The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR 1829 - 8

Winter College on Fibre Optics, Fibre Lasers and Sensors

12 - 23 February 2007

Photonic crystal fibres

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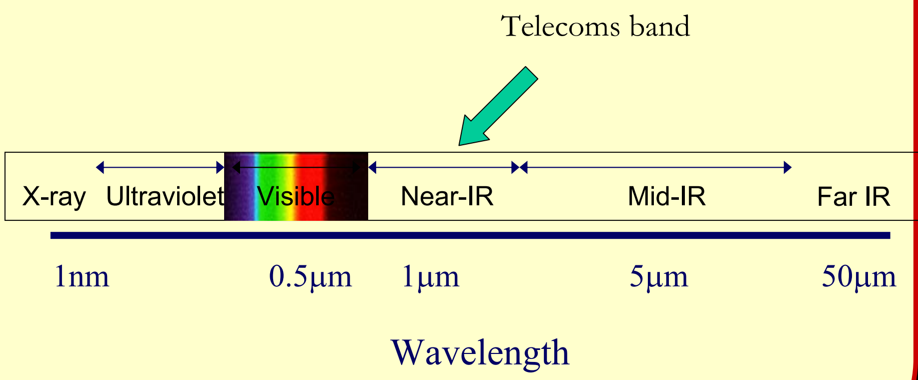
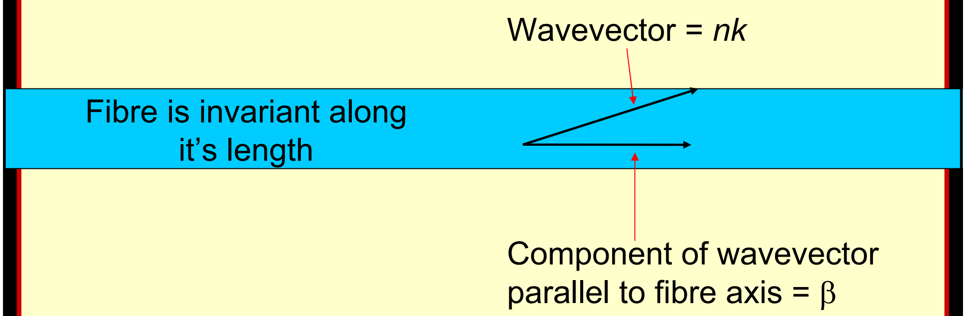
Overview of this lecture

- Introductions
- Reminder about Fourier transforms
- Brief review of fibre optics
- Introduction to photonic crystal fibres
- Fabrication
- Dispersion and number of guided modes in solid-core fibres
- Supercontinuum and soliton optics

The photonic spectrum:



The β-value



In a homogeneous medium with refractive index n, the biggest value β can take is $\beta = nk$, when it is a plane wave.

Once it is confined, we must have $\beta < nk$

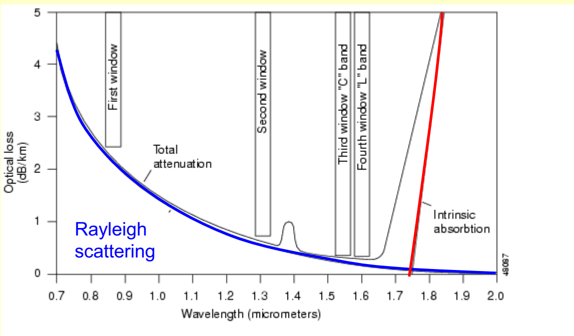
Conventional optical fiber waveguides

n_{clad} $\beta_{max} \leq n_{clad}\, k$

$n_{core} > n_{clad}$ $n_{clad}\, k < \beta < n_{core}\, k$

Core index must be higher than that of cladding material to get guided modes

Attenuation in standard fibres



Group velocity and group index

$$\frac{c}{n} = \frac{\omega}{k}$$

Information actually propagates at the group velocity v_g…

$$v_g = \frac{d\omega}{dk}$$

Knowing v_g we can define a group refractive index

$$n_g = \frac{c}{v_g} = n + \omega \frac{dn}{d\omega}$$

Group velocity dispersion

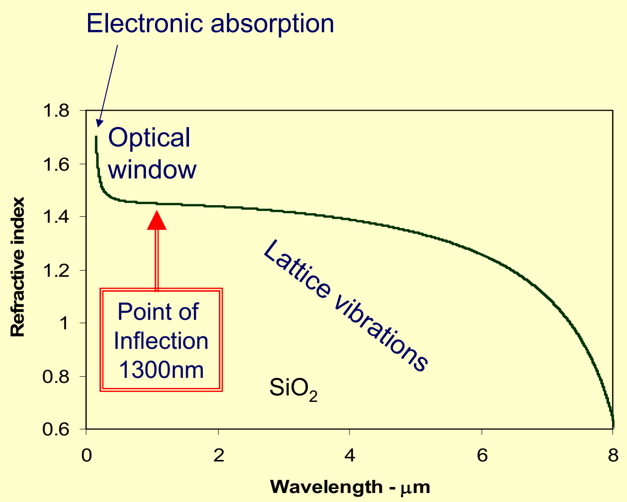
Another important parameter is the group-velocity dispersion (GVD, *D* - variation of v_g with frequency) which determines how pulses spread out (disperse) as they propagate.

Units of *D* = ps/(nm.km)

Where does “dispersion” come from

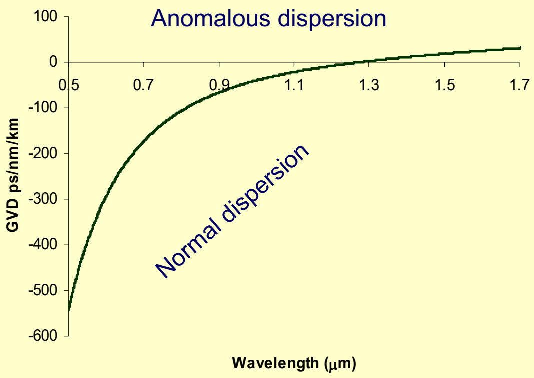
- Material dispersion
- Waveguide dispersion
- “structural” dispersion (in photonic crystals)

Material dispersion – SiO_2



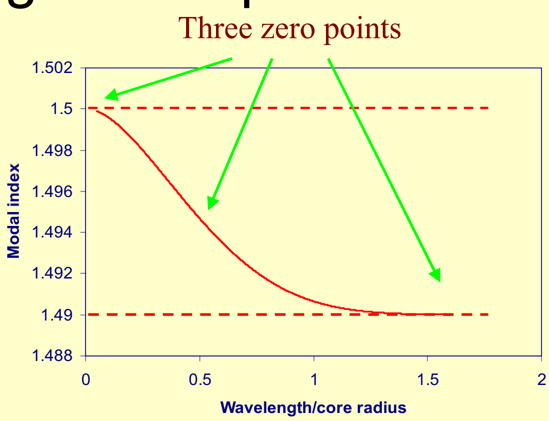
Point of inflection gives zero group-velocity dispersion (GVD) around 1300nm wavelength

Group velocity dispersion (GVD) of silica



Waveguide dispersion

- Mode index changes as mode shape changes
- Has a relatively small effect due to the small index contrast
- Consequently, only significant around the material zero-GVD wavelength

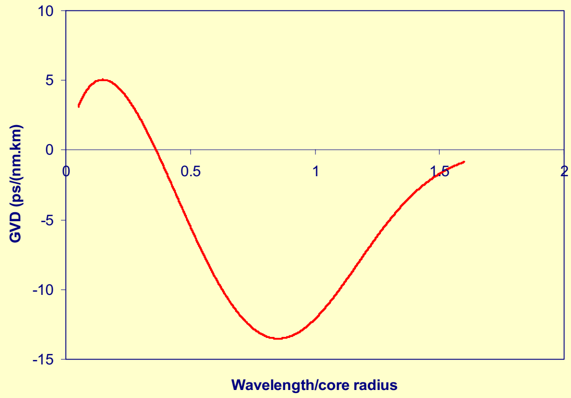


Computations for the fundamental mode in a circular strand of glass index 1.5 surrounded by glass index 1.49

