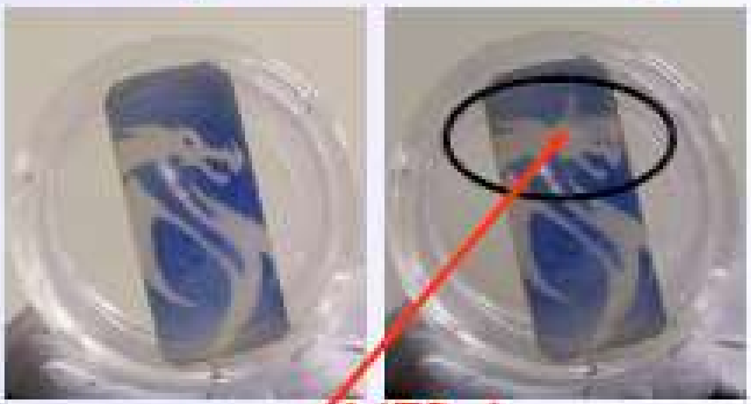
Rb/PG



Diode laser at 1.53eV

180mW/cm^2; 3min

Sample bleaching

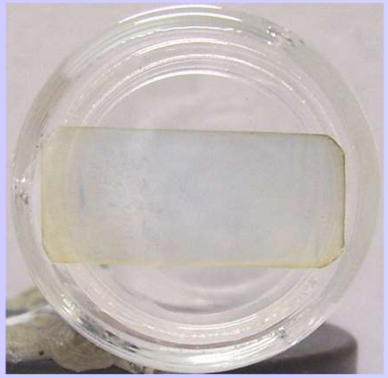


NIR laser

1.53 eV (808 nm) 240 mW/10mm^2

Storing and erasing images in Rb loaded PG

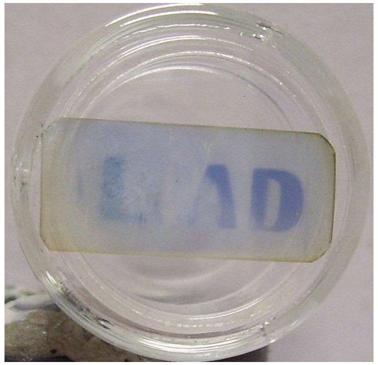
Optics Express 16, 1377 (2008)



