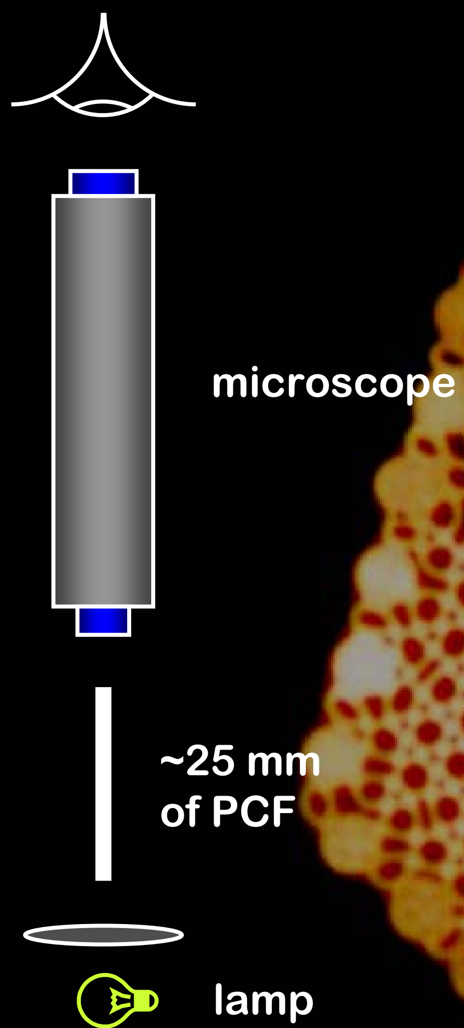
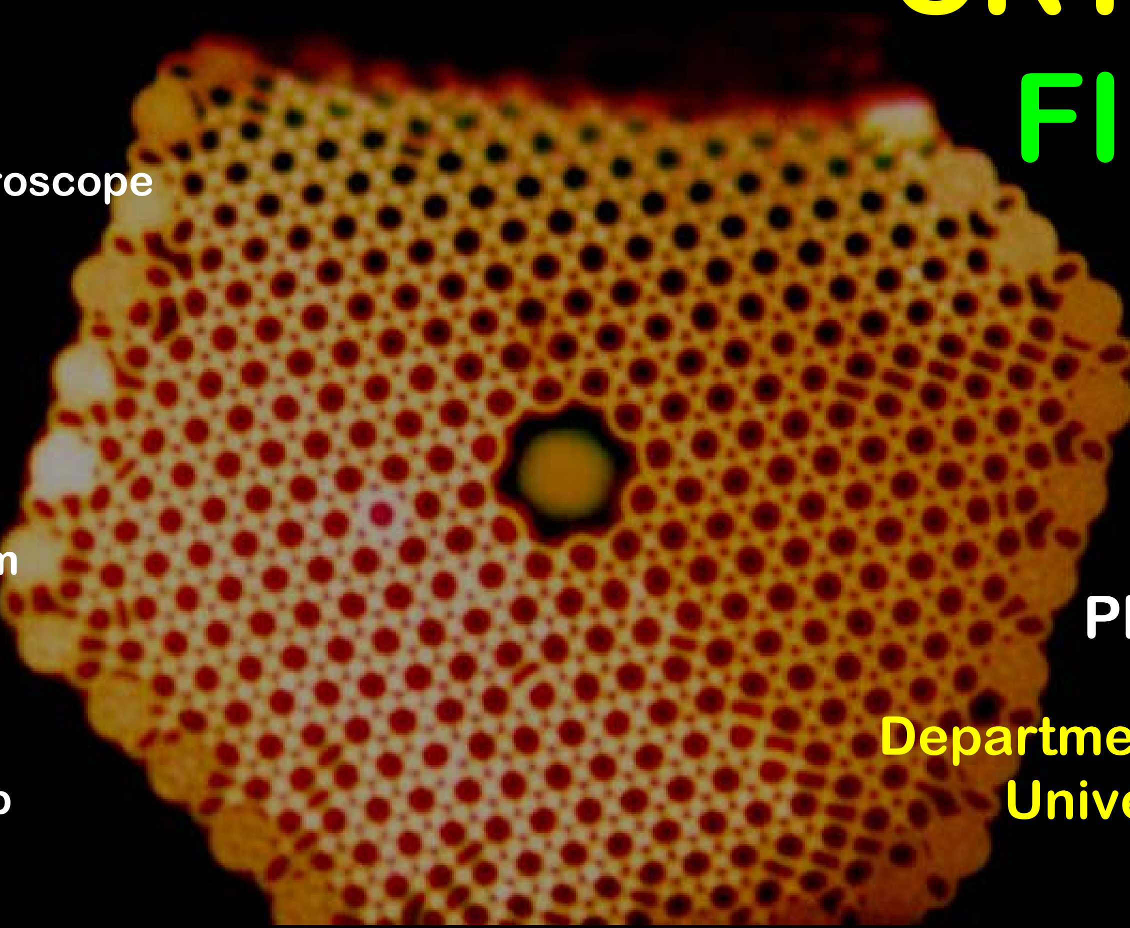
PHOTONIC CRYSTAL FIBRES





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PPMG

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Contents

review papers:
Science 299 (358-362) 2003
Nature 424 (847-851) 2003

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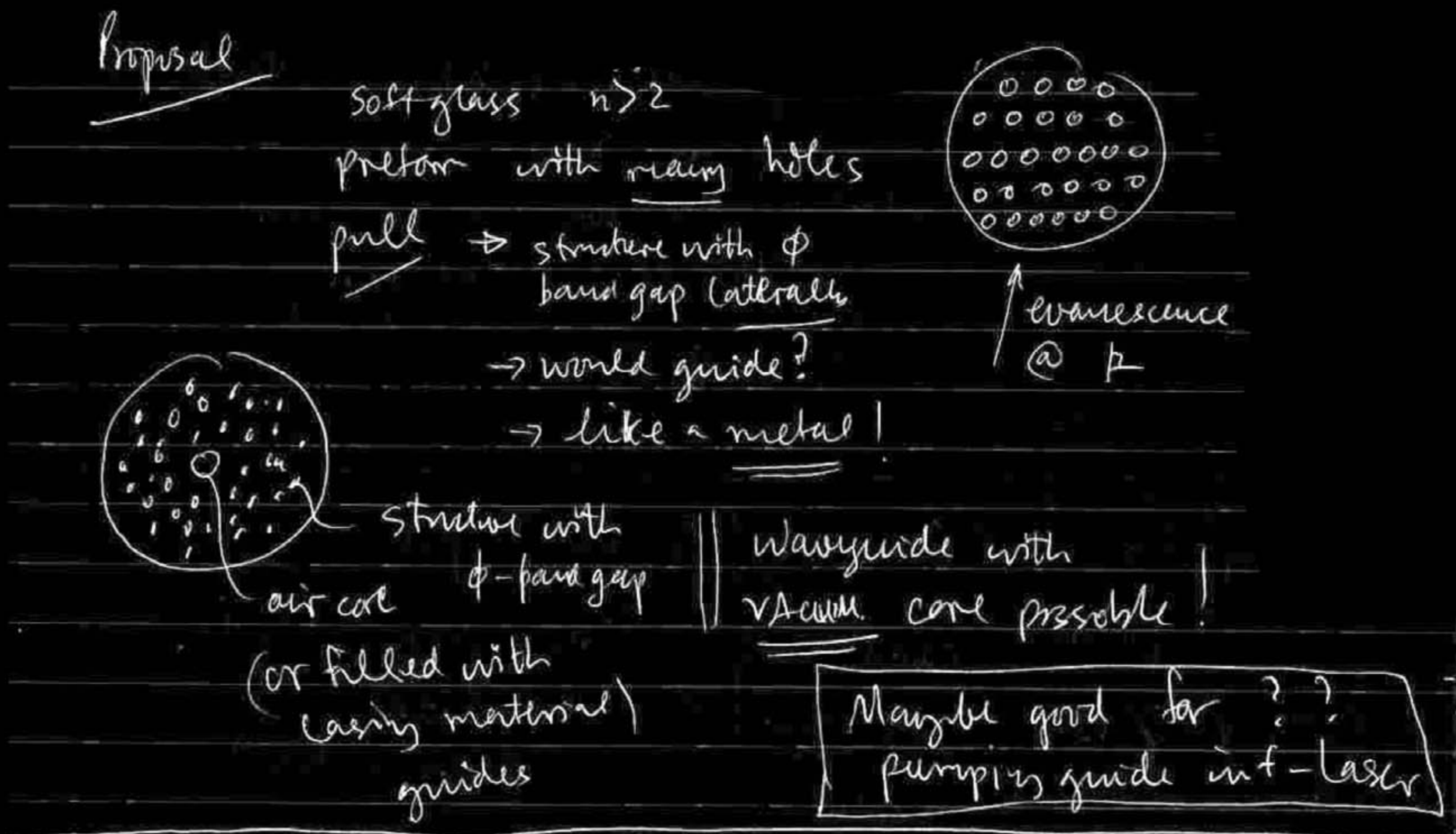
Photonic crystal fibre

1991

notes made at CLEO/QELS, 13th May 1991



"Photonic Bloch waves," NATO ASI, Erice, Sicily, July 1993

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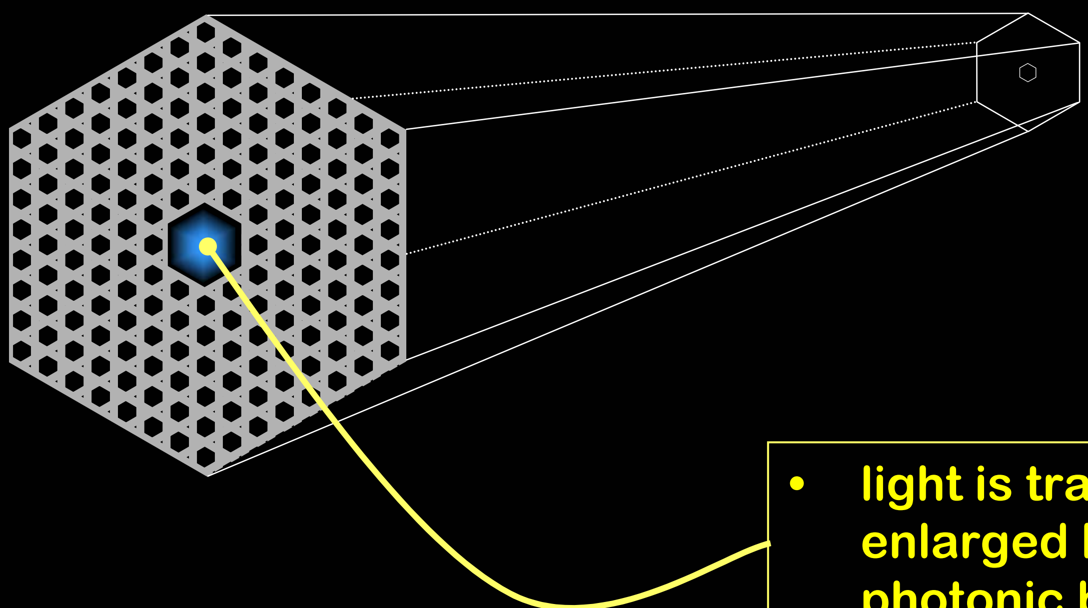
A photonic band gap fibre



- light is trapped inside an enlarged hole by a photonic band gap in the cladding

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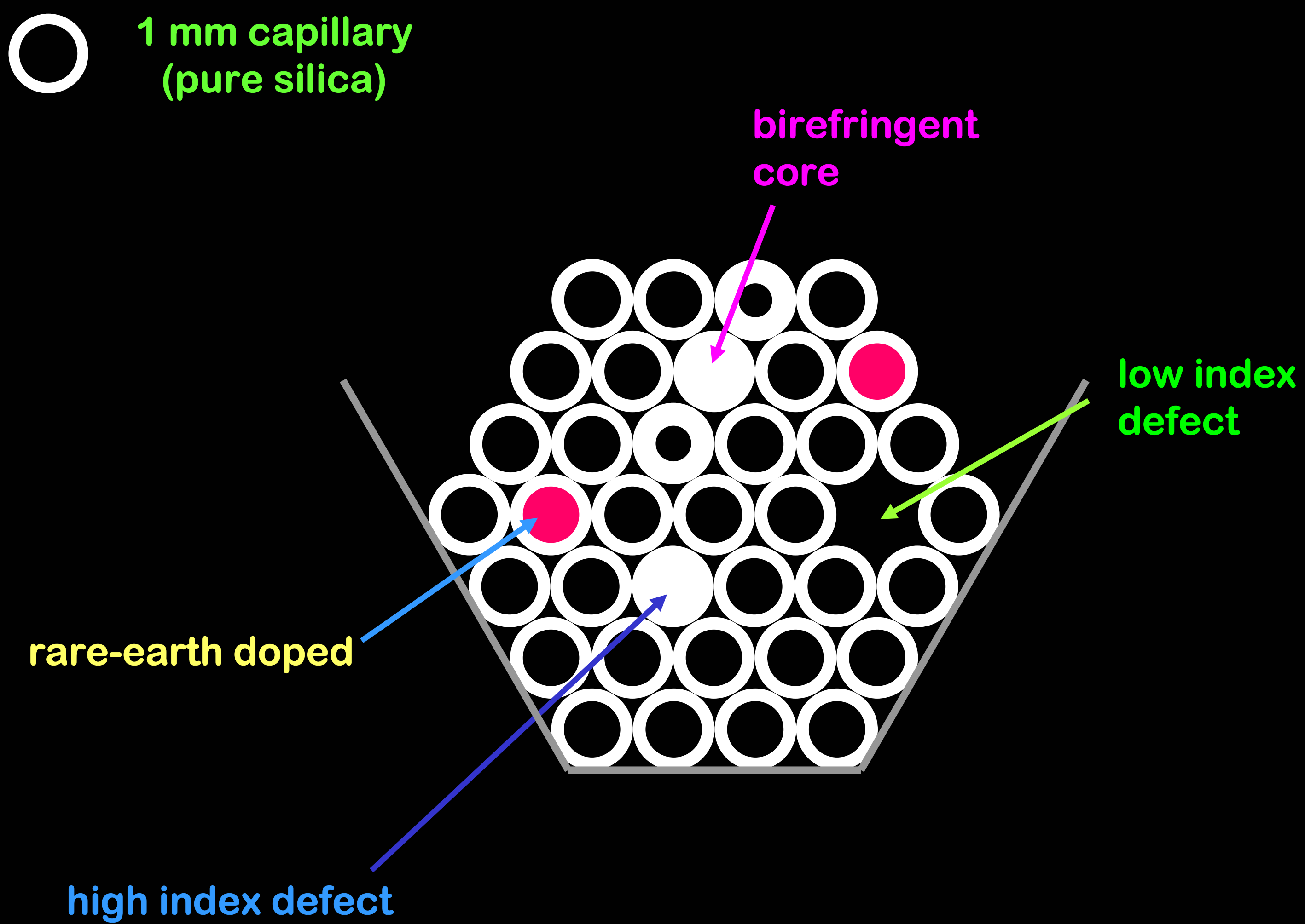
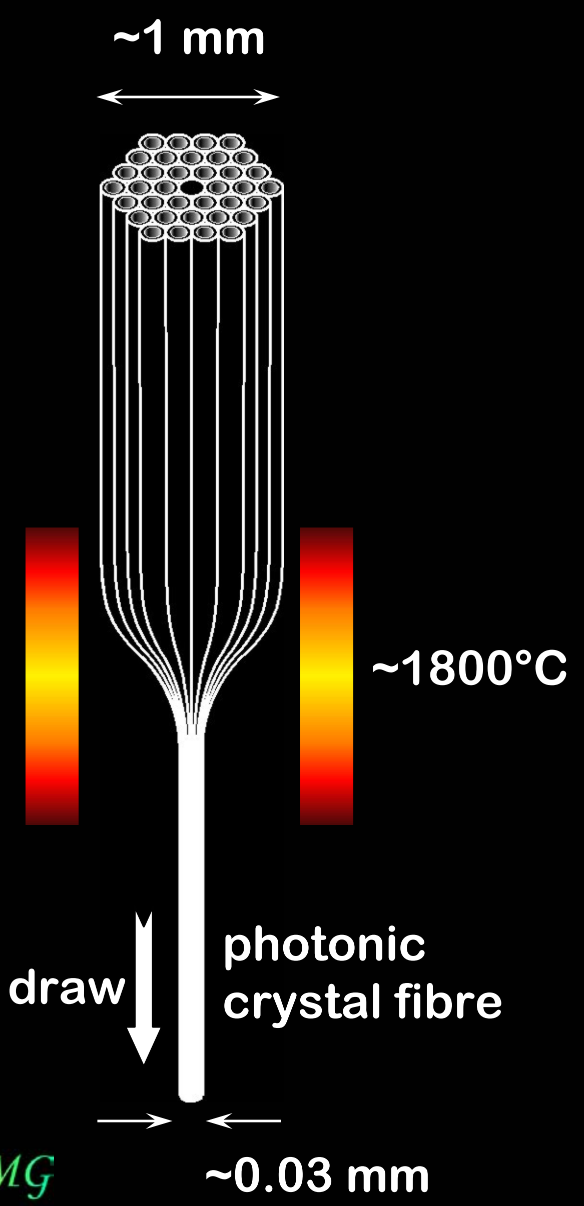
Stacking it up…



...& drawing it down



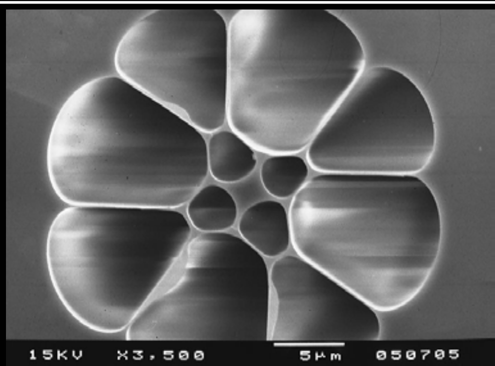
- overall collapse ratios as large as ~10,000×
- solid silica outer cladding incorporated
- continuous holes as small as 25 nm demonstrated

Squeezing it out: extrusion

pasta wheel

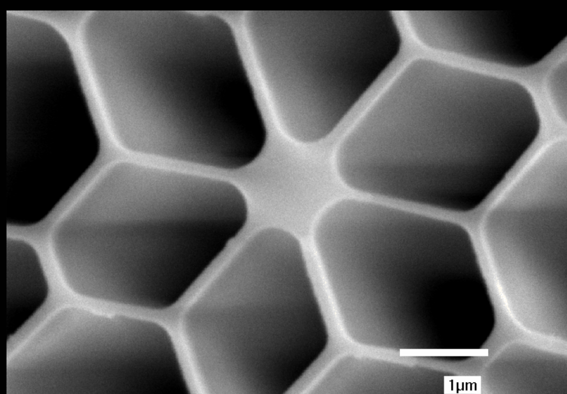
- used successfully for polymers and silica, tellurite & chalcogenide compound glasses

Nano-structurally diverse

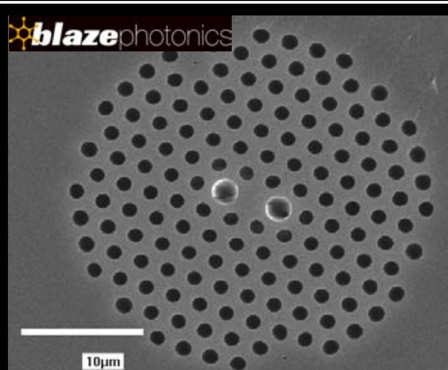


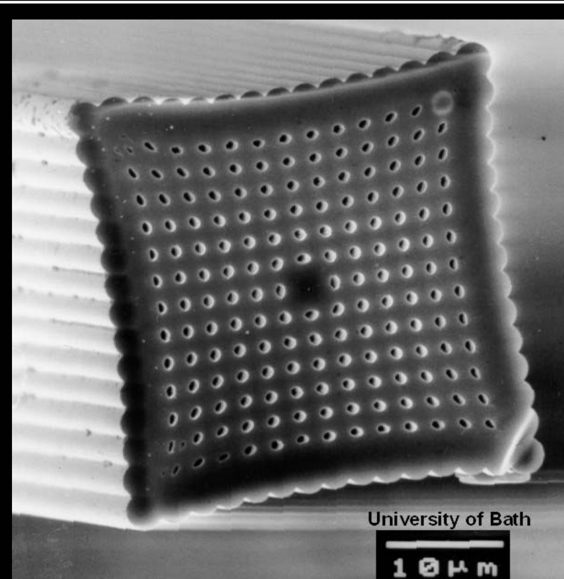
extruded supercontinuum fibre (Schott SF6 glass)

