Photonic crystal and microstructured fibers:

Making fibers better by leaving bits out

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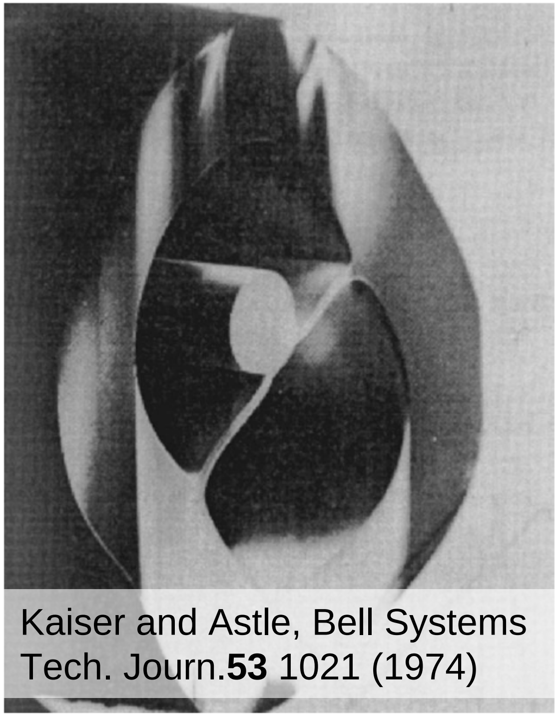
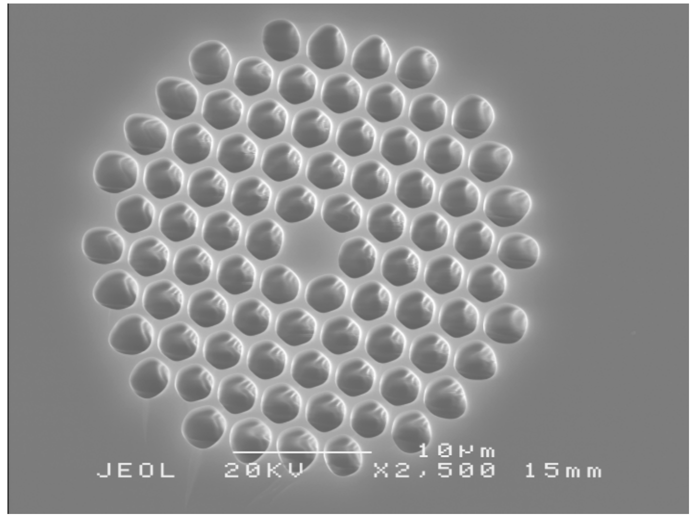
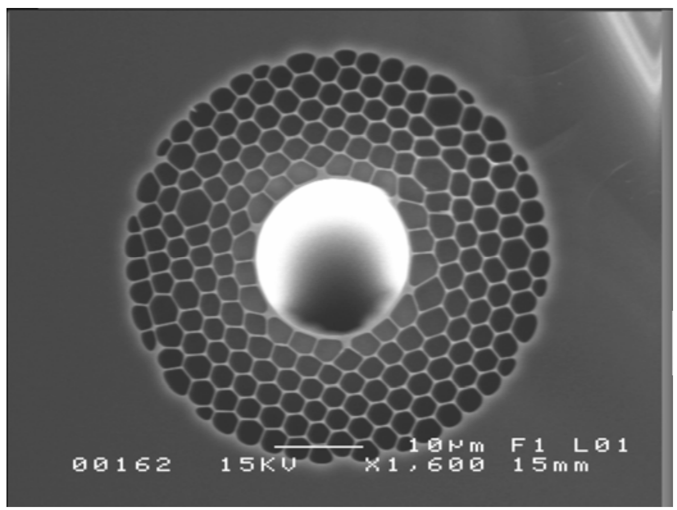
United Kingdom

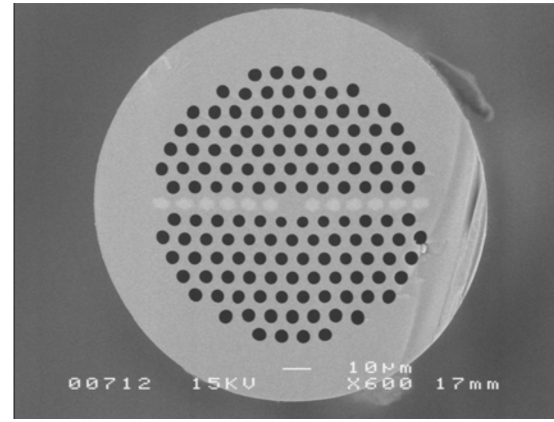
What’s it all about?

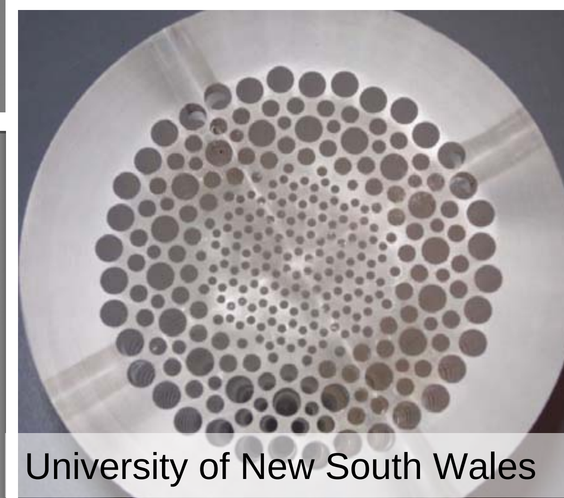


Kaiser and Astle, Bell Systems Tech. Journ.**53** 1021 (1974)









University of New South Wales

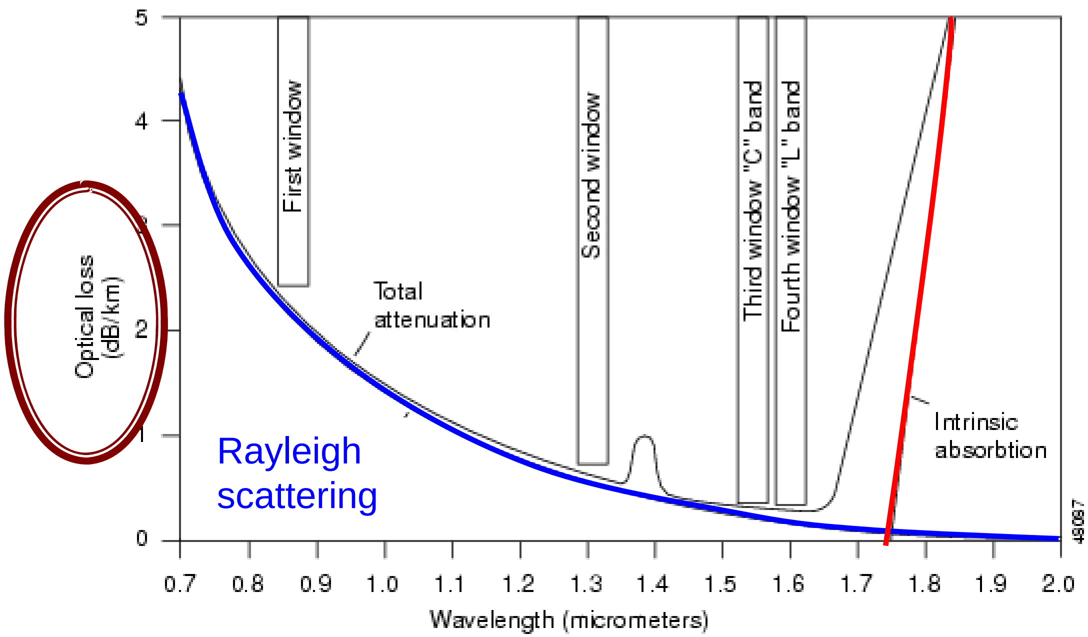
This tutorial

- Photonic crystal fibre concepts
- Practical implementation: actual fibres
- Optical properties
- Application areas

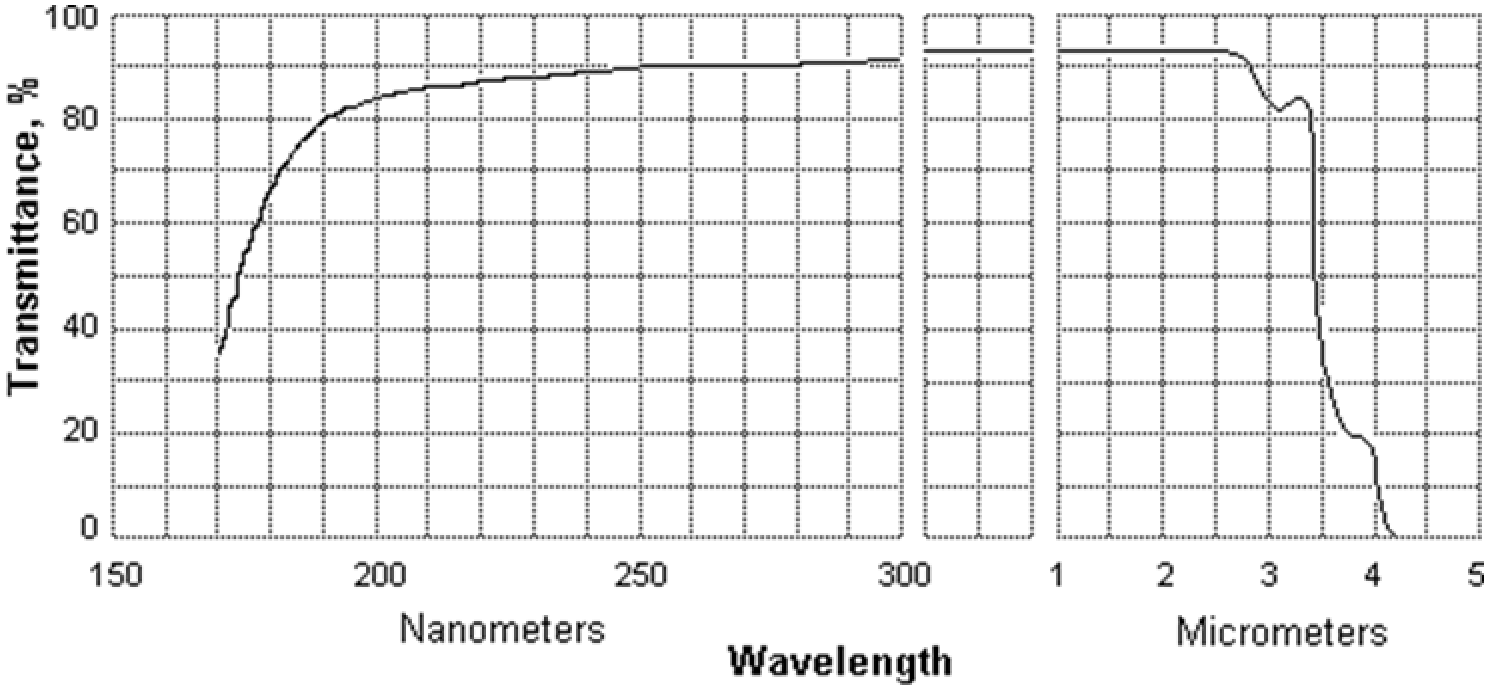
Why bother?

1. Conventional fibres face limitations
2. Re-thinking the basics in the light of alternative technologies
3. Enables the previously unthinkable: hollow-core fibres
4. New application areas for fibres

Transparency of fused silica

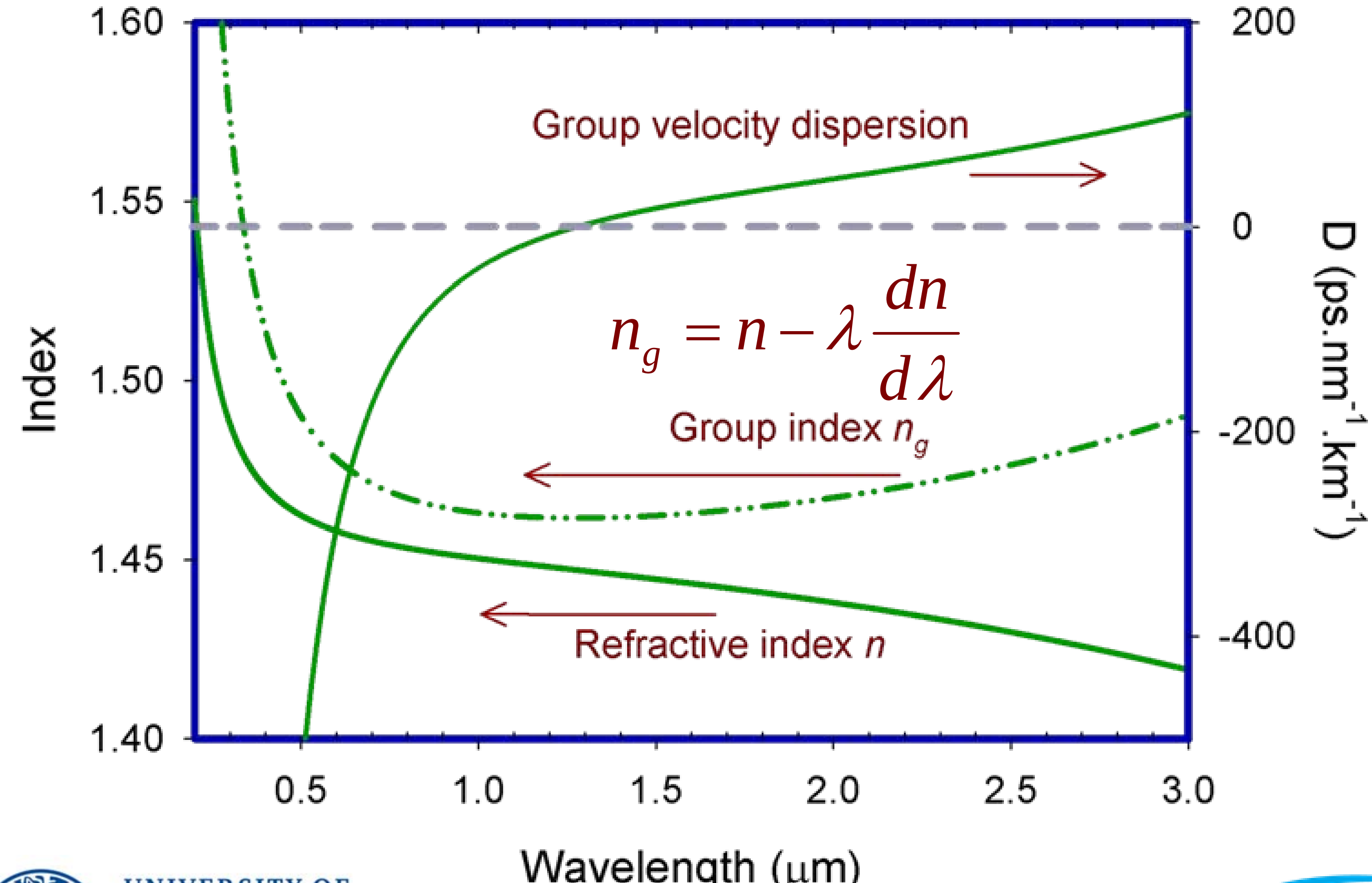


Transparency of fused silica



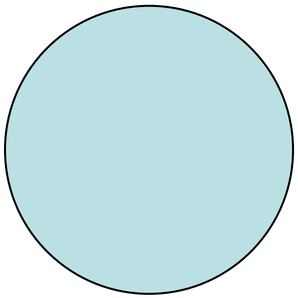
(3mm window)

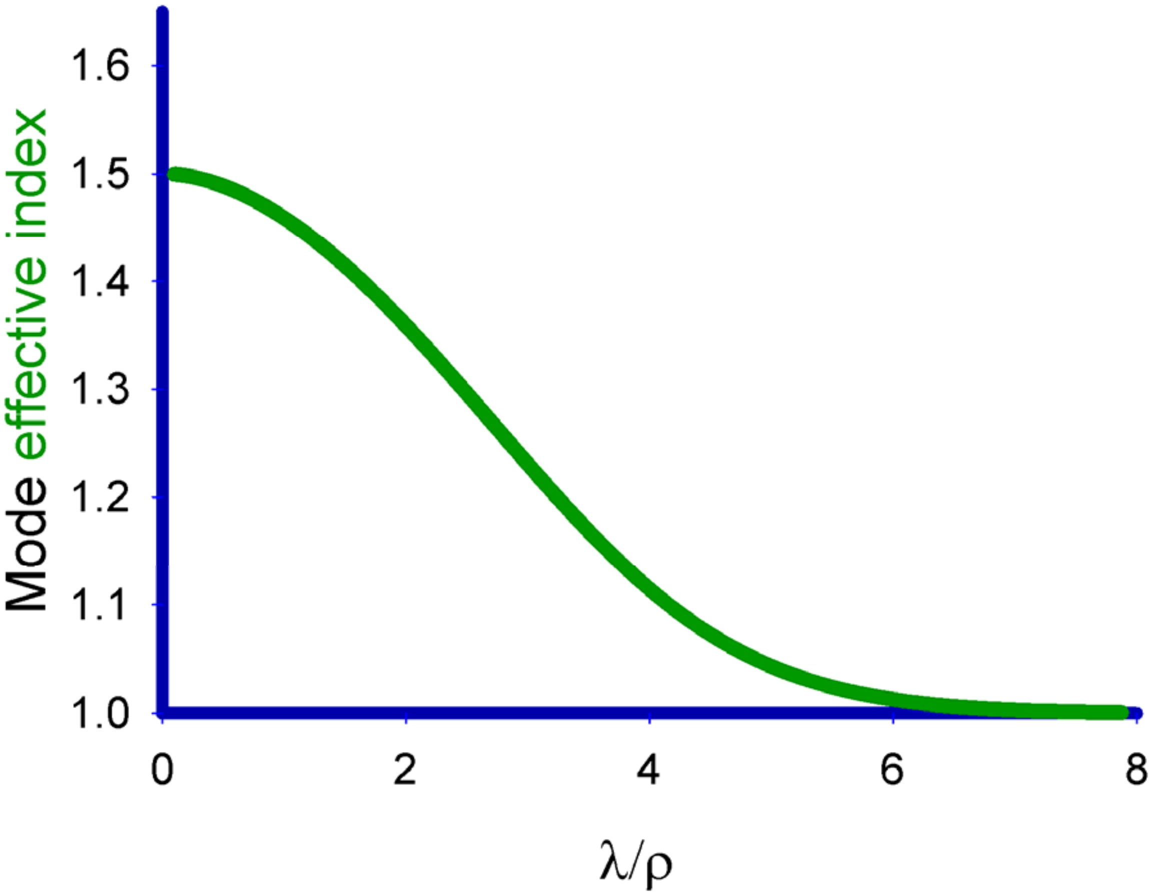
Dispersion of fused silica



Guidance by a strand of glass

- Assumed core $n = 1.5$, no material dispersion
- Assumed cladding $n = 1.0$ (air clad)
- Wavelength λ, core radius ρ

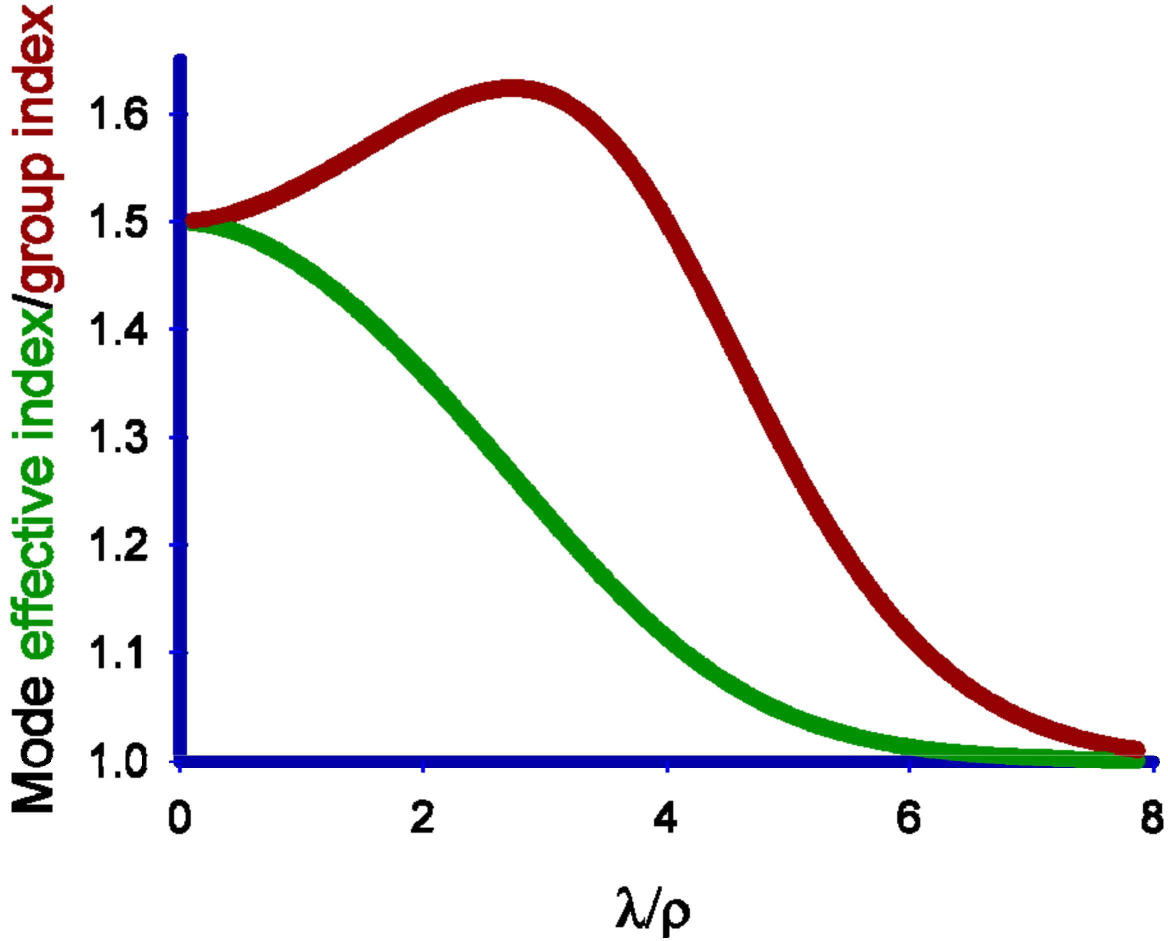




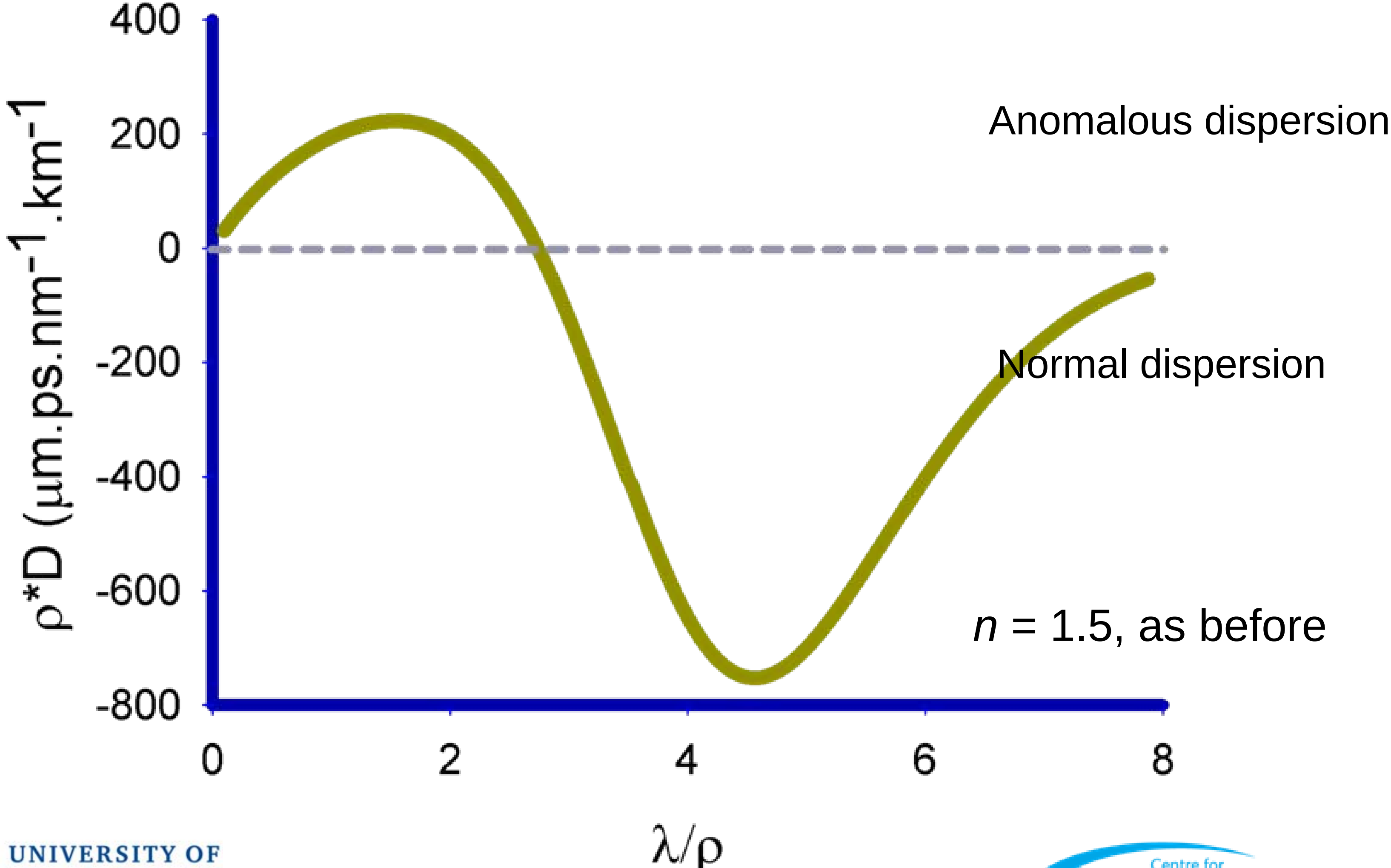
Guidance by a strand of glass

- Assumed core *n* = 1.5, no material dispersion
- Assumed cladding *n* = 1.0 (air clad)
- Wavelength λ, core radius ρ