Waveguide GVD

Can be used to, for example, cancel the material gvd at 1550nm (which is normally 13ps/(nm.km))

Note that the waveguide dispersion has a large curvature



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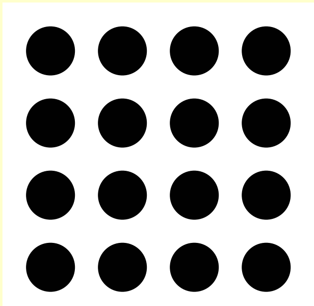
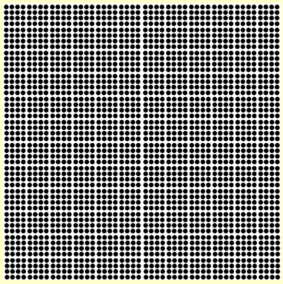
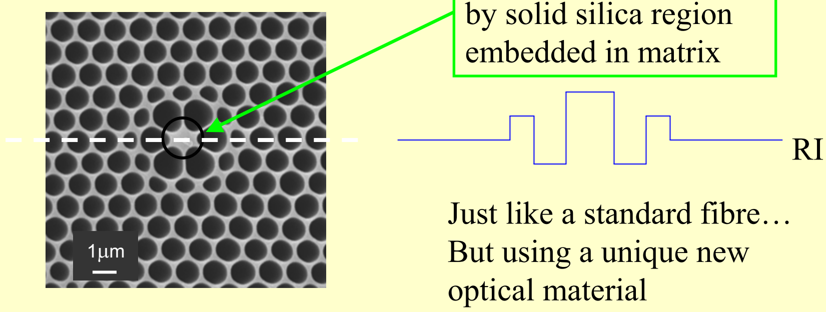
Non-standard optical materials





"Effective index" in photonic crystal fibres

Guiding core formed by solid silica region embedded in matrix



Just like a standard fibre…
But using a unique new optical material

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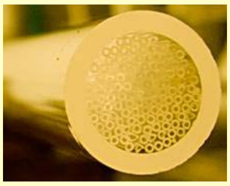
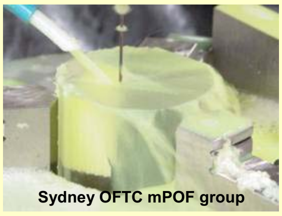
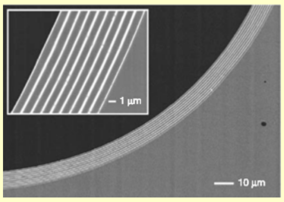
Material systems + fabrication technologies



- Silica – ideal for stack and draw, tubes available commercially
- Silicates – great for proof-of-principle experiments X.Feng et al., Opt. Express, **11** 2225 (2003)
- Polymer: drilled/extruded preforms M. A. van Eijkelenborg, et al. Optics Express Vol. 9, No. 7, pp. 319-327 (2001).
- Tellurite and Chalcogenide glasses (extrusion, rotational casting, stacking)
- Chalcogenides and polymers ("rolling your own")

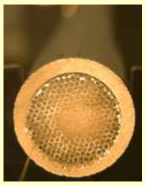


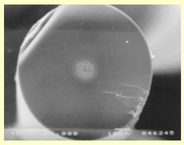


B. Temelkuran *et al*, Nature **420**, 650-653 (2002).

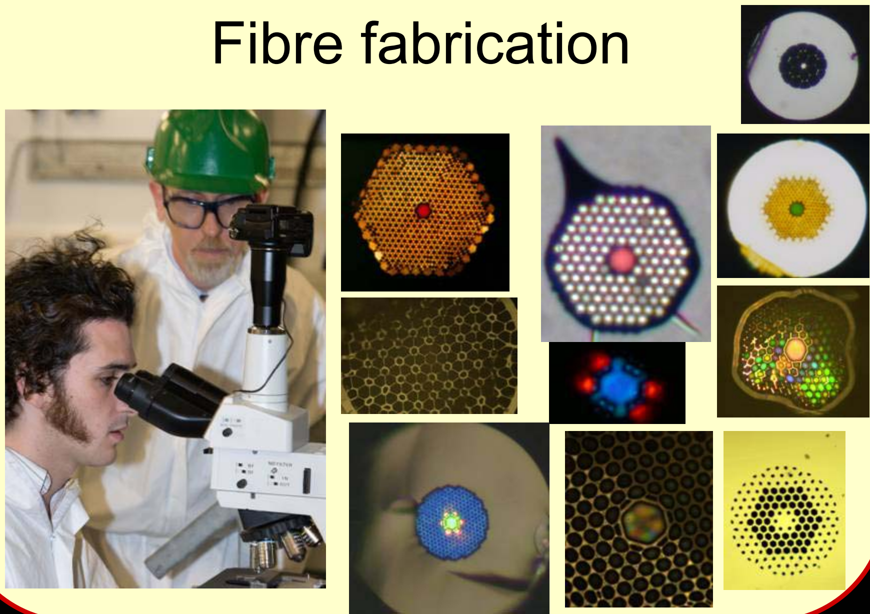
Silica fibre fabrication

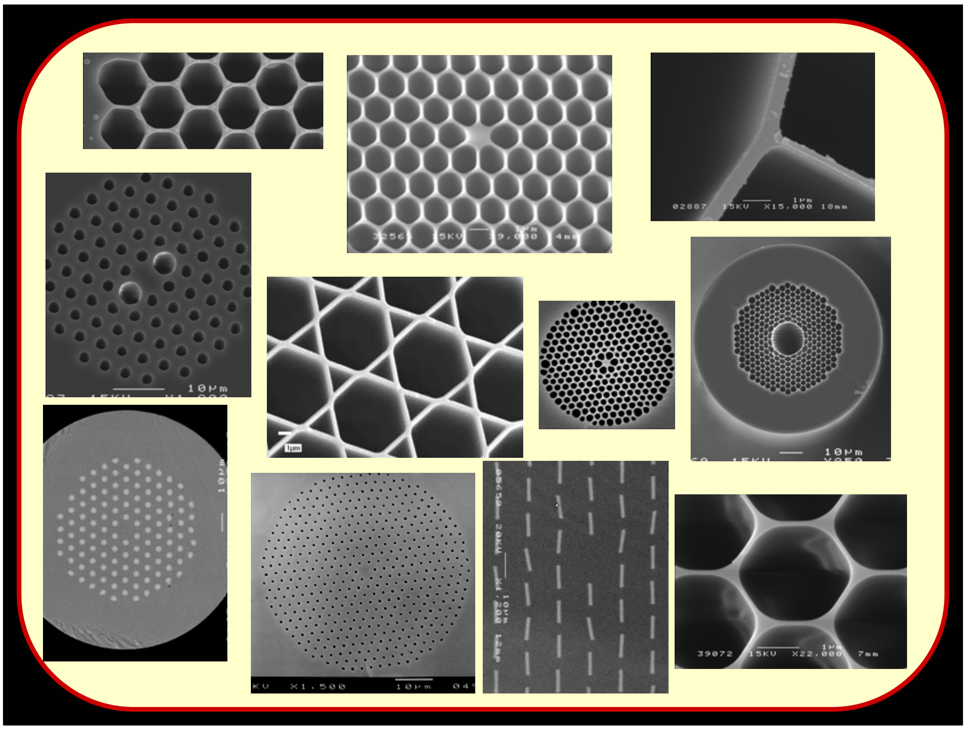
	Length scale
Commercial tubes	1m
Capillary tubes	400m
Stack preform	1m
Draw stack down	100m
Jacket and draw to fibre	1000km