highly nonlinear small core

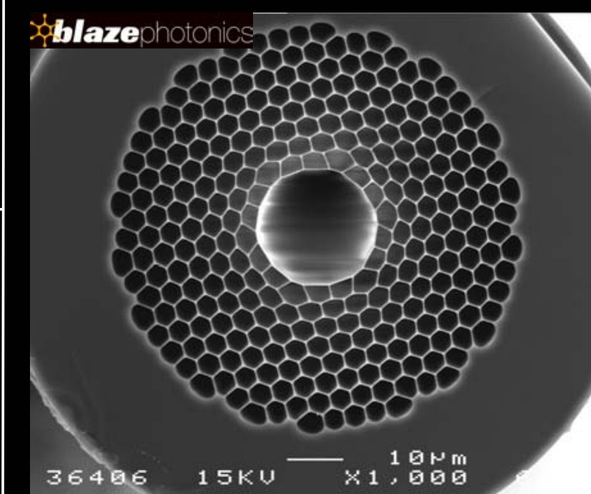


polarisation maintaining



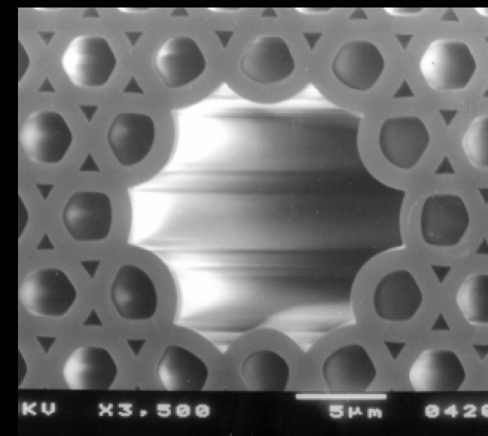


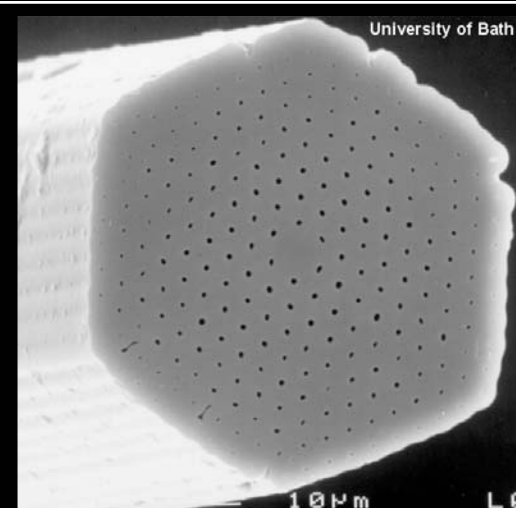
square lattice



state-of-the-art hollow core

hollow core





endlessly single-mode

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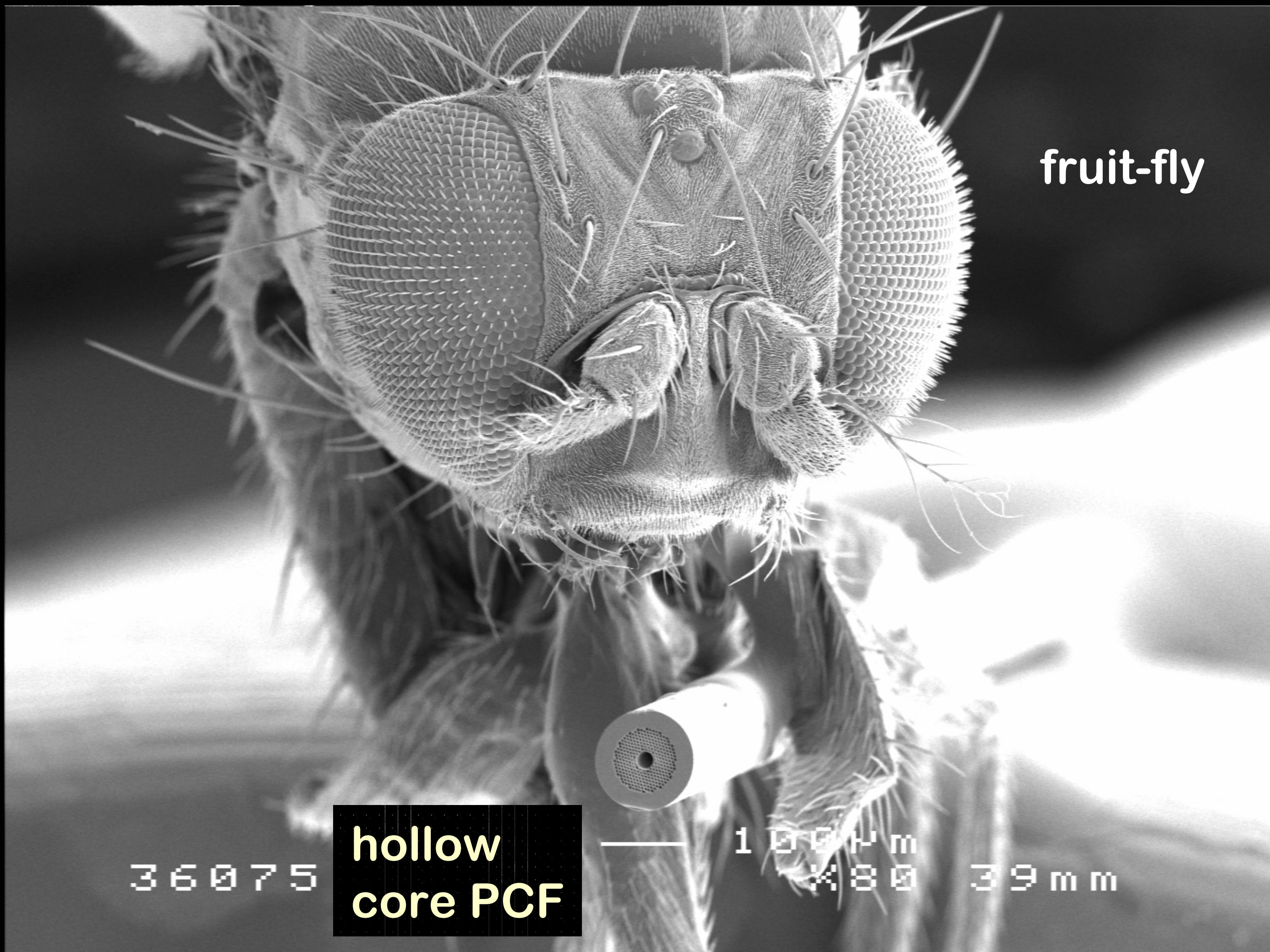
To get things in scale…



To avoid "holy" fibre confusion…

St Nicolas

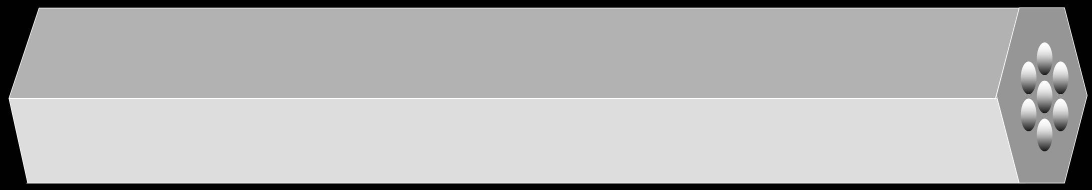
…we call them:

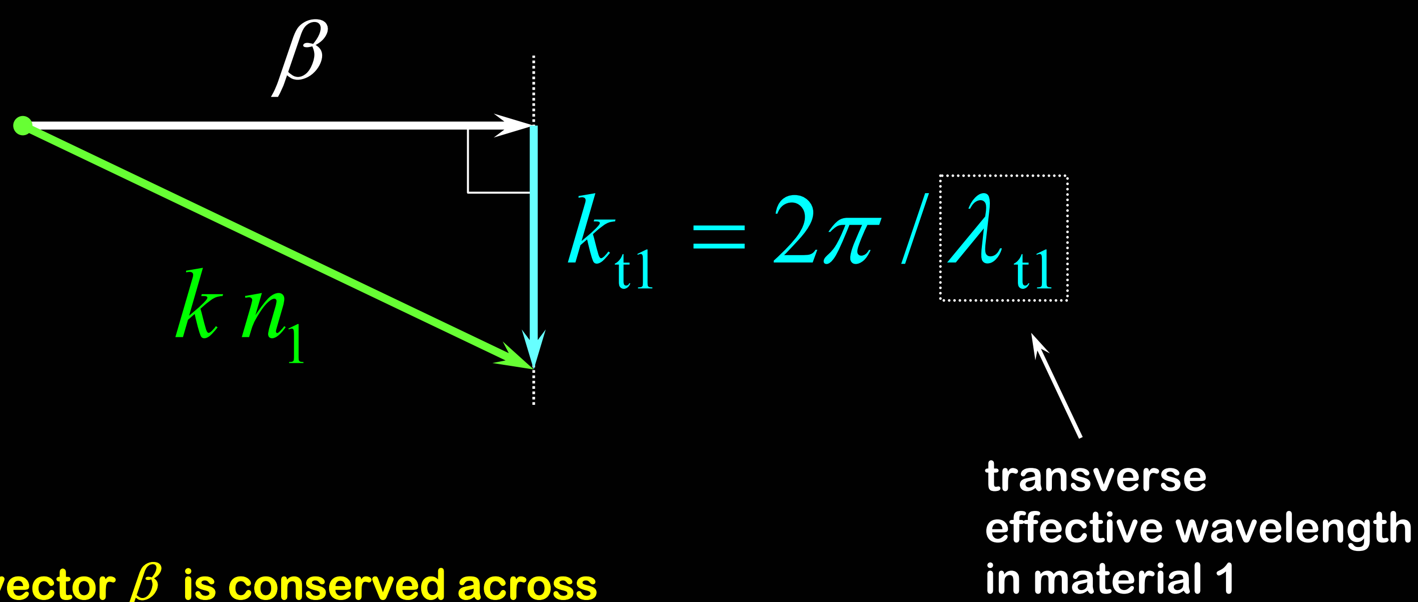
P C F

photonic crystal fibre

Theory & modelling

Wavevectors ...





- **axial wavevector β is conserved across every region of structure**

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Maxwell's equations: k^2 eigenvalue

[Hermitian]

axial wavevector

dielectric constant of structure

eigenvalue

$$\left(\nabla_{\mathrm{p}} + j\beta\hat{\mathbf{z}}\right)\times\left[\varepsilon^{-1}\left(\mathbf{r}_{\mathrm{p}}\right)\left(\nabla_{\mathrm{p}} + j\beta\,\hat{\mathbf{z}}\right)\right]\times\mathbf{H} = k^2\mathbf{H}$$

transverse operators & vectors

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Maxwell's equations: β^2 eigenvalue

[non-Hermitian]

vacuum wavevector

dielectric constant of structure

eigenvalue

$$\left[\nabla_{\mathrm{p}}^2 + k^2 \varepsilon(\mathbf{r}_{\mathrm{p}}) + \nabla_{\mathrm{p}} \ln \varepsilon(\mathbf{r}_{\mathrm{p}}) \times \nabla_{\mathrm{p}} \times \right] \mathbf{H}_{\mathrm{p}} = \beta^2 \mathbf{H}_{\mathrm{p}}$$

transverse operators & vectors

often solved using expansion in plane waves or sets of orthogonal functions

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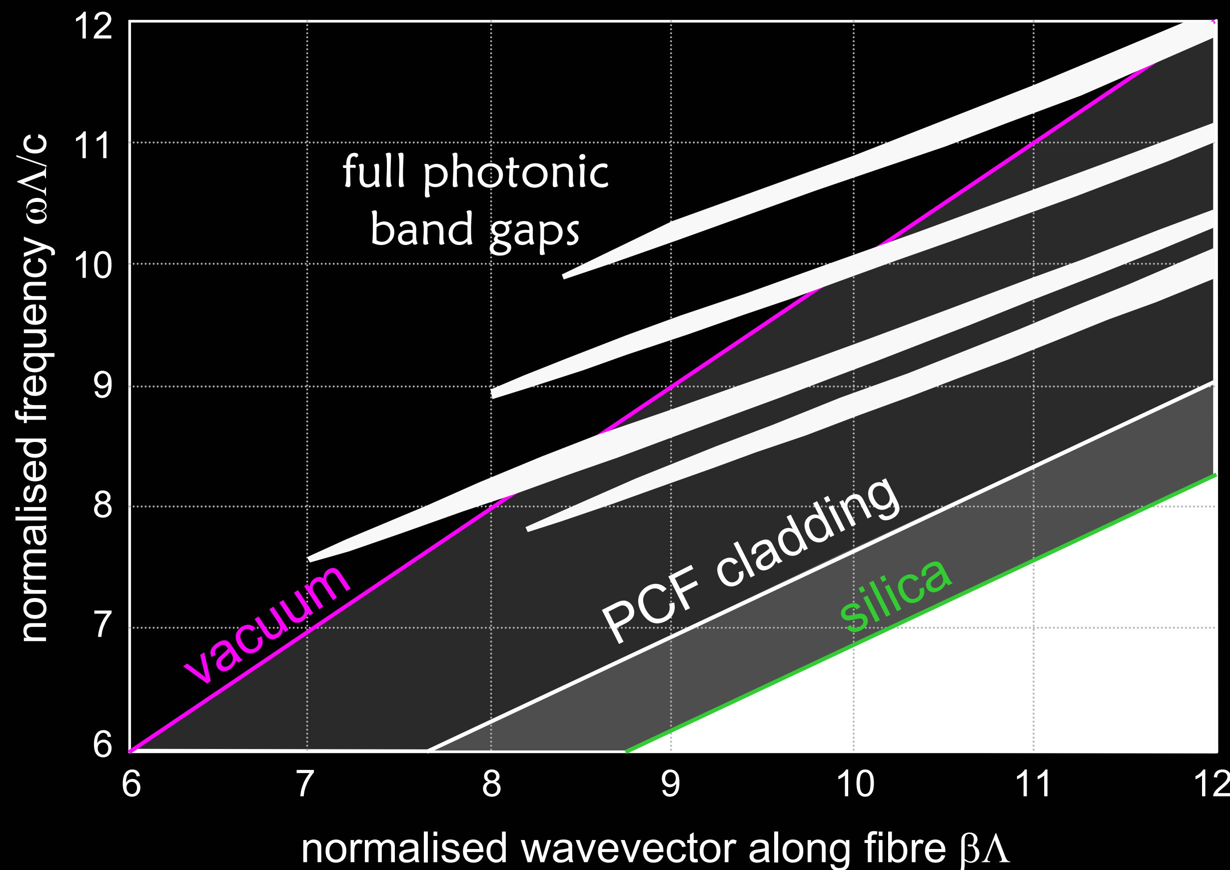
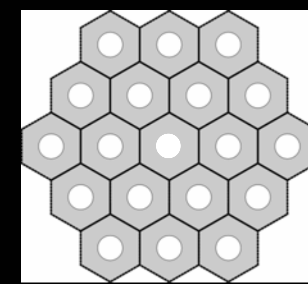
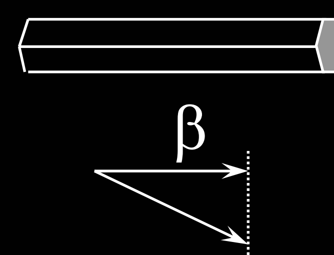
Triangular lattice PCF

Birks et al, Electron.Lett. 31 (1941-1942) 1995





- 45% air filling fraction
- silica:air index contrast 1.46:1



propagation on the left & evanescence on the right of the slanted lines, one for each material in the structure

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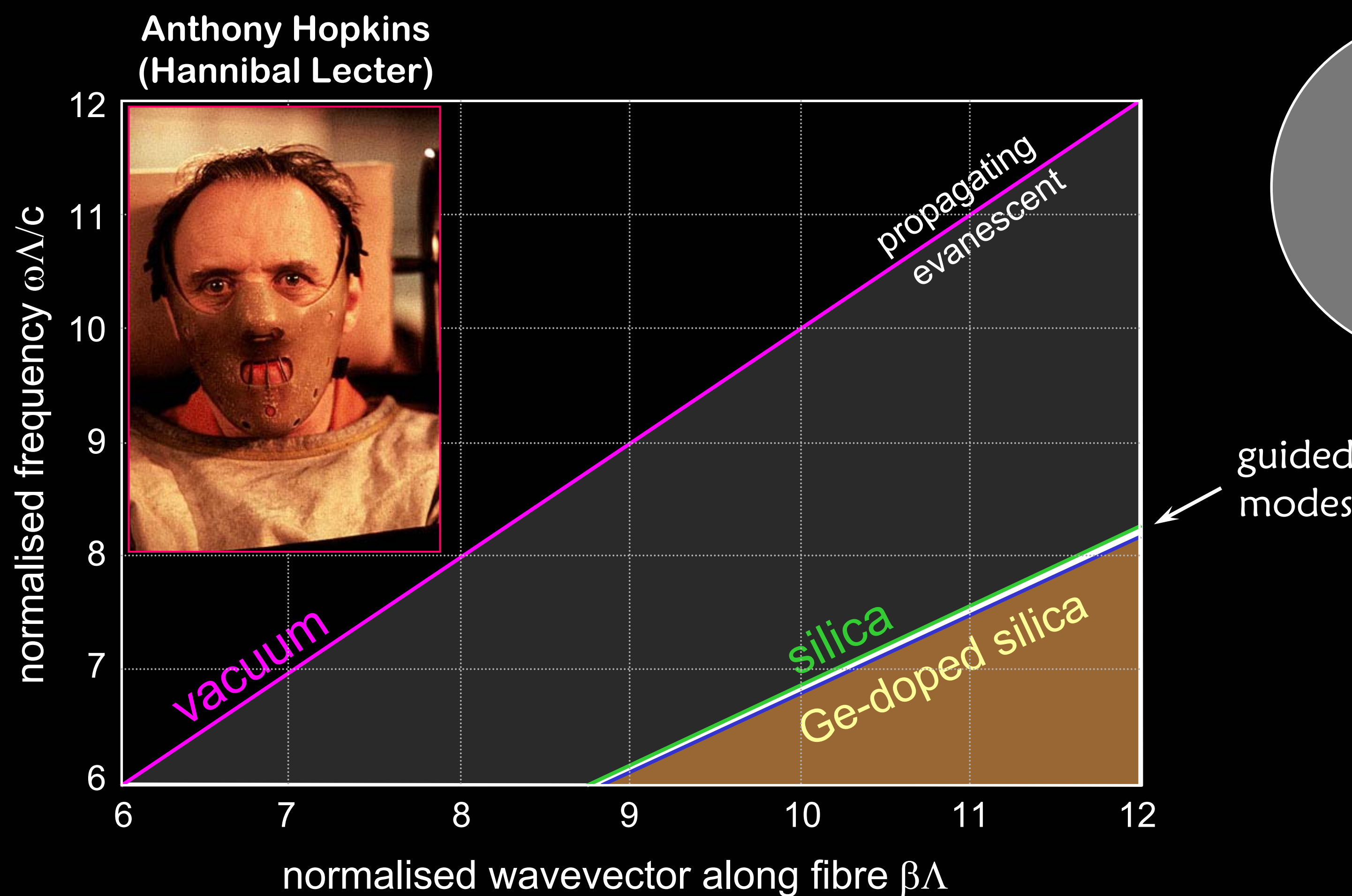
Single-mode fibre strait-jacket



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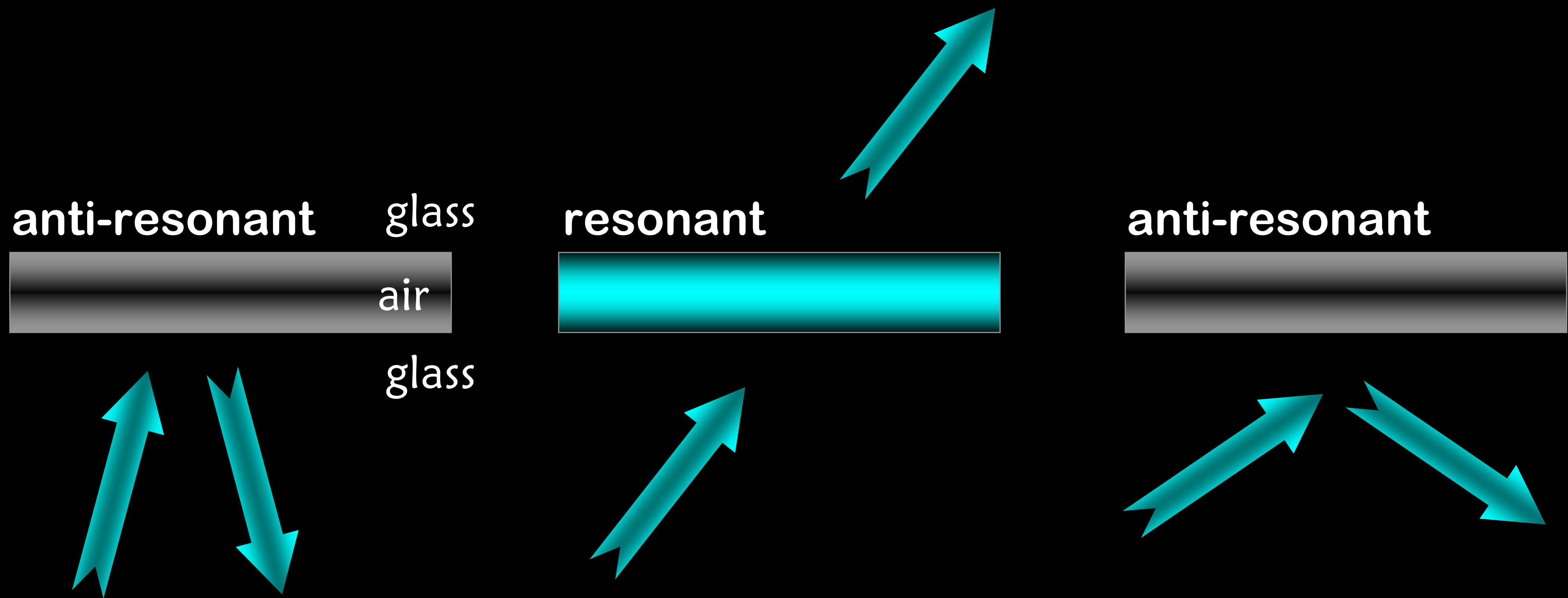
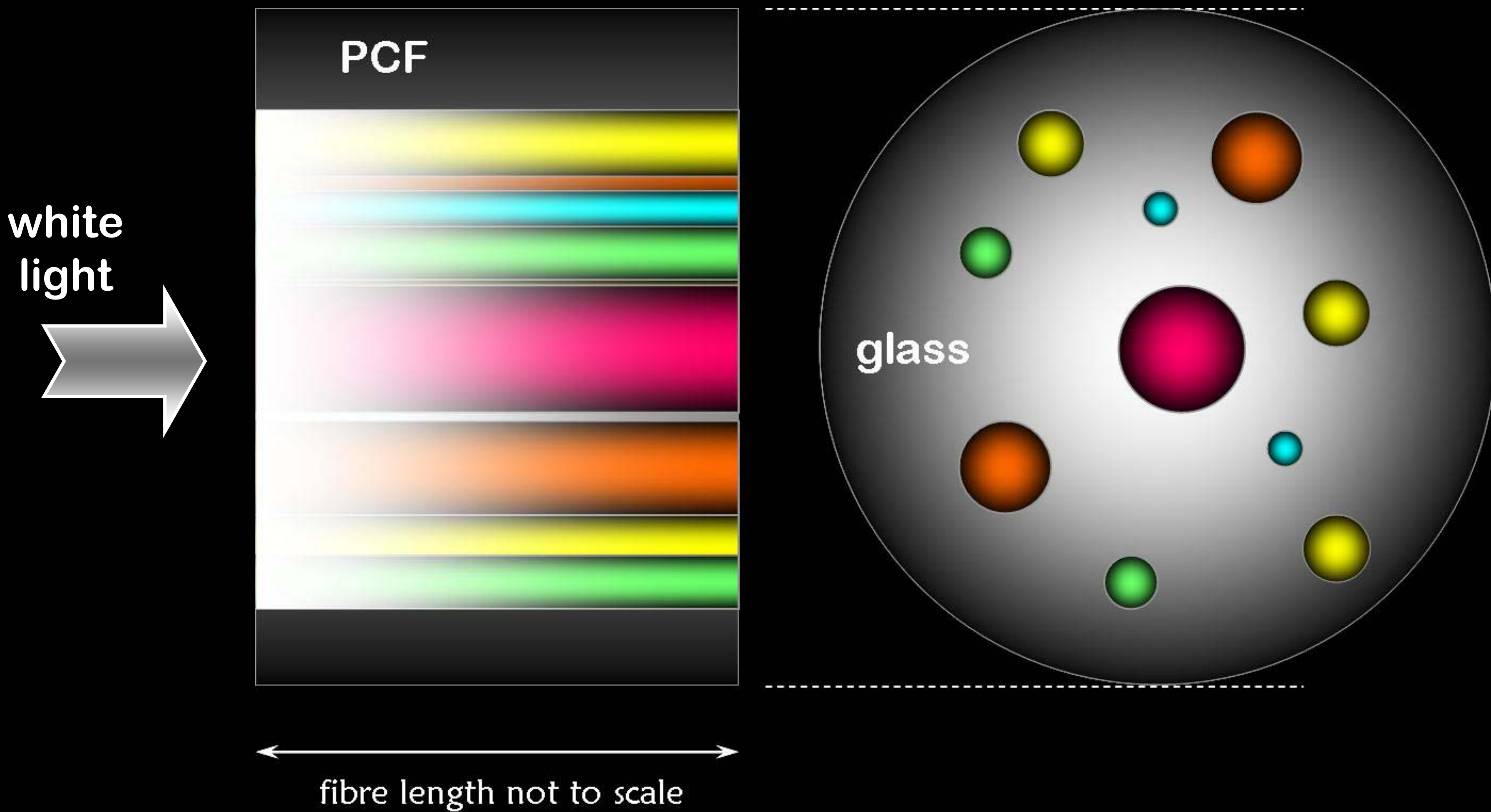
Bars, windows & cages