$$n_g = n - \lambda \frac{dn}{d\lambda}$$



Waveguide Dispersion



UNIVERSITY OF BATH

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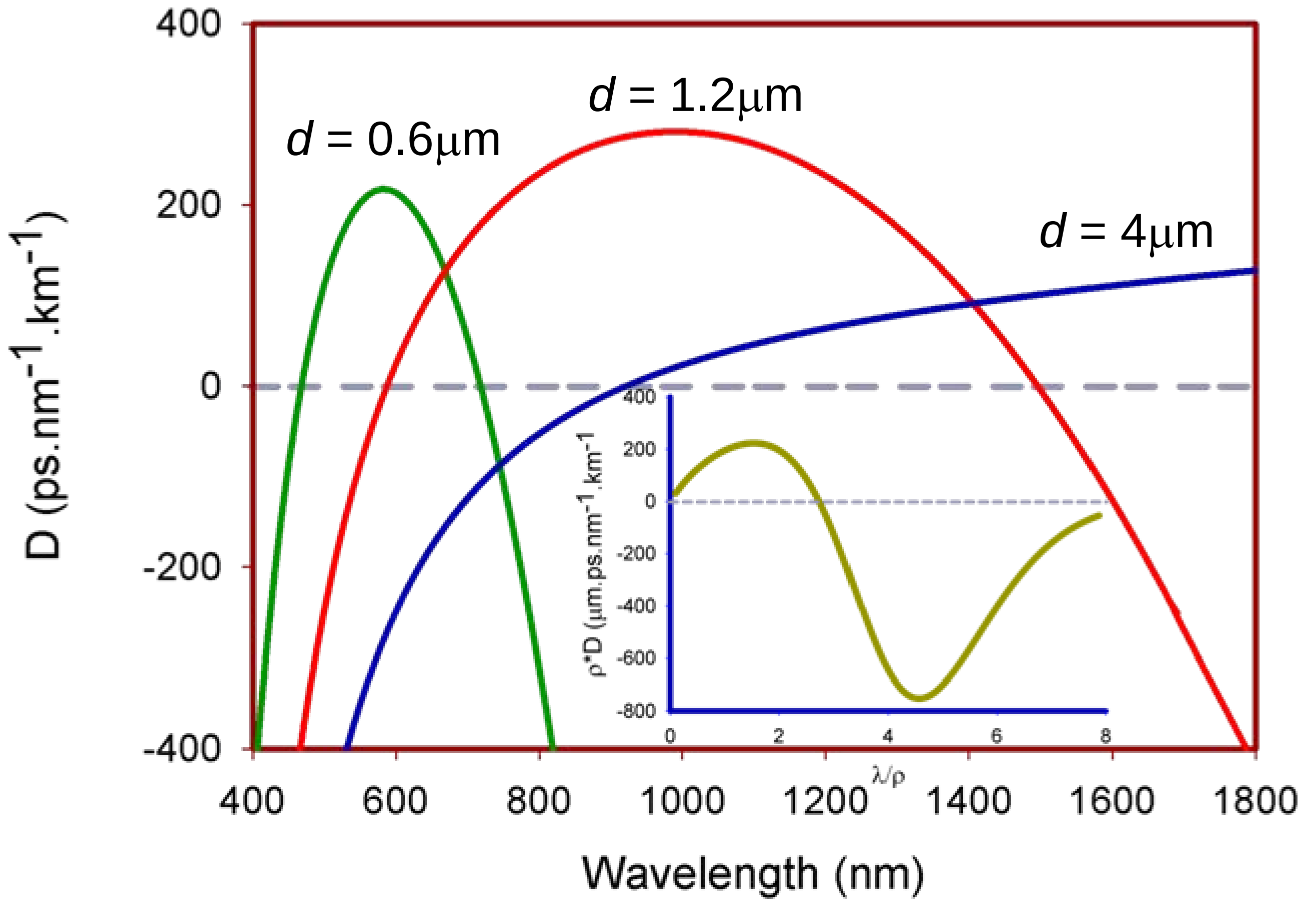
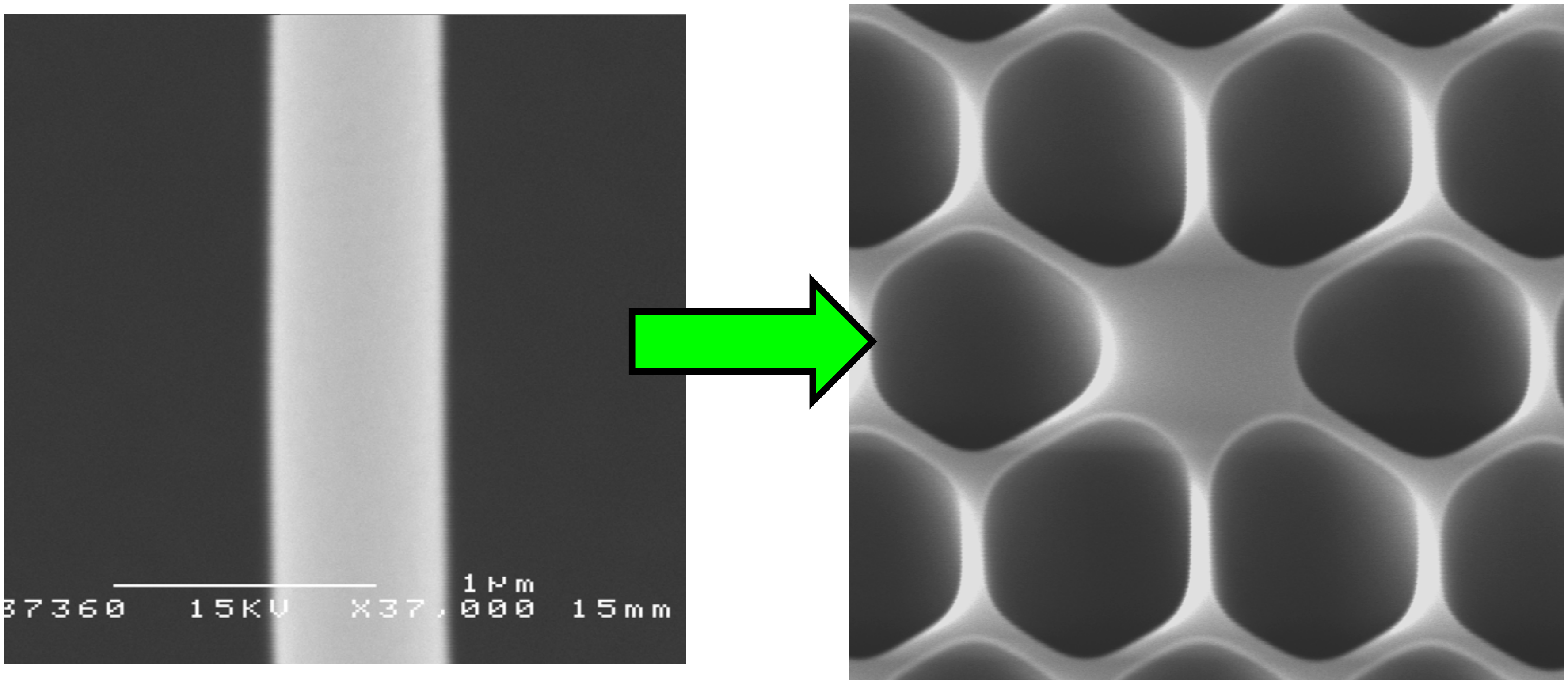
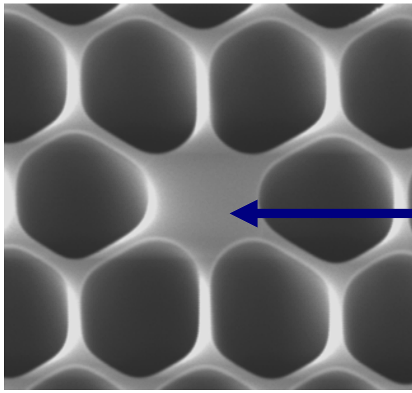
Dispersion of a strand of silica



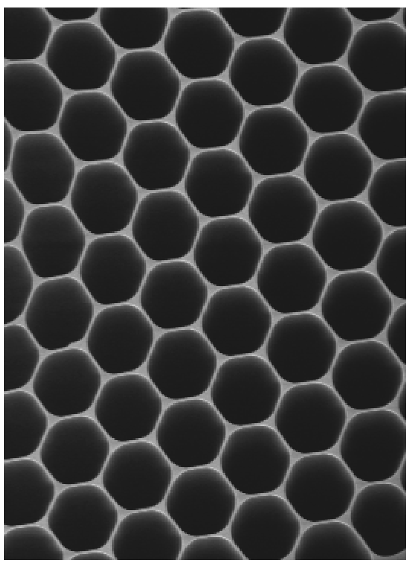
Making the strand of glass into an optical fiber



Fibre with a photonic crystal cladding



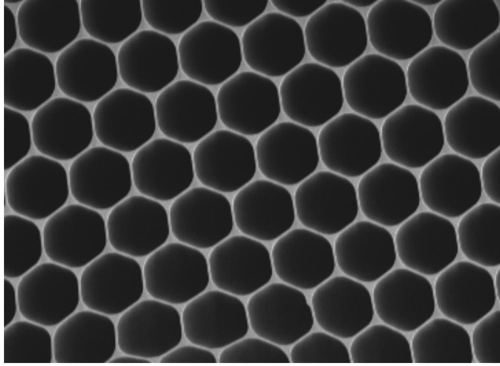
The core

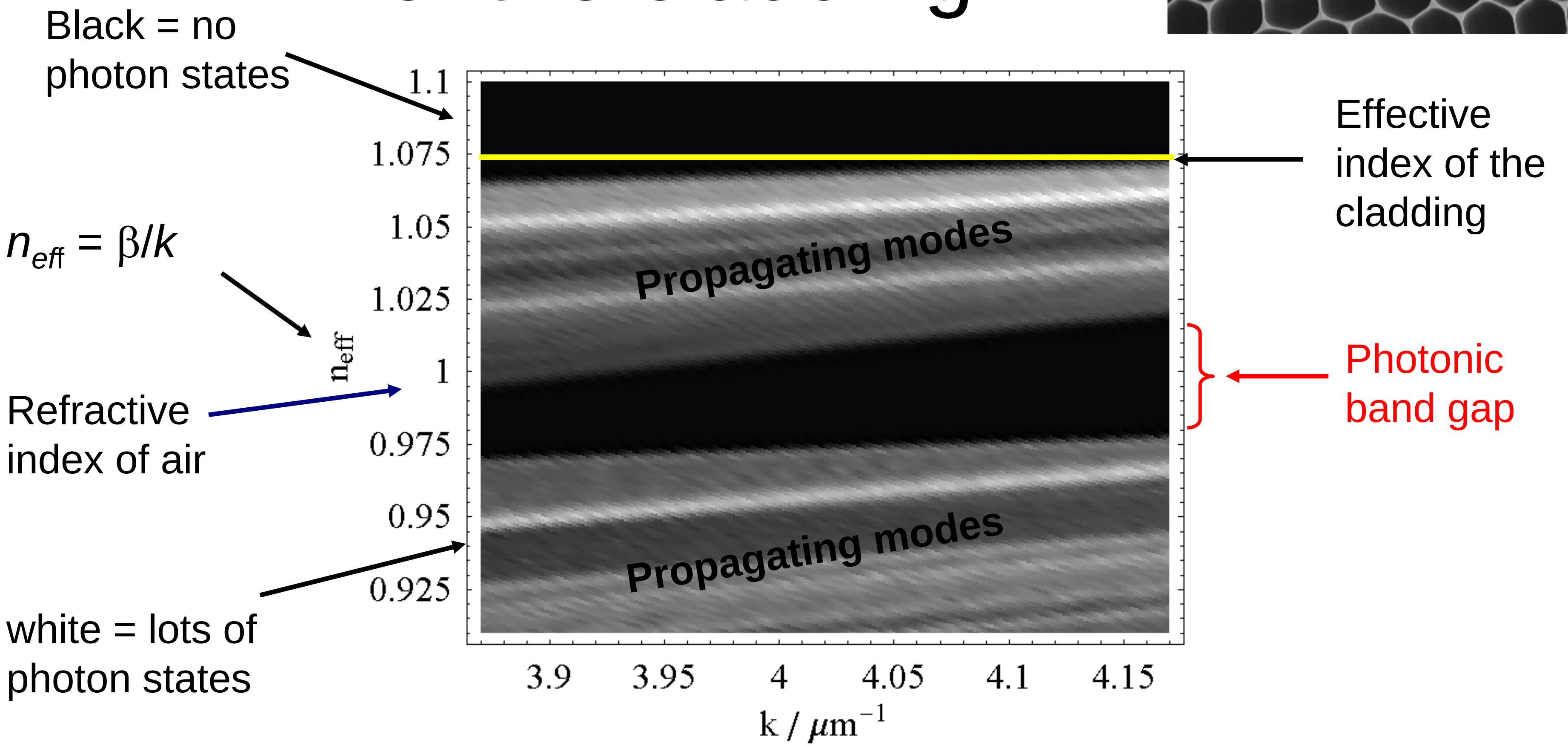


The cladding

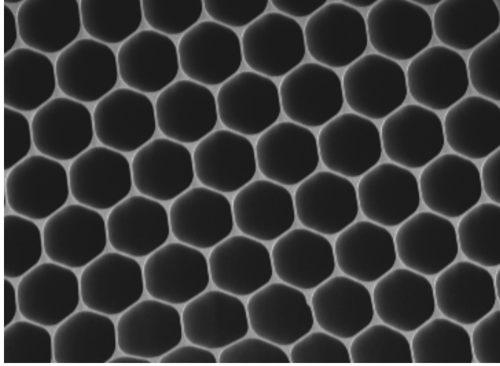
What are the optical properties of the cladding?

Density of States of the cladding





Density of States of the cladding

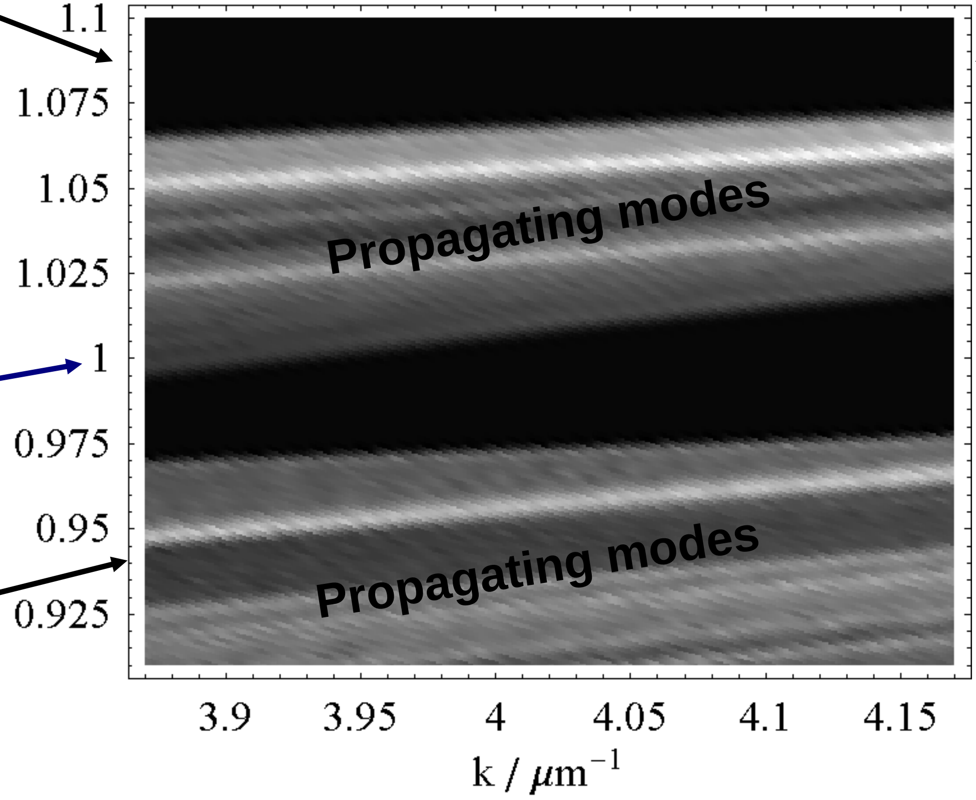


Black = no photon states

$n_{eff} = \beta/k$

Refractive index of air

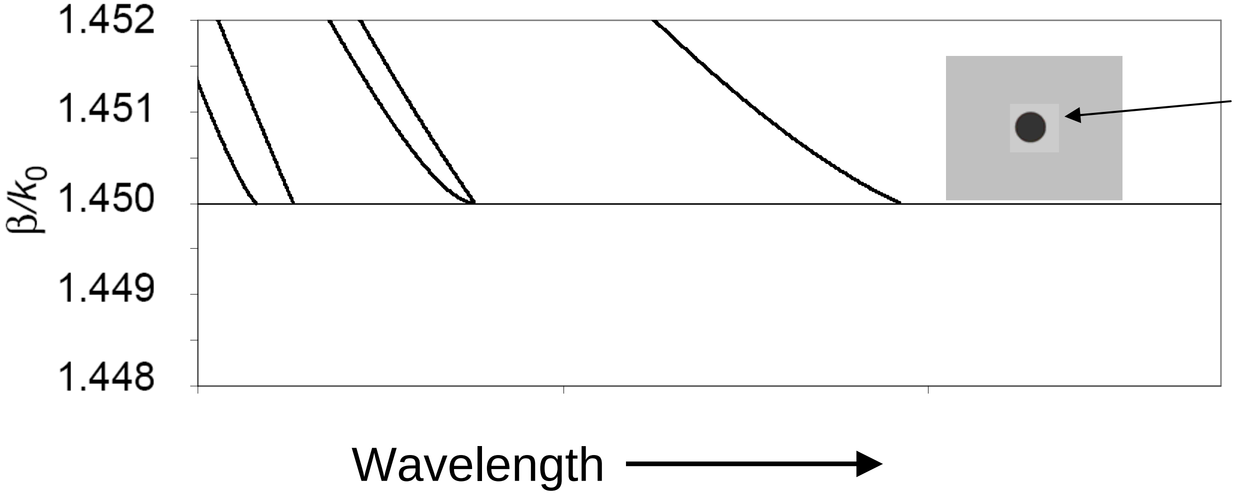
white = lots of photon states



Core mode guided by TIR

Core mode guided by PBG

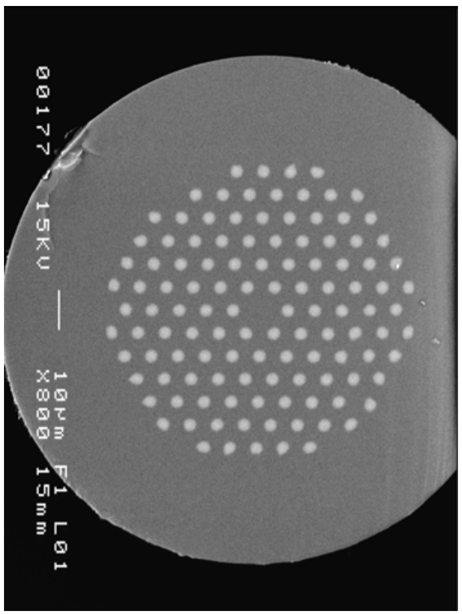
Creating photonic bandgaps

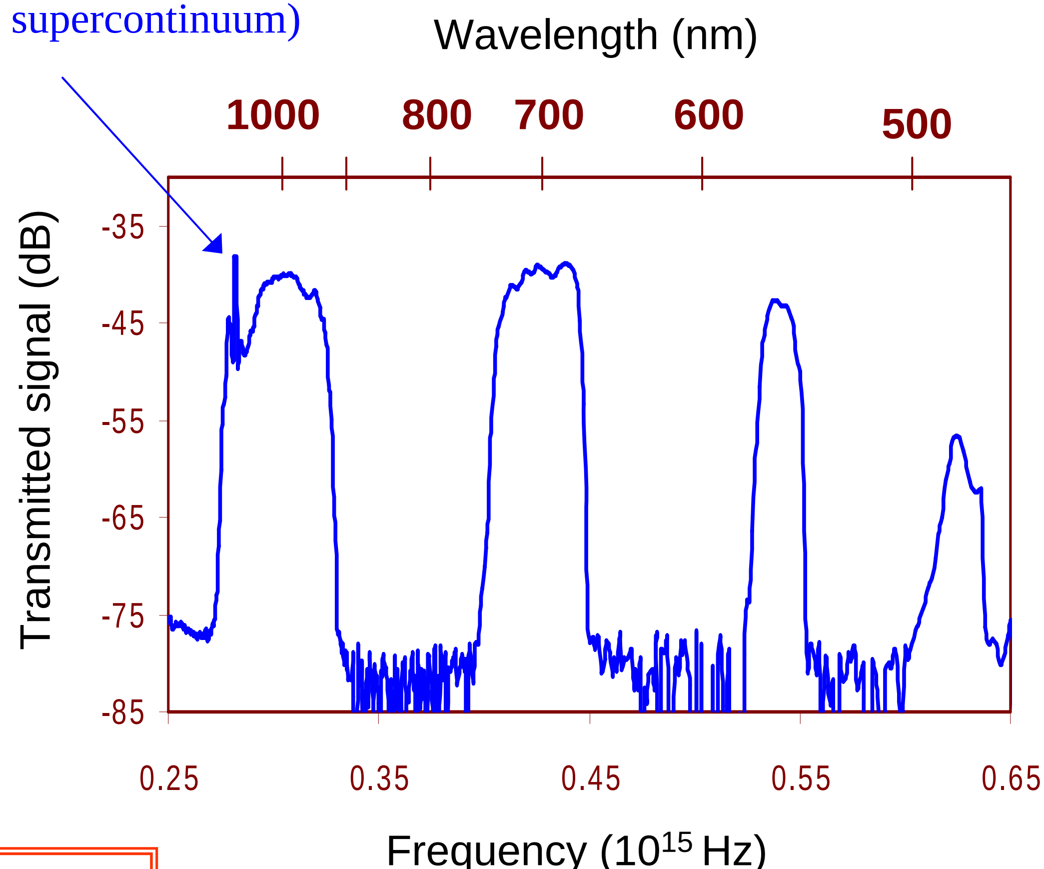


Standard optical fibre
Core n = 1.46
Cladding n = 1.45

Transmission in bandgap fibres

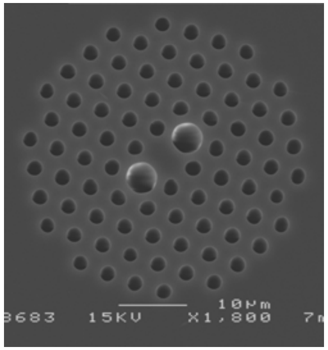
(residual pump for supercontinuum)