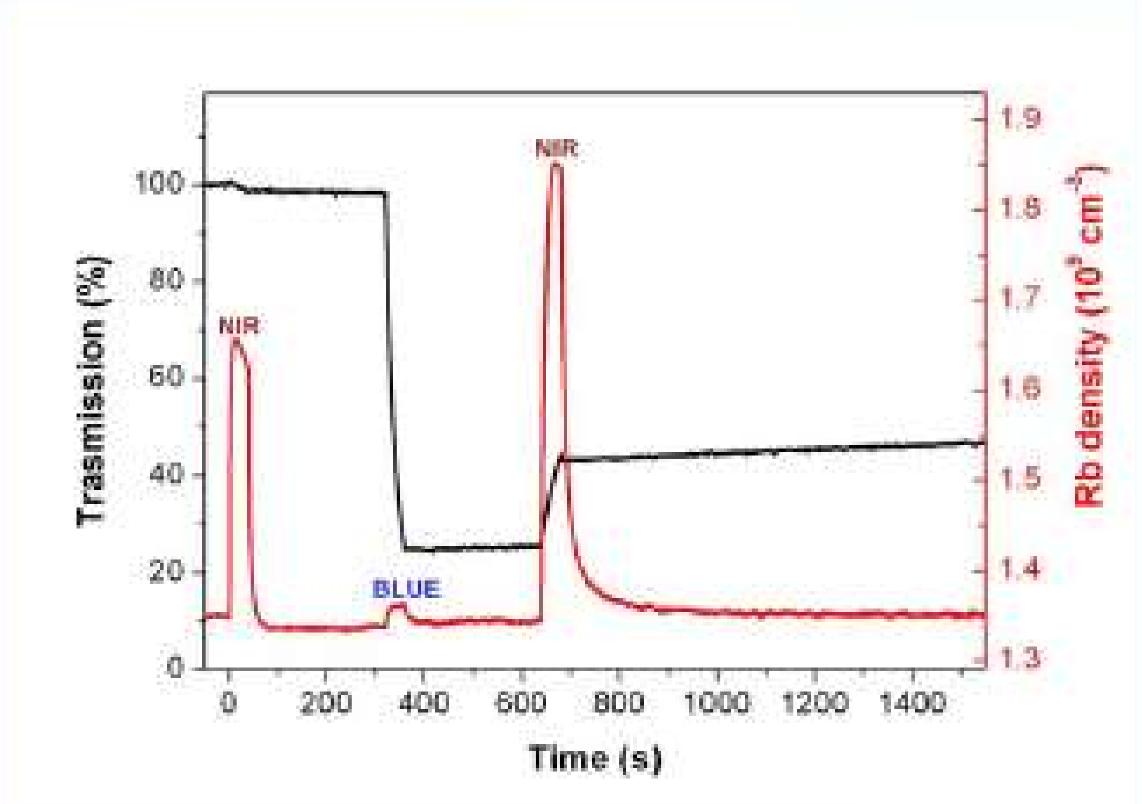
20mW/cm^2 at 2.3eV; 2min

2.5W/cm^2 at 1.5eV; 30s

In the dark the system relaxes to the equilibrium condition



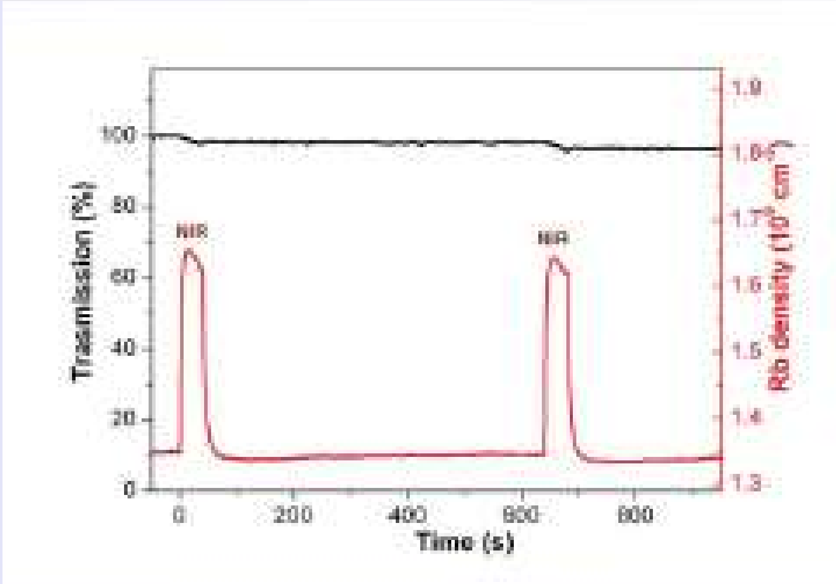
NIR-BLUE-NIR sequence of colours



488nm 5.6mW/cm^2
illuminated area 0.3 cm^2