Resonance & anti-resonance in nano-tube



light fills the tube only at specific angle/colour combinations



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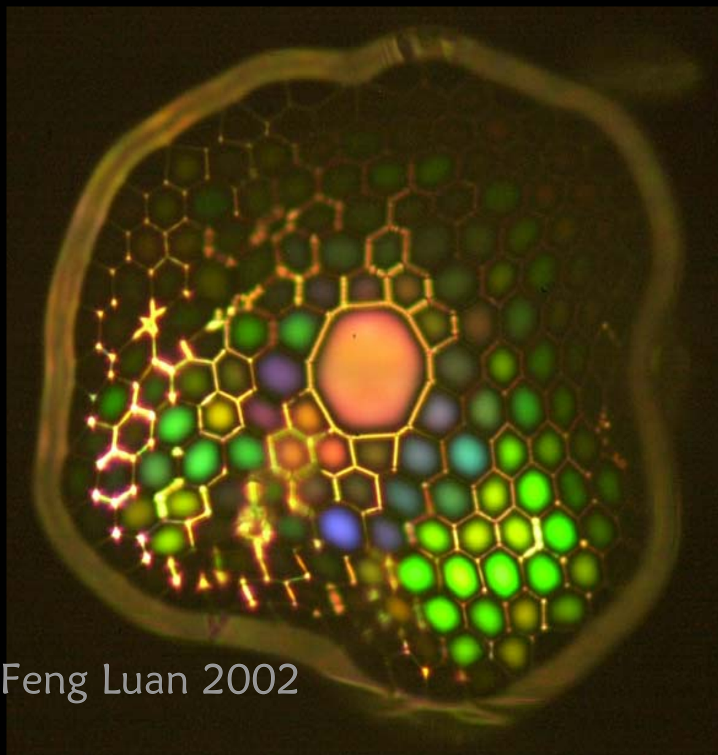
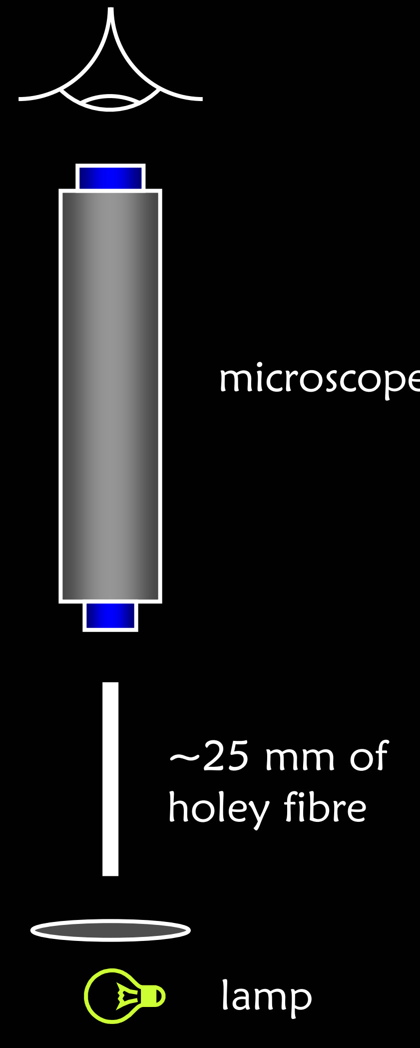
Kandinsky, Klee … or Tiffany?

distorted PCF



~0.1 mm



- the wave nature of light "entangles" it in wavelength-scale structures
- for different colours, a micro-tube of air (or a micro-web of glass) can act like:
  - the bar of a cage (when anti-resonant)
  - a cage or window (when resonant)

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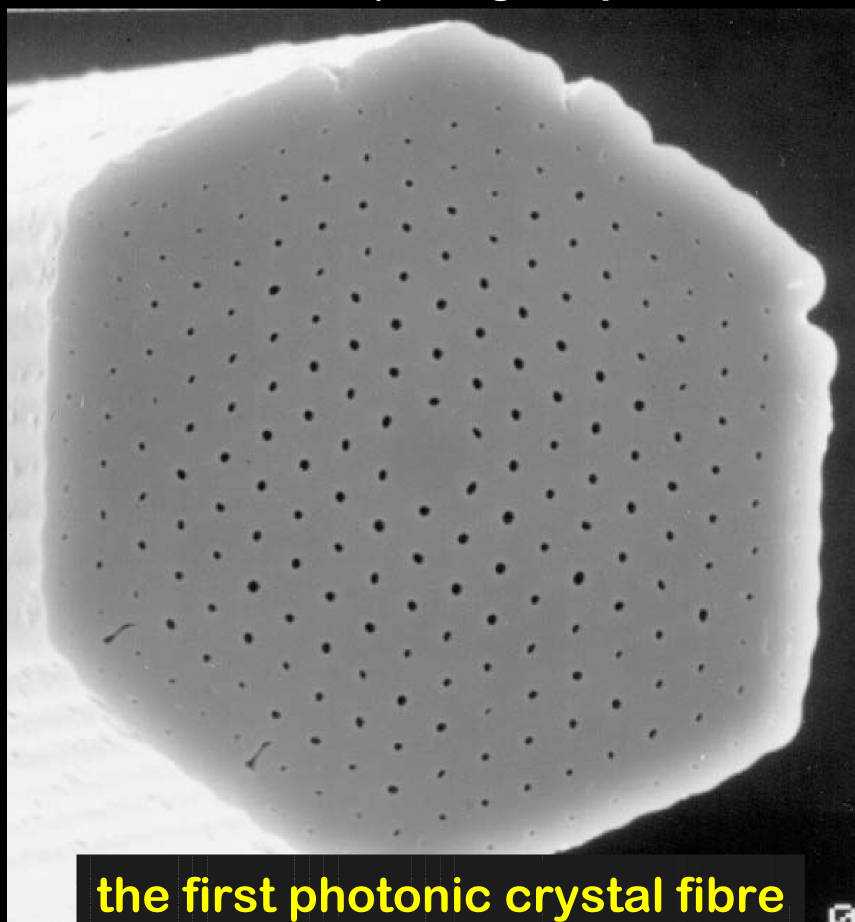
We are keeping light "behind bars"

Modal filtering

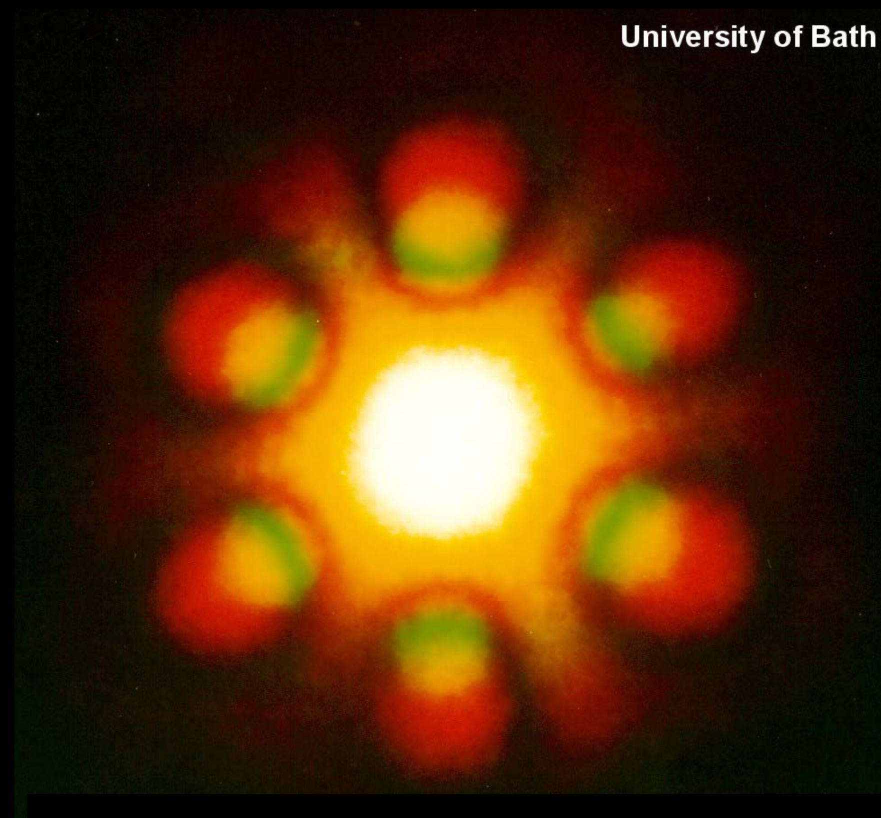
Endlessly single-mode PCF

Knight et al, OFC 1996 PD paper

interhole spacing 2.3 μm



the first photonic crystal fibre



far-field pattern when carrying green & red light

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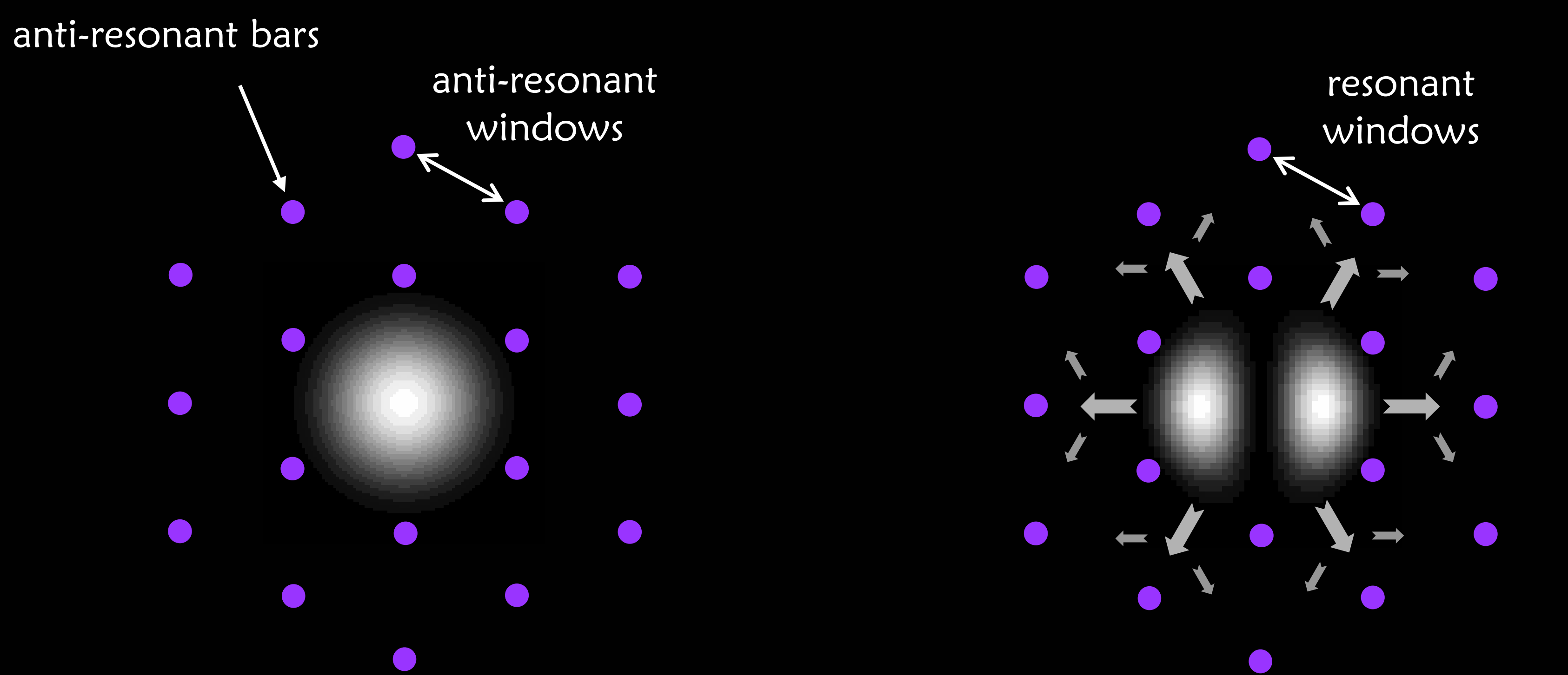
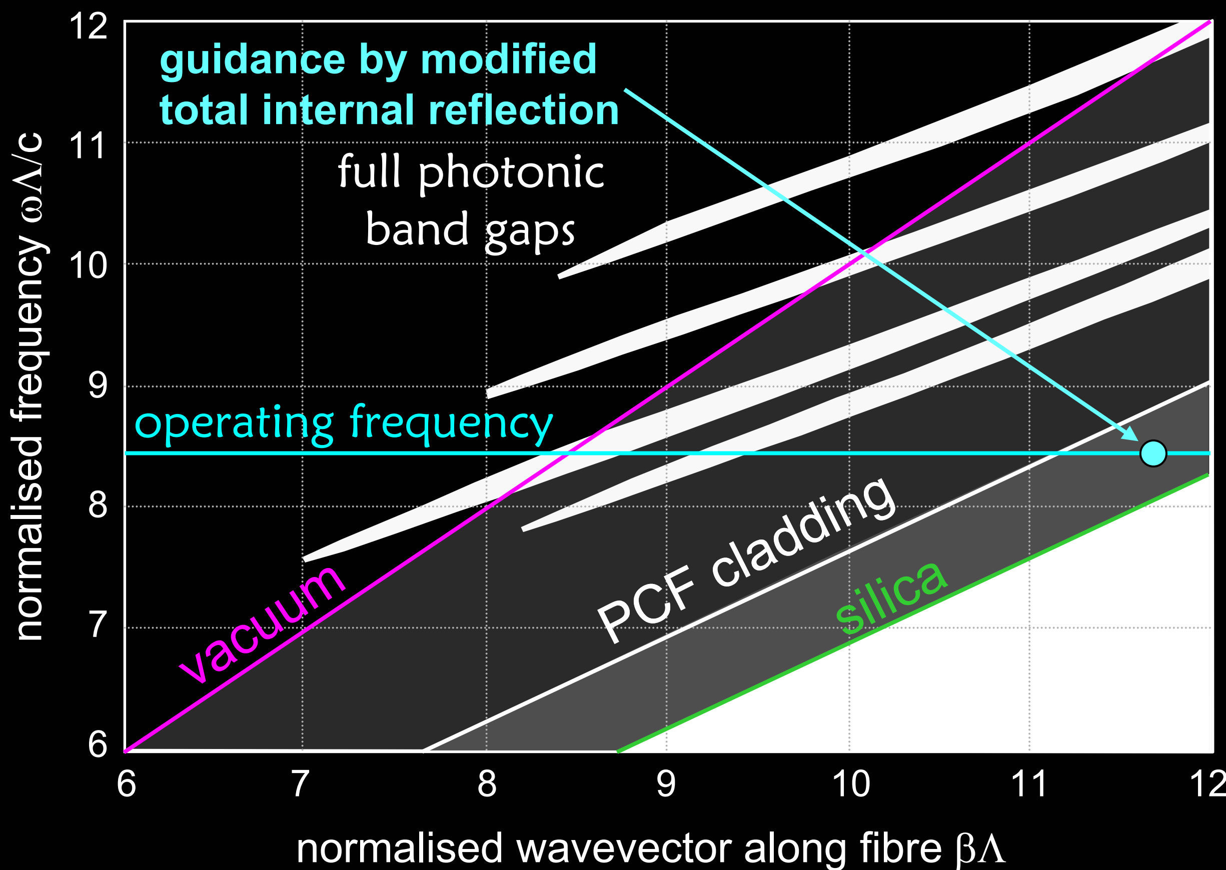
Higher order modes are filtered away

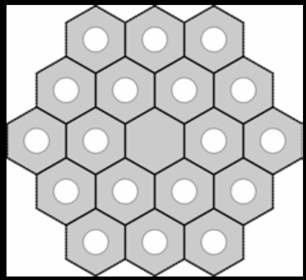


- **fundamental mode cannot squeeze between air-holes**
- **higher-order modes can escape into cladding**

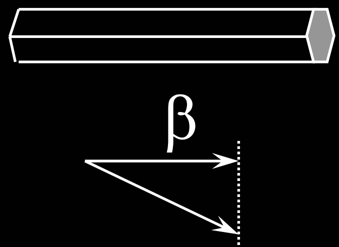
Guidance at filled-in hole

Birks et al, Electron.Lett. 31 (1941-1942) 1995



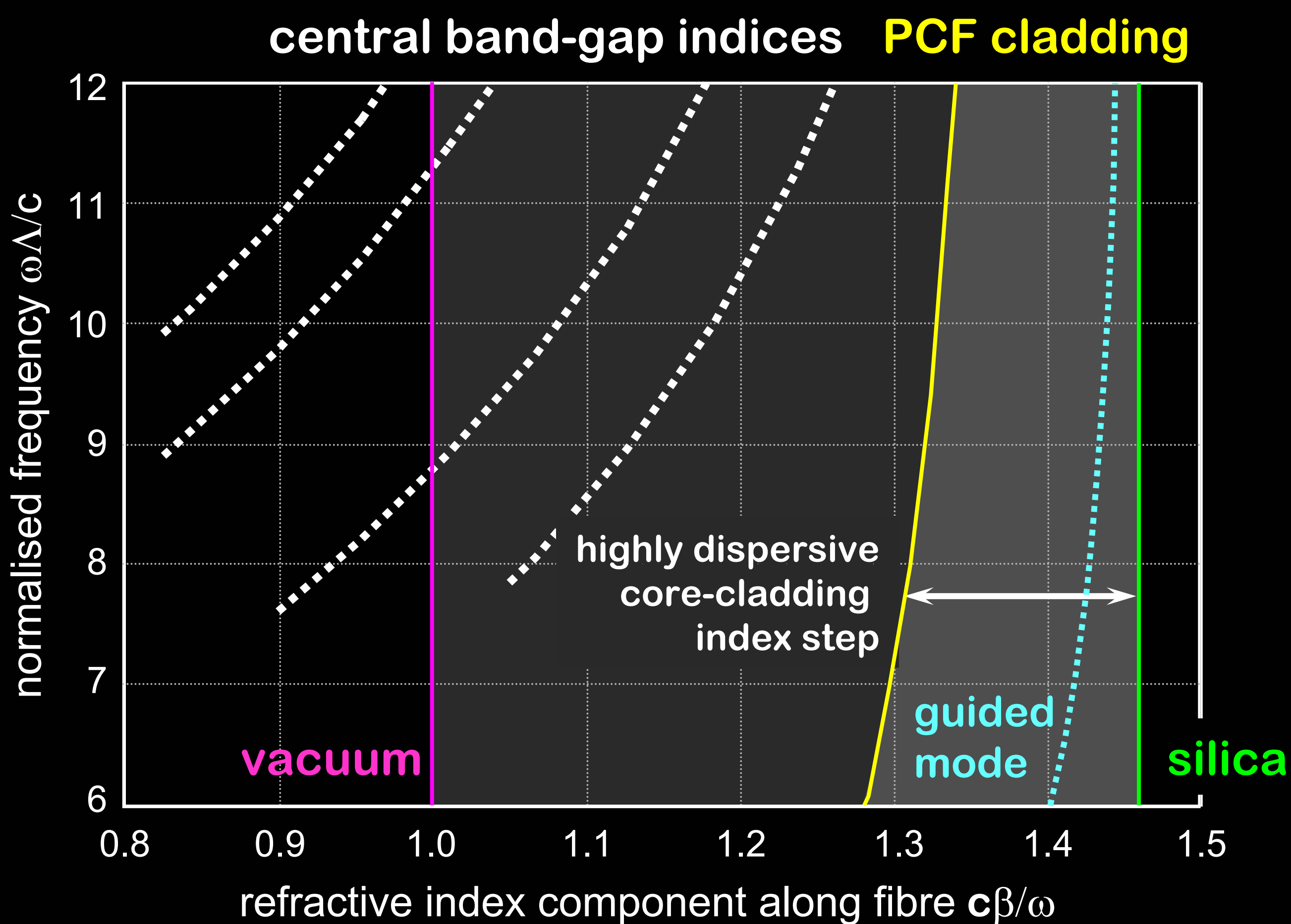


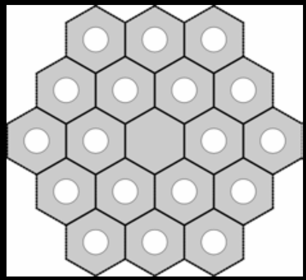
- 45% air filling fraction
- silica:air index contrast 1.46:1



Axial refractive indices

Birks et al, Electron.Lett. 31 (1941-1942) 1995





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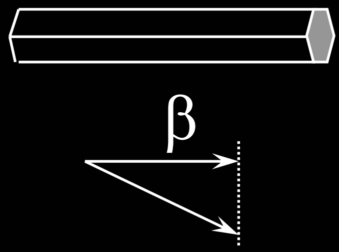