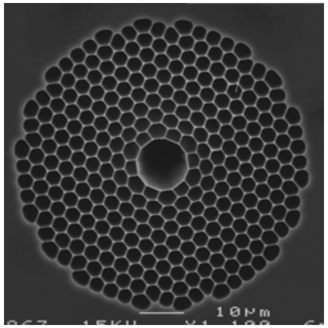


F. Luan *et al,* Opt. Lett. **29** 2369 (2004)
Also see J. Jasapara et al OFC 2002 519 (2002).

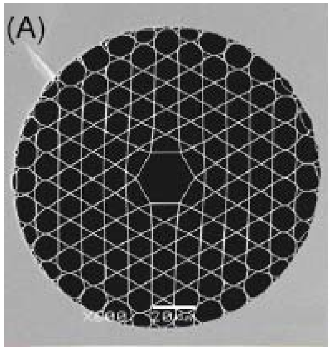
Guidance mechanisms



1. TIR
   - Truly guided modes in high-n core
   - Most like standard fiber



2. Bandgap
   - Truly guided mode in low-n core
   - Finite guidance bandwidth



3. “Kagome”
   - No guided mode – resonances
   - Defined by mode crossings

This tutorial

- Photonic crystal fibre concepts
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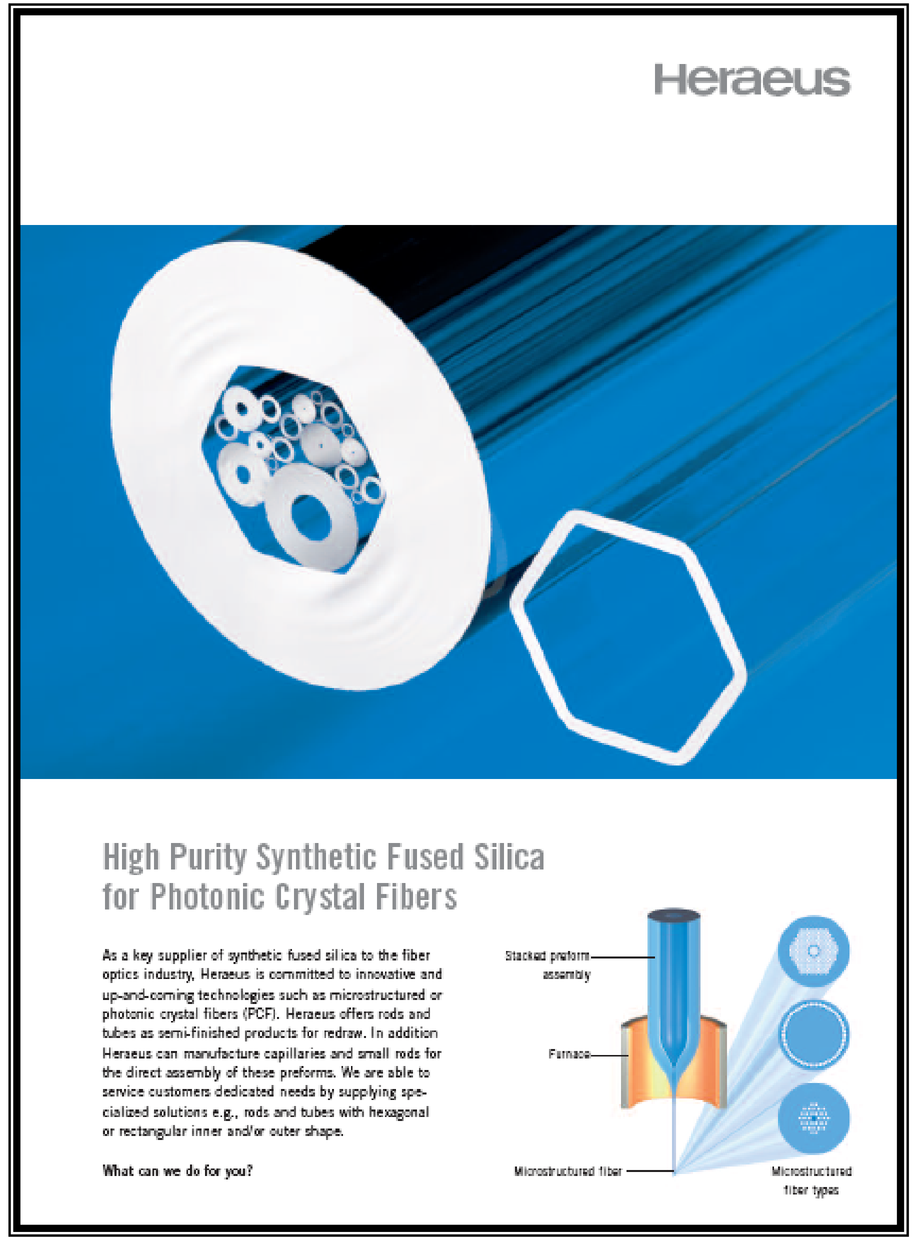
- Optical properties
- Application areas

Synthetic fused silica

- Widely available from commercial suppliers, as rods and tubes, and custom-formed for fabricating photonic crystal and microstructured fibers
- Various grades of material are available, and doped materials as well
- Conventional fibre preforms can also be useful

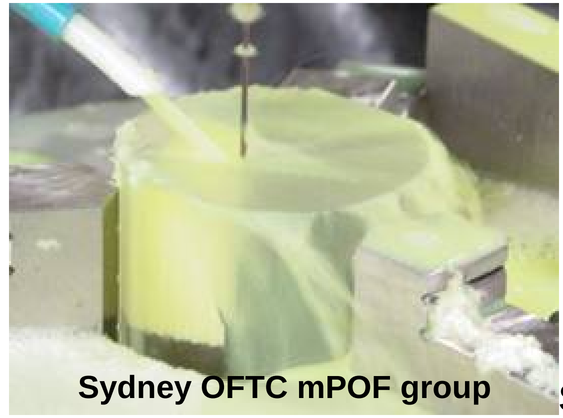

Heraeus

High Purity Synthetic Fused Silica for Photonic Crystal Fibers

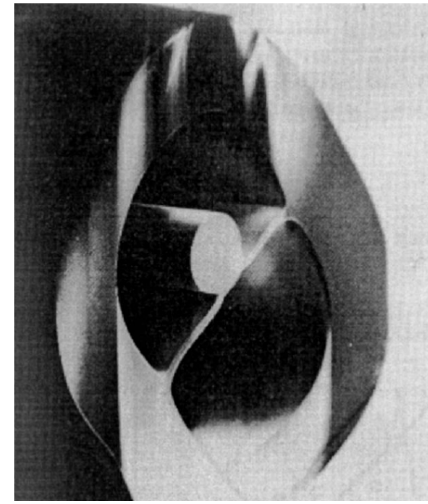
As a key supplier of synthetic fused silica to the fiber optics industry, Heraeus is committed to innovative and up-and-coming technologies such as microstructured or photonic crystal fibers (PCF). Heraeus offers rods and tubes as semi-finished products for redraw. In addition Heraeus can manufacture capillaries and small rods for the direct assembly of these preforms. We are able to service customers dedicated needs by supplying specialized solutions e.g., rods and tubes with hexagonal or rectangular inner and/or outer shape.

What can we do for you?

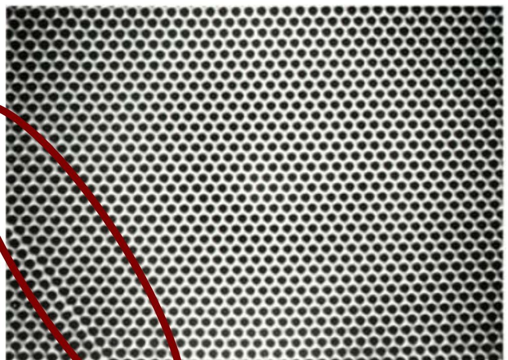
fabrication



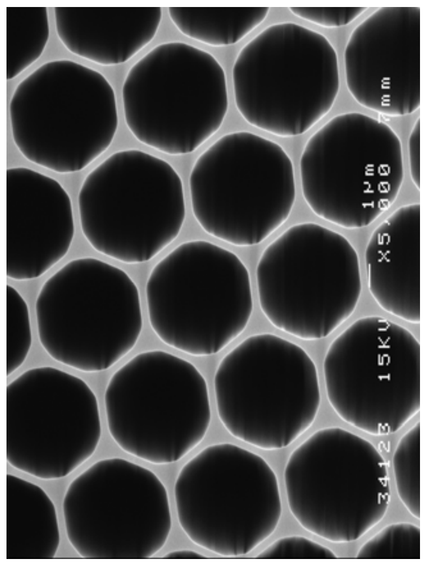
Sydney OFTC mPOF group

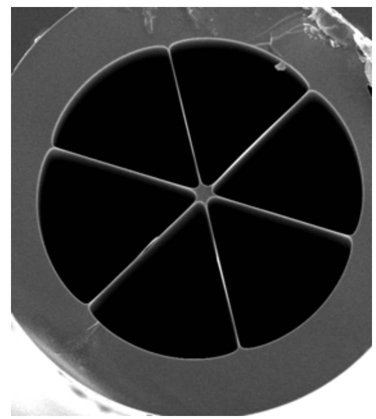


Silica - Kaiser and Astle, Bell Systems Tech. Journ.**53** 1021 (1974)

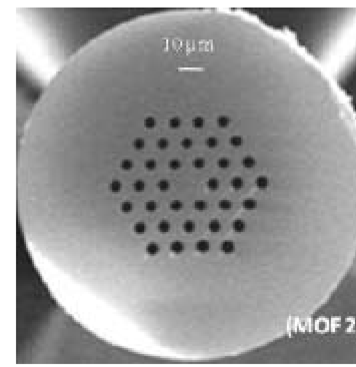


Tonnucci *et al*., Science **258** 783 (1992)



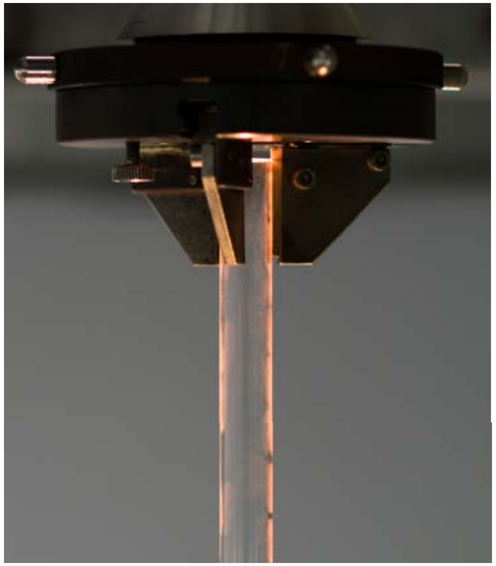


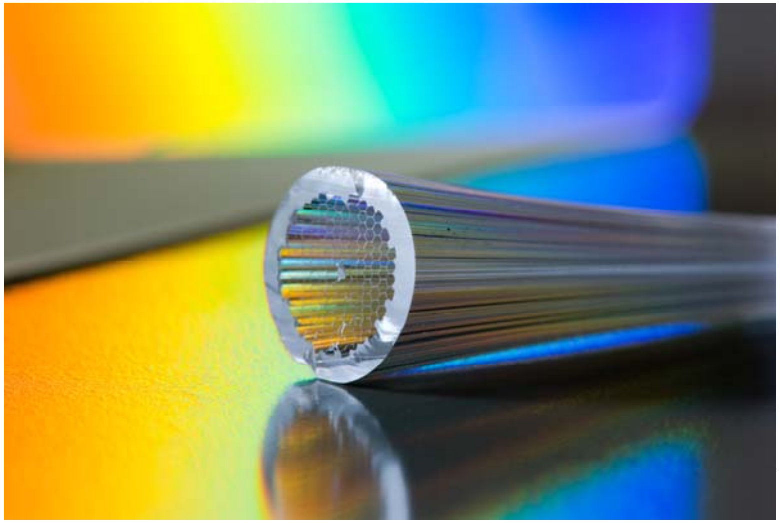
Extrusion tellurite - Kumar *et al*., Opt. Express **11** 2641 (2003)

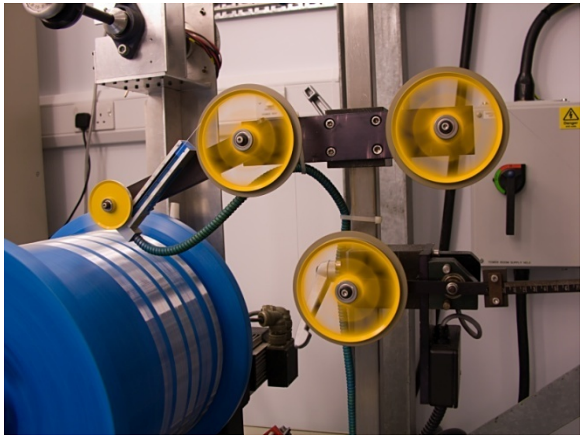


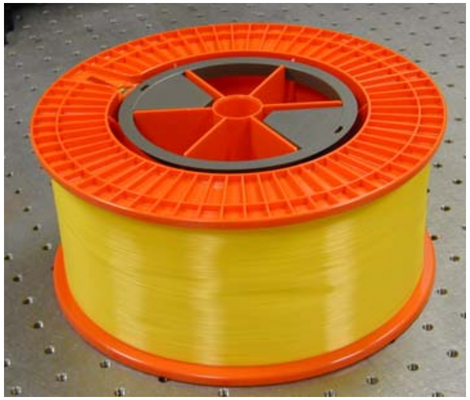
Casting Chalcogenide – J. Trole *et al.,* Opt. Express **18** 26647 (2010)

fabrication









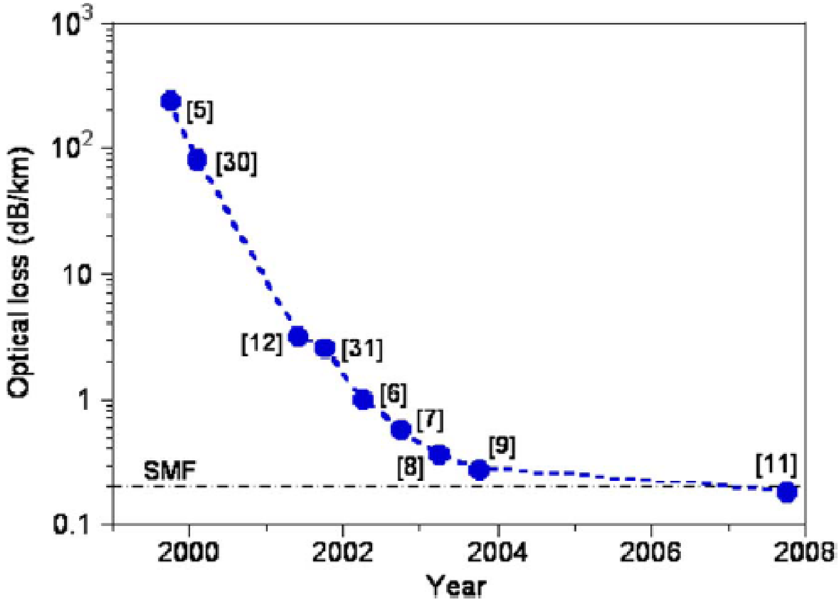
This tutorial

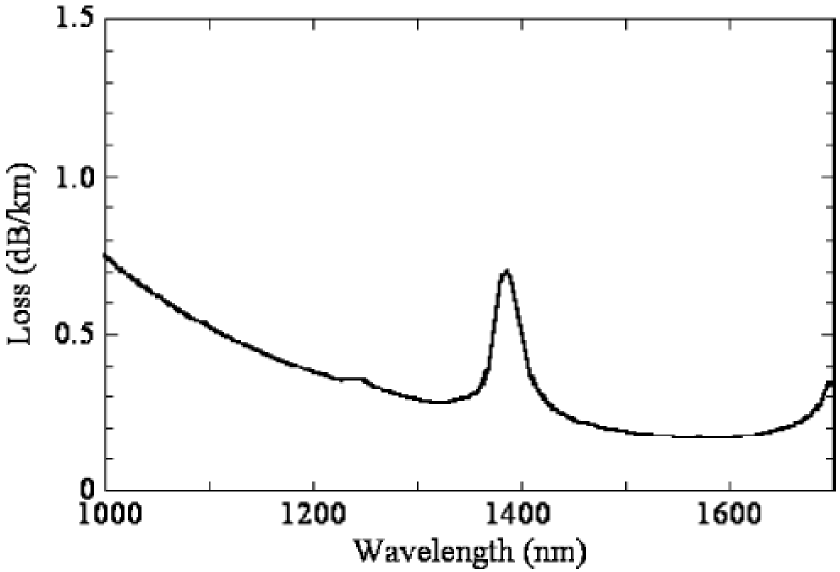
- Photonic crystal fibre concepts
- Practical implementation: actual fibres
- **Optical properties**
- Application areas
- Active research and the future

This tutorial

- Photonic crystal fibre concepts
- Practical implementation: actual fibres
- Optical properties
  - Solid core fibers
  - Hollow core fibers

Attenuation: solid core fibers





Lowest attenuation reported in PCF

0.18dB/km – comparable to conventional smf

Kurokawa *et al.* J Lightwave Technol. **27** 1653 (2009)

Attenuation: solid core fibers

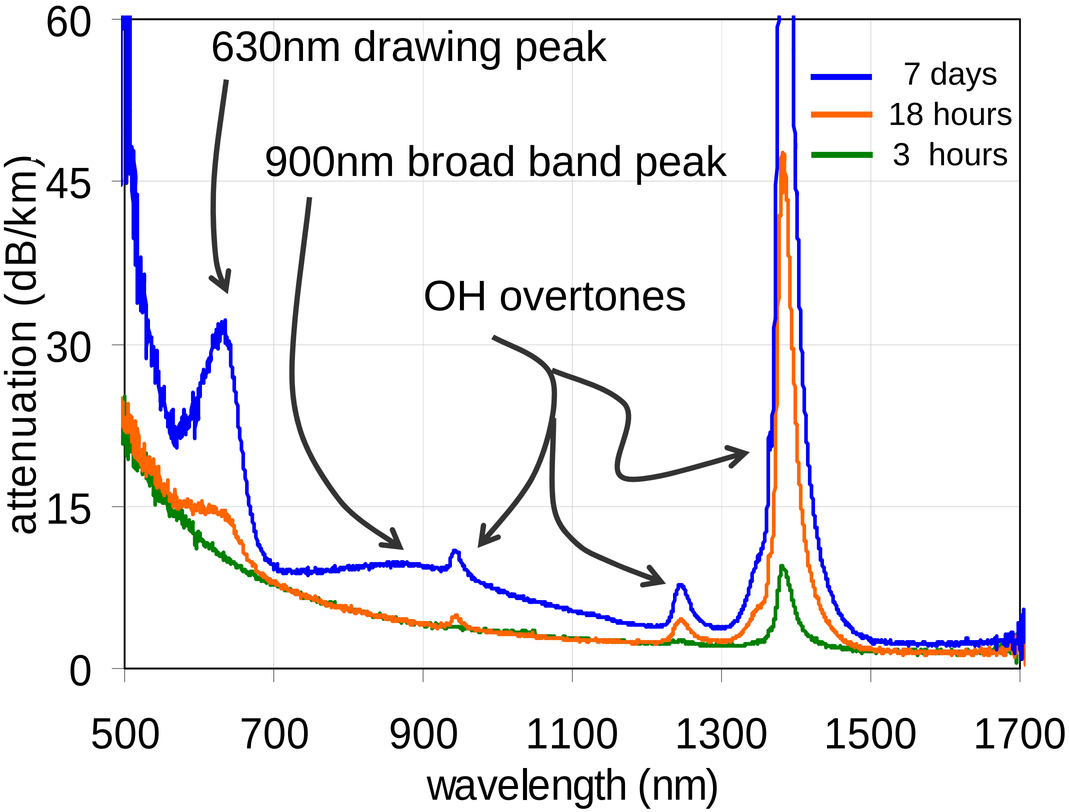
Loss Components of the Lowest Loss PCF and Conventional SMF

	PCF	Conventional SMF
Loss at 1310 nm (dB/km)	0.29	0.33
Loss at 1550 nm (dB/km)	0.18	0.19
Rayleigh scattering coefficient (dB/(km.μm^4))	0.72	1.0
Imperfection loss (dB/km)	0.03	<0.01
OH absorption loss		
at 1310 nm (dB/km)	<0.01	<0.01
at 1550 nm (dB/km)	<0.01	<0.01
IR absorption loss at 1550 nm (dB/km)	0.01	0.01

Kurokawa *et al.* J Lightwave Technol. **27** 1653 (2009)

- 8μm pitch, 4μm hole size (12μm core diameter)
- VAD glass
- OH-free environment
- Dehydration process applied
- Polishing and etching of capillaries
- Diameter variation stated as < 0.5μm
- Up to 100km fiber length reported

Bad things come to those who wait



- Preform canes from a single stack drawn to fibre after different delays
- Correlation between 630nm “draw band” and OH^- peaks
- (5μm core fibres)

Gris-Sanchez et al. OWK1, OFC (2009)