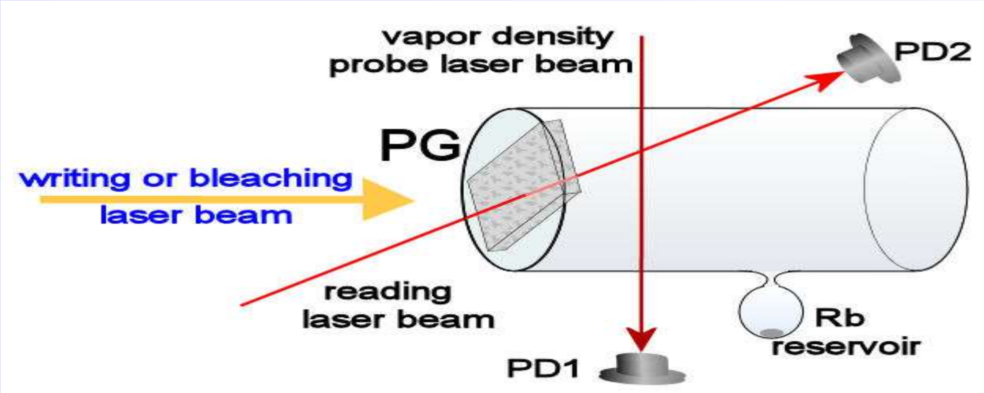
808nm 2W/cm^2
illuminated area 0.1 cm^2

Double NIR illumination

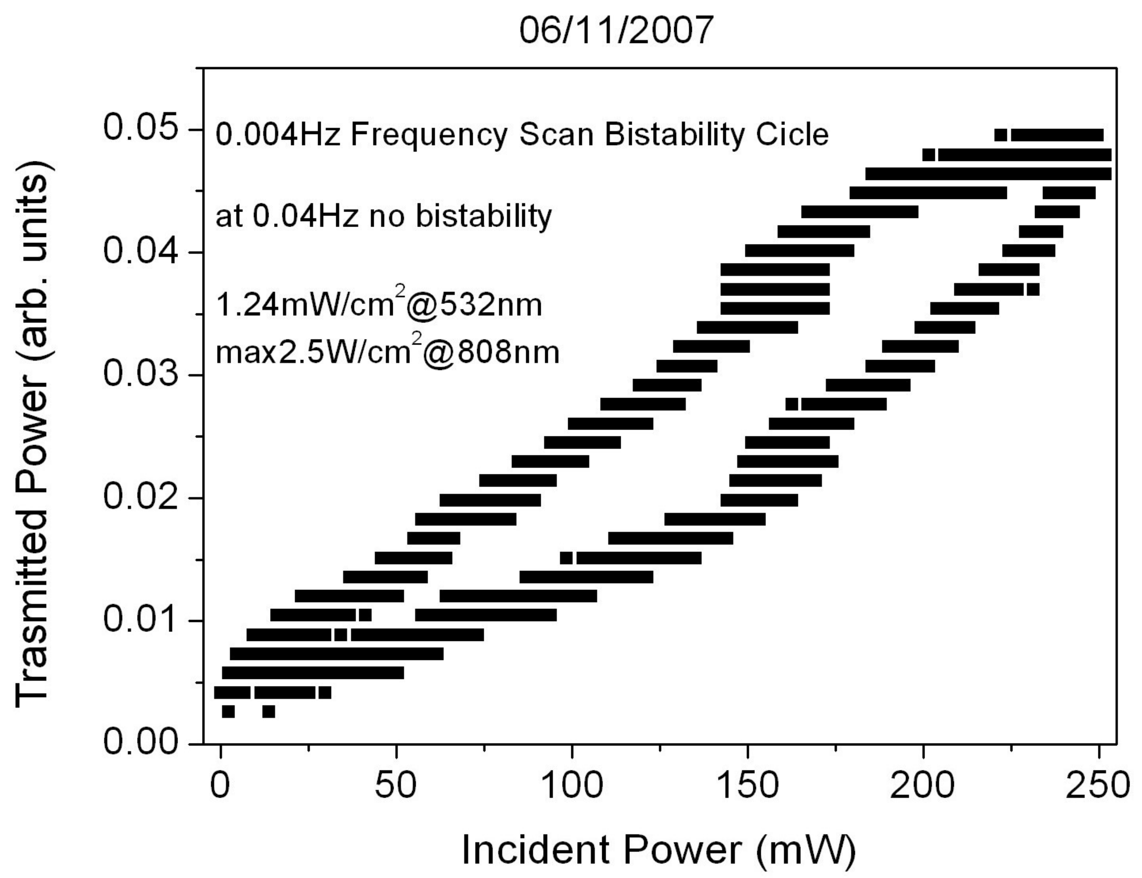


Optical bistability in Rb loaded porous glass

Experimental set-up



preliminary



Work in progress....
thanks for your attention