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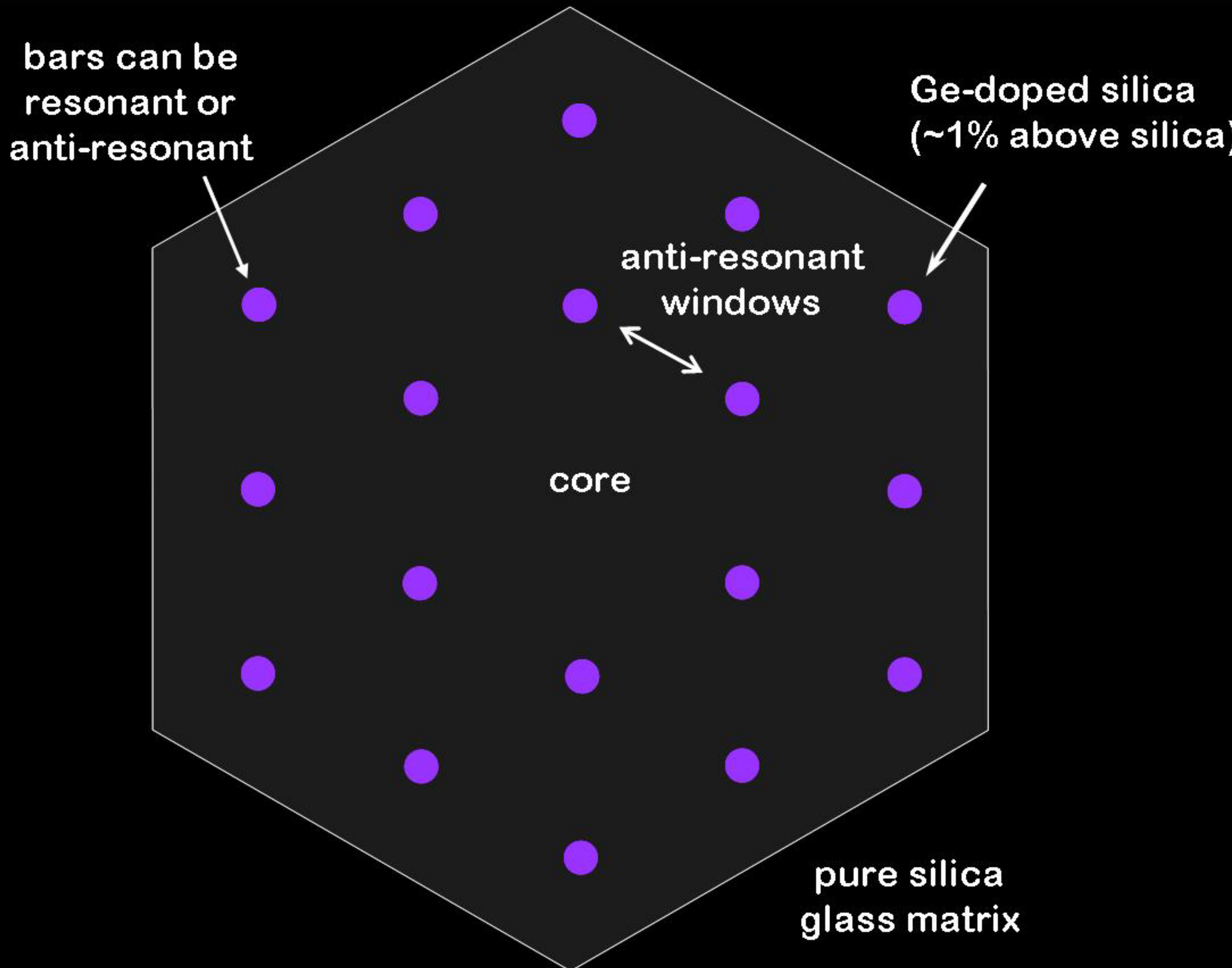
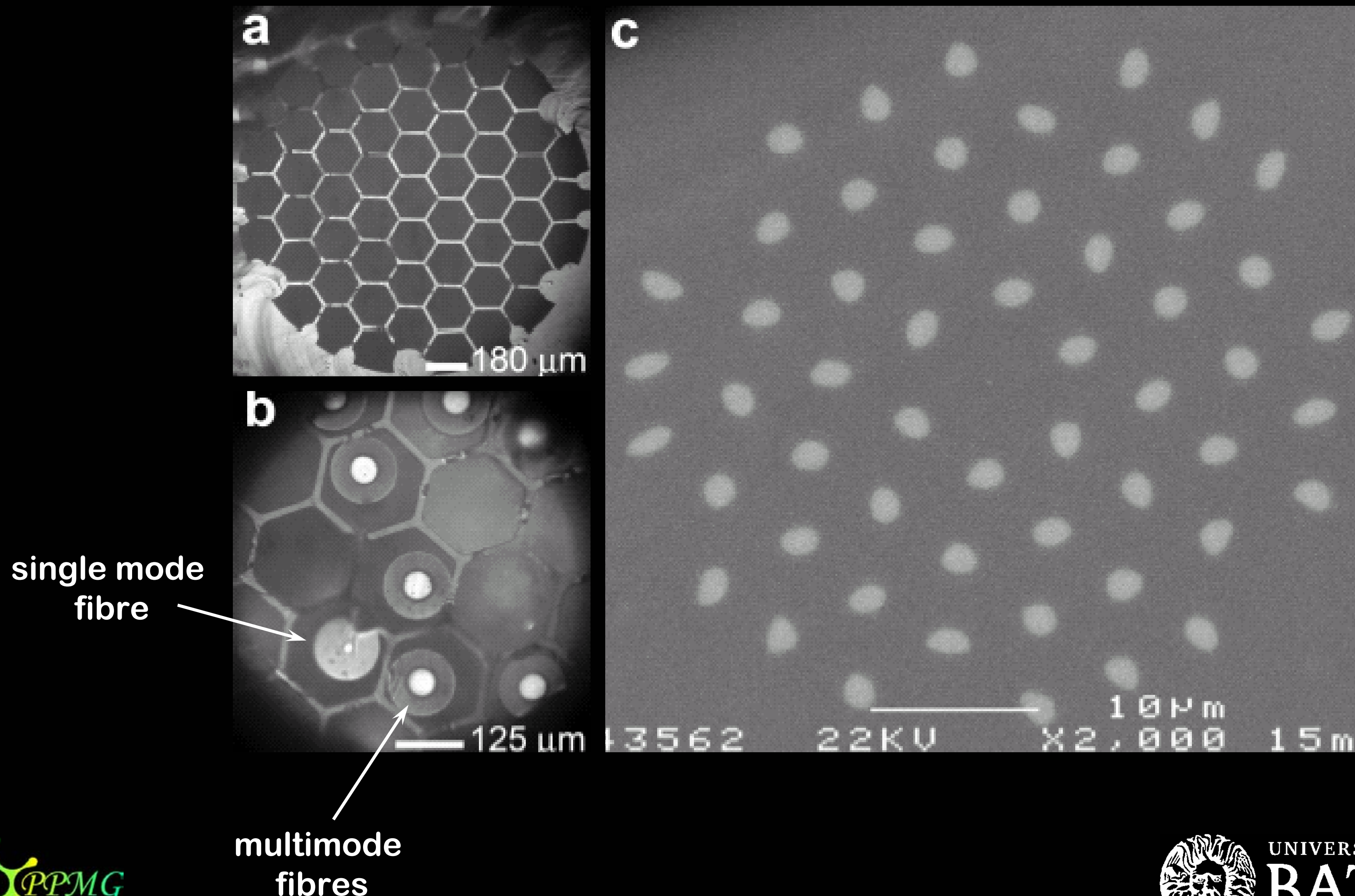
Photonic band gaps at 1% index contrast

Photonic band gaps at 1% contrast



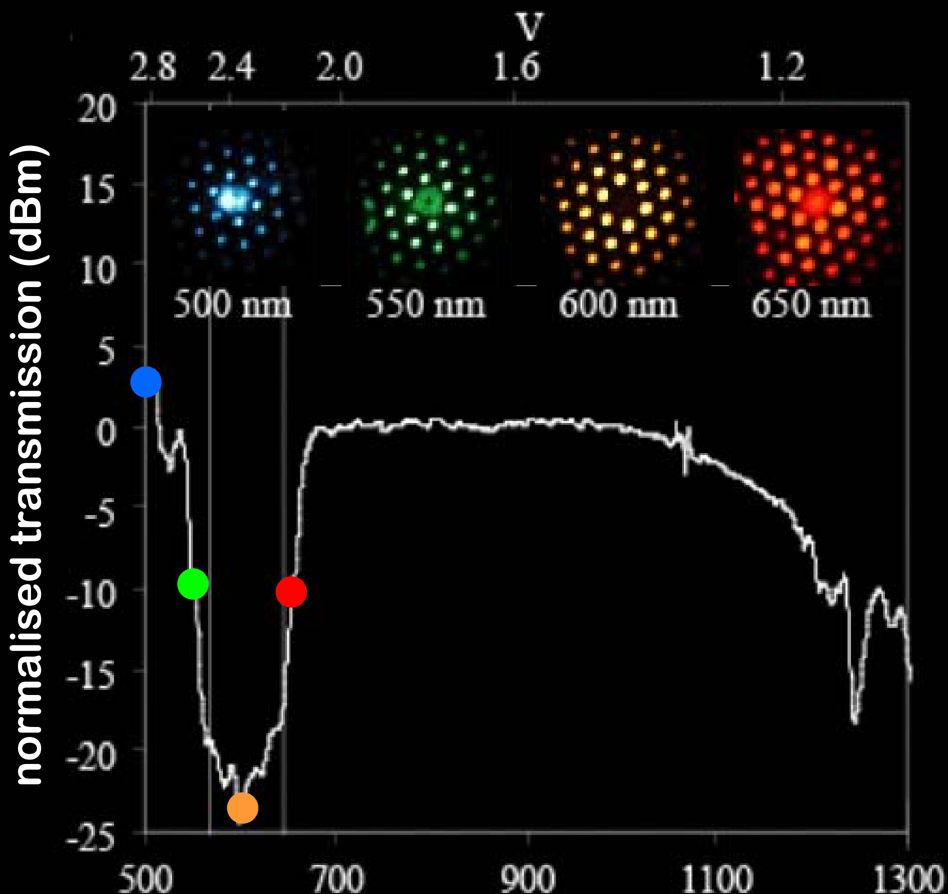
Making an all-solid PCF

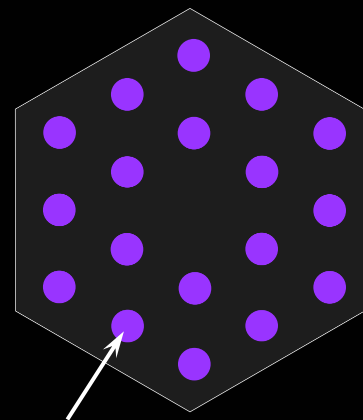
Argyros et al., Opt. Exp. 13 (309-314) 2005



Transmission spectrum

Argyros et al., Opt. Exp. 13 (309-314) 2005

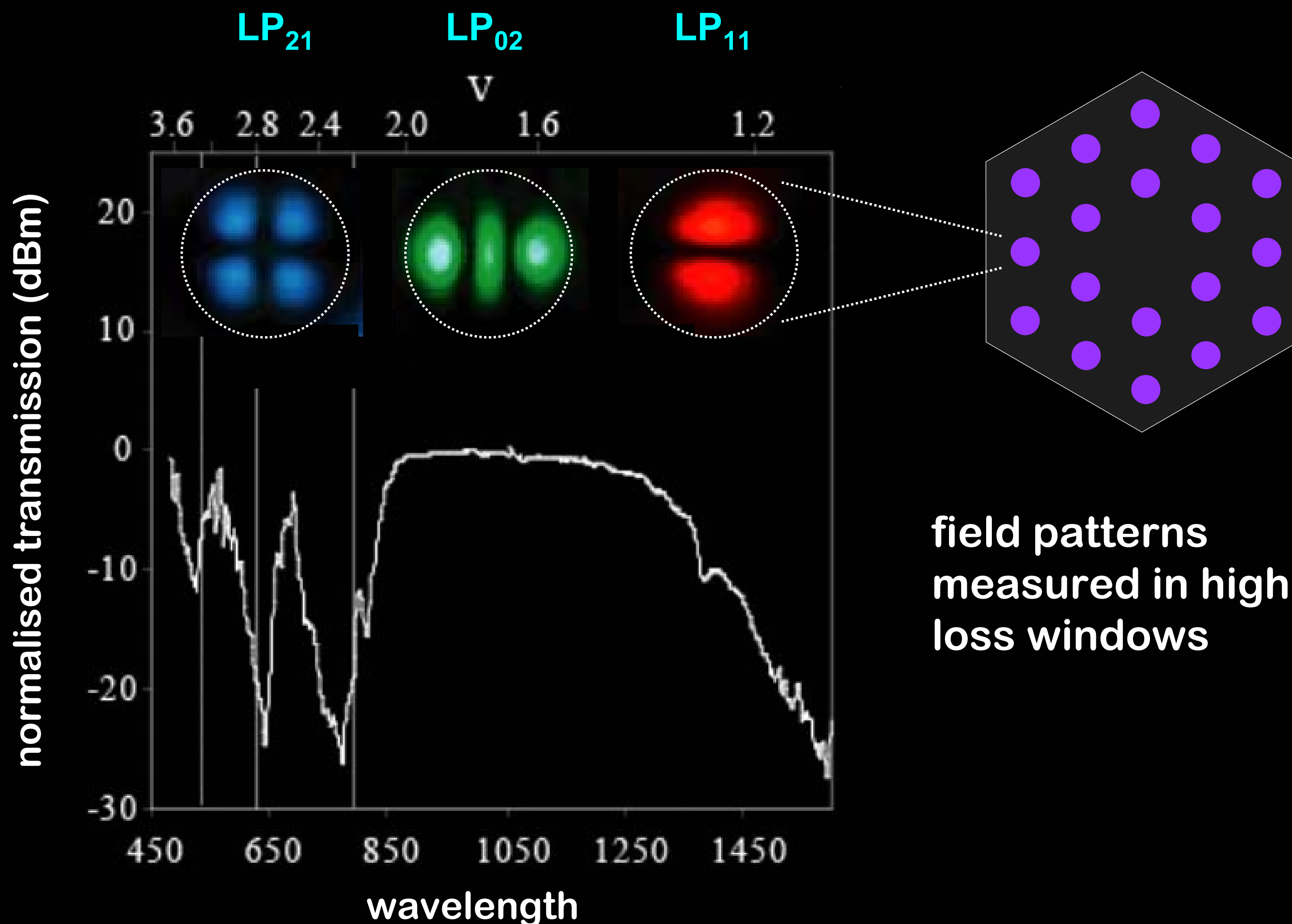




cladding rods become resonant in the visible

Mode patterns in cladding "rods"

Argyros et al., Opt. Exp. 13 (309-314) 2005



field patterns measured in high loss windows

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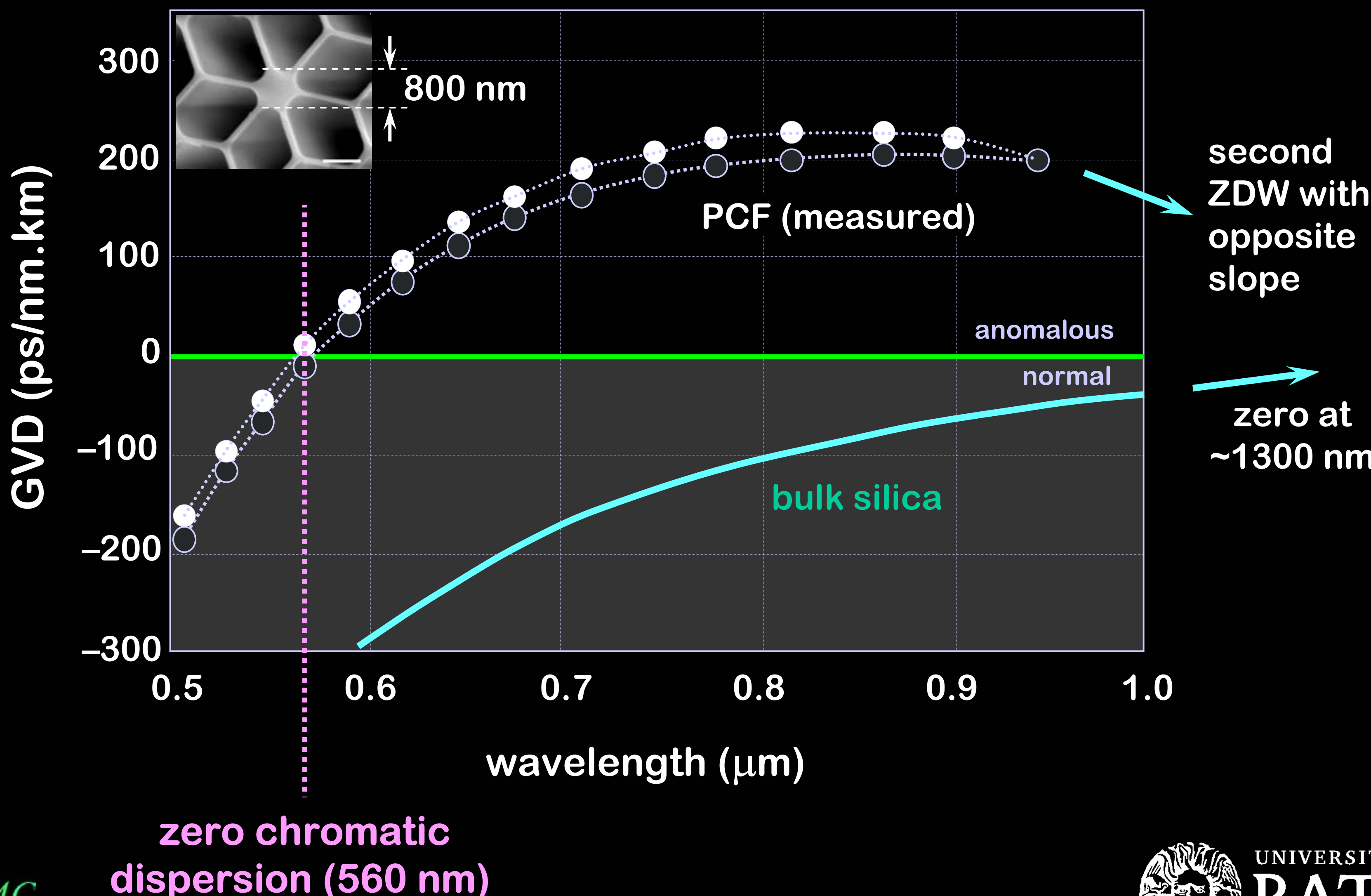
Shifting zeros

Dispersion of 800 nm core PCF

Knight et al, Phot Tech Lett, 12 (807-809) 2000



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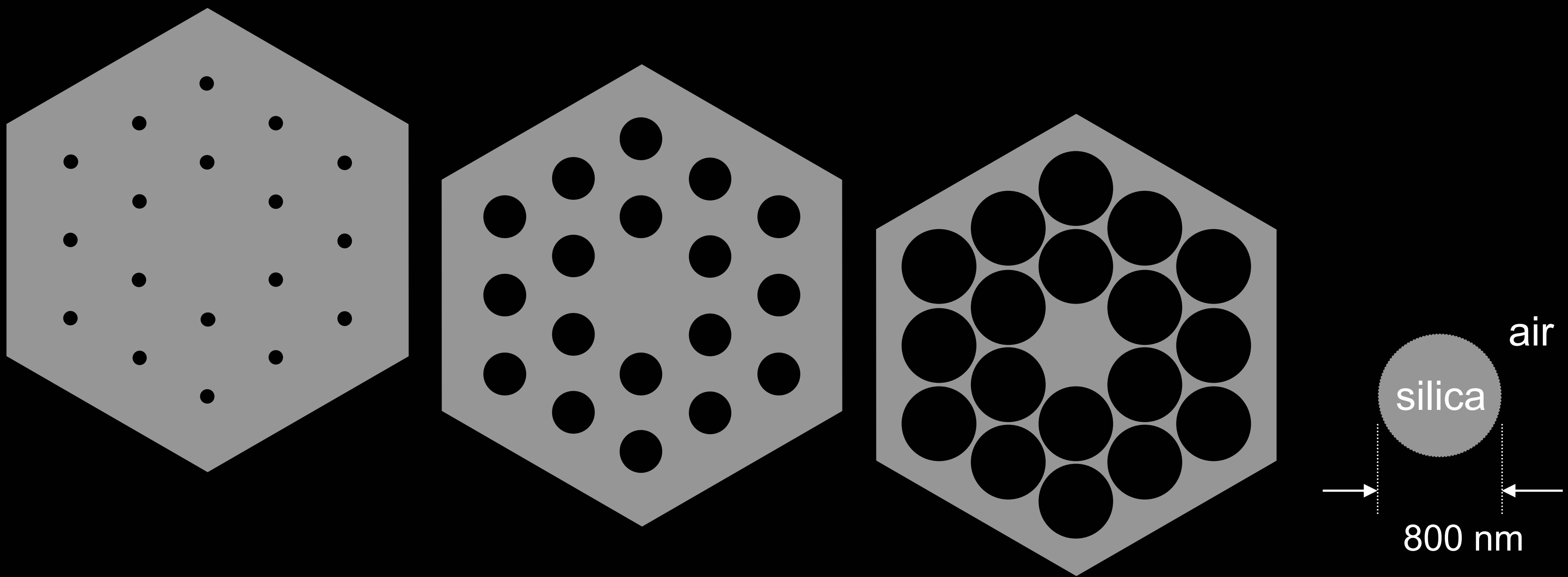
As holes get bigger ...