Annealing and small-solid-core fibres

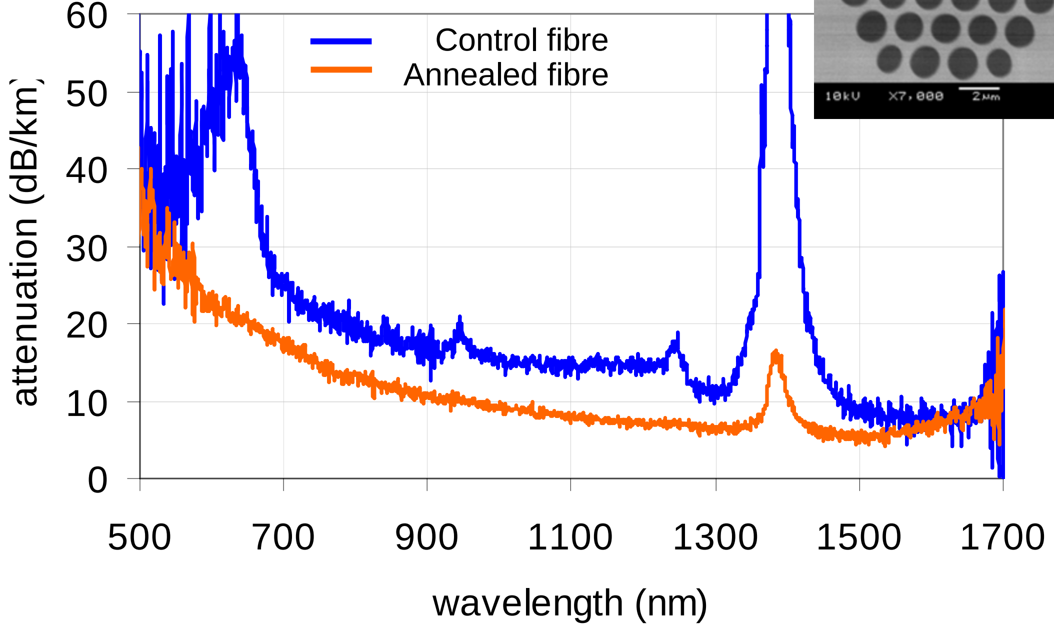
<u>Annealing and N_2 purging</u>

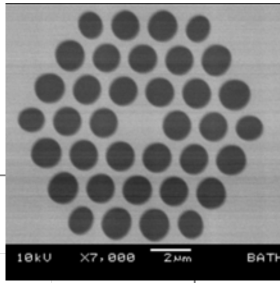
Low attenuation 2 μm core PCF

at 1384nm, 16dB/km

at 1550nm, 5.5dB/km

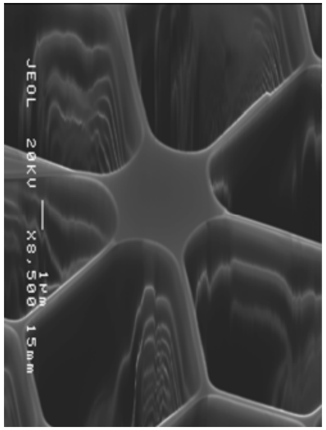
Simple and repeatable process

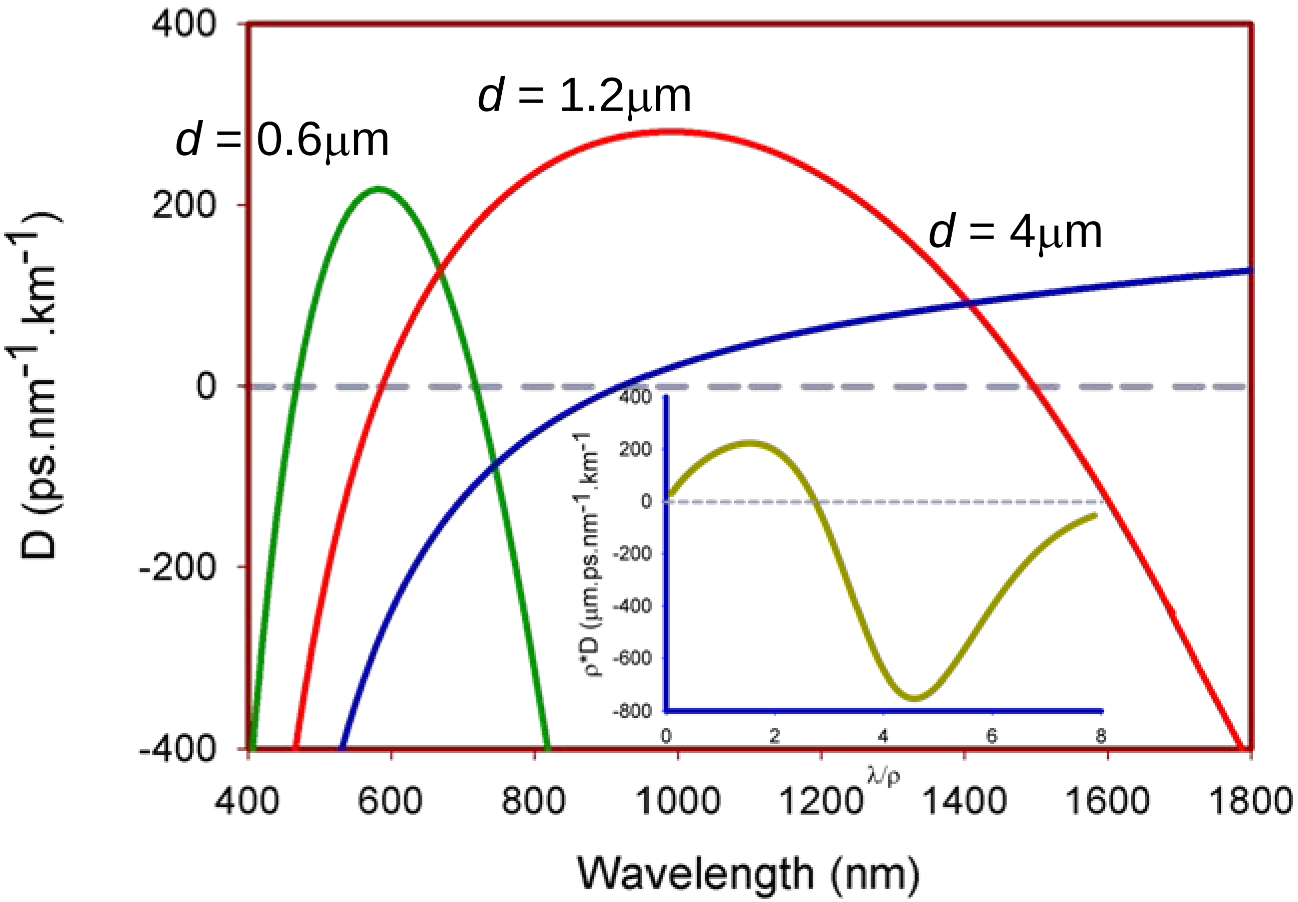




I. Gris Sanchez et al, submitted to Optics Express

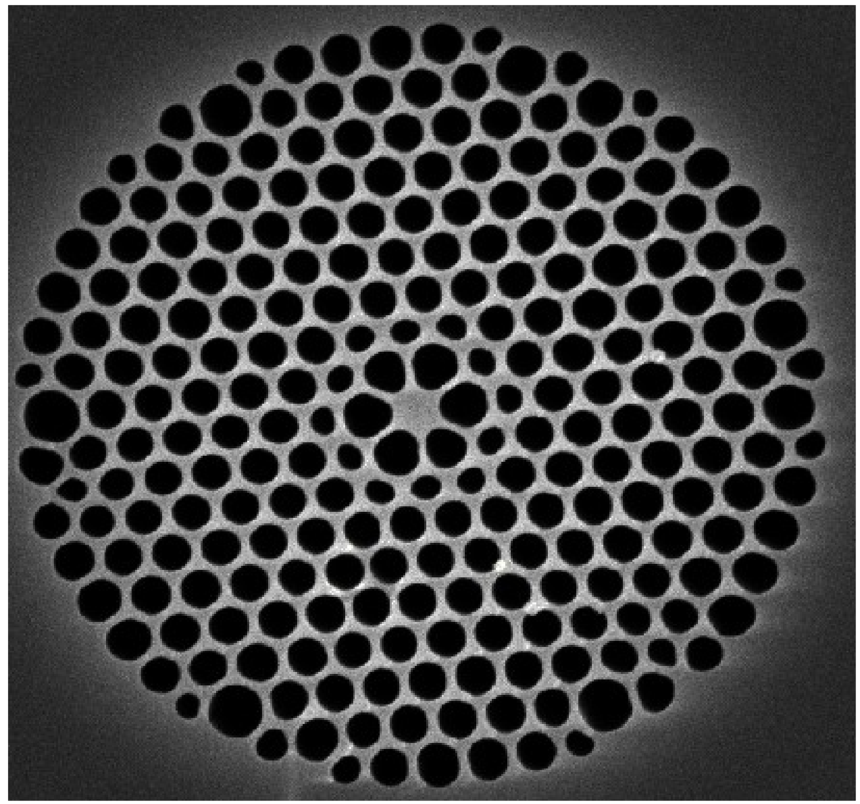
Dispersion of a strand of silica

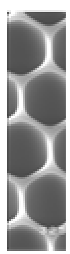




Dispersion curves

- For fixed core size, varying hole size provides variation of D(λ)
- Further control can be provided by superstructure within the cladding
- Generally, the bigger the dispersion, the harder to control!





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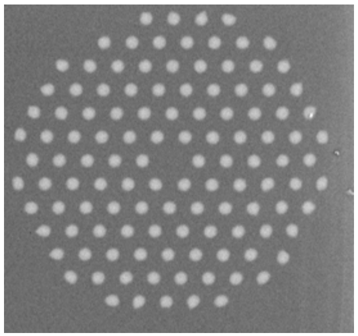
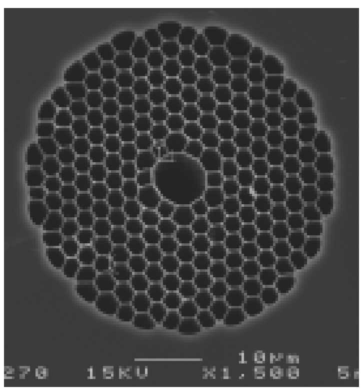
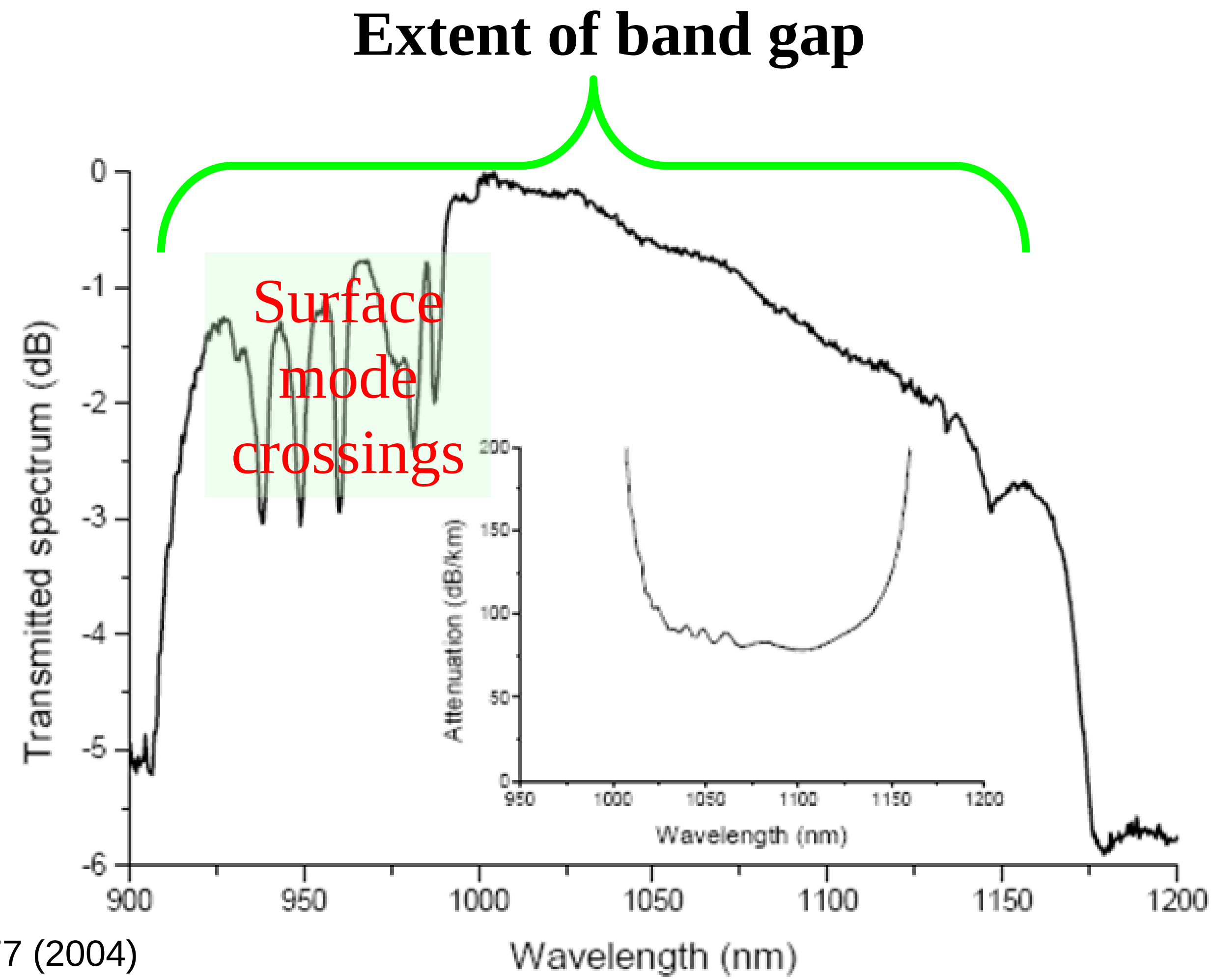
Guidance in hollow-core fibres

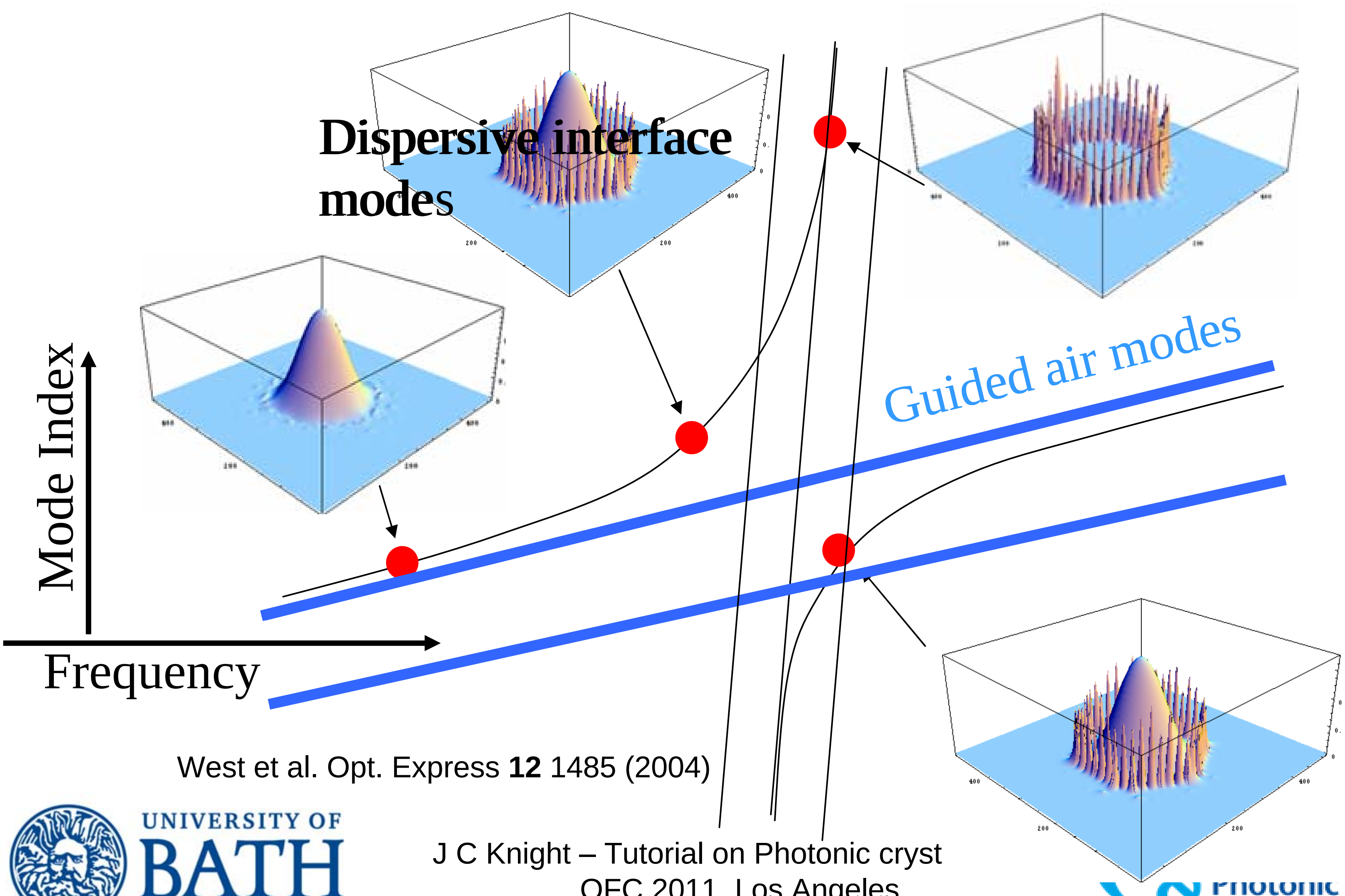






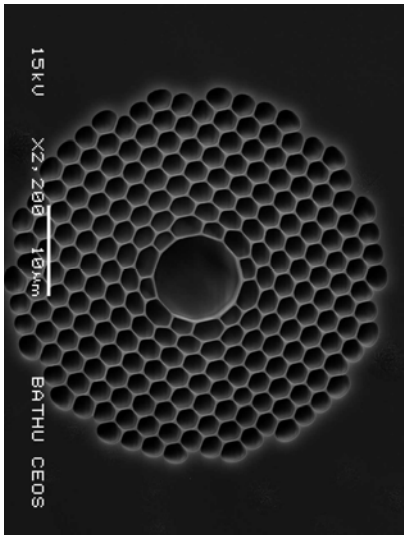
Humbert *et al.* Opt. Express **12** 1477 (2004)

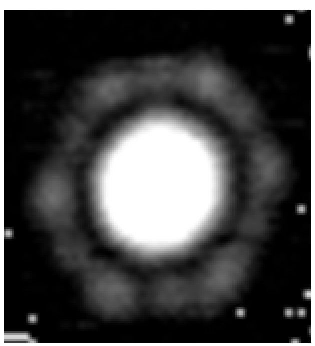
Two classes of core-guided modes

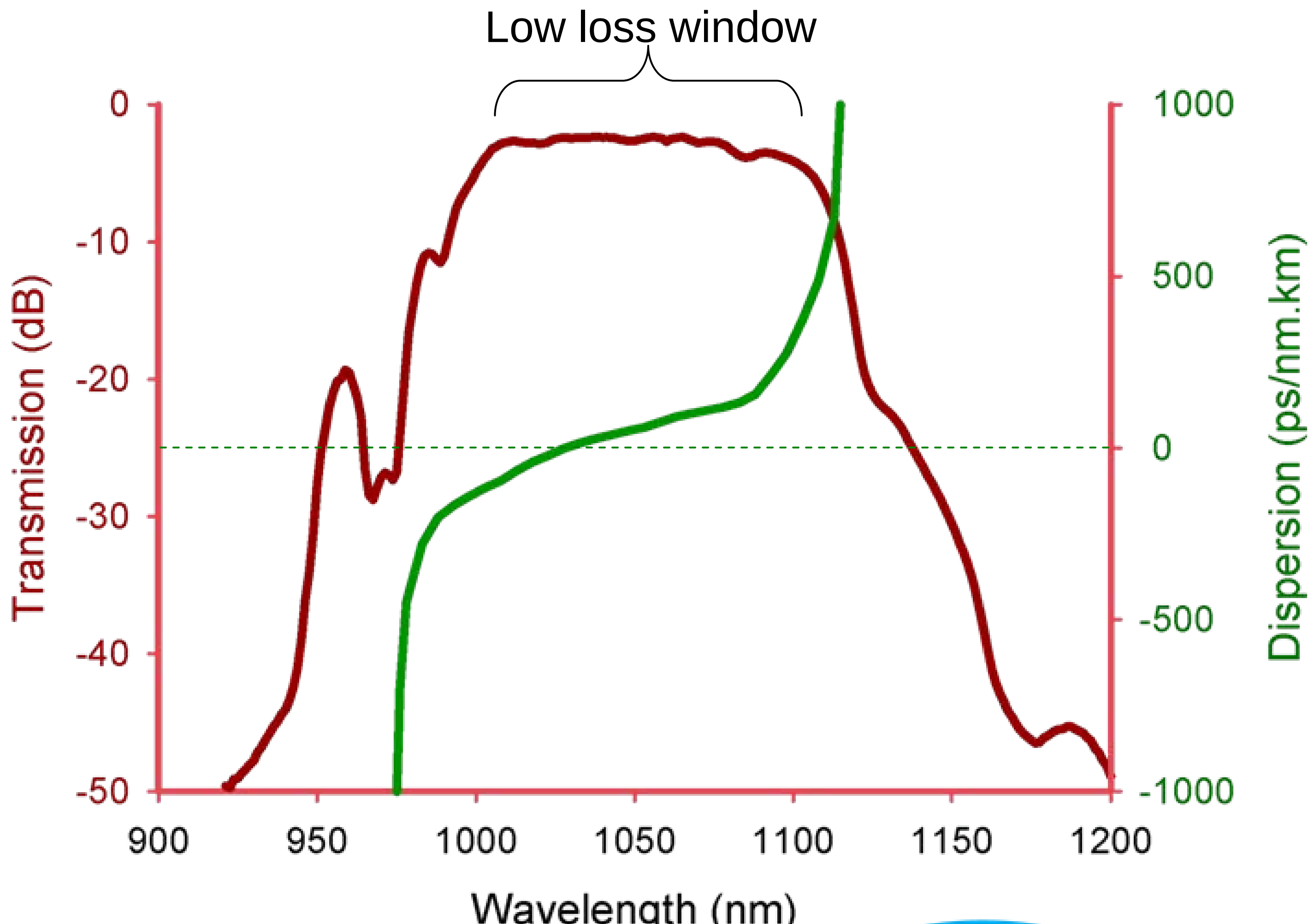


West et al. Opt. Express **12** 1485 (2004)

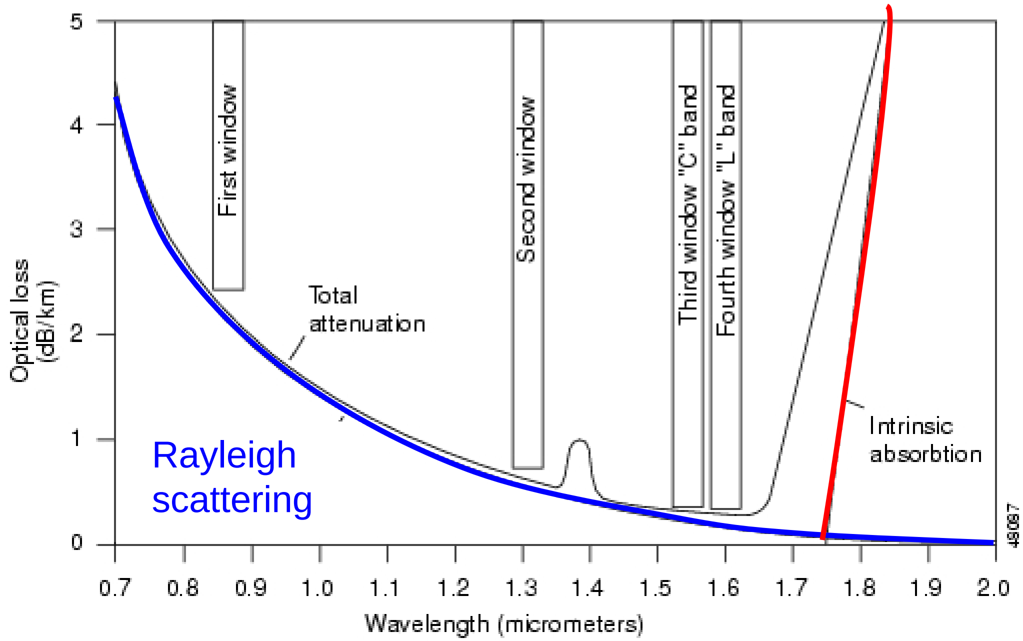
Dispersion in hollow-core fibres



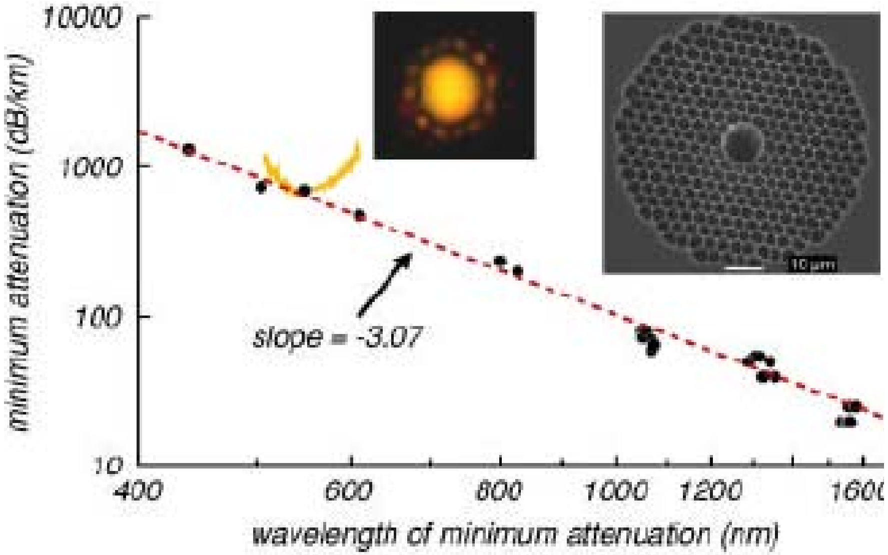




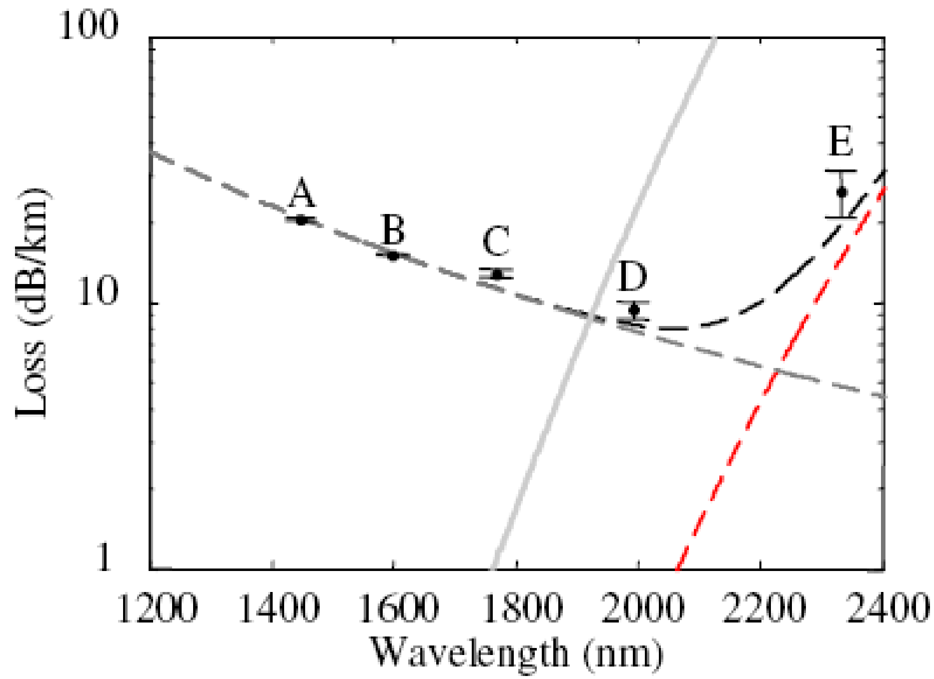
Transparency of fused silica



Attenuation: hollow core fibers

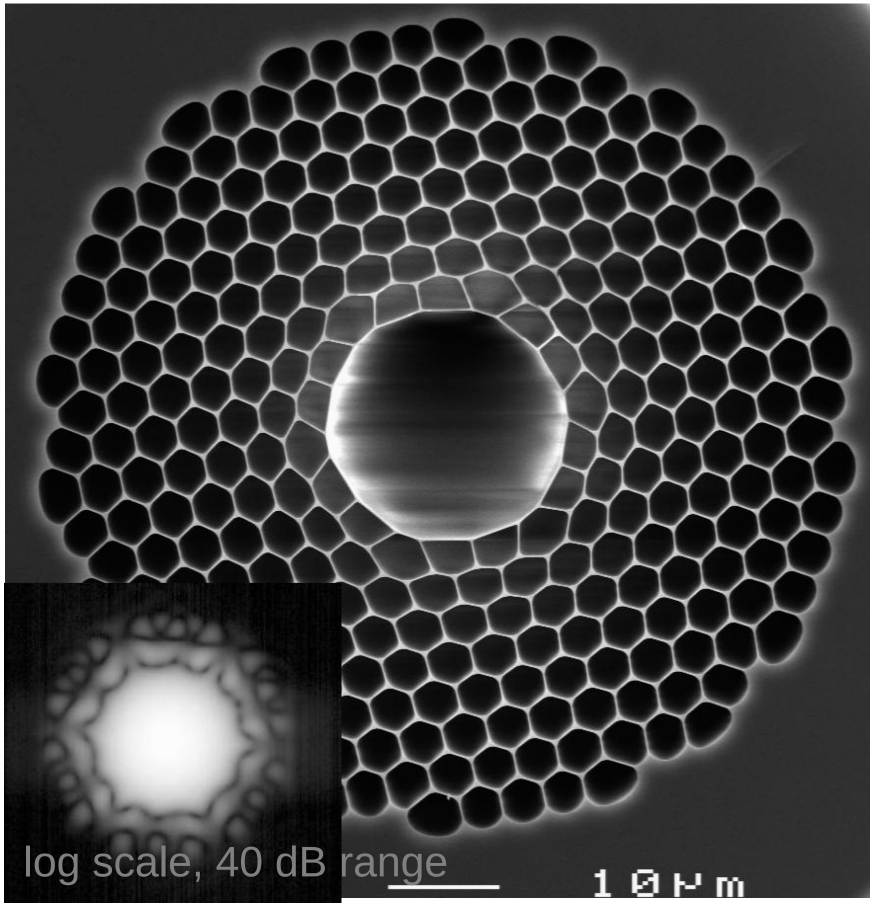


Mangan et al., Opt. Express **13** 241 (2004)