Fibre fabrication

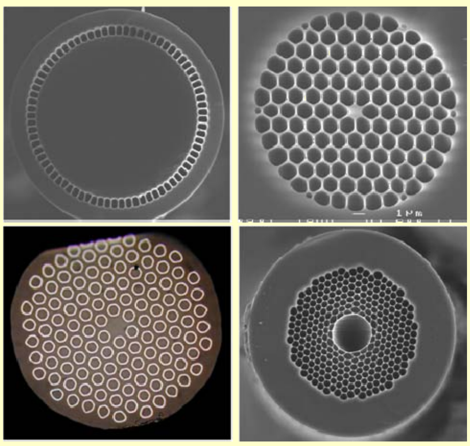




Forms of PCF

High numerical aperture,multimode

Highly nonlinear fiber with anomalous dispersion



Photonic bandgap fiber with solid core

Photonic bandgap fiber with hollow core

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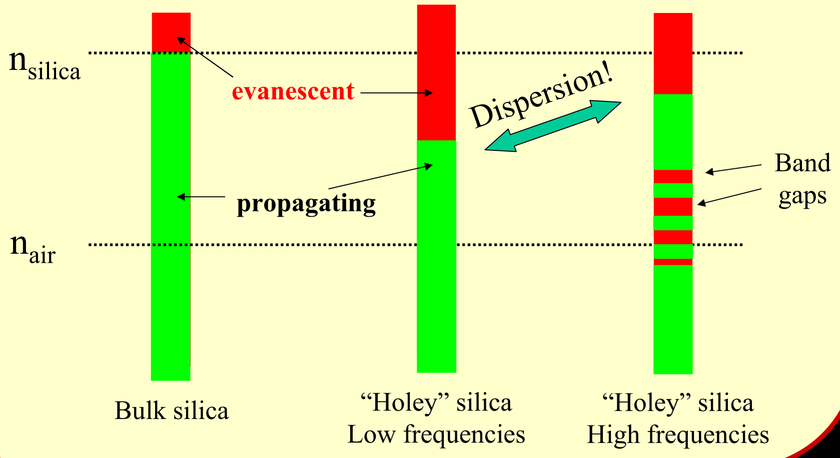
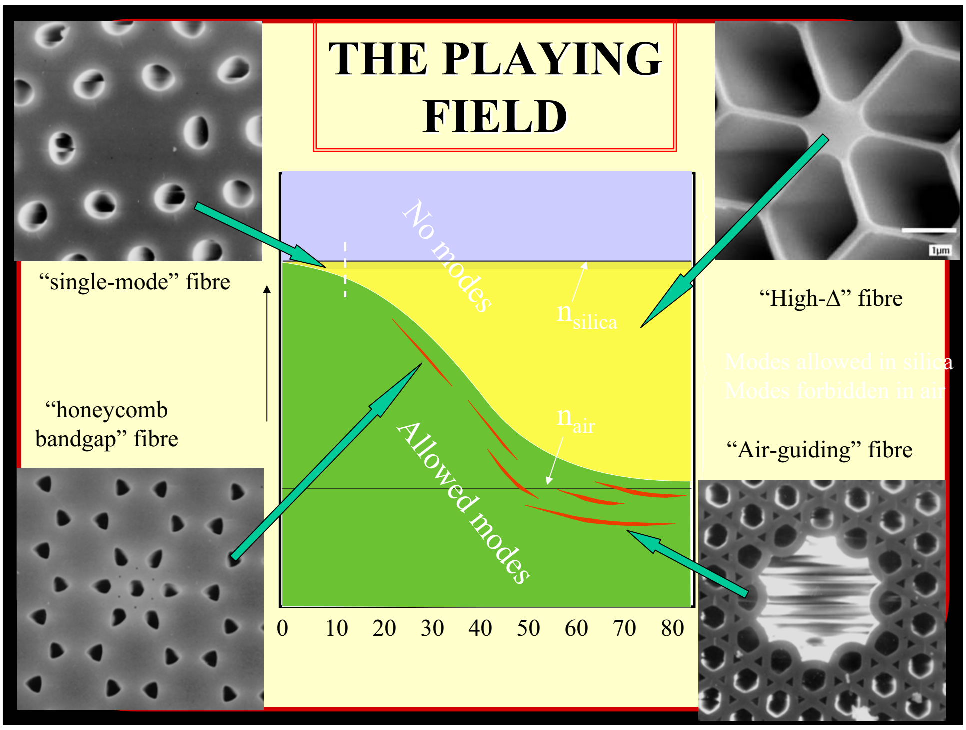
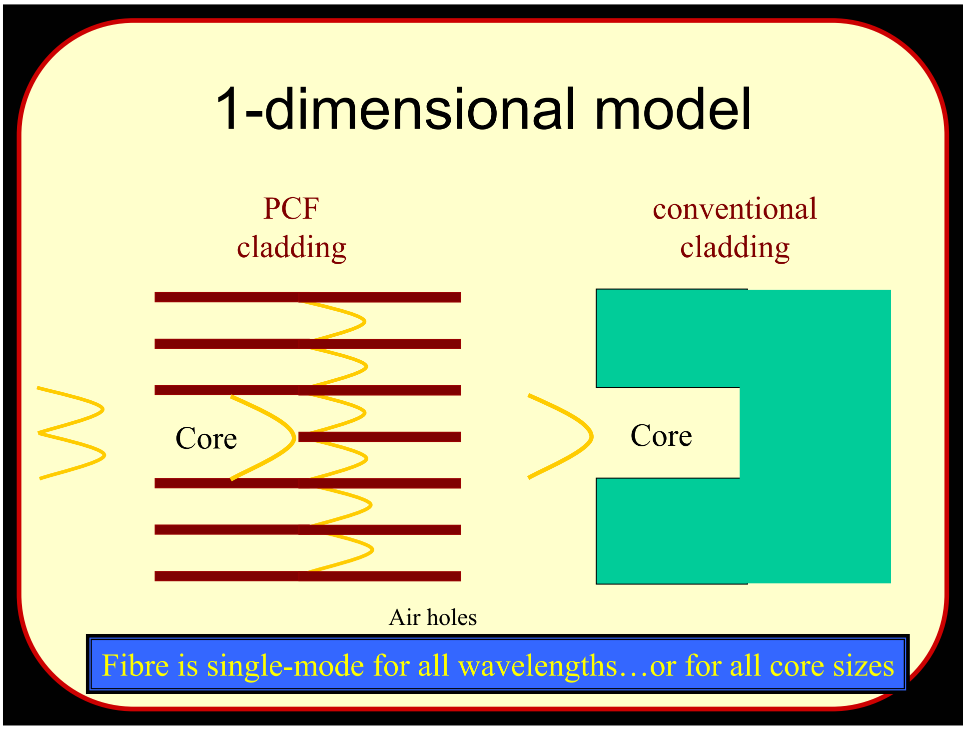
Working at fixed frequency:

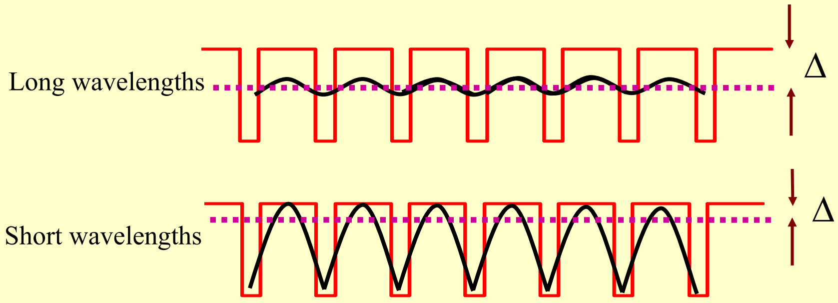
Define an **effective index** for the "holey" material as $n_{eff} = \beta/k$