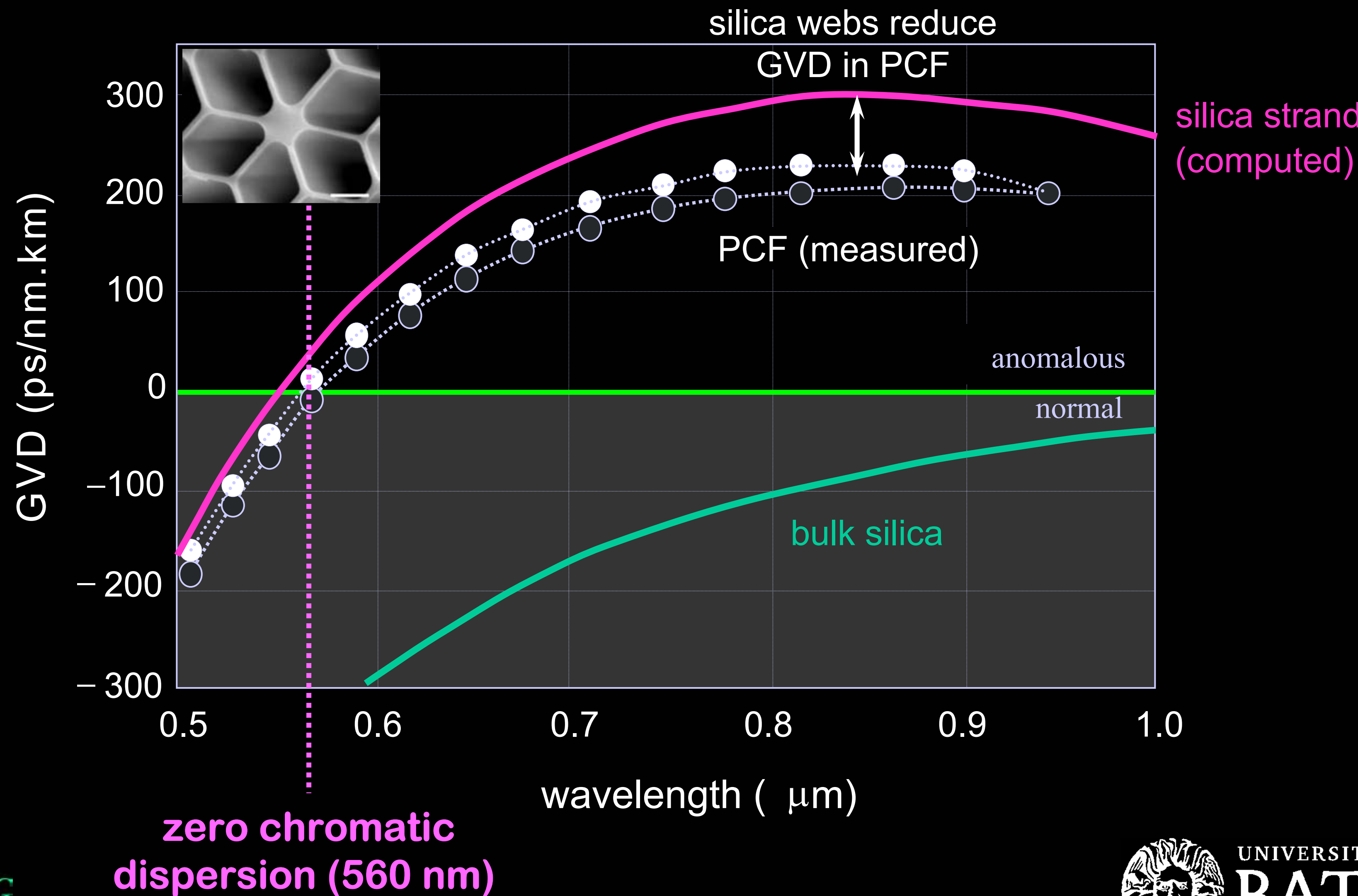


... core becomes more & more isolated

... & starts to look like isolated strand of silica

Comparison with silica strand in air

Knight et al, Phot Tech Lett, 12 (807-809) 2000



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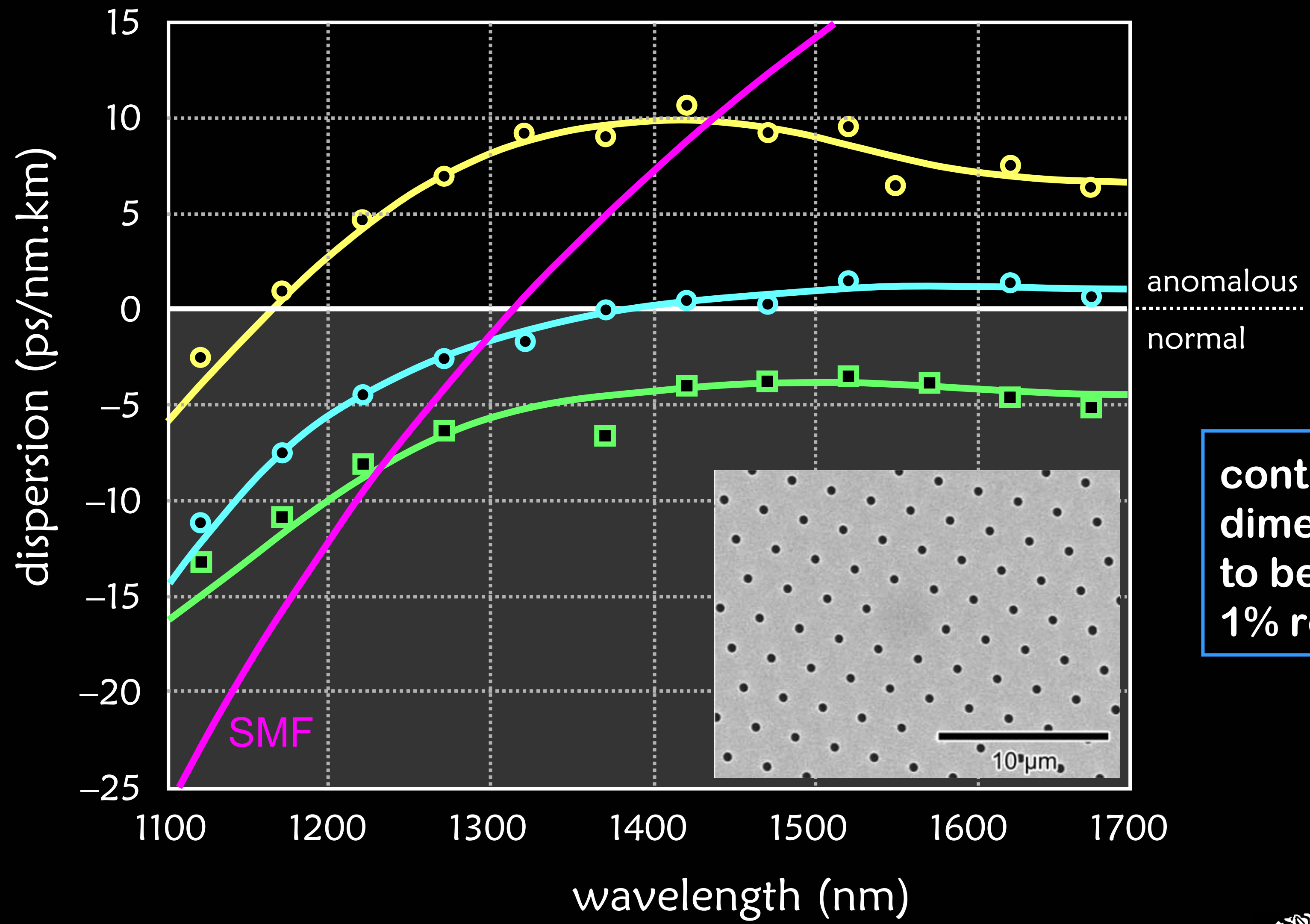
Dispersion control

Reeves et al., Nature 424 (511-515) 2003



control of dimensions to better than 1% required

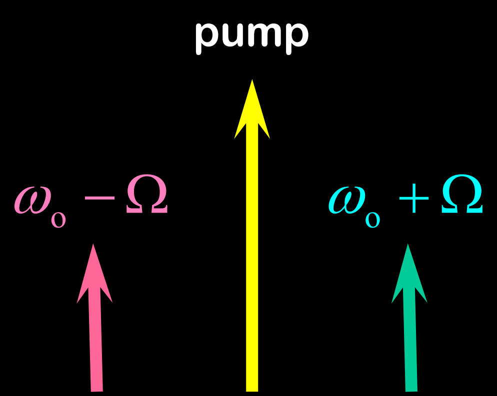
dispersion & nonlinearity

Nonlinear gain condition

wavevector

neglect

$$\beta(\omega_o + \Omega) = \beta_o + v_g^{-1}\,\Omega + \frac{\beta_2}{2}\Omega^2 + \sum_{m=3}^{\infty}\frac{\Omega^m \beta_m}{m!}$$



for nonlinear gain:

nonlinear coefficient

power

$$\beta_2 < \frac{-4\gamma P}{\Omega^2}$$

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Effects of higher order dispersion

Reeves et al., Nature 424 (511-515) 2003
Biancalana et al., Phys. Rev. E 68 (046603) 2003

$$\beta_2(\omega) = \sum_{m\geq 2}^{\infty} \frac{\beta_m(\omega_o)}{(m-2)!}\Omega^{m-2}$$

$$\text{gain} = \text{Im}\left[\sqrt{Q(Q+2\gamma P)}\right]$$

$$\beta_2\Omega^2/2 + \beta_4\Omega^4/24 + \beta_6\Omega^6/720$$

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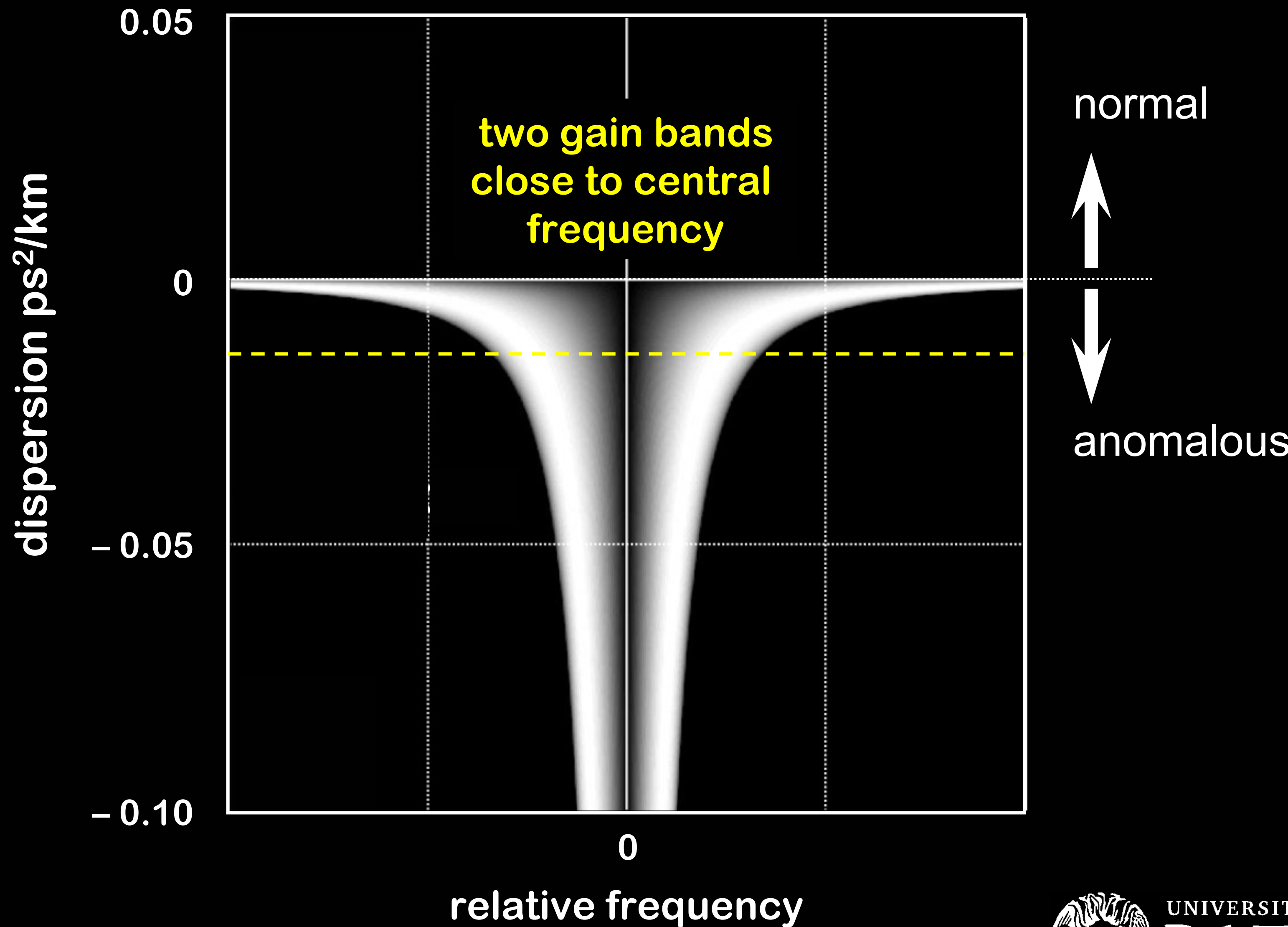
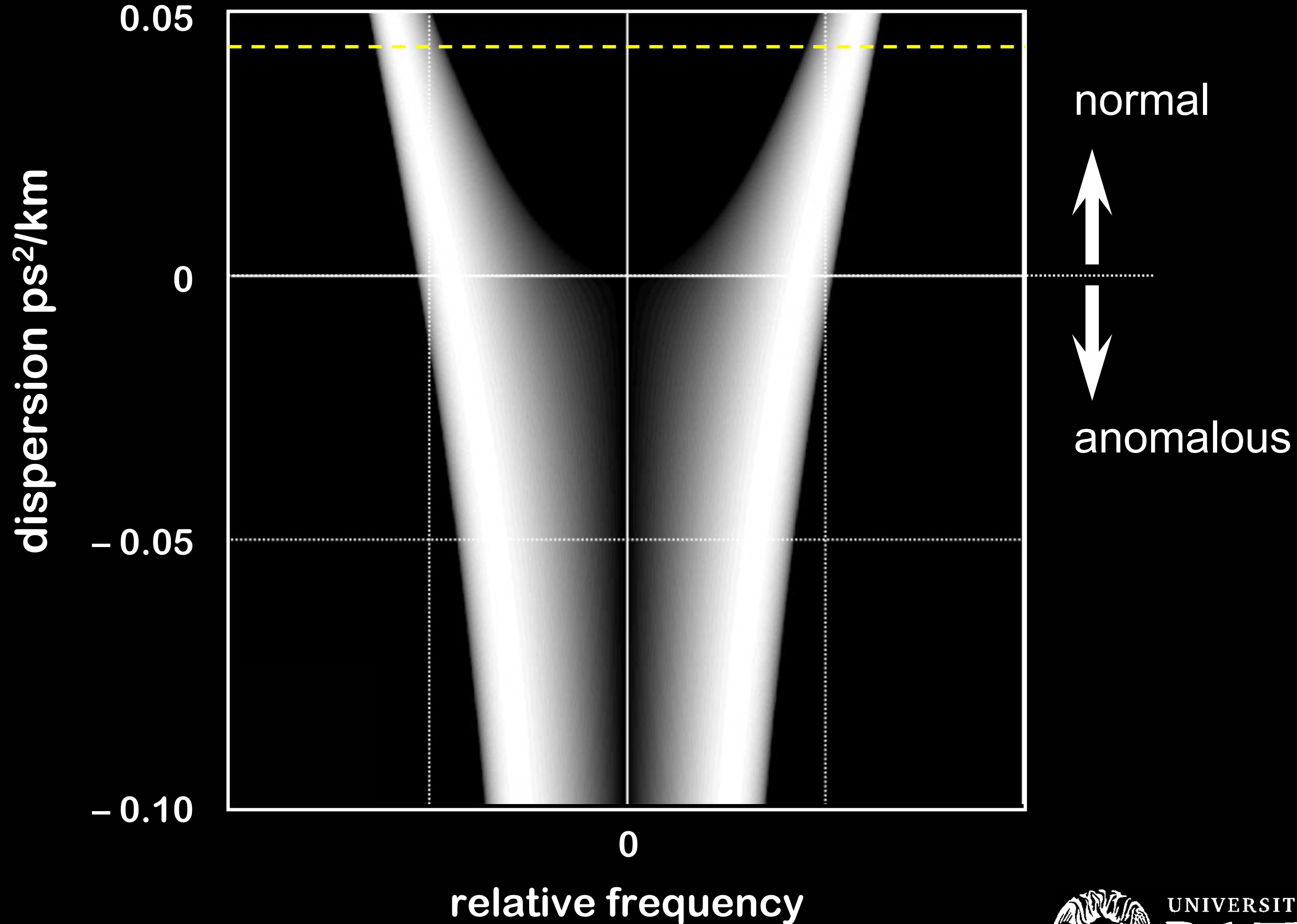
$$\beta_4 = 0,\ \beta_6 = 0$$



$$\beta_4 < 0,\ \beta_6 = 0$$

two gain bands widely spaced in frequency



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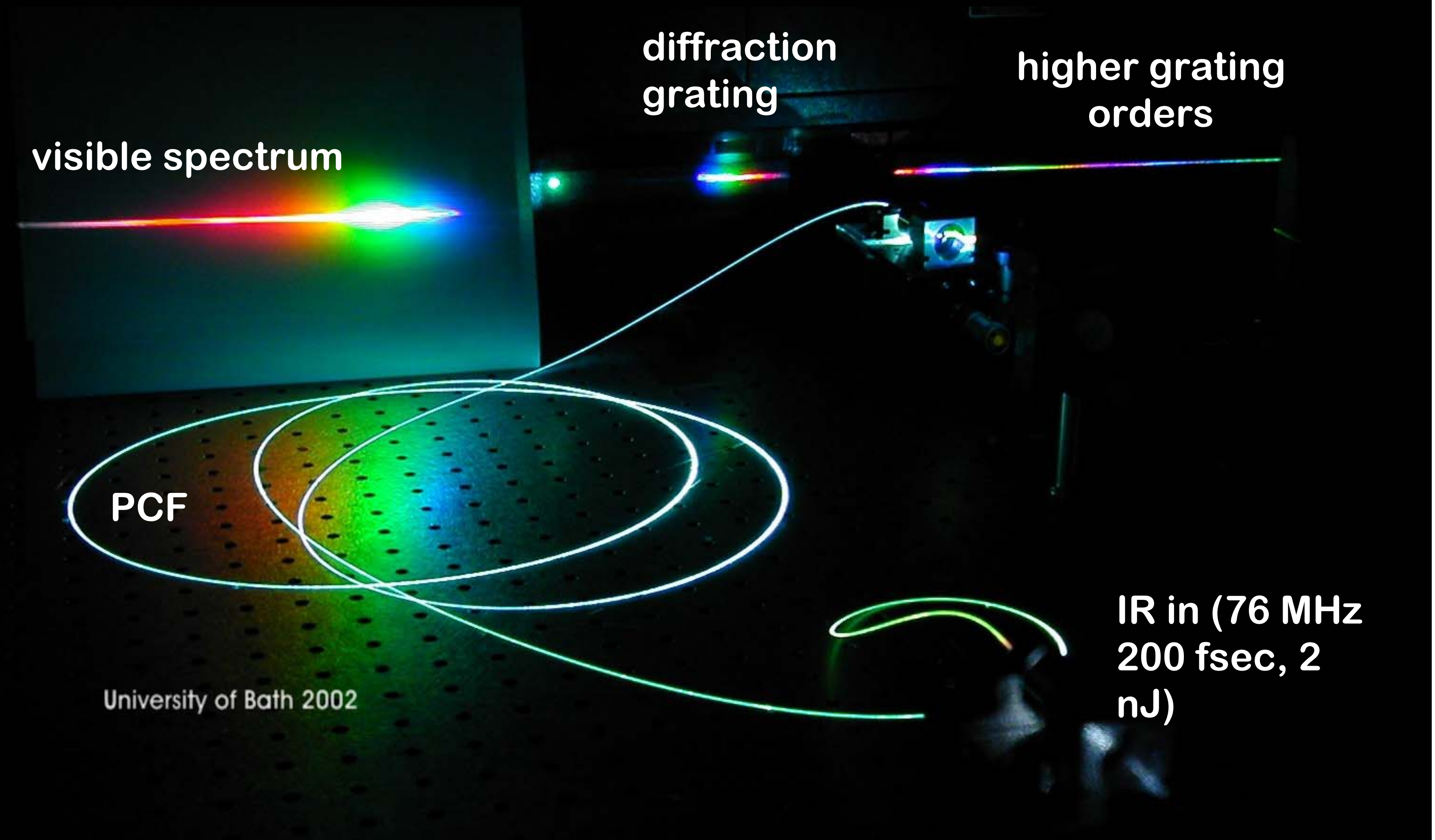
White light lasers

take solid-core PCF with zero dispersion point close to a pulsed laser wavelength

A sunlight laser: multiple rainbows

Ranka et al, Opt. Lett. 25 (25-27) 2000



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... some 10,000× brighter than the sun, yielding more than 100 GW $m^{-2}sterad^{-1}$

Applications of sunlight laser

- frequency metrology
- optical coherence tomography
- spectroscopy

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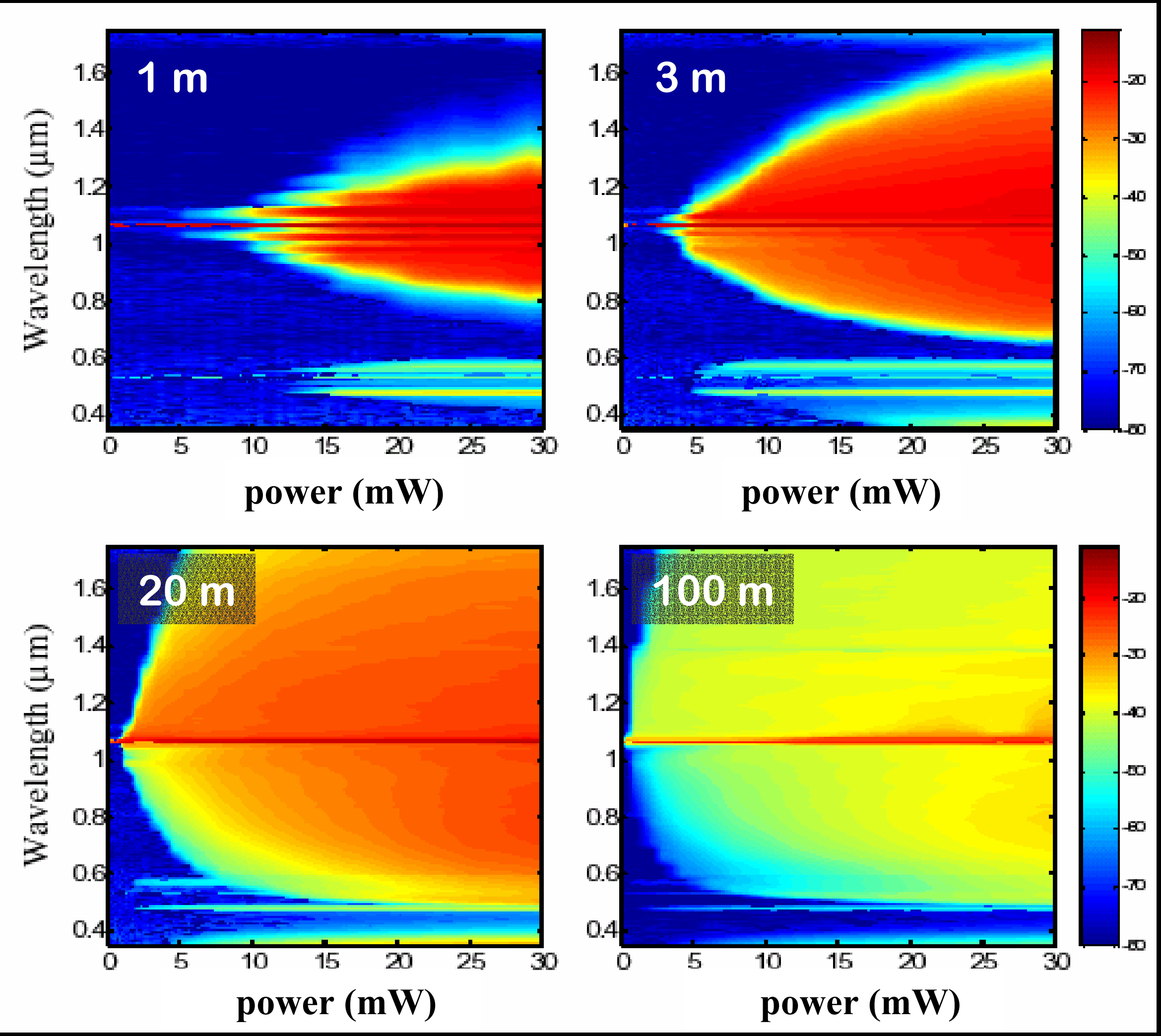
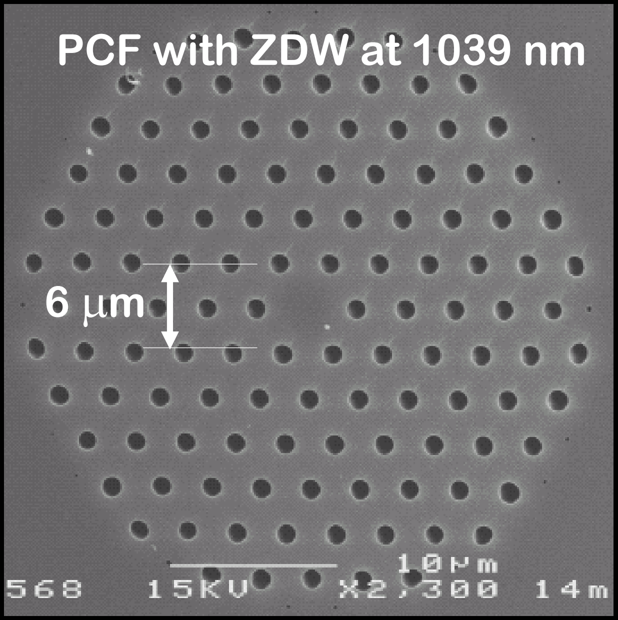
Microchip laser (600 ps, 1064 nm)