Lyngsø et al., Opt. Express **17** 23468 (2009)

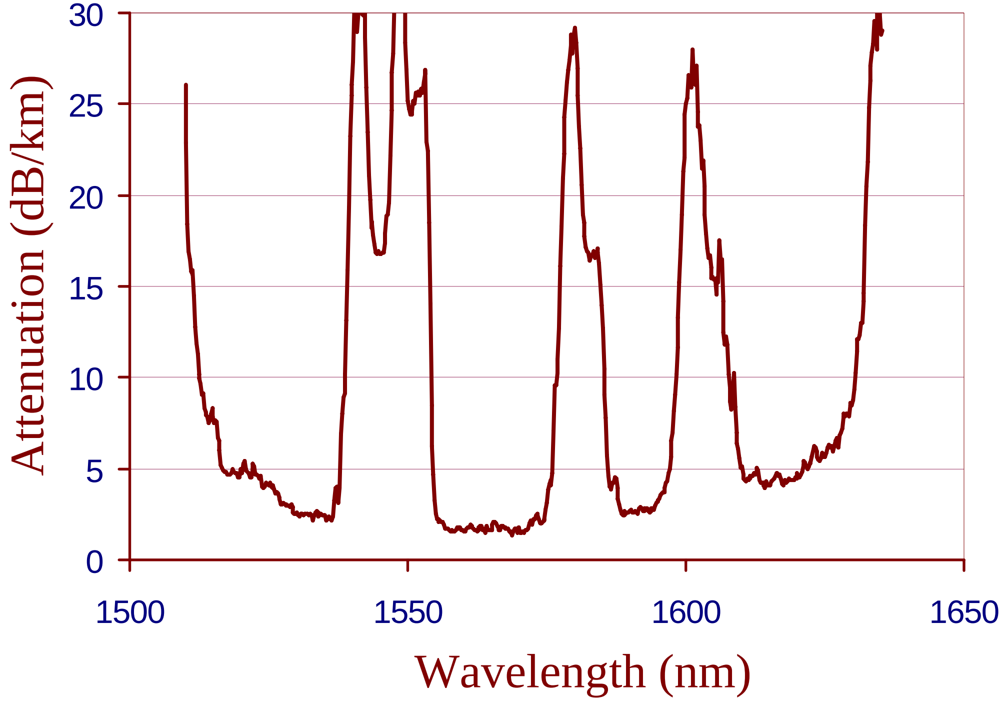
Low-loss fibres: larger core



- Attenuation is due to scattering from glass
- Larger cores reduce overlap of mode with glass
- Overlap remains sensitive to core surroundings
- In particular, core wall thickness must be anti-resonant

Fiber with 19-cell hollow core

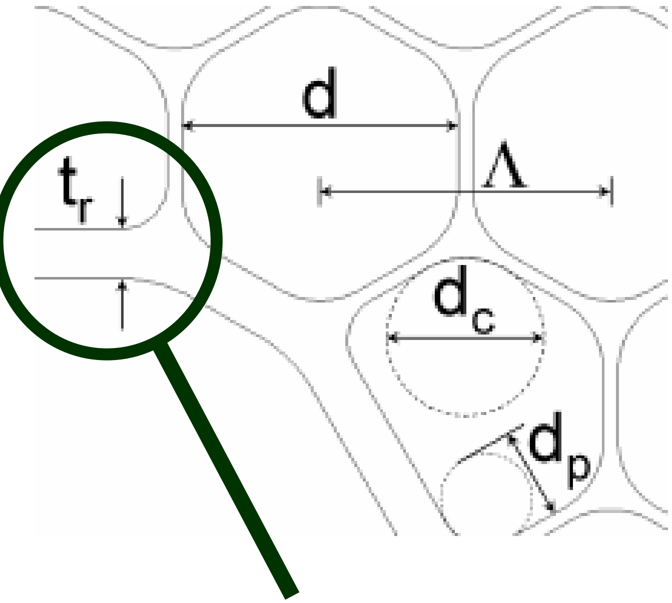
Attenuation in a large-core fibre

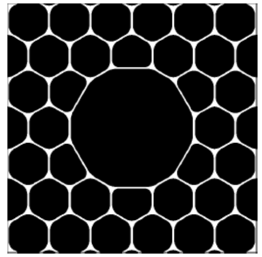


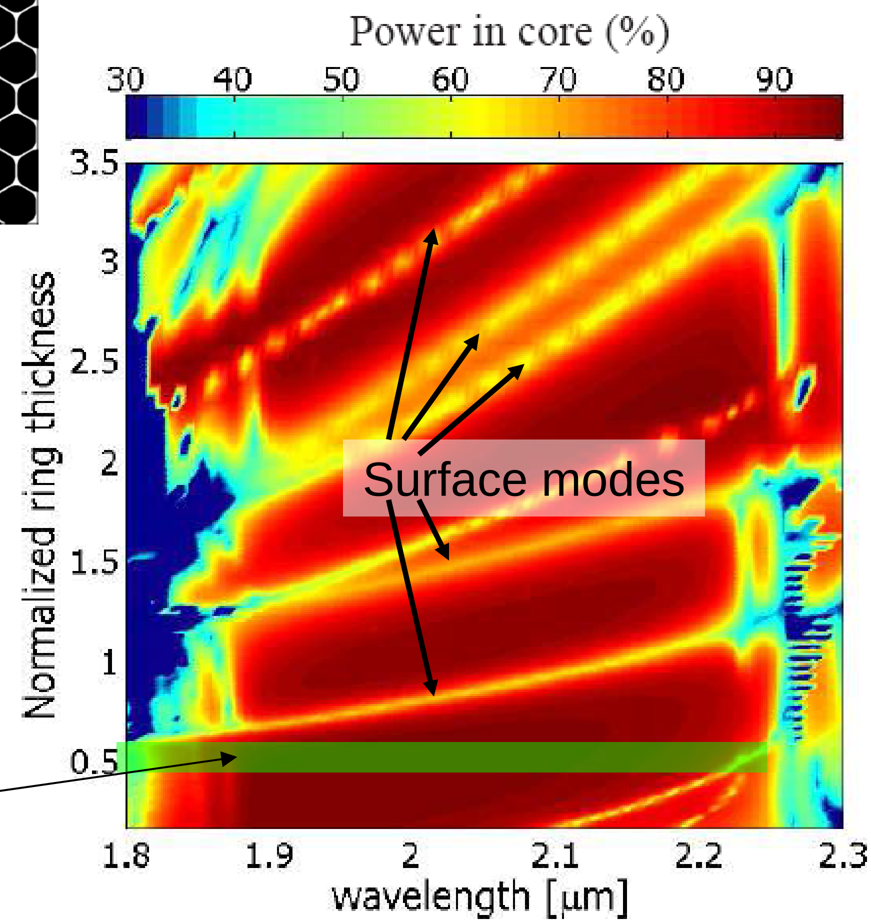
- Attenuation is due to glass
- Larger cores reduce overlap of mode with glass
- Overlap is sensitive to core surroundings
- But larger core perimeters support a higher density of surface modes…

P. J. Roberts *et al*, Opt. Express **13** 236 (2005)

Getting rid of surface modes



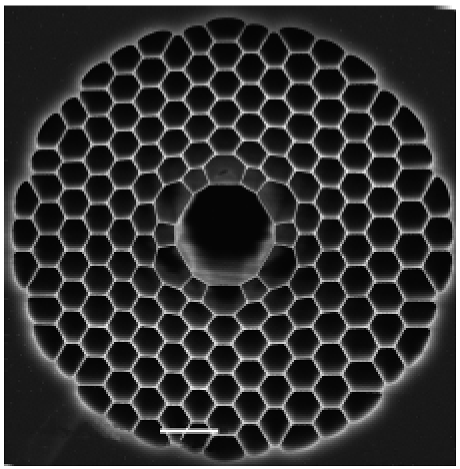




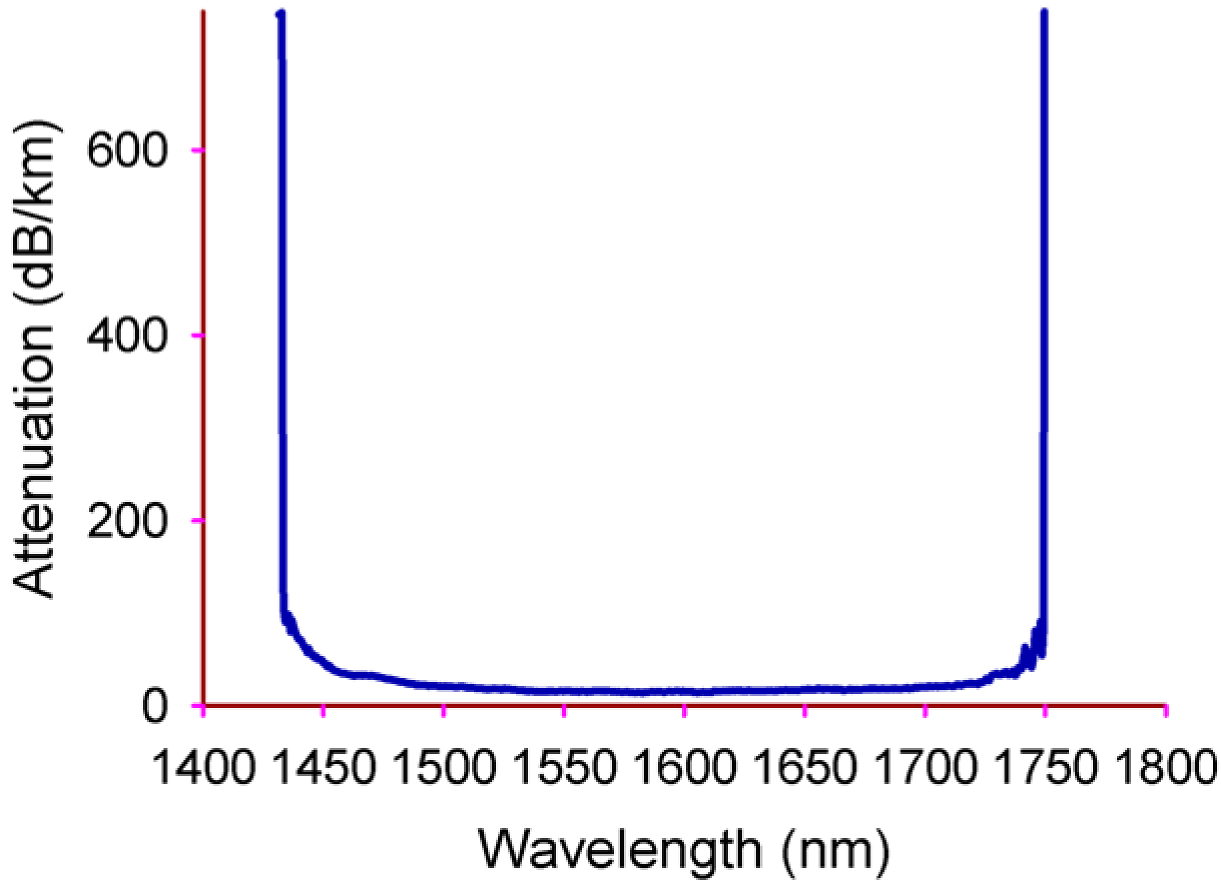
- Ring thickness t_r is critical parameter
- Normalized in units of cladding wall thickness
- Best t_r is 0.5!!

Amezcua-Correa et al., Opt. Expr. **14** 7974 (2006)

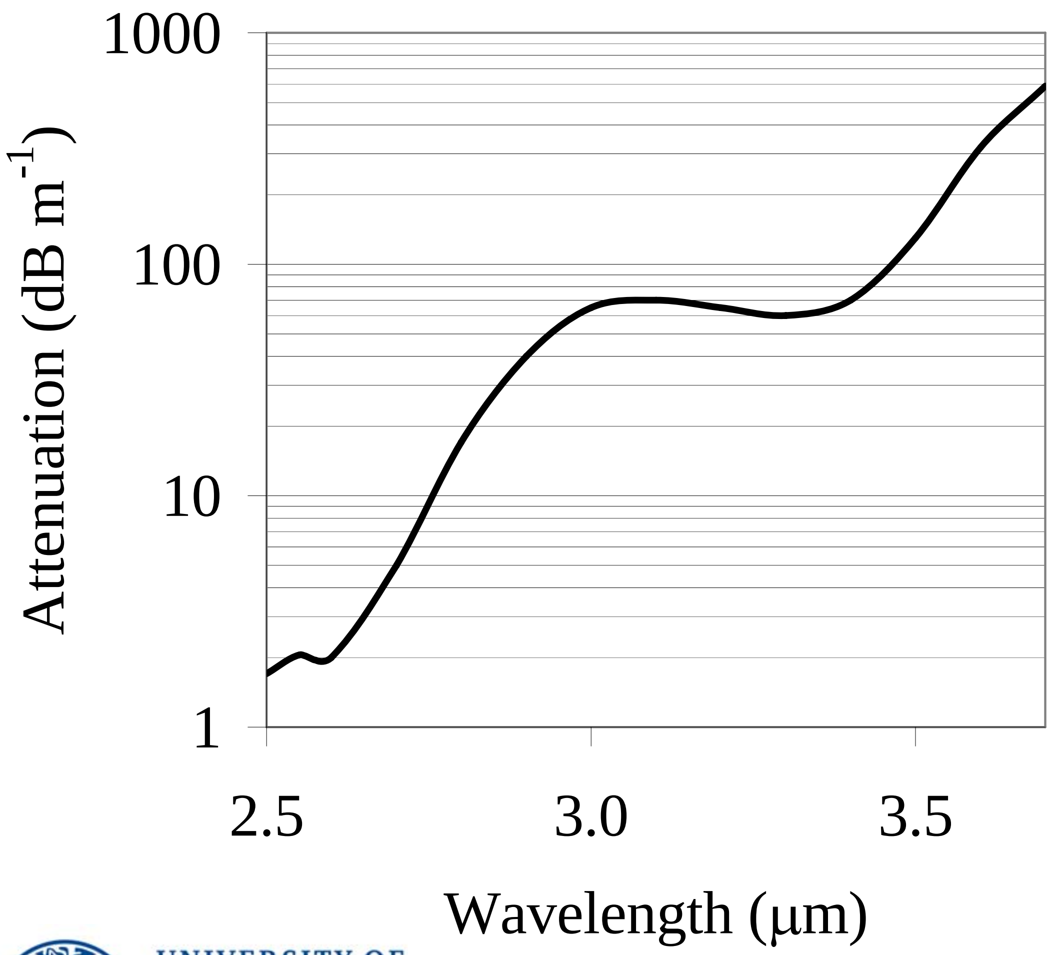
Broadband hollow-core fibre



Amezcua Correa *et al.* Opt. Express 16 1142 (2008)



Attenuation of bulk silica

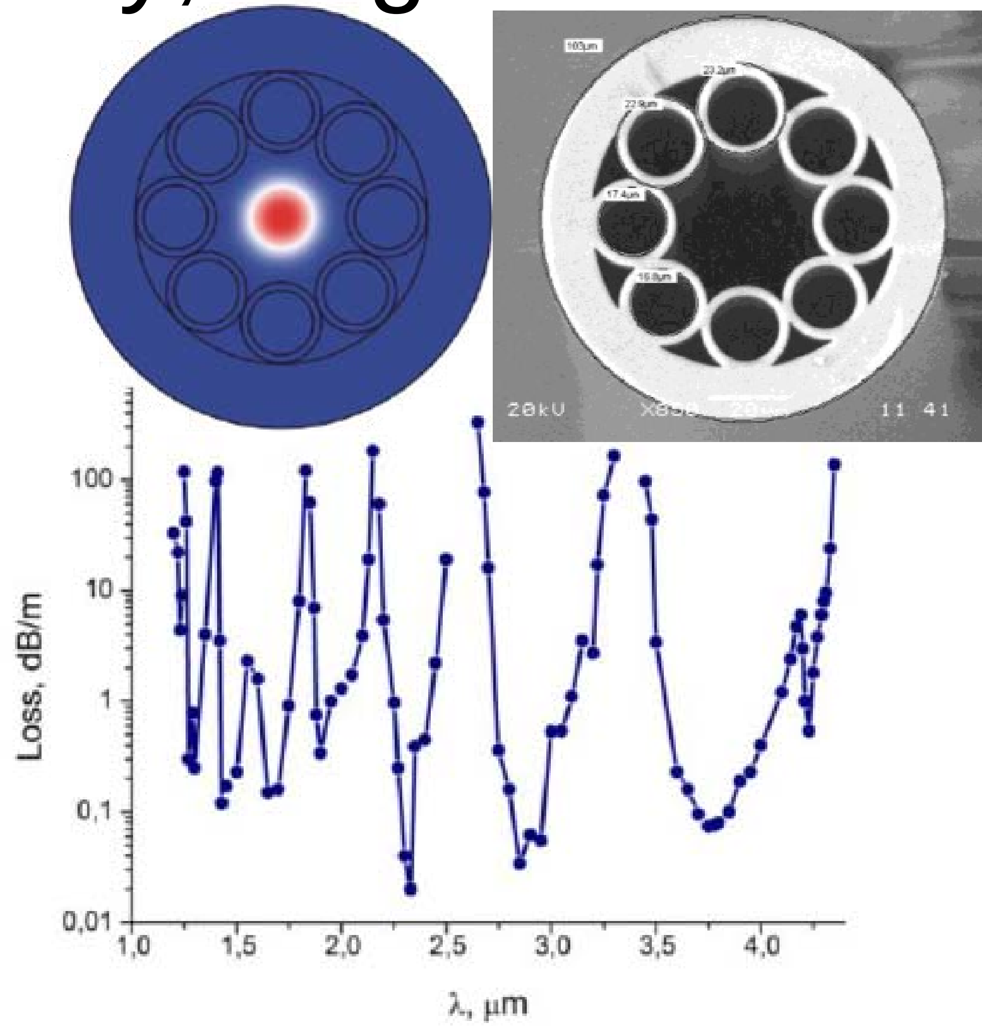


At 1% overlap…silica fibres have ~1dB/m at 3.5 μm

Shephard et al., Opt. Express **13** 7139 (2005)

Mid-IR light delivery, single-mode

- Resonant guidance, no band gap
- A single ring of air holes is good enough
- Negative curvature of core wall reduces leakage rate
- Attenuation below 0.1dB/m at 3.75μm wavelength



Pryamikov et al., Opt. Express **19** 1441 (2011)

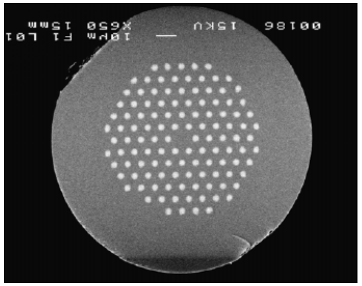
This tutorial

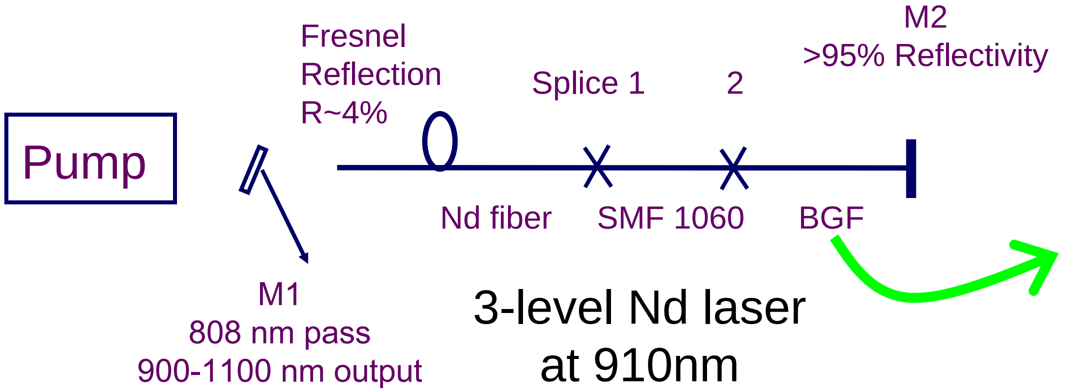
- Photonic crystal fibre concepts
- Practical implementation: actual fibres
- Optical properties
- **Applications**