THE PLAYING FIELD
No modes
"single-mode" fibre
n_{silica}
"High-Δ" fibre
Modes allowed in silica
Modes forbidden in air
"honeycomb bandgap" fibre
n_{air}
"Air-guiding" fibre
Allowed modes
0 10 20 30 40 50 60 70 80


1-dimensional model
PCF cladding
conventional cladding
Core
Core
Air holes
Fibre is single-mode for all wavelengths…or for all core sizes

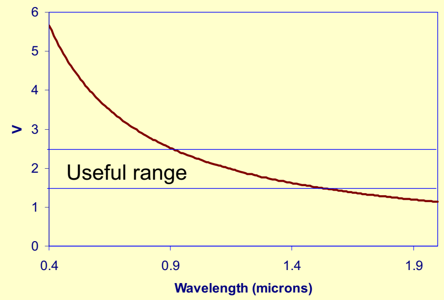
“Effective index” view of cladding index



But $V = \frac{\pi D}{\lambda}(n_{core}^2 - n_{clad}^2)^{1/2}$

Normalised frequency: conventional fibre

- Fibre useful over a limited range of frequencies
- Limited on long wavelength edge by bend loss
- Limited on short wavelength edge by 2nd mode cutoff



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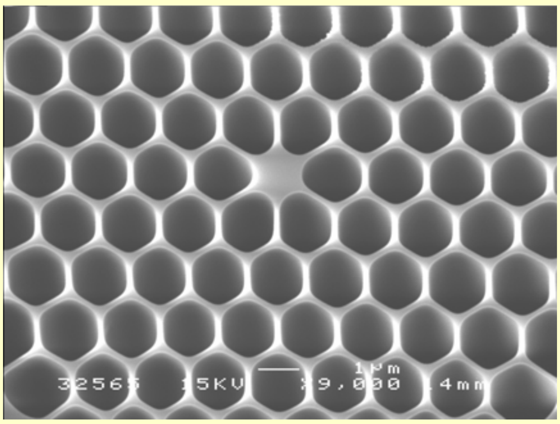
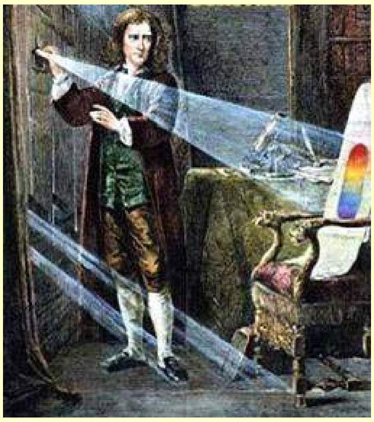
Nonlinear optics

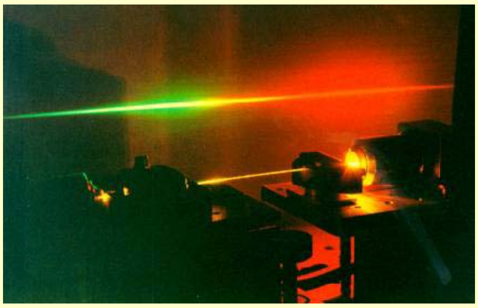


High nonlinear response (small core)
Strong waveguide dispersion

The importance of dispersion…

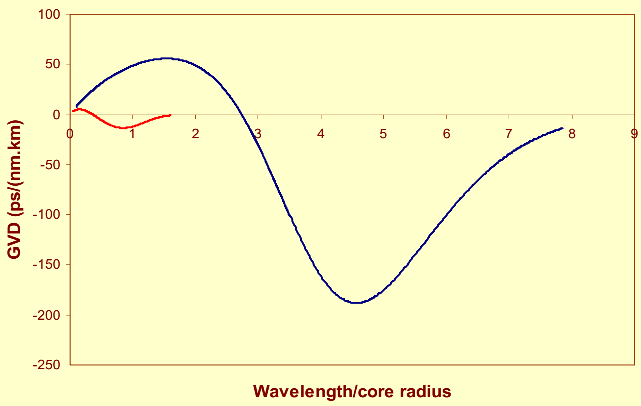


Dispersing a white-light spectrum



Generating white light from a laser source in a photonic crystal fibre

Waveguide dispersion in a PCF

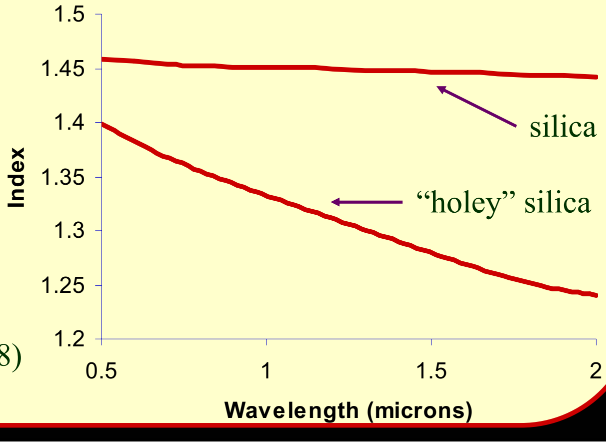


Sources of dispersion

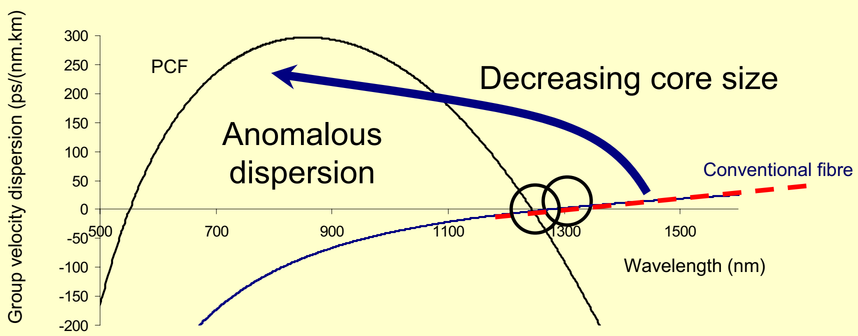
- Material dispersion of silica
- Waveguide dispersion
- Dispersion of the “holey” material

Index of the “fundamental space-filling mode”

(Λ = 2µm, d/Λ=0.8)



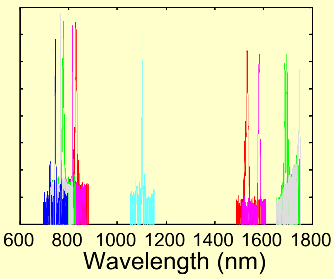
What can PCF do for nonlinear optics?

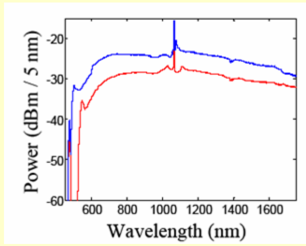


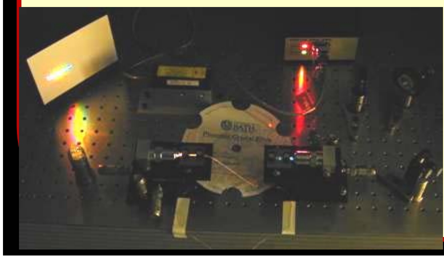
- Widely adjustable zero-GVD point
- Anomalous dispersion throughout the visible and near-IR
- High nonlinear coefficient
- Large values of dispersion and slope

Sub-ns pulses

- Typical pump Q-switched laser source eg Nd:YAG microchip, relatively narrow linewidth
- Pump close to zero-dispersion wavelength
- Sidebands generated through FWM/MI, at specific wavelengths, as well as SRS peaks
- Ultimately, a temporally incoherent supercontinuum