Wadsworth et al, Opt Exp 12 (299-309) 2004

30 mW average at 7.25 kHz
= pulse energy 4.1 μJ & peak power 6.9 kW





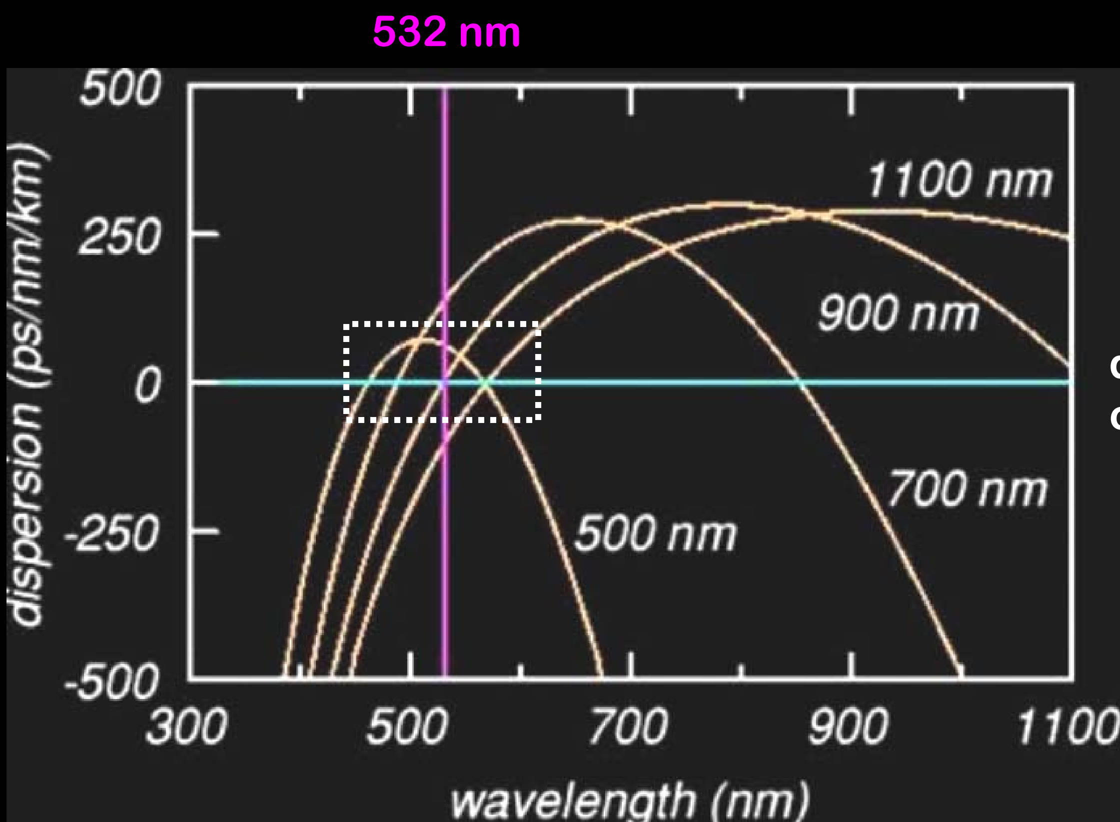
anomalous dispersion

Nano-tapering

how to achieve a zero dispersion wavelength at 532 nm?

Why is it a problem?...

Birks et al, Opt. Lett. 25 (1415-1417) 2000



dispersion at different core diameters

- very hard to make by fibre drawing
- very difficult to launch light into

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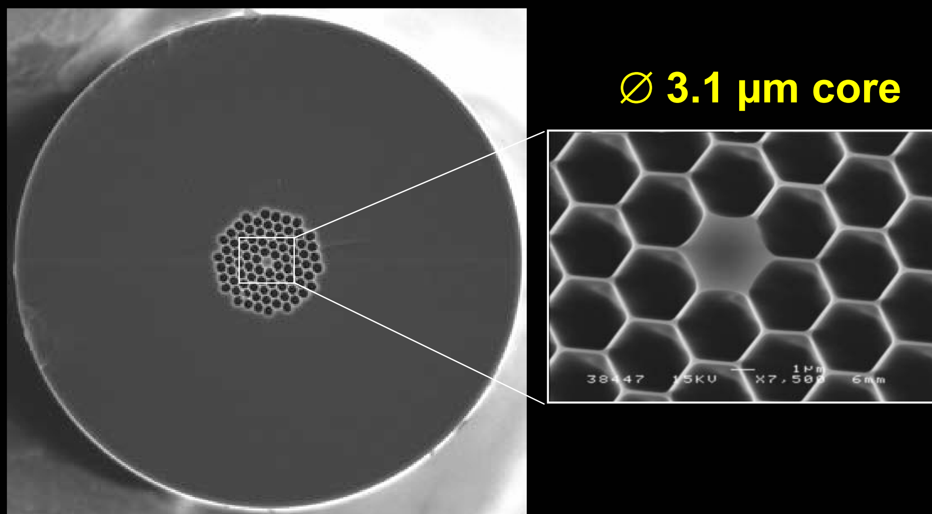
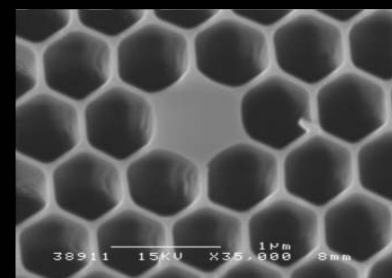
Heating & stretching…

Leon-Saval et al, Opt Exp 12 (2864) 2004

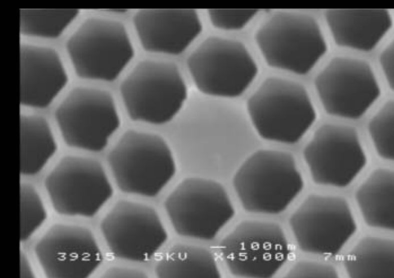
∅ 3.1 µm core

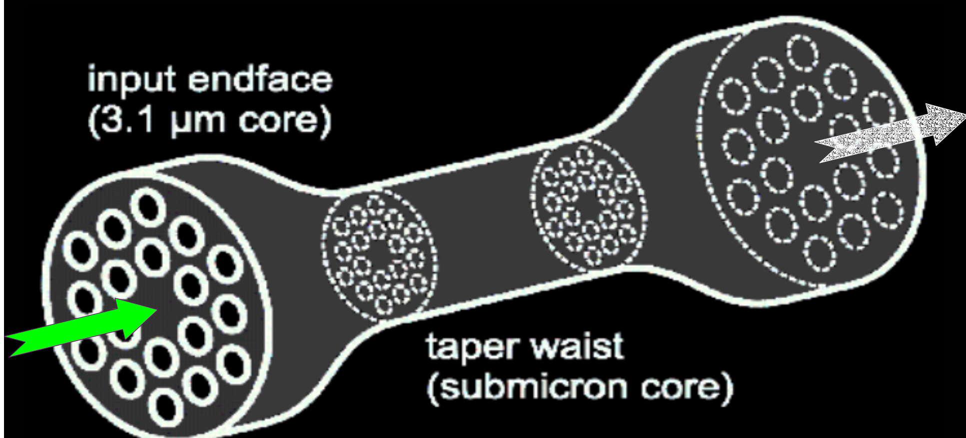


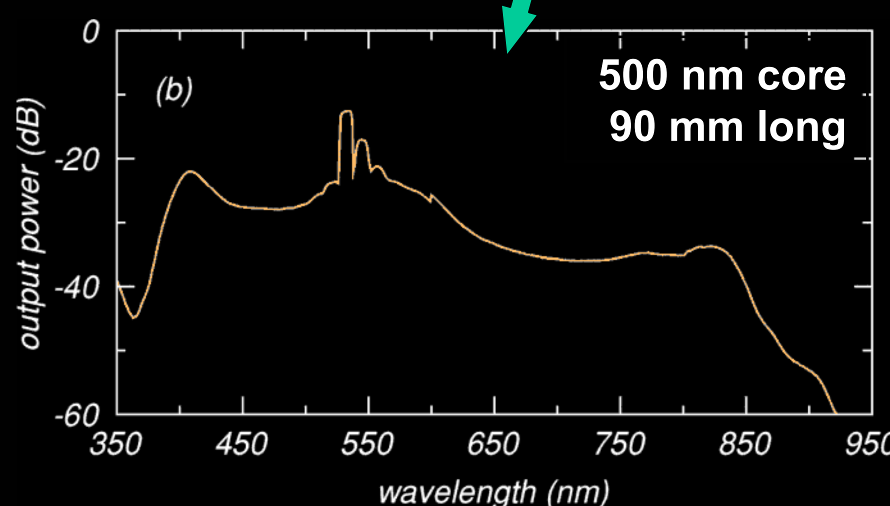
∅ 700 nm core



∅ 500 nm core







average input laser power ~ 1.7 mW

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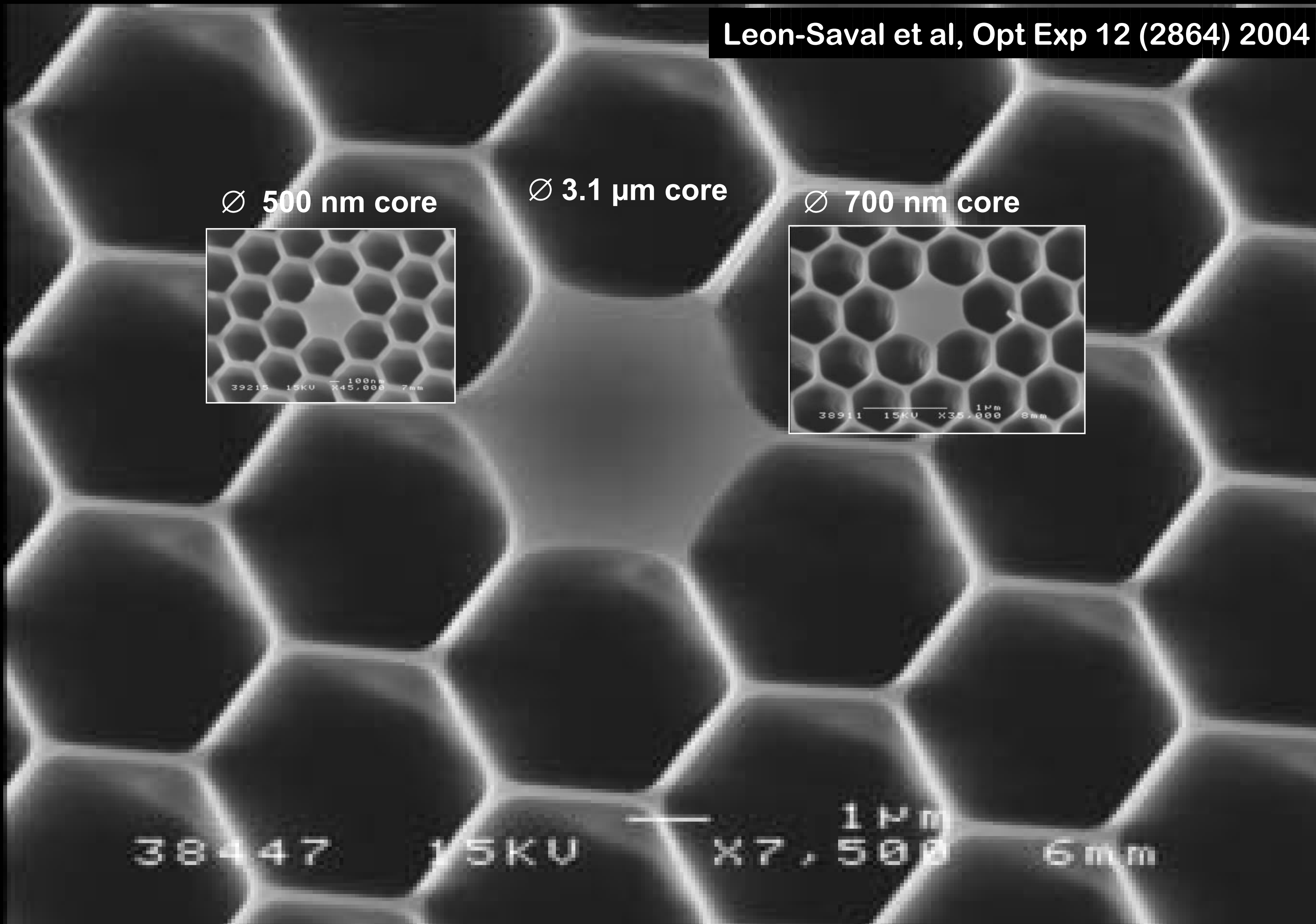
How it looks…

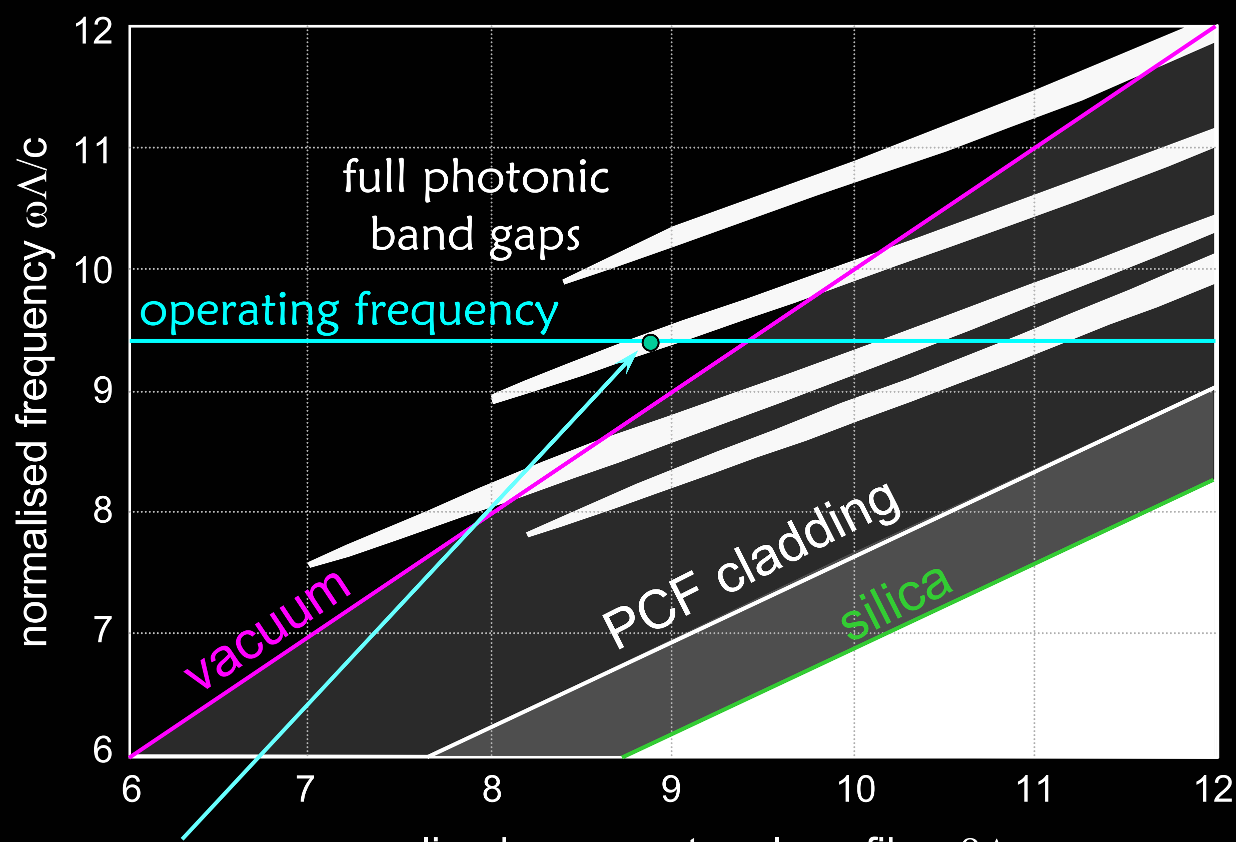
pump light | white light | red filter | orange filter | blue filter

Leon-Saval et al, Opt Exp 12 (2864) 2004

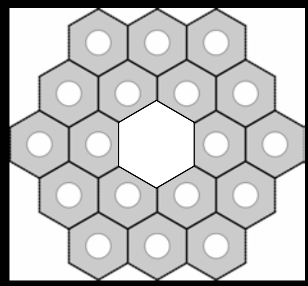


Photonic band gap guidance

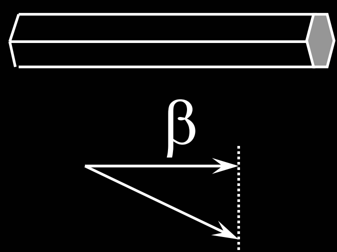
Guidance condition



photonic band gap guidance:
light can propagate in air but not in photonic crystal cladding



- **45% air filling fraction**
- **silica:air index contrast 1.46:1**



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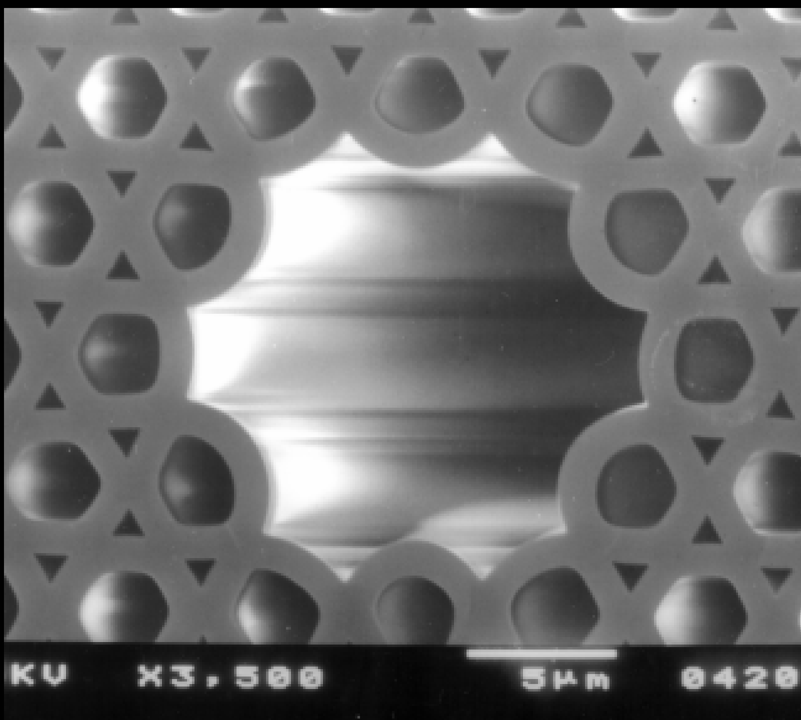
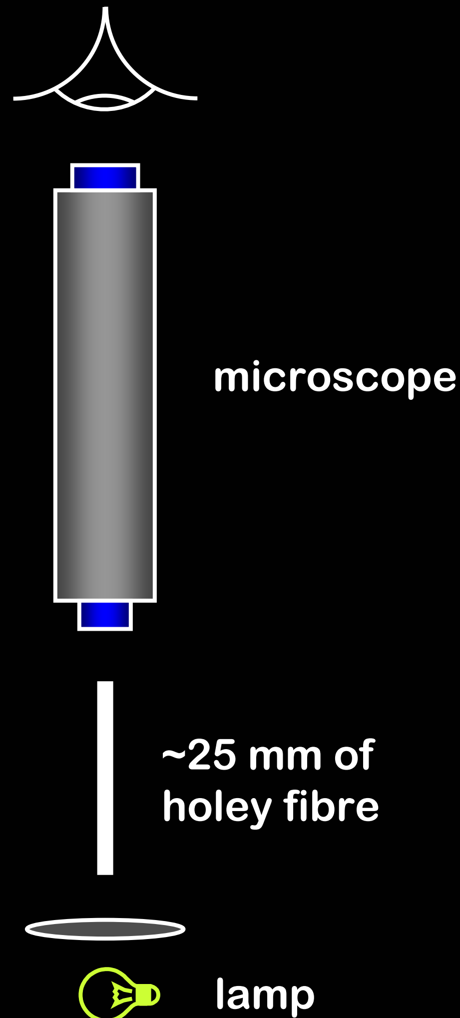
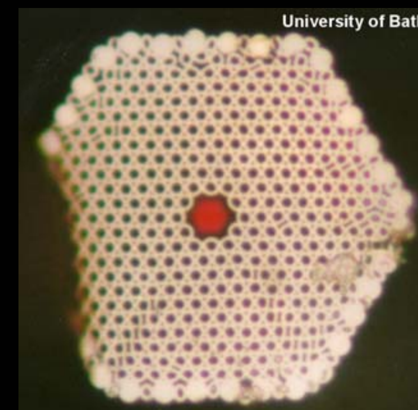
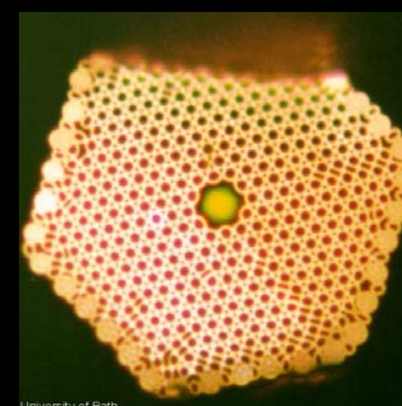
Hollow core PBG fibres