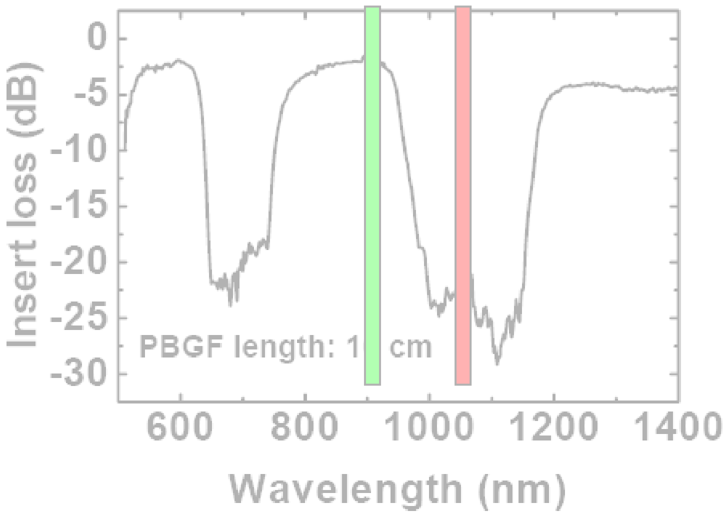
This tutorial

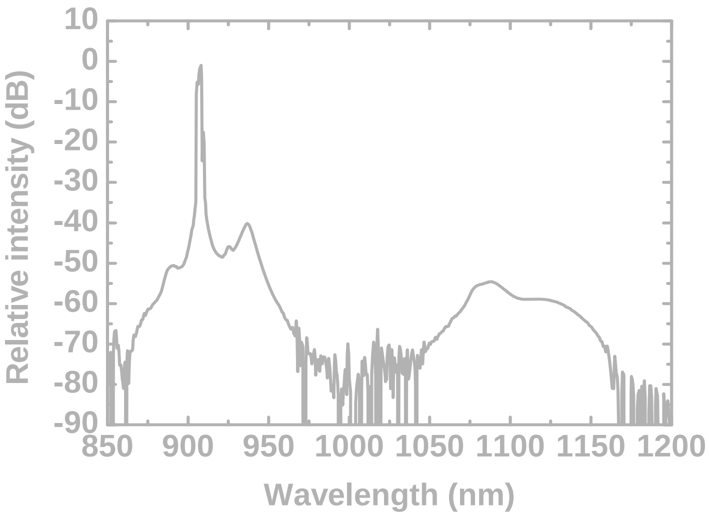
- Applications
  - Light sources
  - Pulse delivery and manipulation
  - Atomic and molecular optics

Distributed spectral filtering







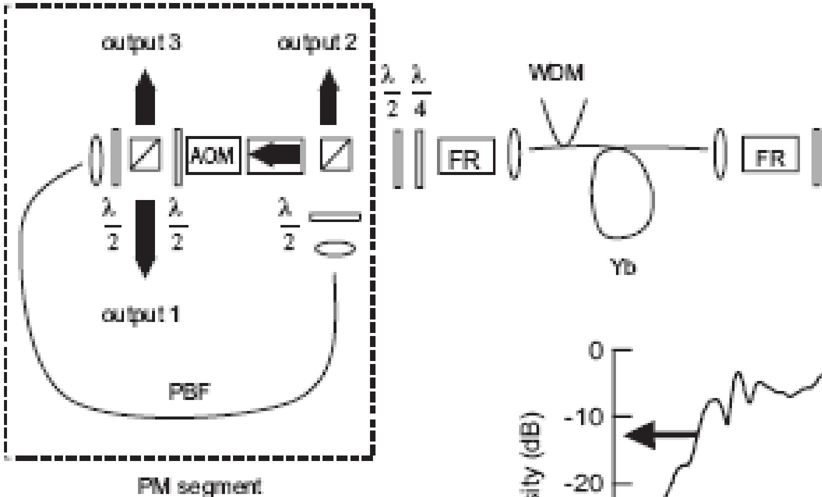


A. Wang et al. Optics Lett. **31** 1388 (2006)

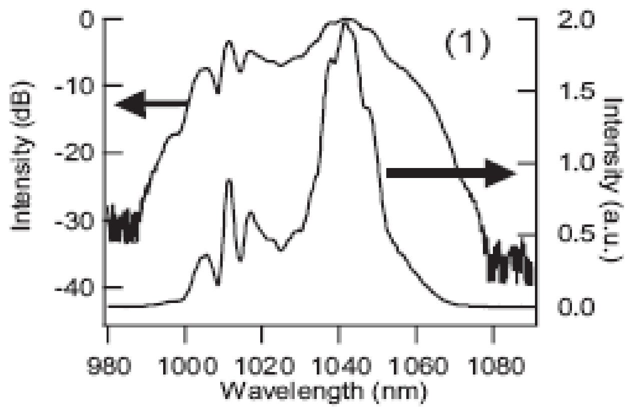
+

Long-λ Yb3+ laser: Optical Fiber Technol. 16 449 (2010)
ASE suppression: Microwave Opt. Tech. Lett. 52 2629 (2010)
Er3+ superfluorescence: IEEE PTL **21** 1843 (2009)
High power lasers: IEEE JSTQE **15** 20 (2009)

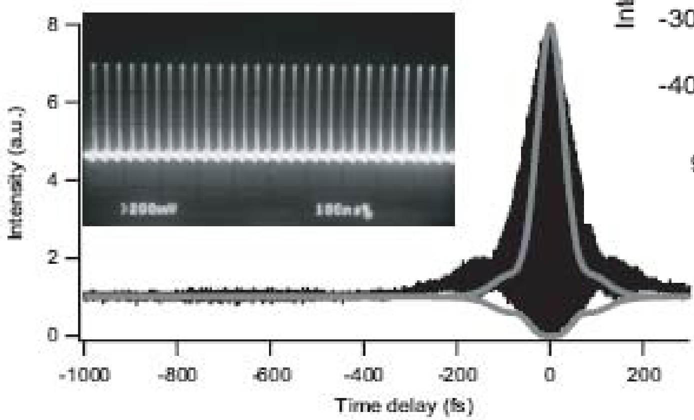
Mode-locked laser



Hollow-core fiber provides linear, birefringent, anomalous dispersion element around 1000nm wavelength

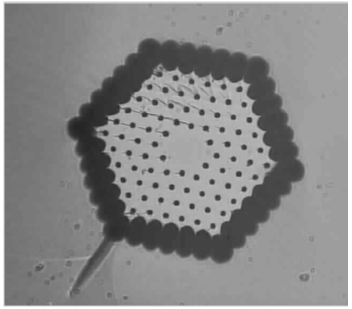


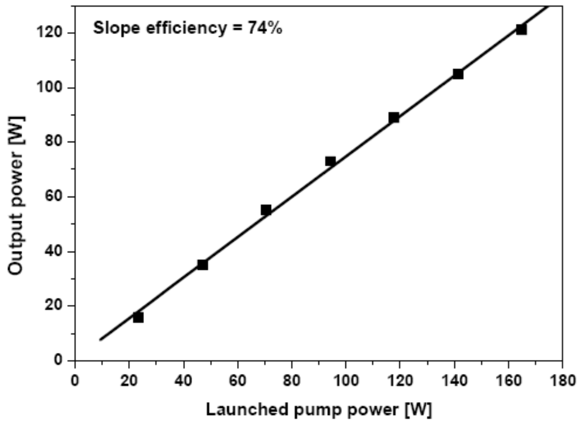
Environmentally stable fs laser operation

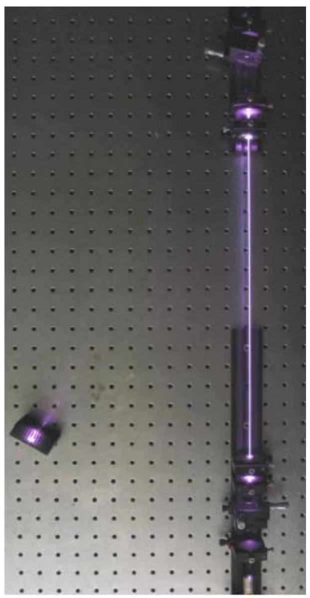


Lim *et al.* Opt. Express **13** 3460 (2005)

Large mode area lasers

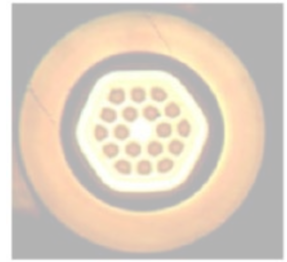


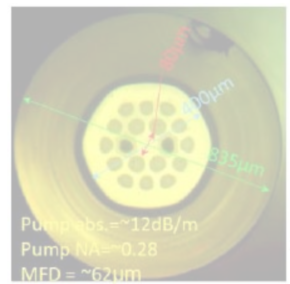


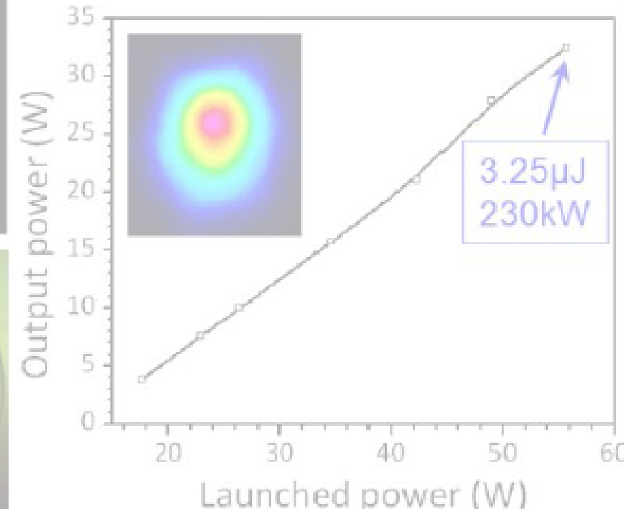


- Large core in the form of a cane – not a flexible fiber
- High-NA outer cladding
- High gain
- 74% slope efficiency and 120W output power

Limpert *et al.* Opt. Express **13** 1058 (2005)





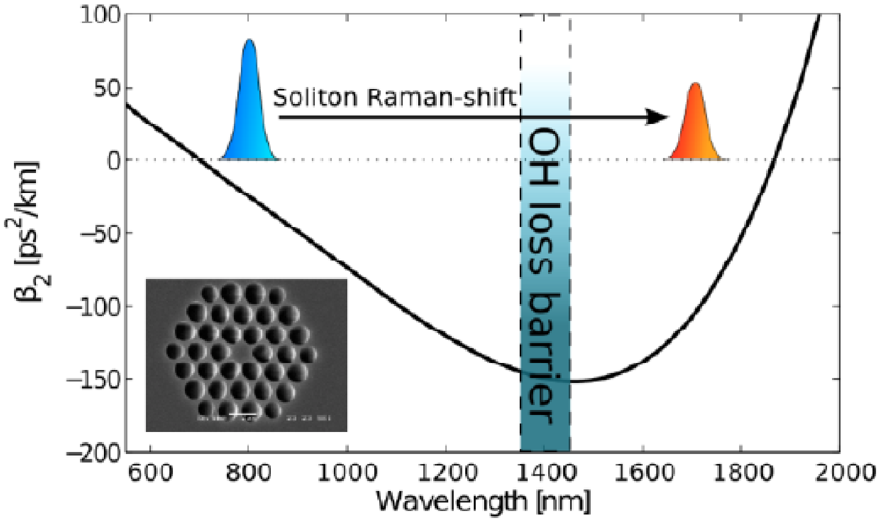


- Large core (eg 50μm)
- Leakage channel for HOM ensures excellent beam quality
- Reasonable bend radius (eg 20cm)

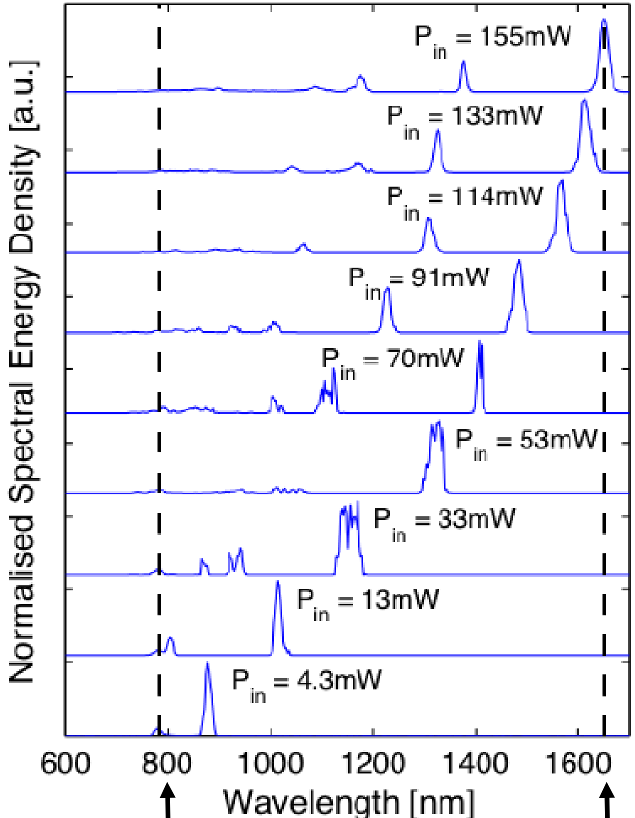
Dong *et al.* Opt. Express **17** 8962 (2009)

Soliton self-frequency shift

- SSFS – reasonably efficient pulse conversion
- Requires anomalous dispersion, low attenuation
- Decreasing dispersion accelerates frequency change through soliton compression



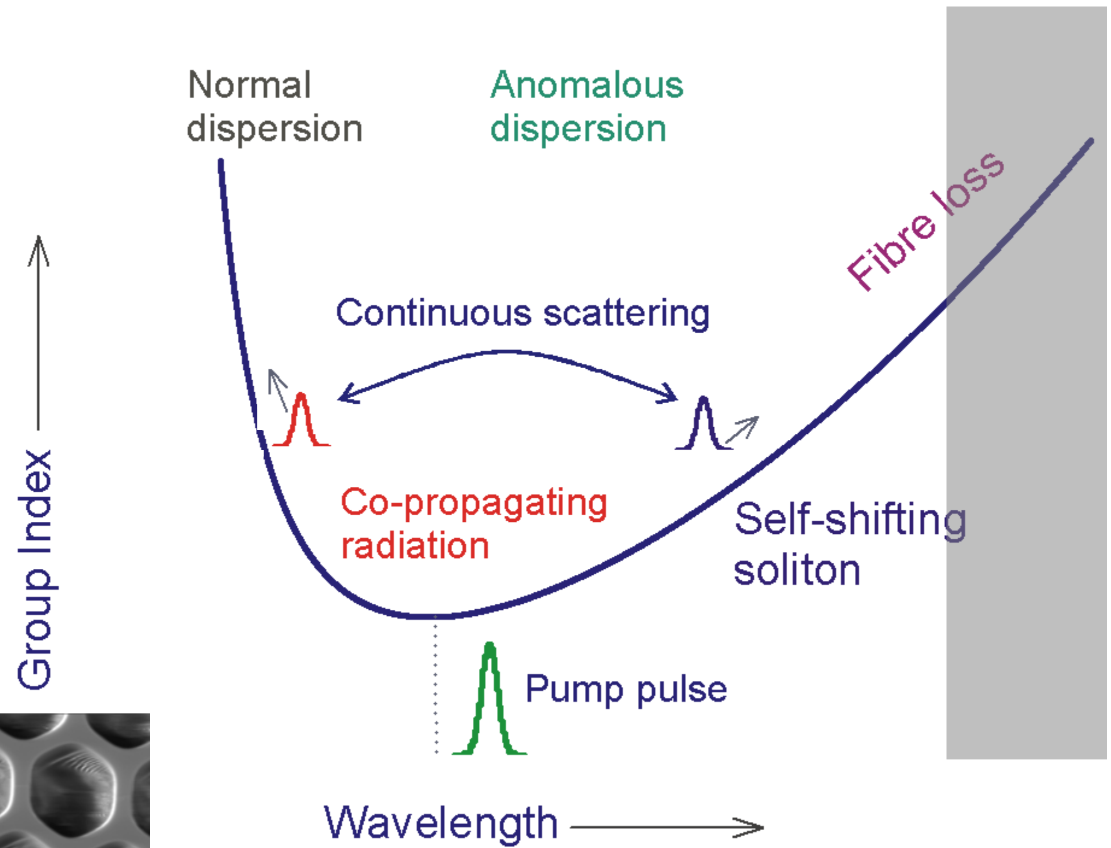
Dekker *et al.* paper PDPB6, FiO (2010)

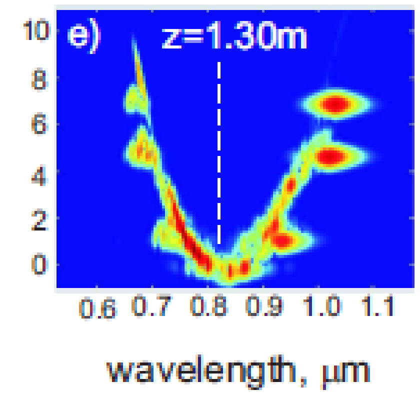


783nm pump pulse

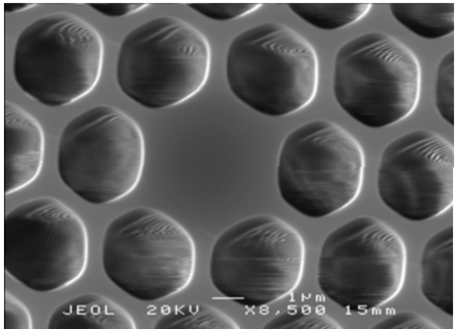
1650nm output pulse

Supercontinuum source

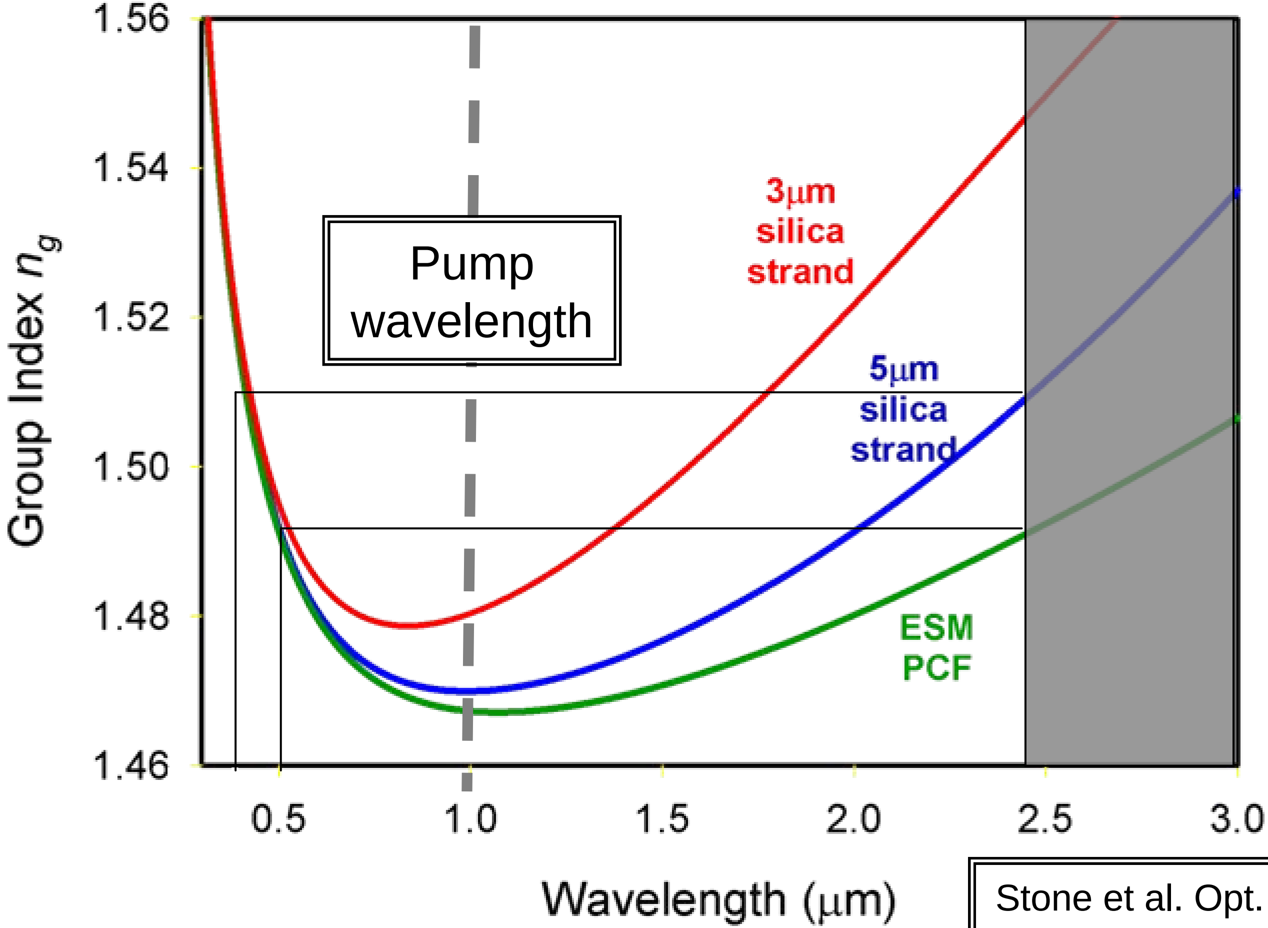


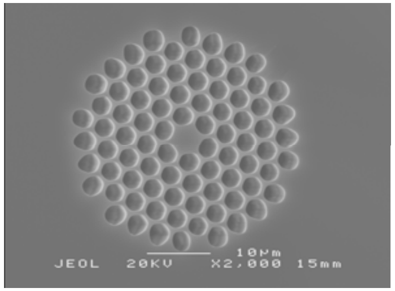


Gorbach et al., Opt. Express **14** 9854 (2007)

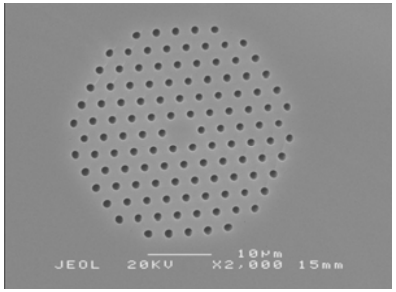


How to increase the group index at long wavelengths?