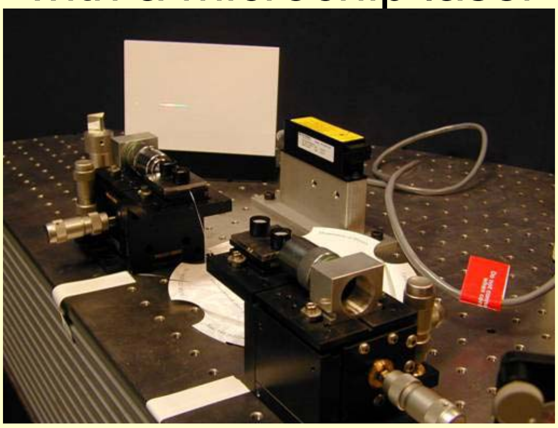






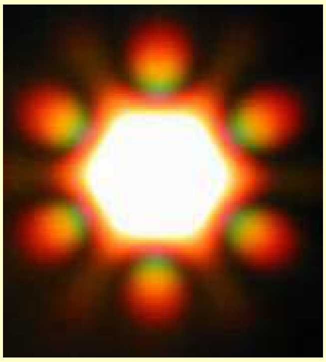
S. Coen, JOSA B **19** 753 (2002)
J. D. Harvey, Opt. Lett. **28** 2225 (2003)
W. J. Wadsworth, Opt. Express **12** 299 (2004)

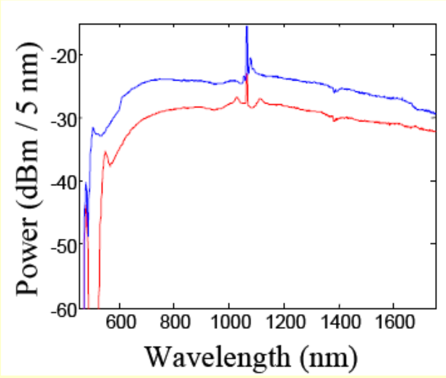
Single-mode white light source with a microchip laser



Nd: -based 1064nm microchip laser, sub-ns pulses, 7kHz rep rate, 30mW average power

Broadband single-mode white light source

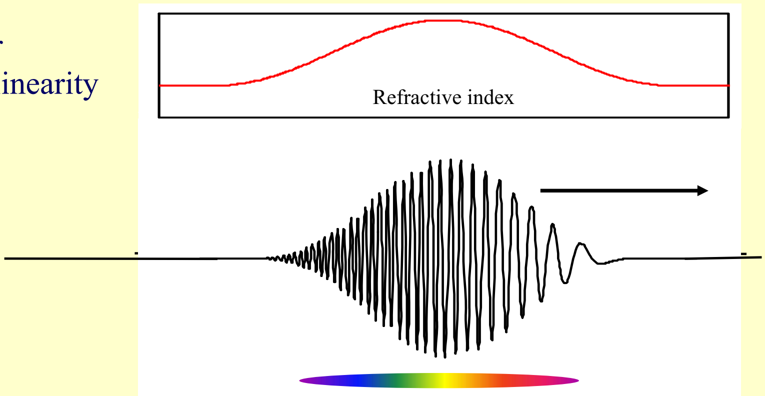




Applications: single-mode light source

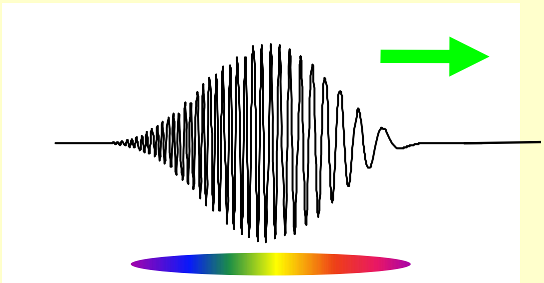
Optical transmission – nonlinear regime

Kerr nonlinearity



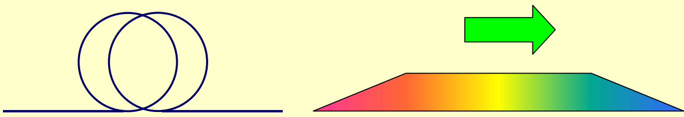
"Self phase modulation"

Self-phase modulation (nonlinear)



+

"Anomalous" dispersion fibre (linear)



Soliton propagation

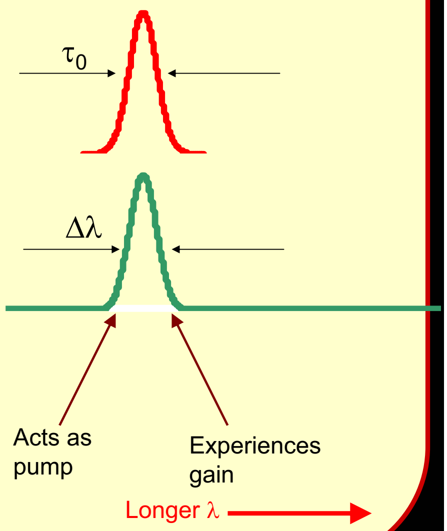
Magical energy for soliton propagation

Linear dispersion and nonlinear self-phase modulation are matched at just one peak power, which can be found be matching the dispersion and nonlinear lengths

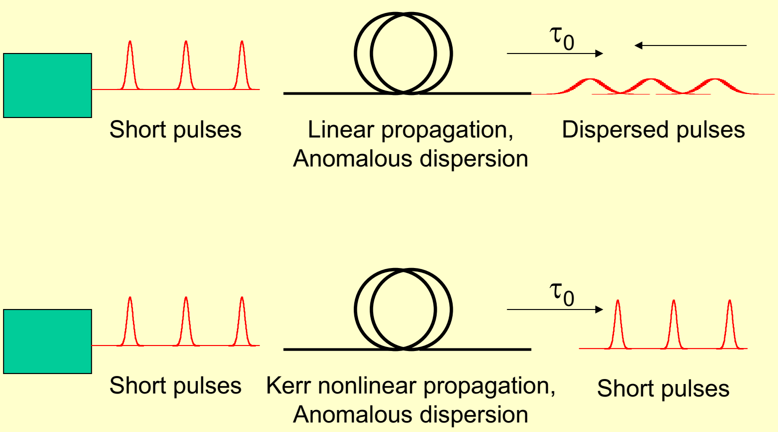
$$P_0 = \frac{3.11\lambda^3 D A_{eff}}{4\pi^2 c n_2 \tau^2}$$

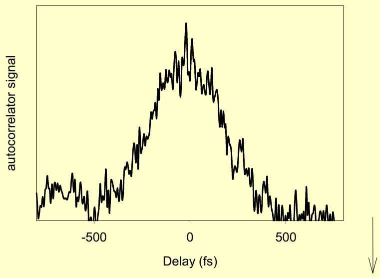
Soliton self-frequency shift

- Solitons are short pulses, and so must have a relatively broad spectral width
- The Raman gain spectrum, which peaks around 12THz, gives non-zero gain down towards zero frequency shift
- Consequently, a soliton can “pump itself” by SRS
- The long-wavelength edge experiences gain as it is pumped by the short-wavelength edge
- This leads to a continuous downshift of the soliton central frequency during propagation



Soliton propagation in a PCF

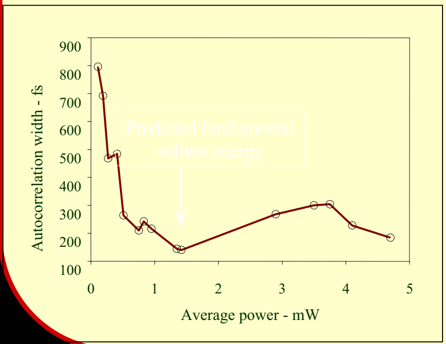




Soliton effects at 850nm

Autocorrelation signals of 100fs pulses transmitted through 3.1m of fiber at 1.35mW average power.