Cregan et al, Science 285 (1537-1539) 1999









guidance is typically narrow-band

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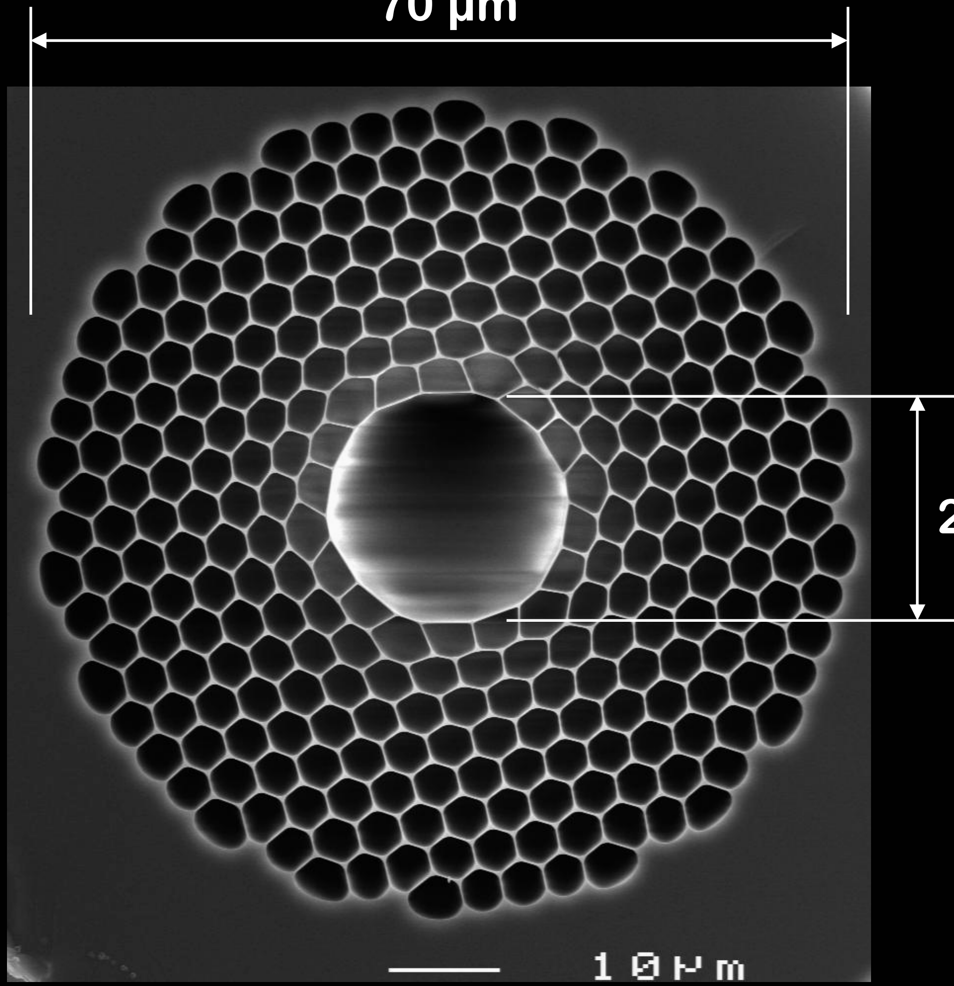
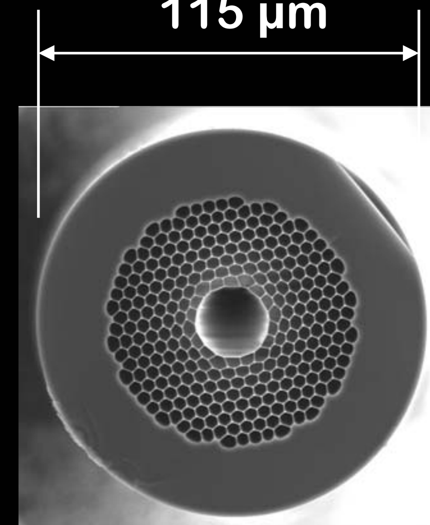
State-of-the-art HC PCF

Mangan et al, OFC 2004, paper PDP24

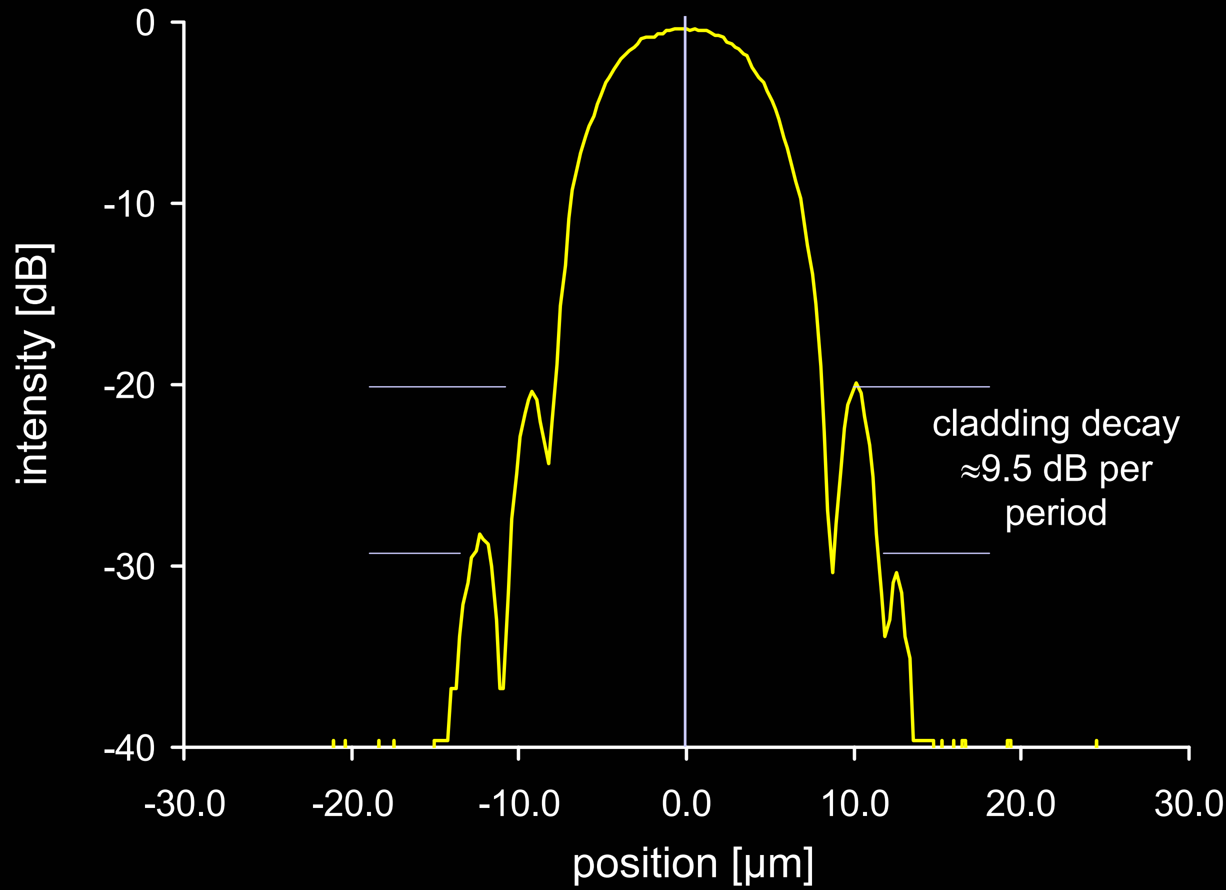


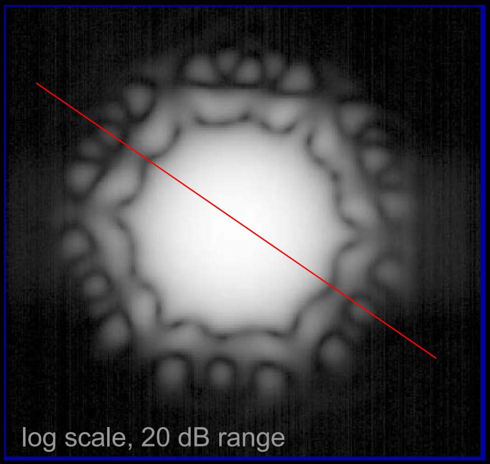


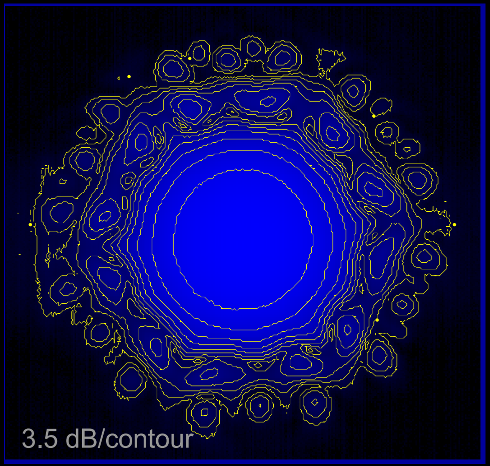
1.7 dB/km at 1550 nm

Near-field intensity distribution

Mangan et al, OFC 2004, paper PDP24

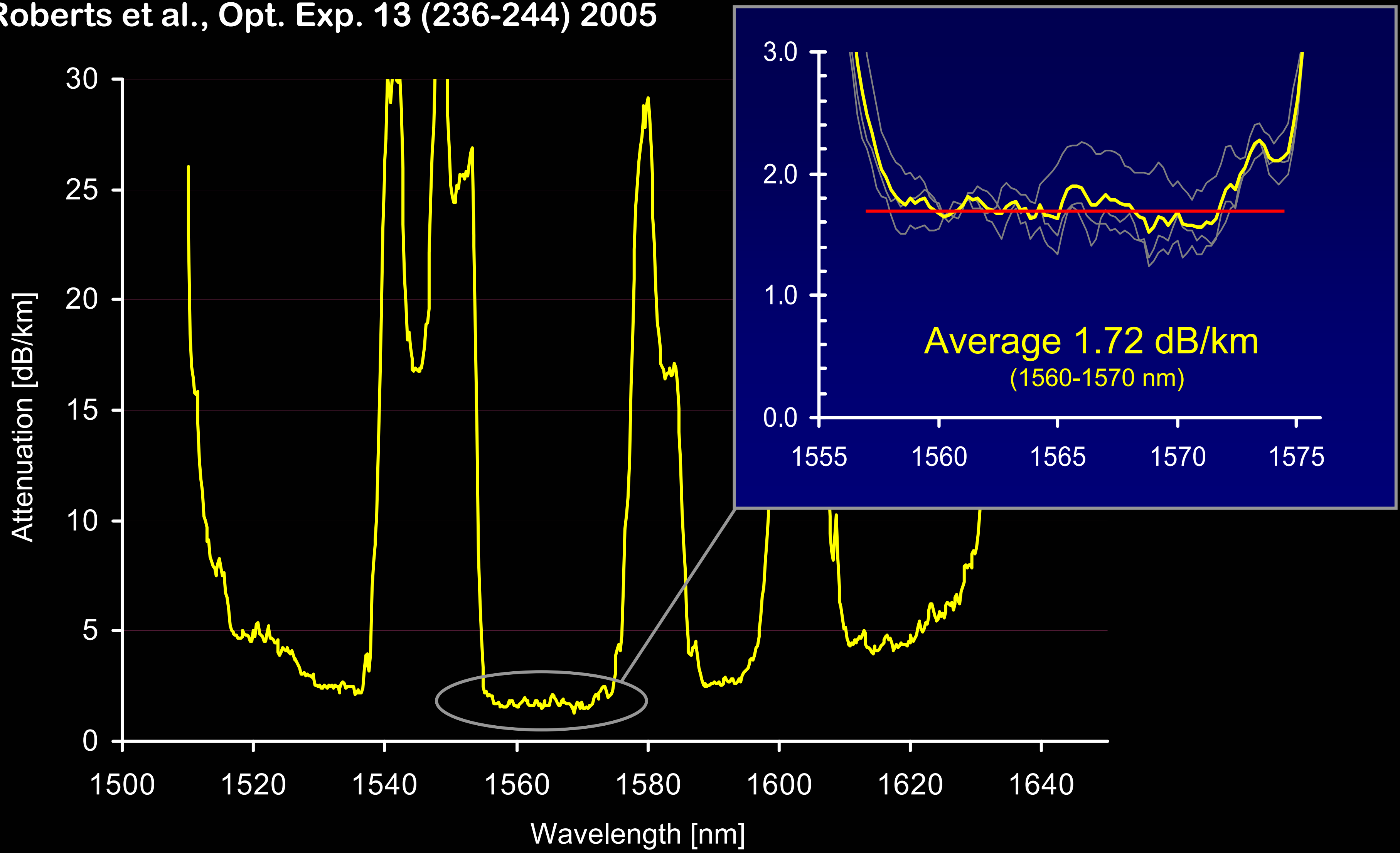






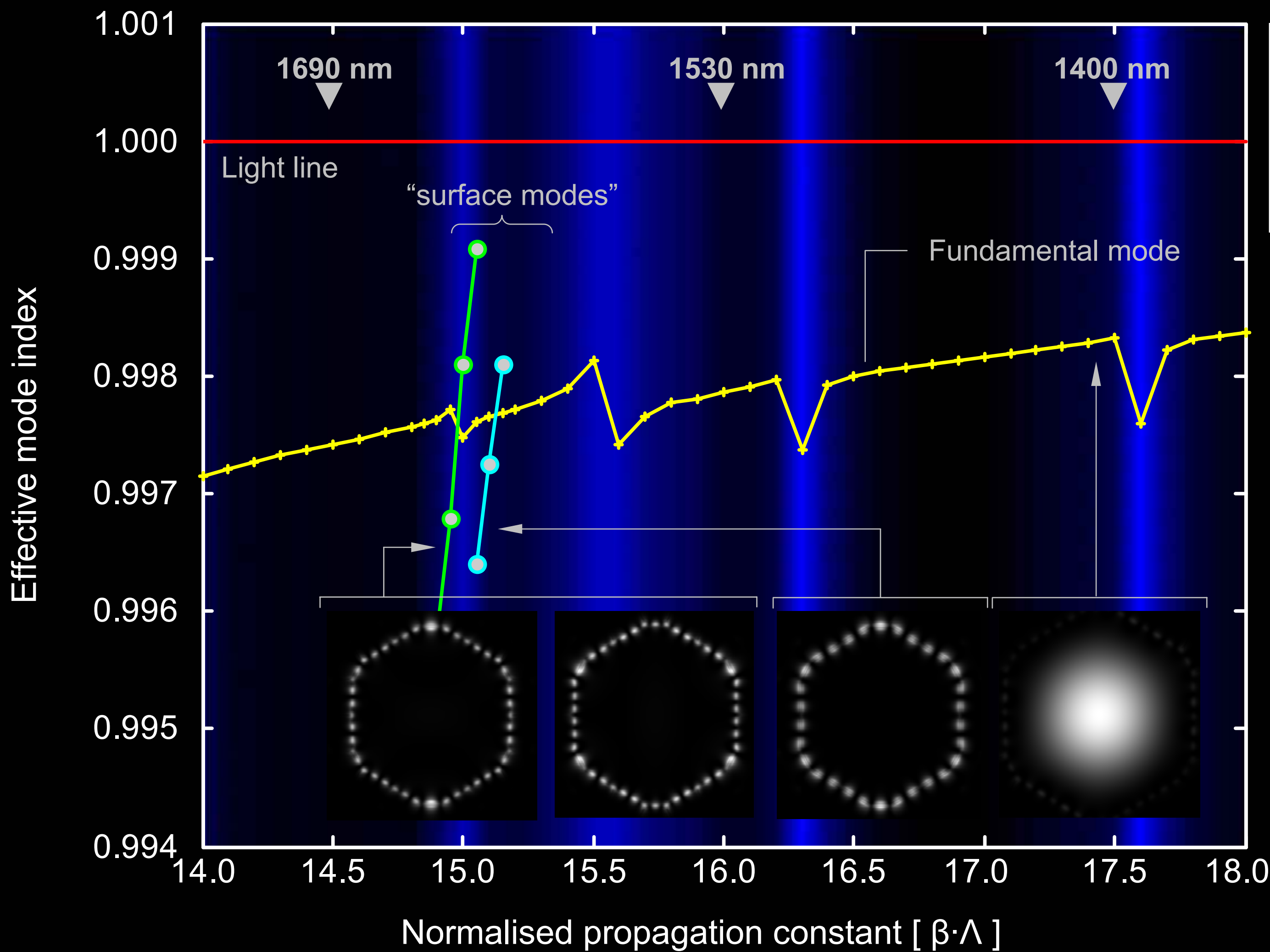
Attenuation

Roberts et al., Opt. Exp. 13 (236-244) 2005



Loss induced by mode crossings

Roberts et al., Opt. Exp. 13 (236-244) 2005

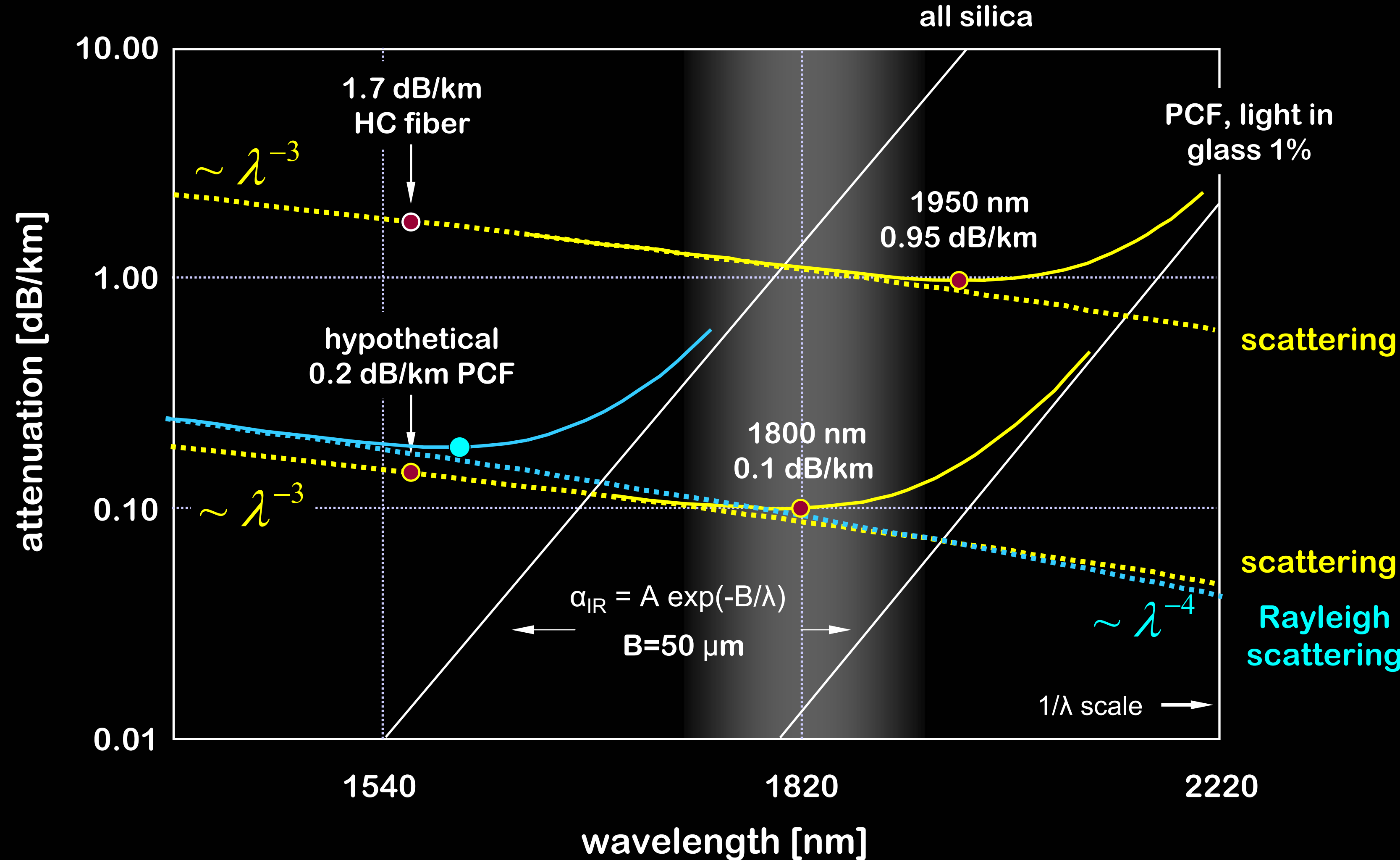


blue shading indicates light-in-glass fraction

A new window

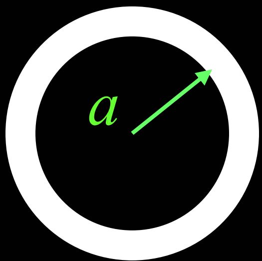
New telecommunications window?