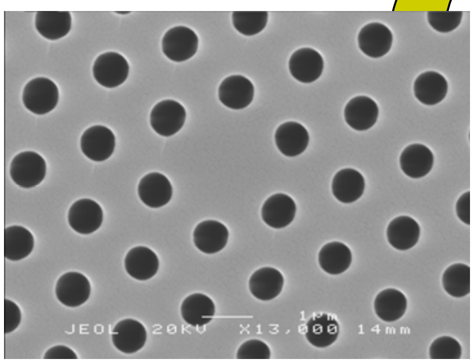
$$n_g = n - \lambda \frac{dn}{d\lambda}$$

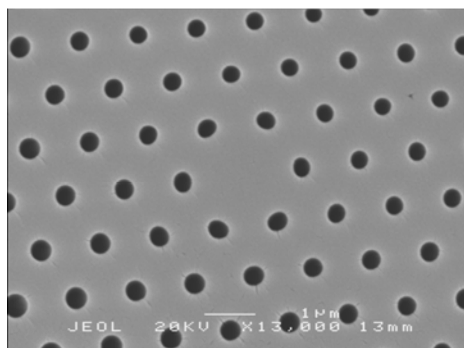


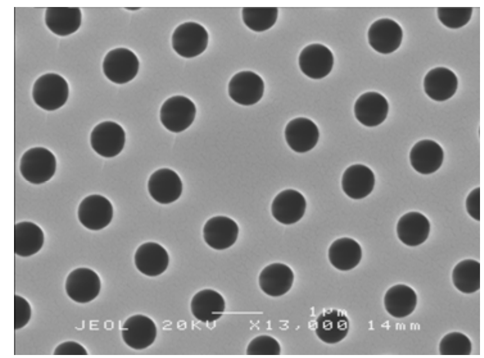
Stone et al. Opt. Express 16 2670 (2008)

Tapered fibers

- Fibre properties varied as a function of length
- Individual control of air hole size
- Length scales from a few metres to kilometres

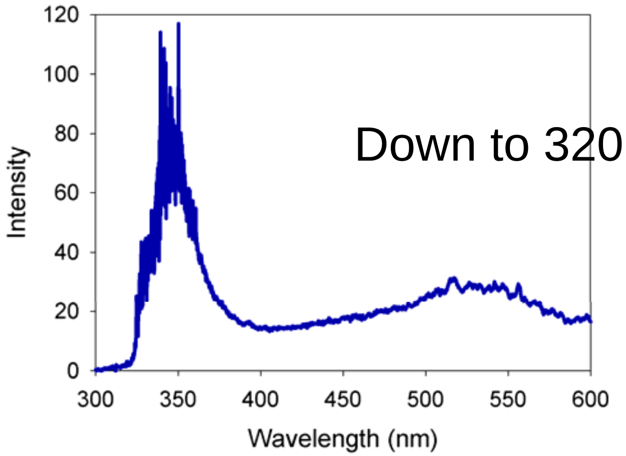




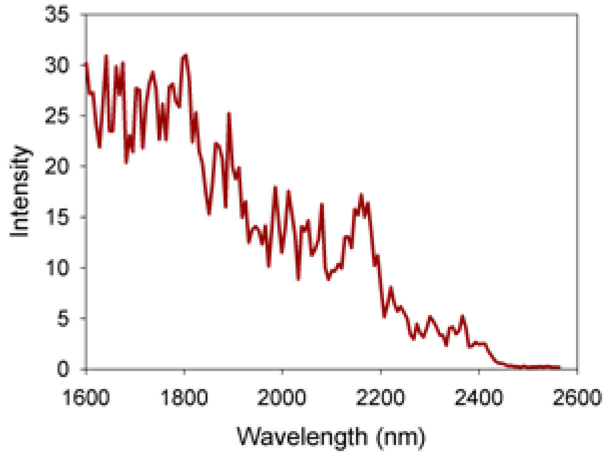


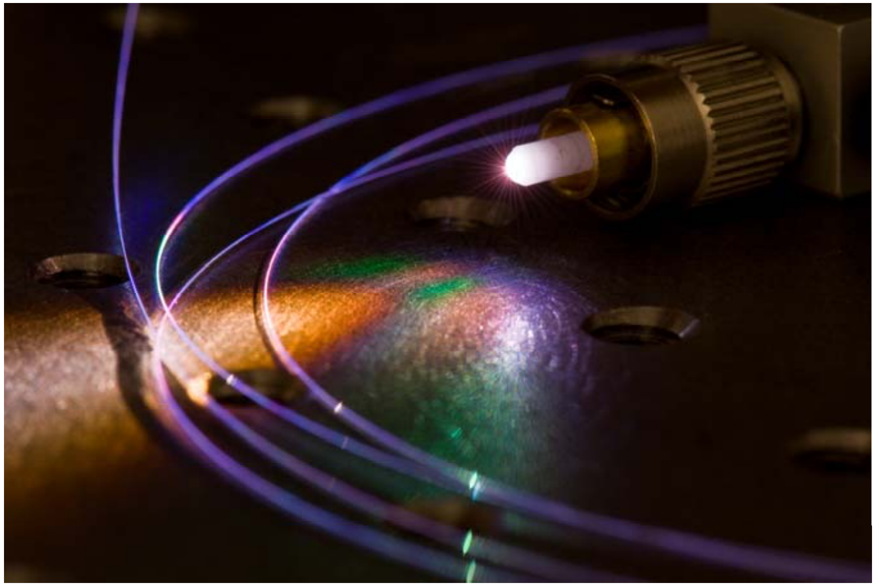
Kudlinski *et al*. Opt. Express **14** 5715 (2006)
See e.g. Tse *et al.* Optics Lett **31** 3504 (2006) for pulse compression results

Only limited by transparency…



Down to 320nm



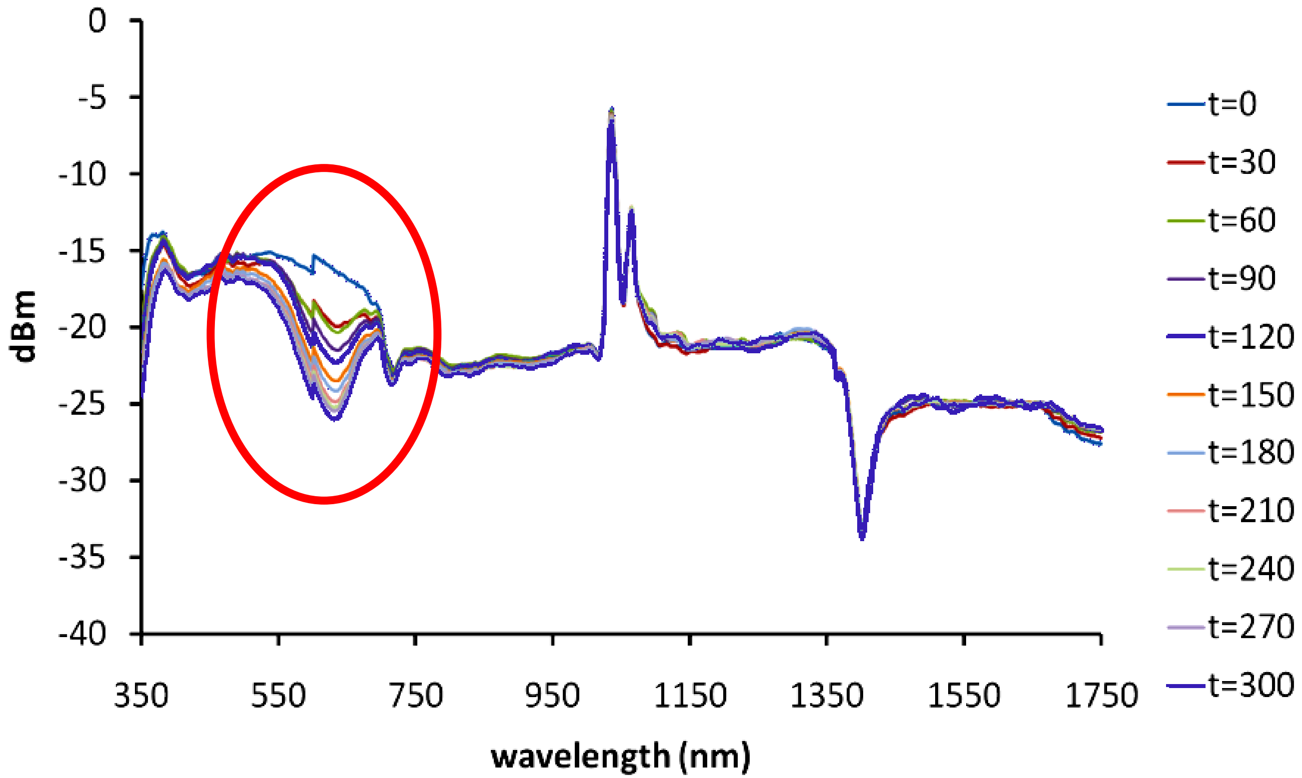


Out to 2400nm

…and photodarkening!

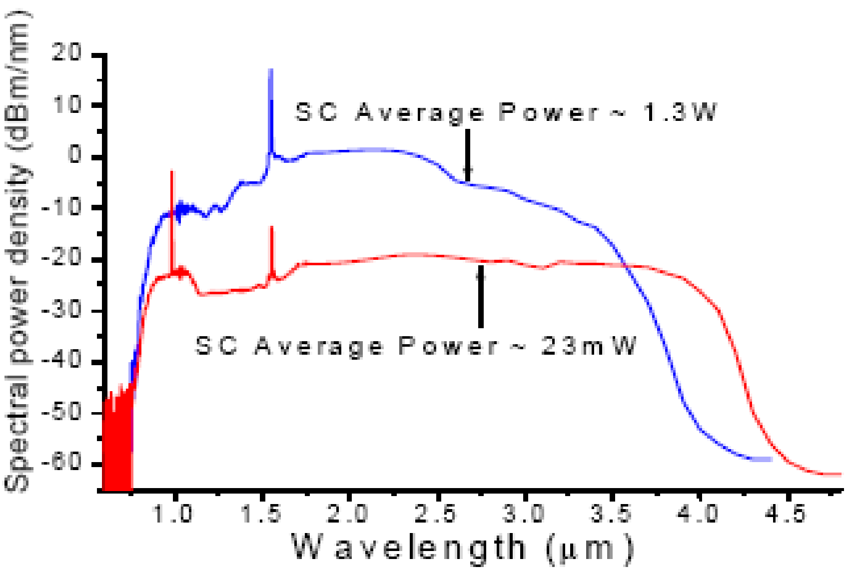
…and photodarkening!

Time in minutes
ps pump source
240mW input power
1MHz repetition rate



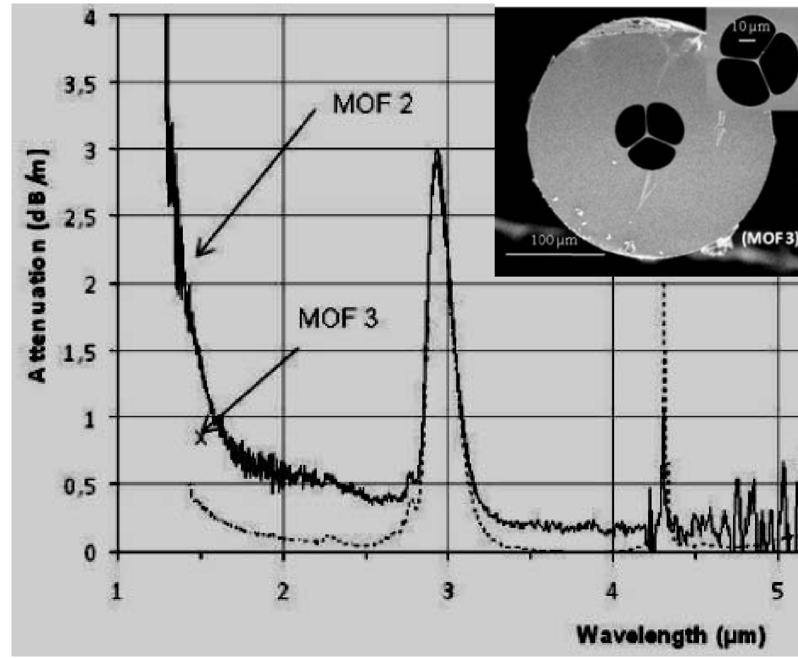
Unpublished data courtesy of Dr J Stone

IR supercontinuum



Xia et al., Opt. Express **15** 865 (2007)

Amplified diode laser pump 1548nm
Pulse breakup in SMF
Followed by ZBLAN fibre (not PCF)



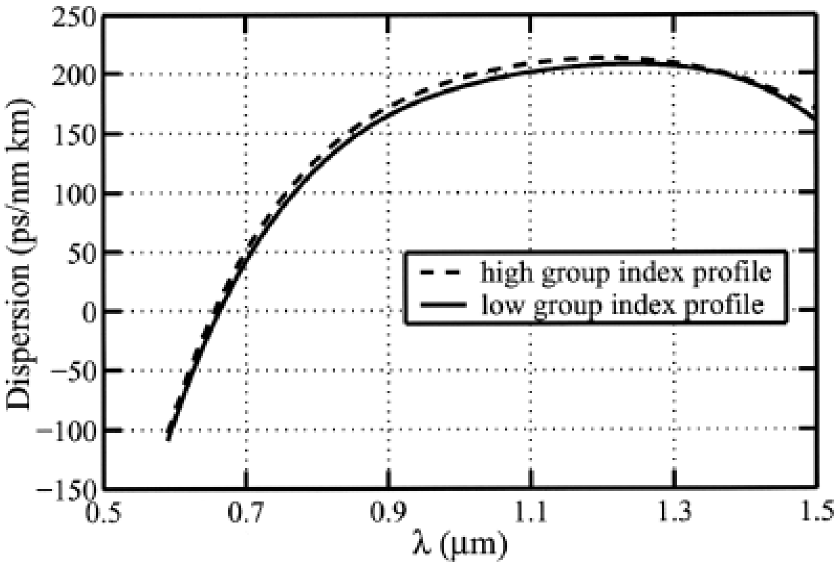
Trole *et al.*, Opt. Express **18** 26647 (2010)

Low attenuation AsSe fiber formed by casting

Wavelength conversion using Four Wave Mixing

Conventionally:

$$k = \pm\left[\left(\frac{\beta_2\Omega^2}{2}\right)\left(\frac{\beta_2\Omega^2}{2} + 2\gamma P\right)\right]^{1/2}$$



Including higher order dispersion gives

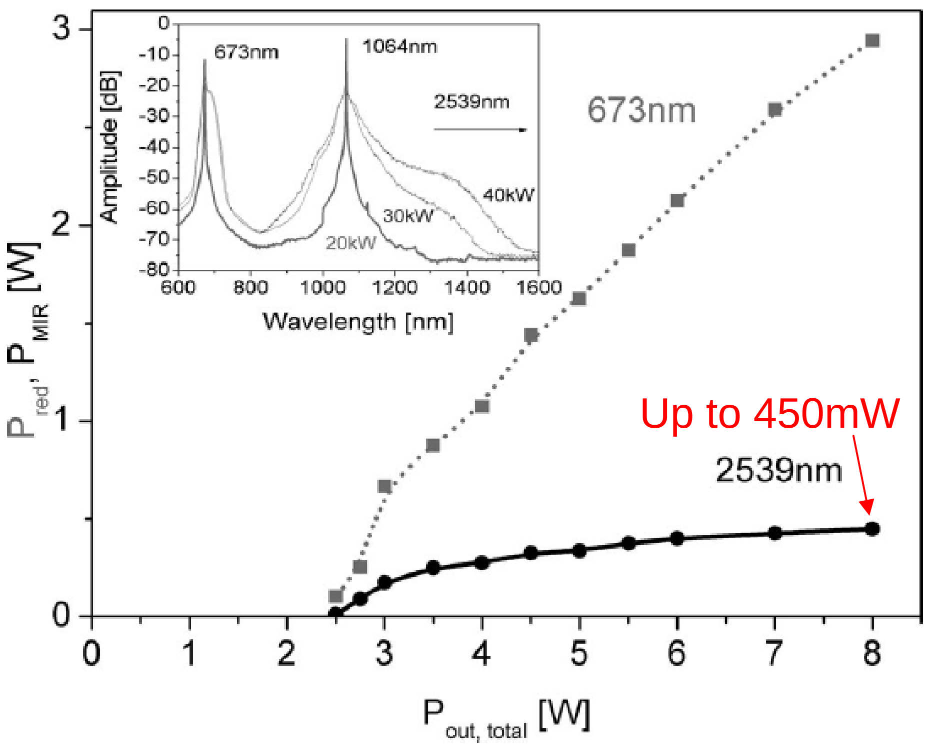
$$k = \frac{\beta_3\Omega^3}{6} \pm\left[\left(\frac{\beta_2\Omega^2}{2}\right)\left(\frac{\beta_2\Omega^2}{2} + \frac{\beta_4\Omega^4}{24}\right).\left(\frac{\beta_2\Omega^2}{2} + \frac{\beta_4\Omega^4}{24} + 2\gamma P\right)\right]^{1/2}$$

Strong higher-order dispersion enables new phase-matching opportunities

Harvey *et al.* Optics Lett. **28** 2225 (2003)

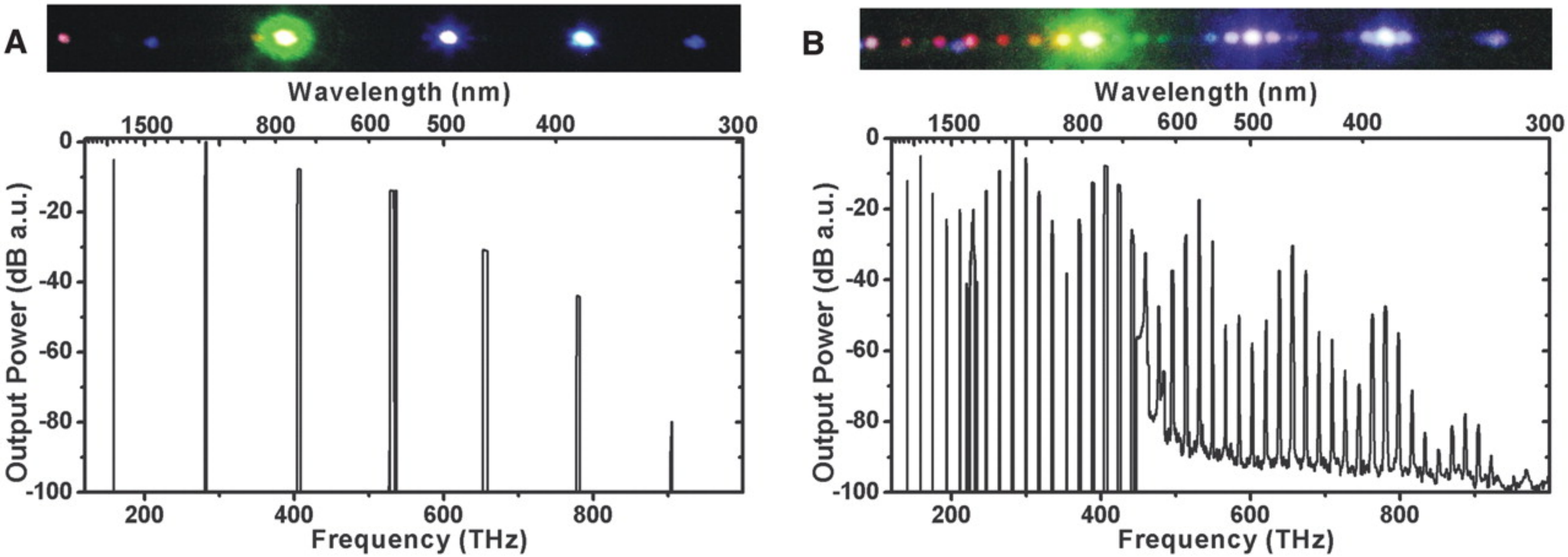
IR from a silica fiber

- 1.4m fibre length
- 200ps pulse duration, 4pm FWHM
- 1MHz rep rate
- Approaching 0.5W at 2.5μm wavelength
- Should be able to extend this to 3.45μm



D. Nodop et al., Opt. Lett. **34** 3499 (2009)

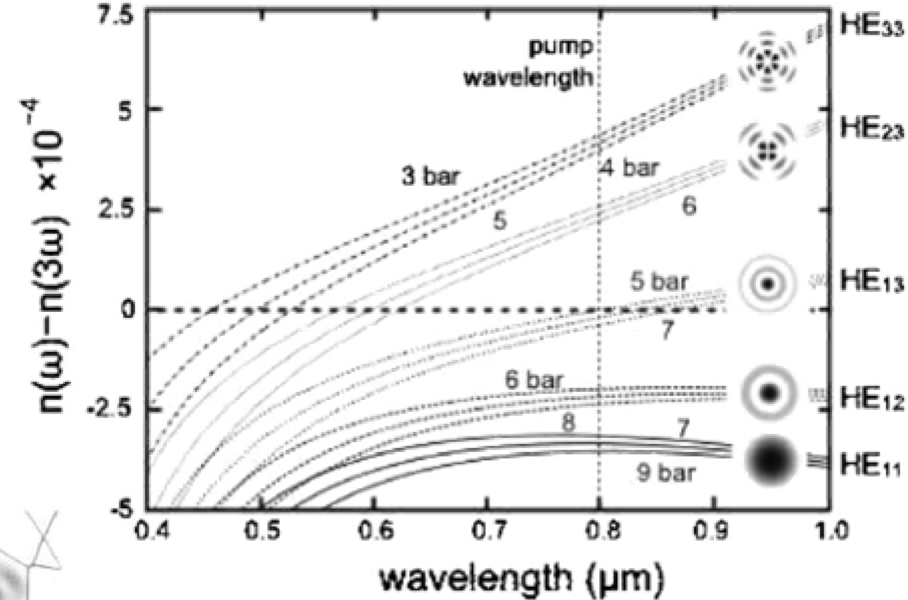
Raman frequency comb in Hydrogen gas

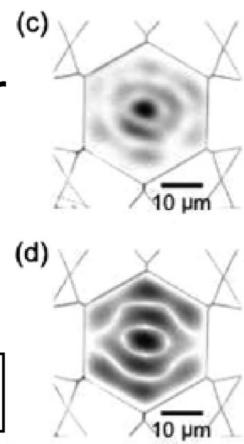


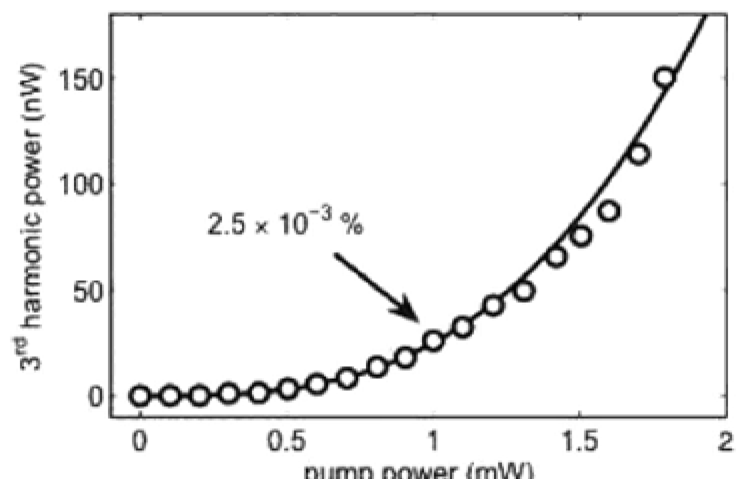
F Couny et al. Science **318** 1118 (2007)

Modal phase matching for 3rd harmonic generation in Argon

- Pressure-tunable modal-phase-matched 3rd-harmonic generation from 30fs 800nm 2μJ pump pulses.
- Kagome fiber at 5Bar pressure





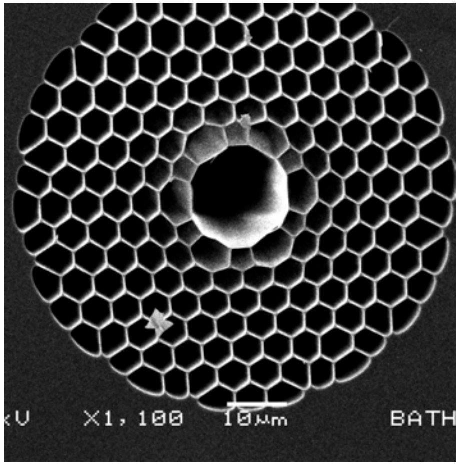


J. Nold *et al.,* Opt. Lett. **35** 2922 (2010)

This tutorial

- Applications
  - Light sources
  - Pulse delivery and manipulation
  - Atomic and molecular optics

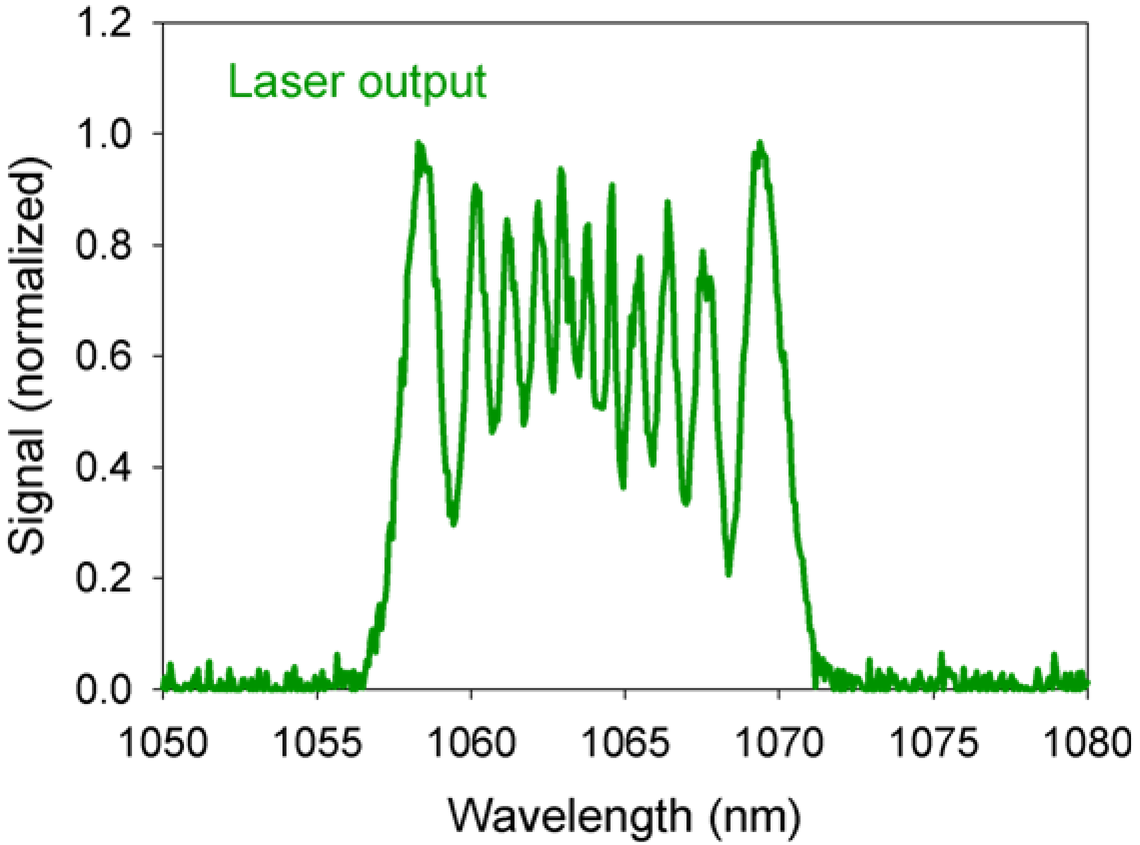
High-power pulse manipulation:



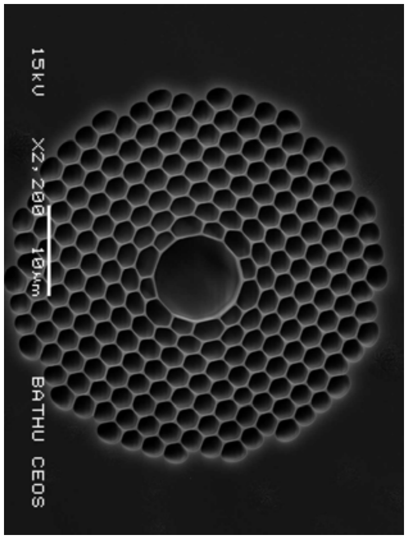
1. Chirped-pulse recompression
   - Linear compression
   - At most, returns to transform-limited pulse
2. Soliton pulse delivery
3. Soliton effect compression
   - Short fibre length, anomalous dispersion
   - Energy above fundamental soliton energy, compressed pulse not transform-limited
4. Adiabatic soliton compression
   - Decrease dispersion as function of length (tapered fibre), transform limited
5. Raman self-frequency shift
   - Continuous tuning

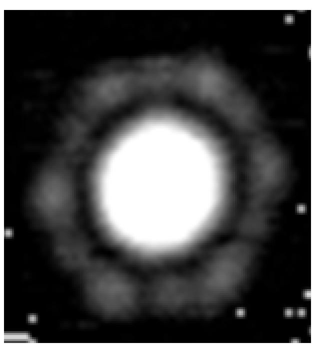
Output of an amplified fibre laser

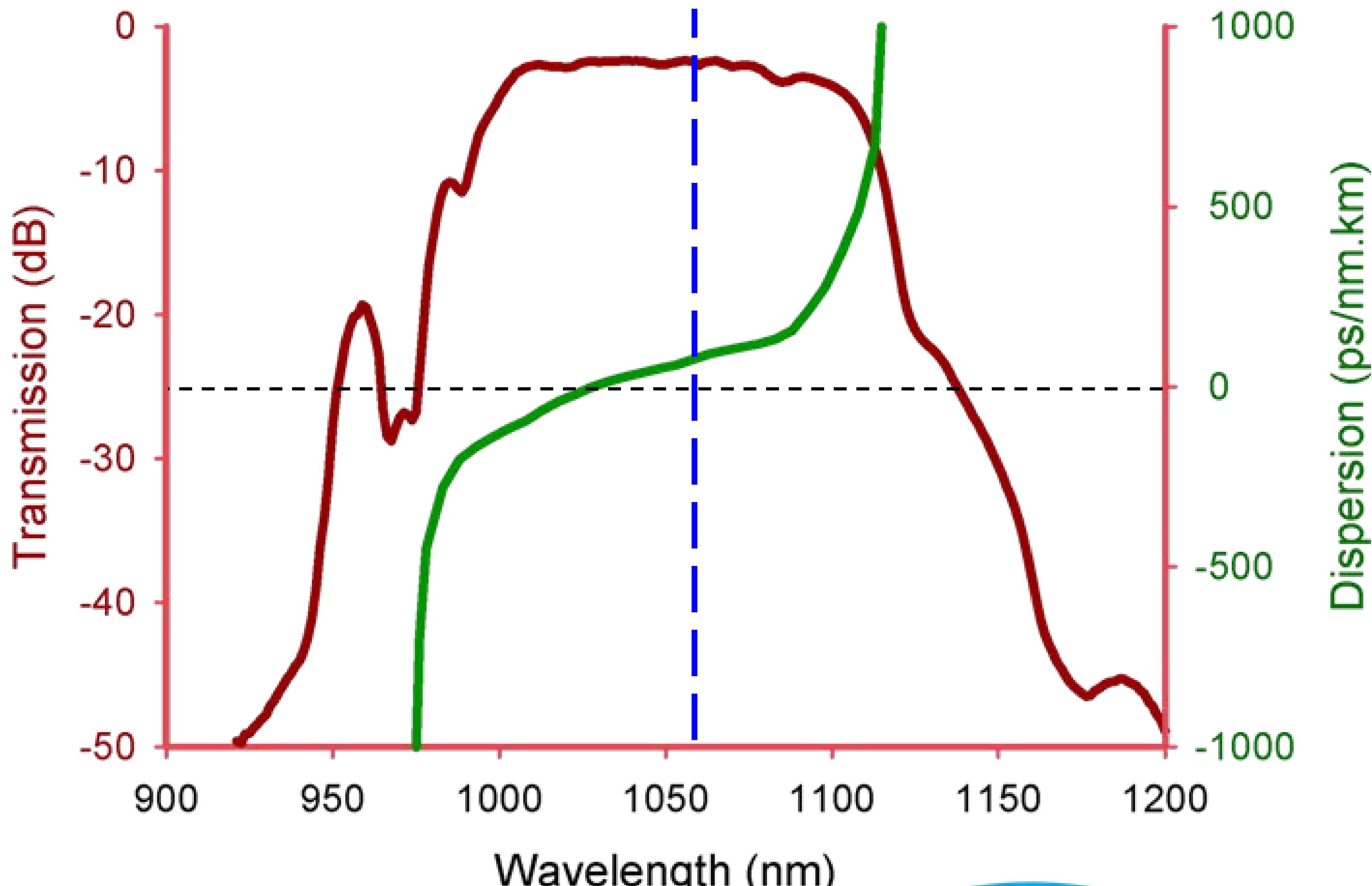
5.5ps, strongly chirped,
up to 1μJ - 0.2MW peak power



Dispersion in hollow-core fibres

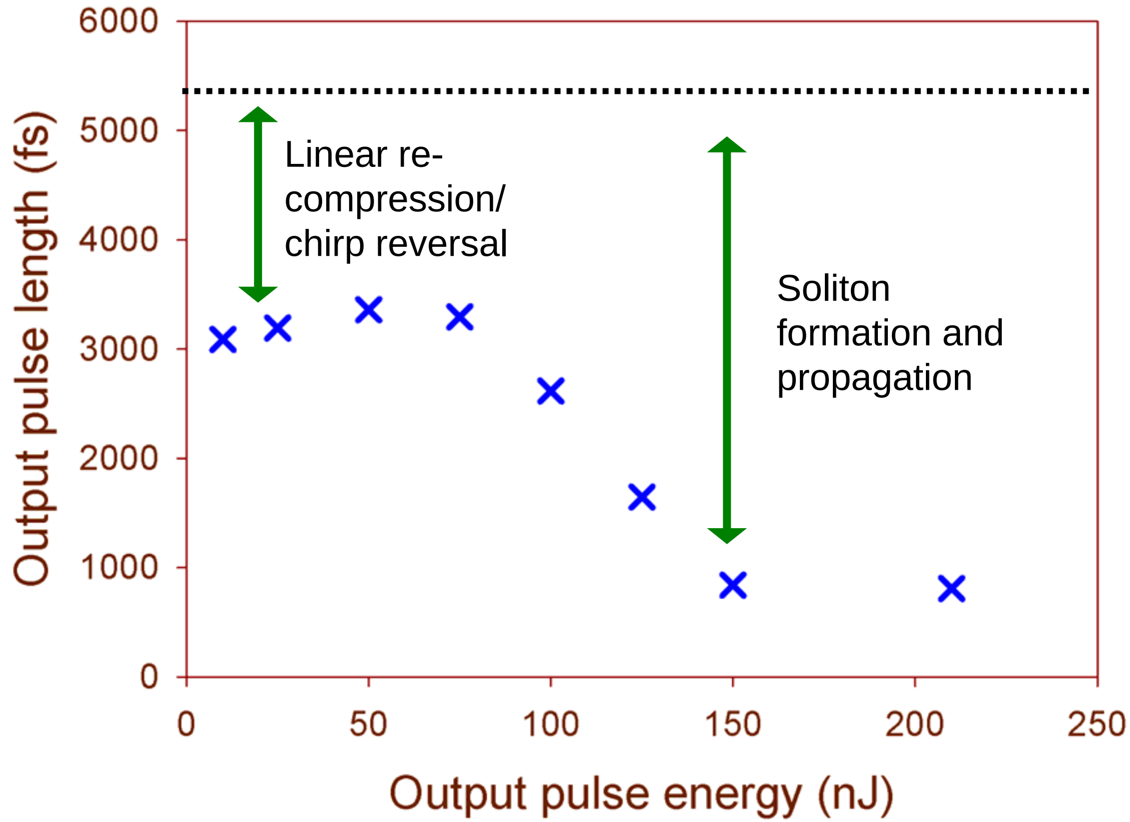






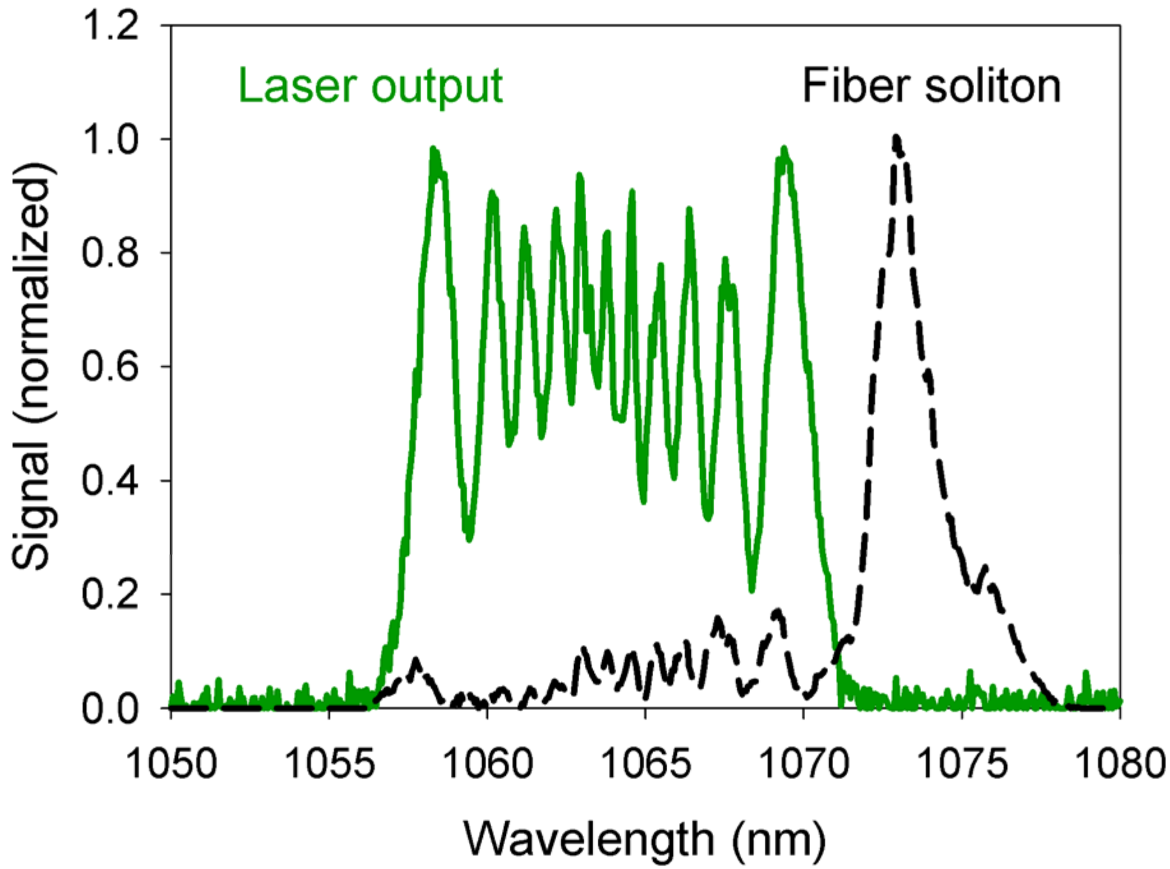
Pulse lengths after 8m of hollow-core fibre

- 4m of hollow-core fiber needed to de-chirp pulse
- Nonlinear evolution into soliton (at high energies)
- Soliton propagation over remaining few metres
- Soliton self-frequency shift



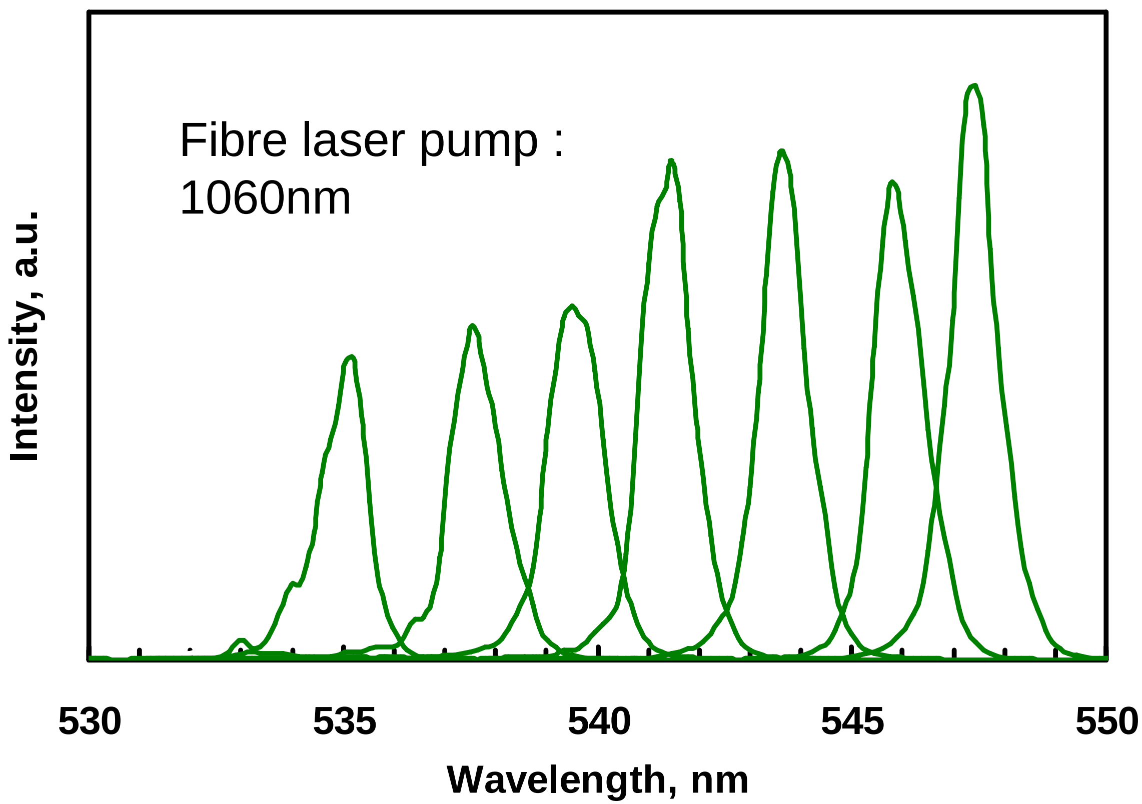
Nonlinear pulse compression and soliton propagation

- Hollow-core fibers have 1000x lower nonlinear response than standard fibers
- Enable powerful ultrashort pulse propagation
- Spectral evolution – SSFS tunability



Solitons in hollow-core fiber: Ouzounov et al., Science **301** 1702 (2003)

One way to clean up the spectrum…frequency doubling



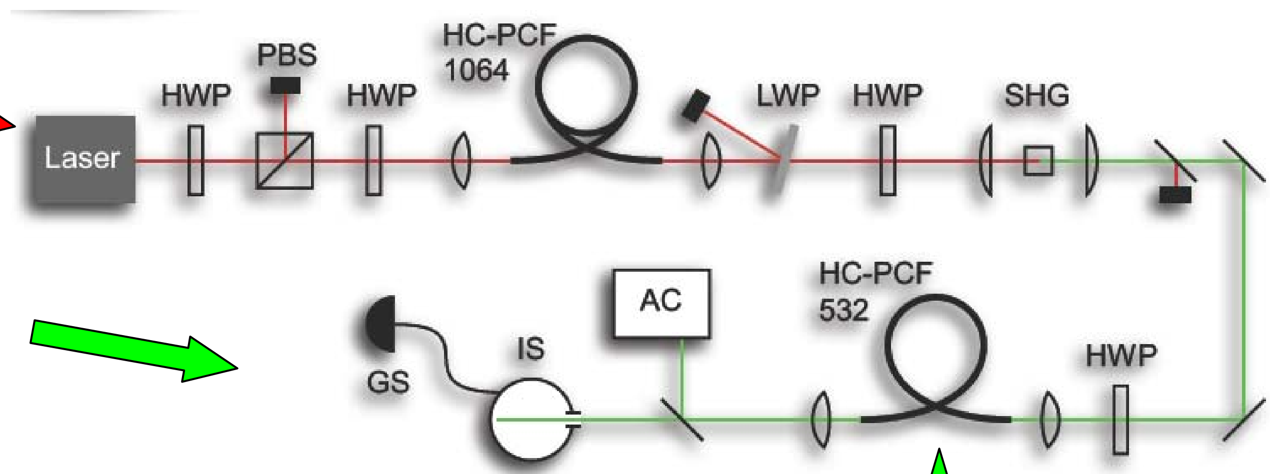
- Frequency doubling in LBO
- SHG efficiency 55-60%
- Total efficiency (laser-green) 25-30%
- 300fs transform-limited green output pulses

F. Gerome et al., Optics Express 16 2381 (2008)

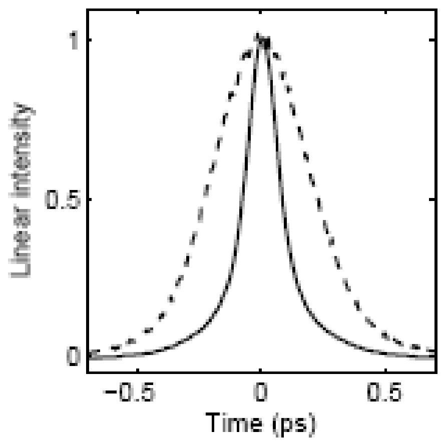
Compression of green pulses

1060nm, 500nJ
200kW peak power

540nm, 100fs, 30nJ
600kW peak power



1m fibre length



Mosley et al. Optics Lett. **35** 3589 (2010)

This tutorial

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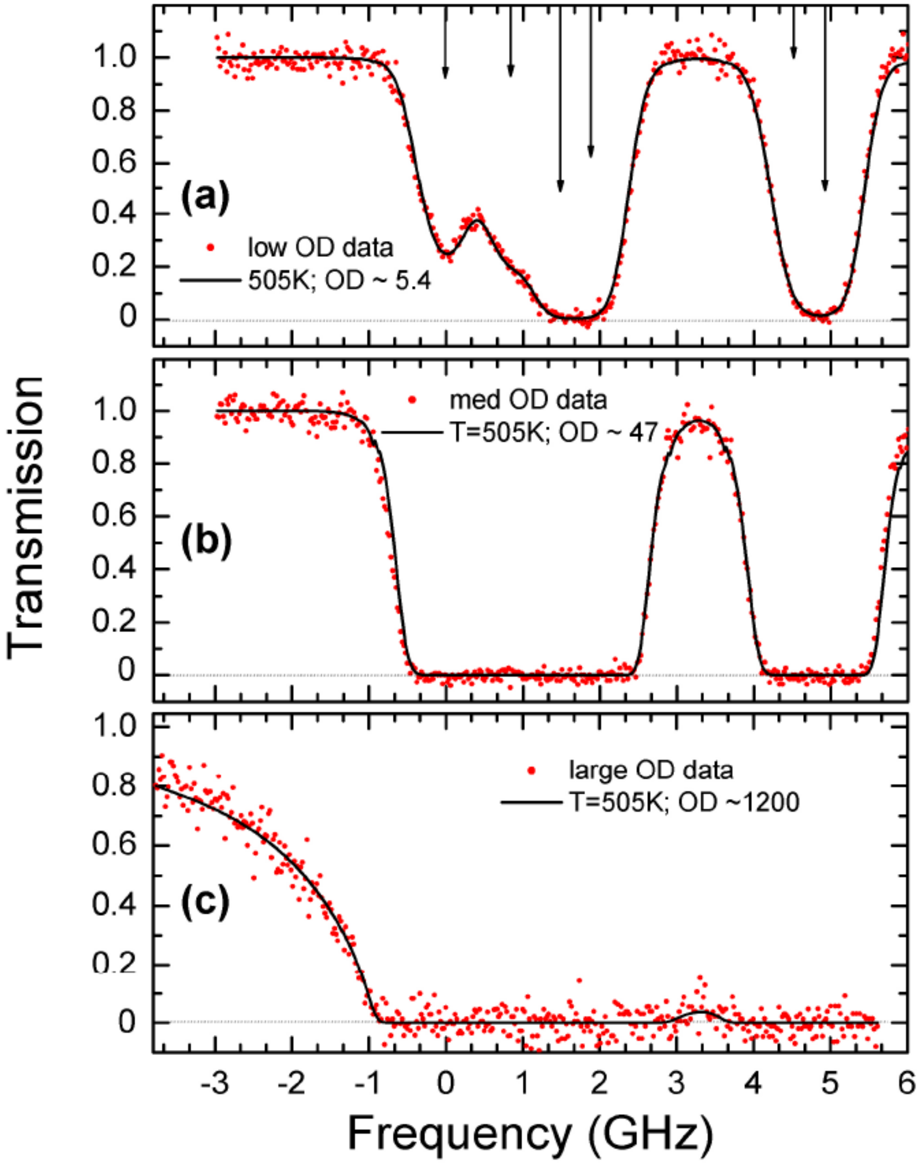
Atomic optics: on-demand Rb



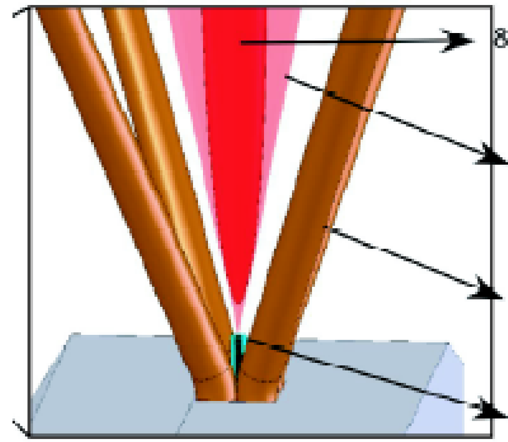
- Laser-induced atomic desorption
- D_1 transition of Rb^{87} and Rb^{85} vapor in a hollow-core fiber
- Untreated hollow-core fiber previously exposed to Rb vapor
- Optical depth exceeding 1000 on timescale of a few seconds

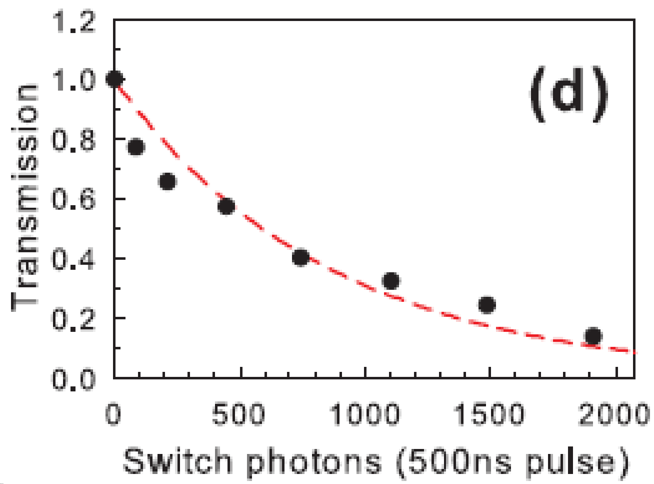
Slepkov *et al.* Opt Express **16** 18976 (2008)

Centre for Photonics & Photonic Materials

All-optical switching

- Cold atoms from a MOT
- Atom funnel formed by guide wires
- Dipole trap along the fibre length
- EIT and EIT switching





M. Bajcsy *et al.* Phys. Rev Lett. **102** 203902 (2009)

That's not all…

…but it's all we have time for.

Thank you.