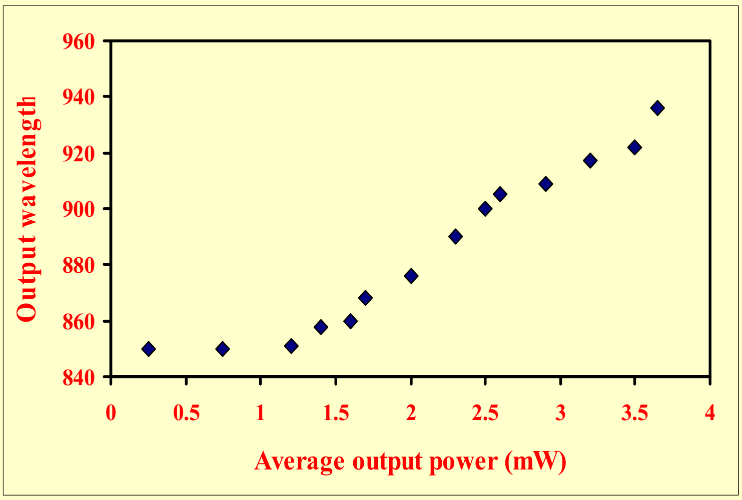
Wavelength - 850nm
Dispersion - 50ps/nm/km
Core diameter - 2.1μm
Fundamental soliton energy ≅ 16pJ
Soliton length ≈ 1m



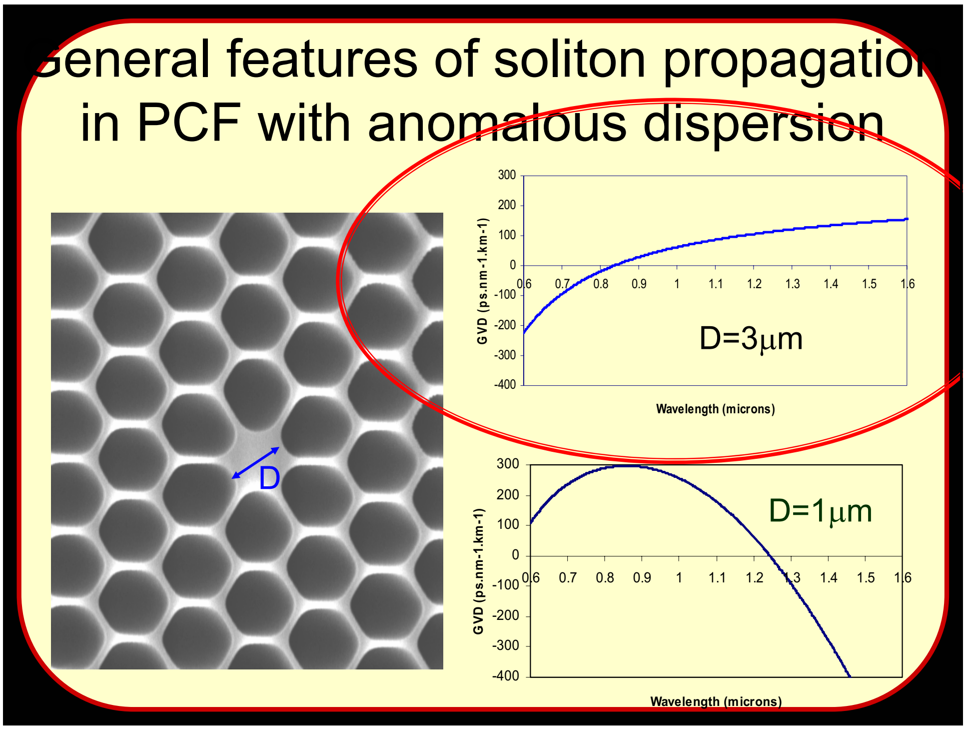
Autocorrelation width of transmitted pulse as a function of power.

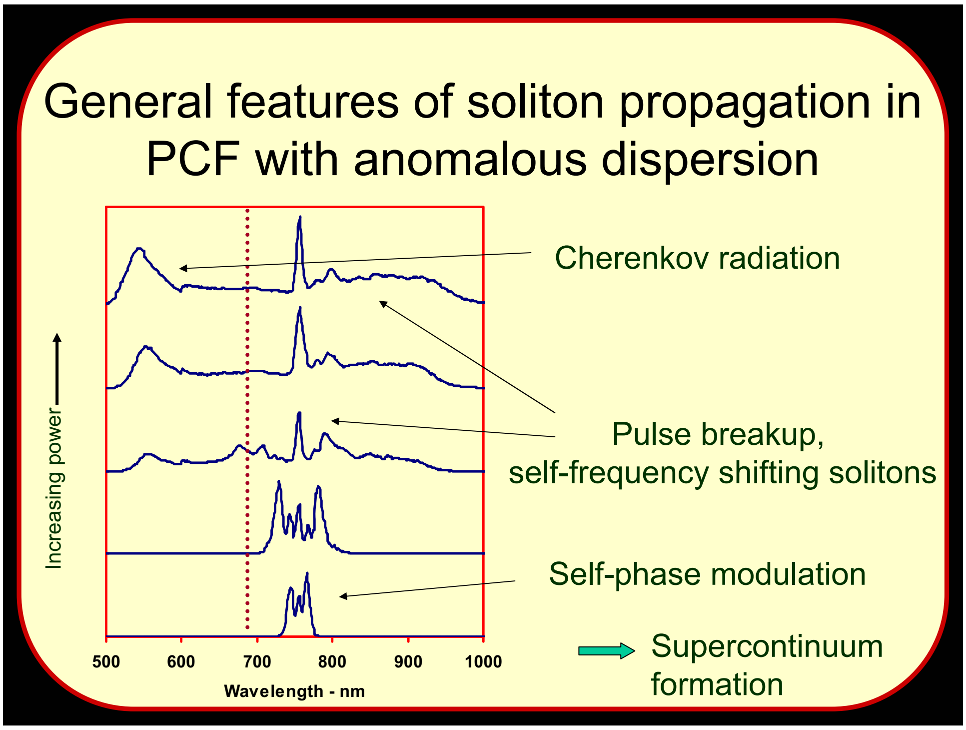
W. J. Wadsworth et al, Electron. Lett. **36** 53 (2000)

Soliton self-frequency shift from 850nm

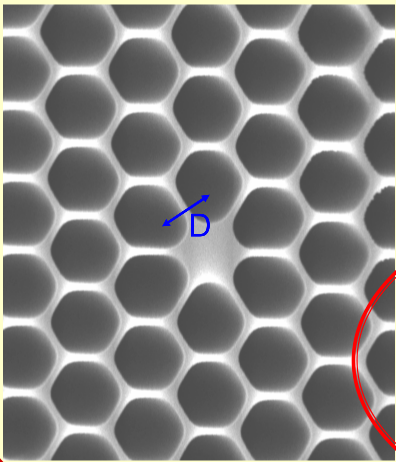


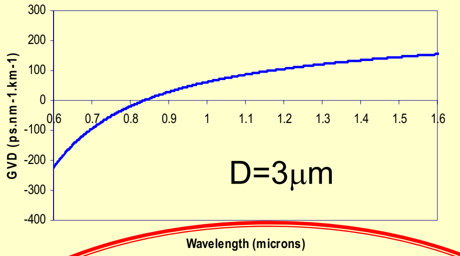
Fiber length 6m, pulse length 200fs, rep rate 76MHz

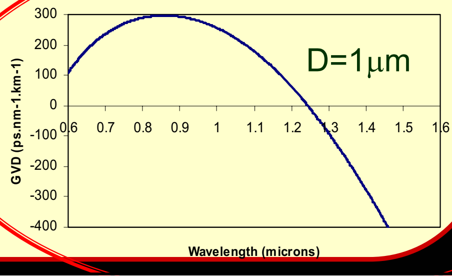

General features of soliton propagation in PCF with anomalous dispersion
D
GVD (ps.nm-1.km-1)
300
200
100
0
-100
-200
-300
-400
0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6
D=3μm
Wavelength (microns)
D=1μm
Wavelength (microns)