Mangan et al, OFC 2004, paper PDP24

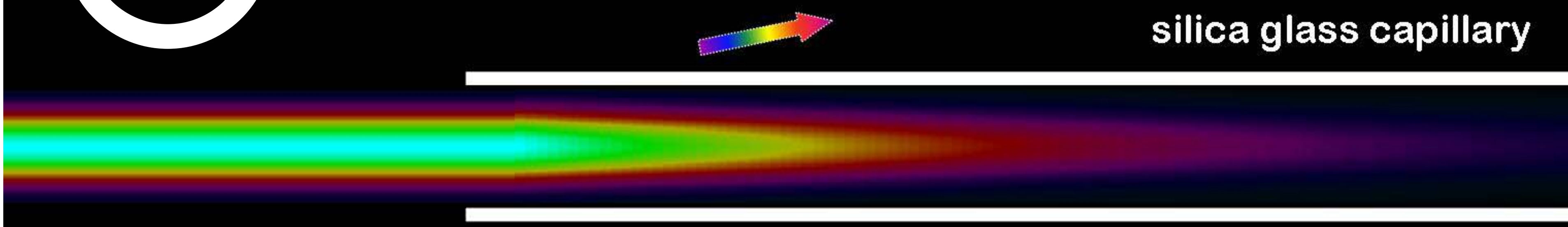


Gas-laser interactions

Capillaries always leak



Renn et al., J Vac Sci Tech 16 (3859) 1998



wavelength (850 nm)

$$\text{loss}\ (\text{m}^{-1}) = \frac{\lambda^2 \sqrt{n^2+1}}{6.8\, a^3 (n^2-1)}$$

hole radius

refractive index (1.46)

reducing radius from 100 μm to 5 μm increases loss 8000×

Nonlinear figure-of-merit

wavelength

how far does the light travel before it is absorbed?

$$\frac{\lambda L_{\text{loss}}}{A_{\text{eff}}}$$

area of light mode (small is good)

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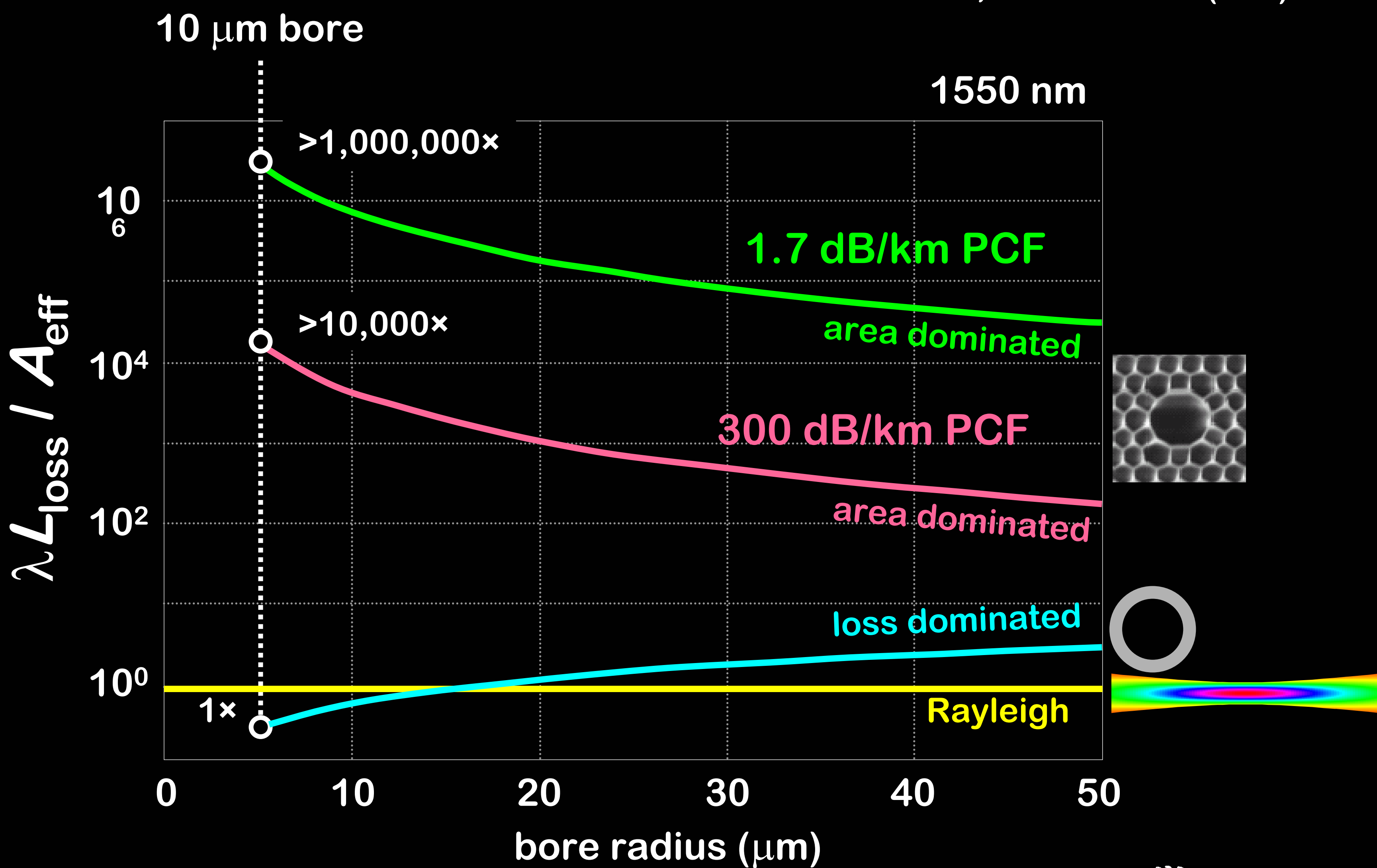
Comparison

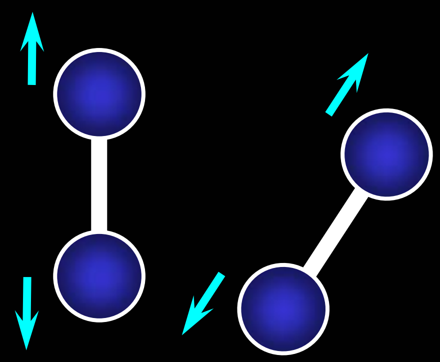
Benabid et al, Science 298 (399) 2002



Stimulated Raman scattering

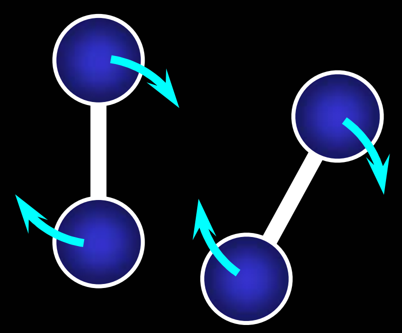
Molecular oscillations in H_2

$Q_{01}(1)$



vibrational
(usually dominant)
125 THz

$S_{00}(1)$



rotational
(usually much weaker)
18 THz

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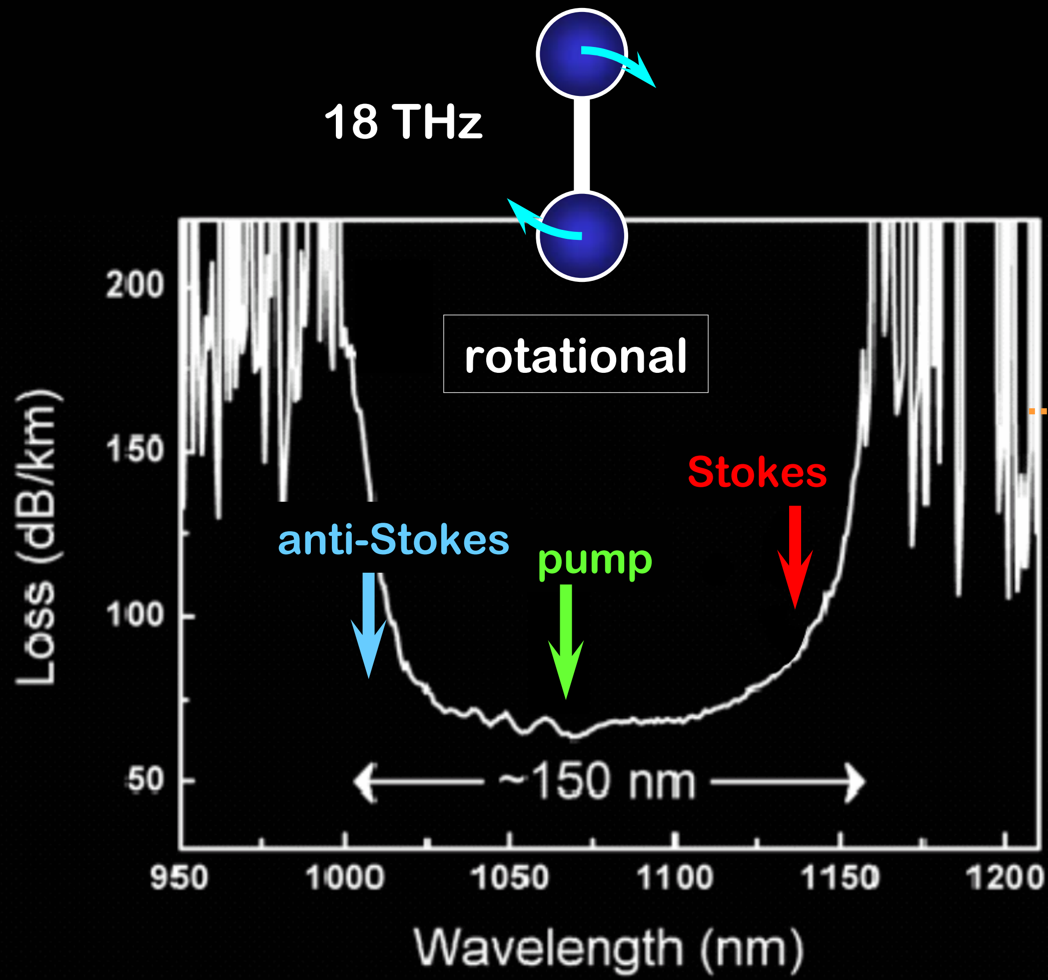
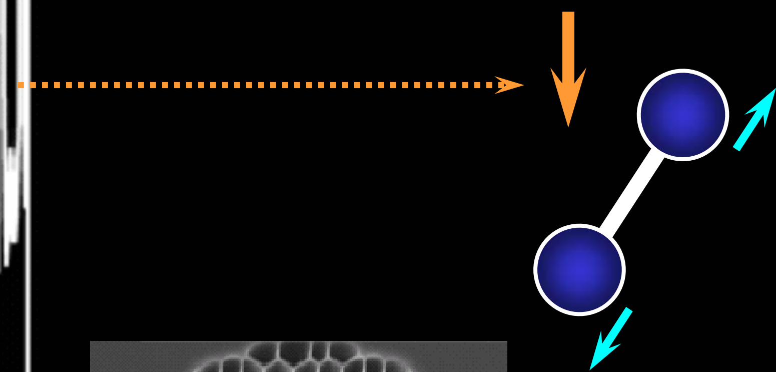
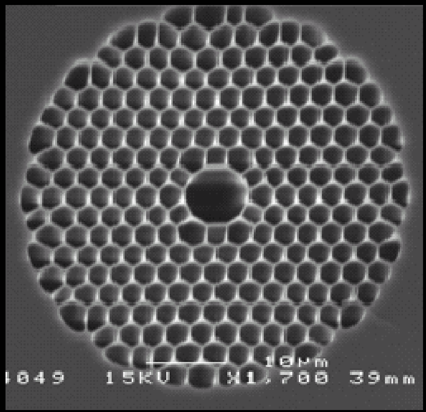
Hollow core PCF for rotational SRS

Benabid et al, PRL 93 (123903) 2004

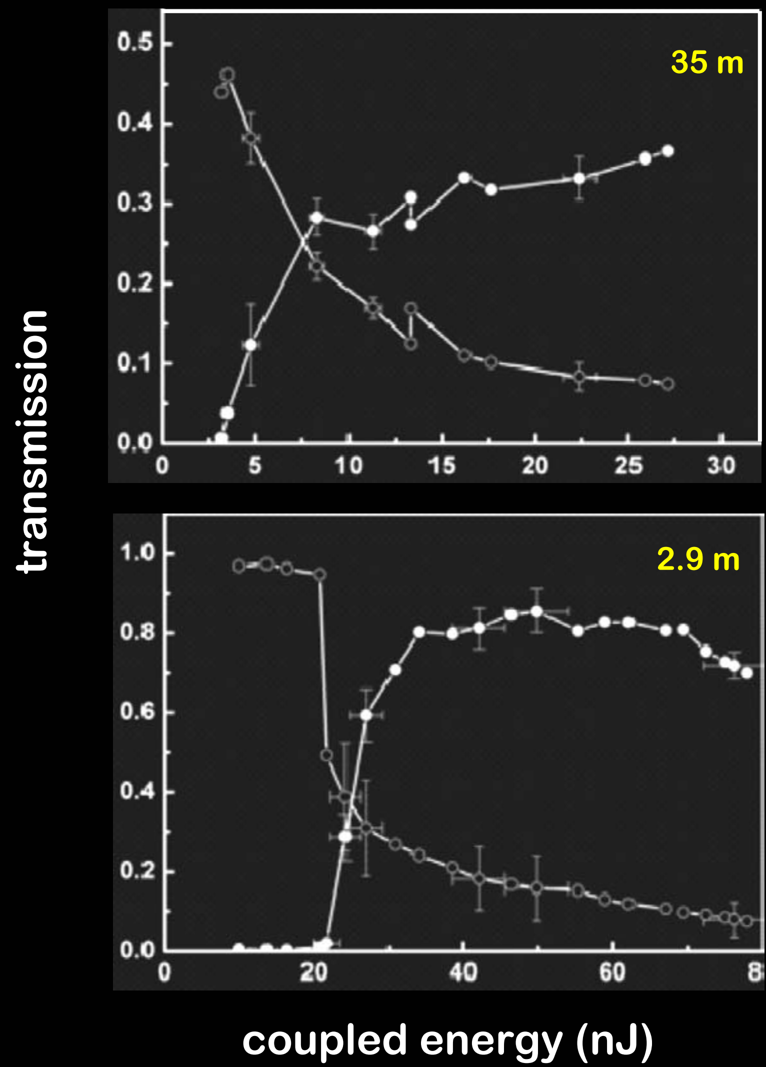


very high attenuation
for vibrational Stokes





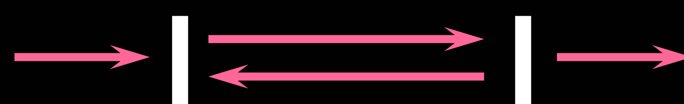
SRS conversion



Benabid et al, PRL 93 (123903) 2004

- single-pass threshold at energy 1,000,000 times lower (35 m)
- near-perfect quantum efficiency achieved (2.9 m)

multi-pass: Meng et al., Opt. Lett. 27 (1226) 2002



hydrogen pressure 7 bar
loss at second Stokes is 0.6 dB/m

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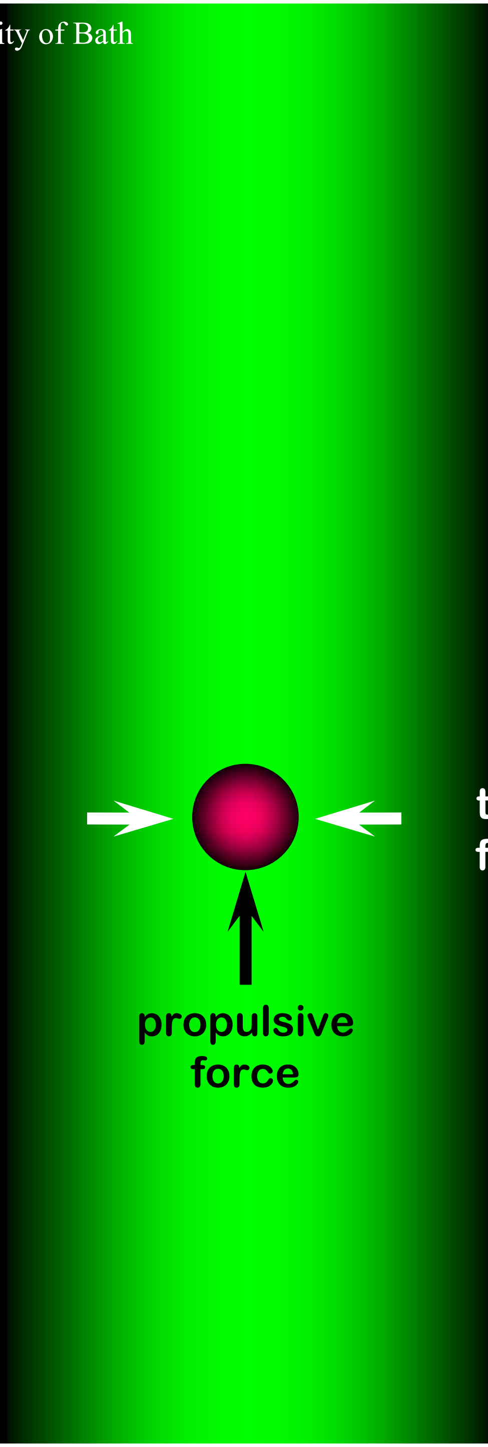
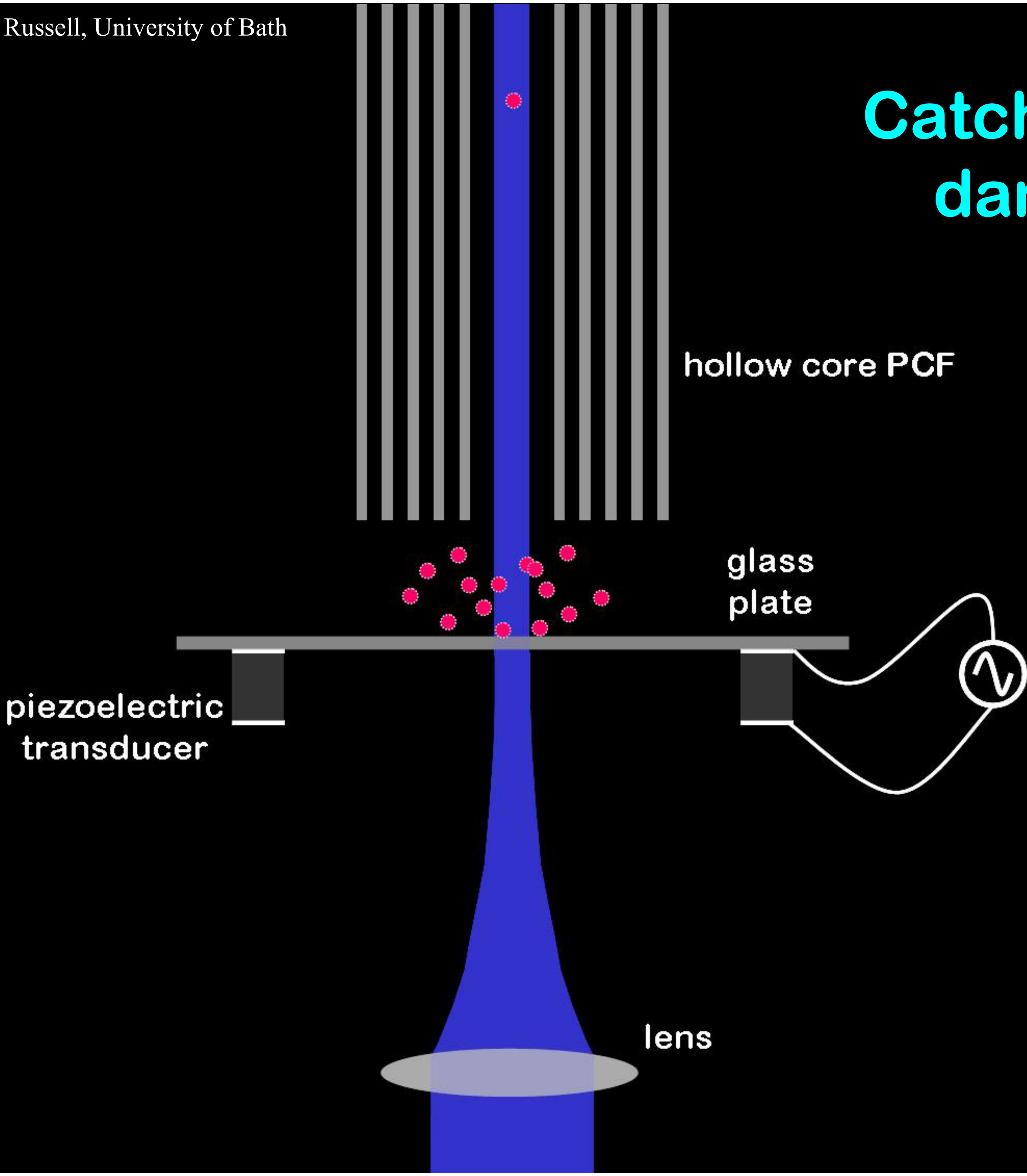
Catching the dancers

Laser tweezer forces



Catching the dancers



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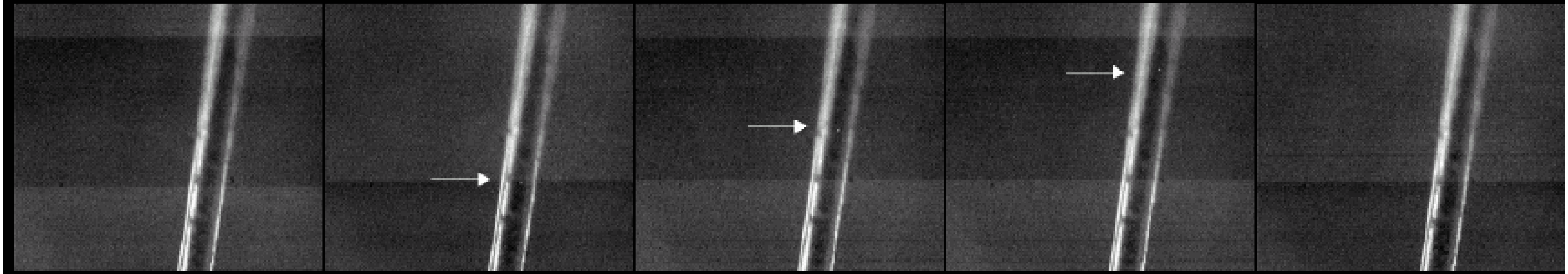
Piped particle

Benabid et al, Opt. Exp. 10 (1195-1203) 2002



- 20 μm diameter hollow core
- 5 μm diameter polystyrene spheres
- 80 mW at 514 nm
- terminal velocity 1.5 cm/sec

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Finally…

Impacts and prospects

transforming fibre optics
intra-fibre devices
biomedical/chemical sensors

cold atom guidance
particle/cell guidance
gas-laser interactions

dispersion control
solitons at new wavelengths
transforming nonlinear optics

supercontinuum generation
frequency metrology
non-silica glass fibres

polymer fibres
fibre lasers & amplifiers
high power & energy transmission

Photonics & Photonic Materials Group
12th October 2004