General features of soliton propagation in PCF with anomalous dispersion
Cherenkov radiation
Pulse breakup,
self-frequency shifting solitons
Self-phase modulation
Supercontinuum formation
Increasing power
500 600 700 800 900 1000
Wavelength - nm

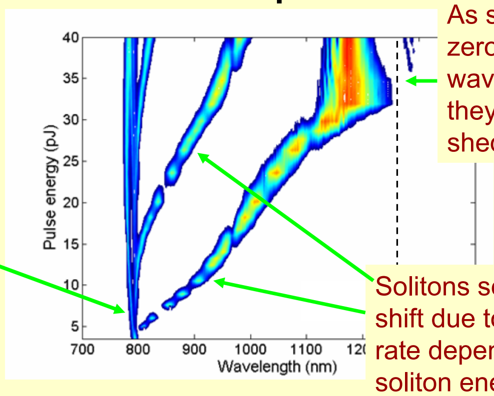
General features of soliton propagation in PCF with negative dispersion slope







General features of solitons in PCF with negative dispersion slope



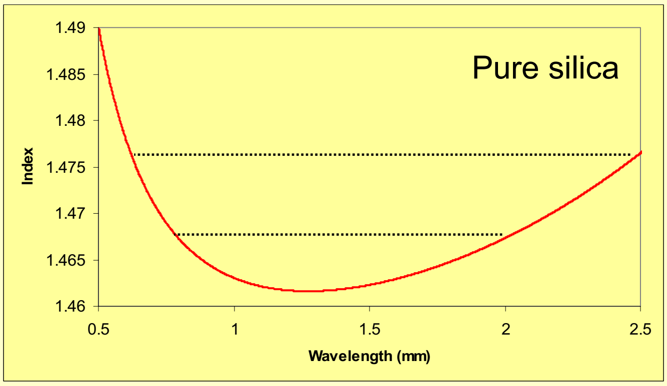
As solitons approach zero-dispersion wavelength (dotted line) they stop shifting and shed radiation.

Incident pulse breaks up into several fundamental solitons with different energies

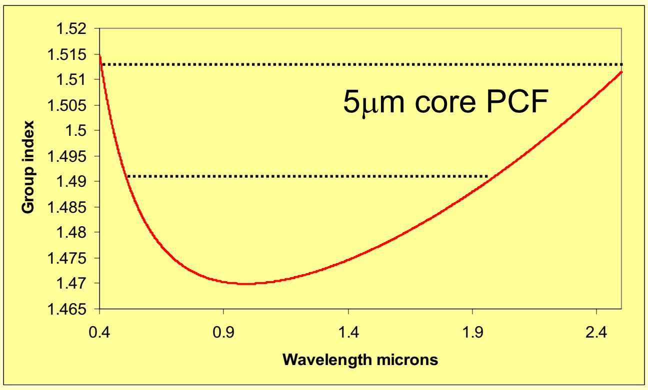
Solitons self-frequency shift due to Raman, with rate depending on soliton energy

D. V. Skryabin *et al.* Science **301** 1705 (2003)

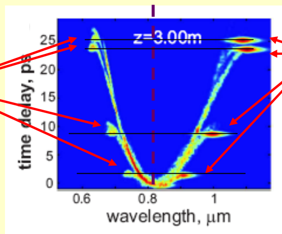
Group-index matching



Group-index matching



Normal gvd | Anomalous gvd



These peaks are not solitons, but are trapped by the solitons at longer wavelengths. They get blue-shifted by FWM interaction with the solitons

Solitons are continually self-frequency shifting due to Raman

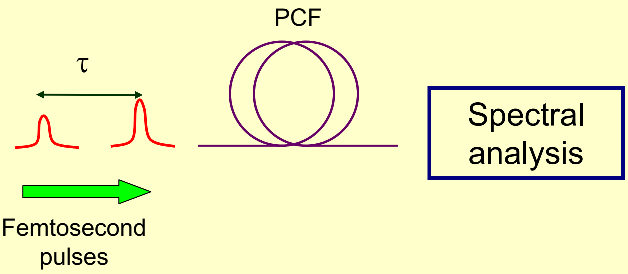
This means they are always slowing down (as n_g increases)

Thus, blue-shifting will stop when group-index matching becomes impossible!

Wavelength (microns)

See also N. Nishizawa and T. Goto, Opt. Lett. **27** 152 (2002)

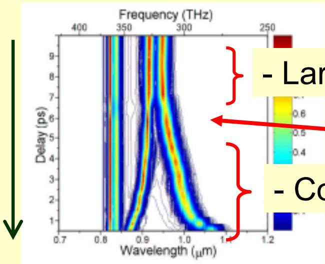
Energy exchange between colliding solitons



The experiment

Energy exchange between colliding solitons

Decreasing delay



- Large delay – solitons don't collide

Solitons collide at the end of fibre

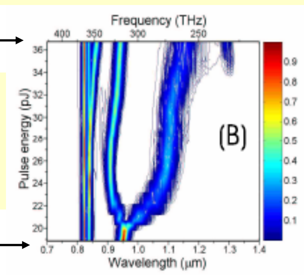
- Collision moves towards input end

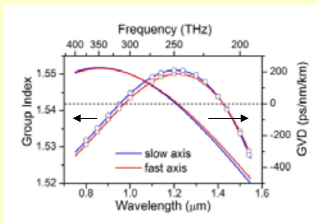
Energy exchange between colliding solitons

- Delay is kept fixed at 1.5ps
- First pulse energy is varied
- Higher energy causes faster SSFS

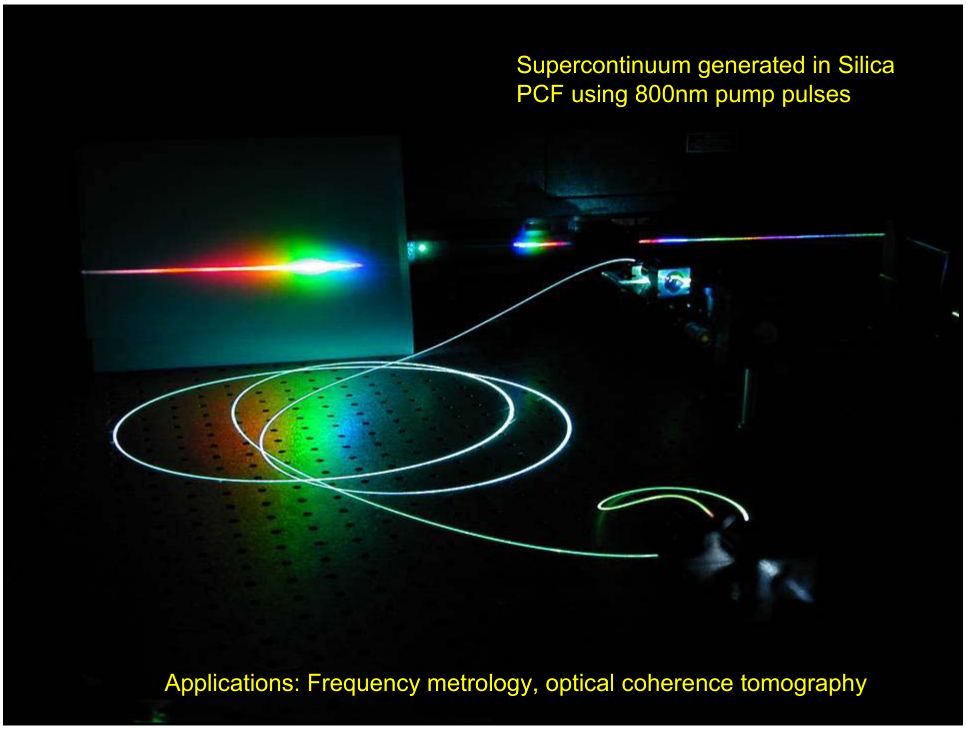
Different energies

Similar energies





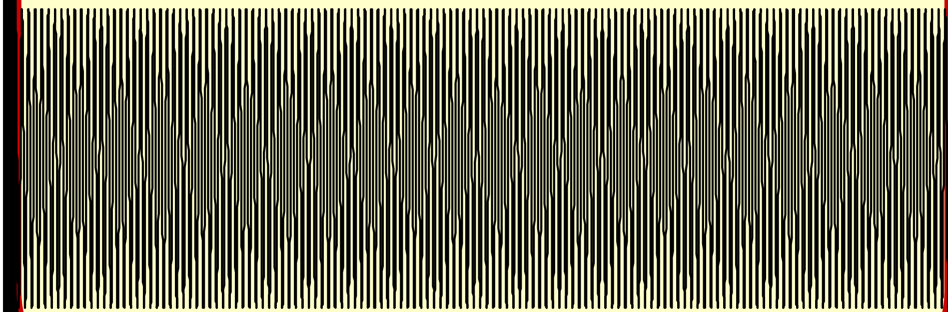
"Energy exchange between colliding solitons in photonic crystal fibers", F. Luan *et al*, to appear in Optics Express, 2006



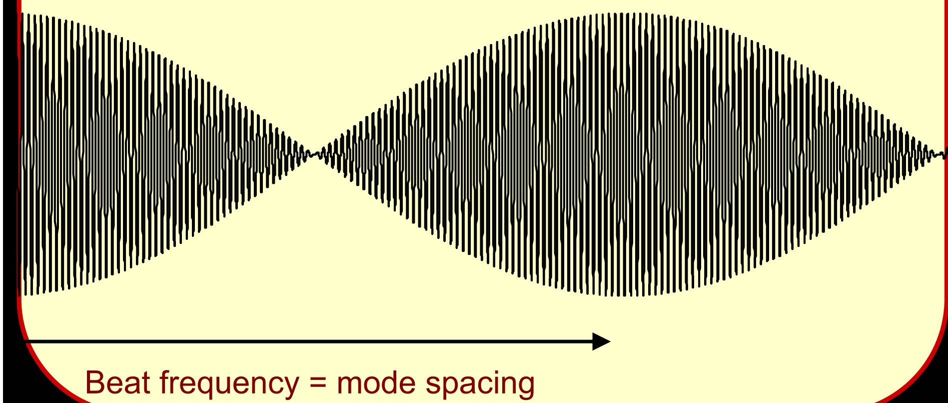
Overview of this lecture

- Introductions
- Reminder about Fourier transforms
- Brief review of fibre optics
- Introduction to photonic crystal fibres
- Fabrication
- Dispersion and number of guided modes in solid-core fibres
- Supercontinuum and soliton optics
- Frequency metrology, Optical coherence tomography

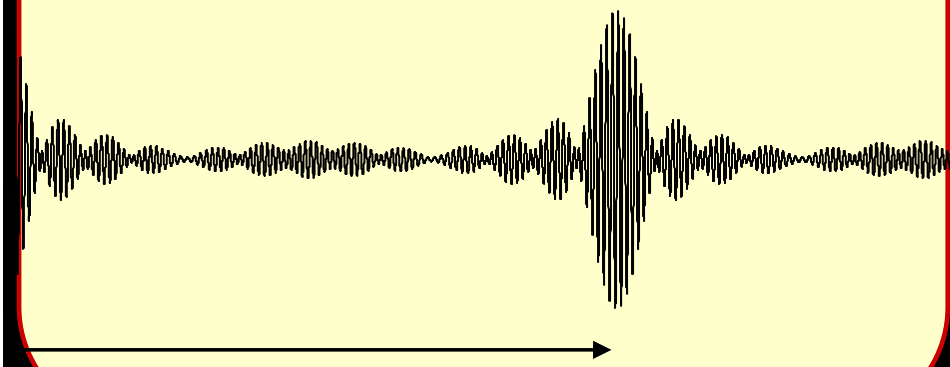
A single-mode laser (continuous wave)



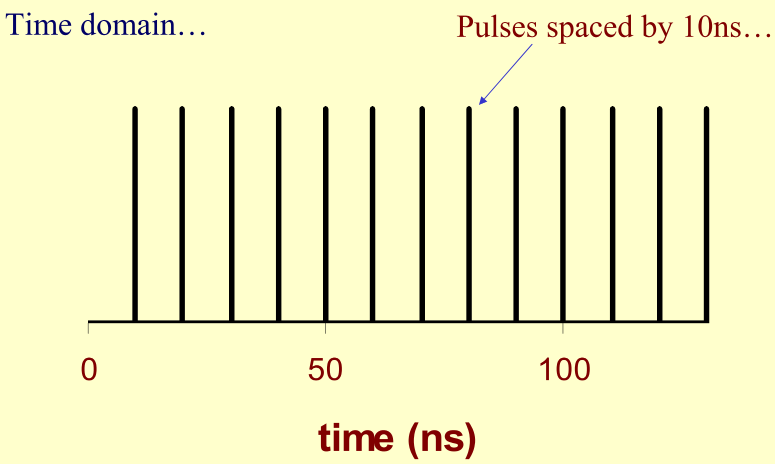
A laser running on two longitudinal modes

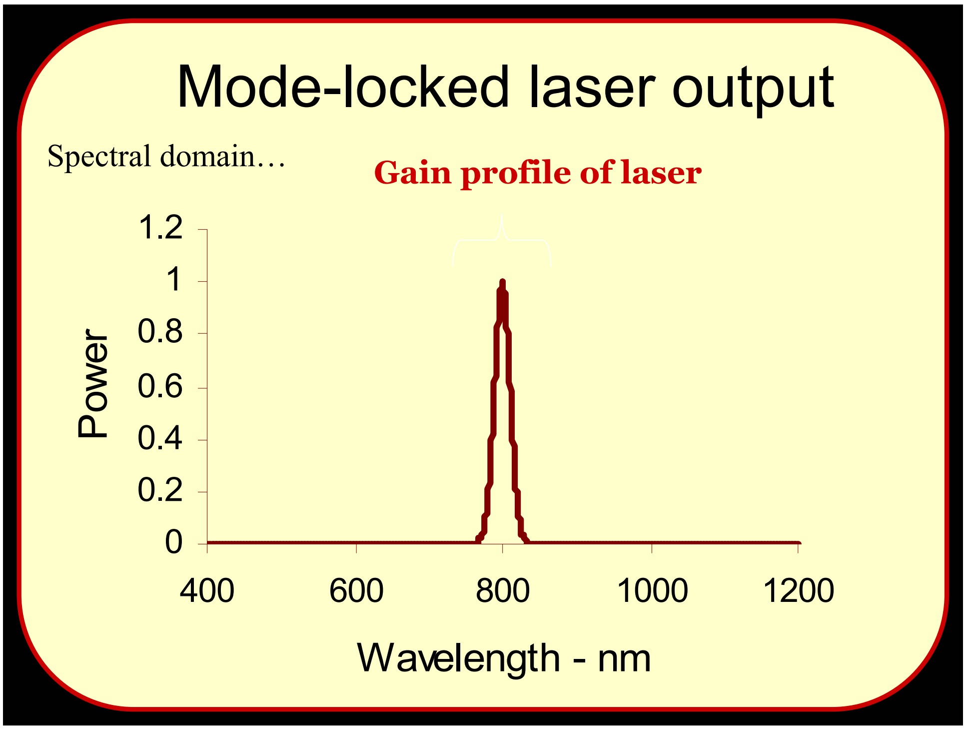


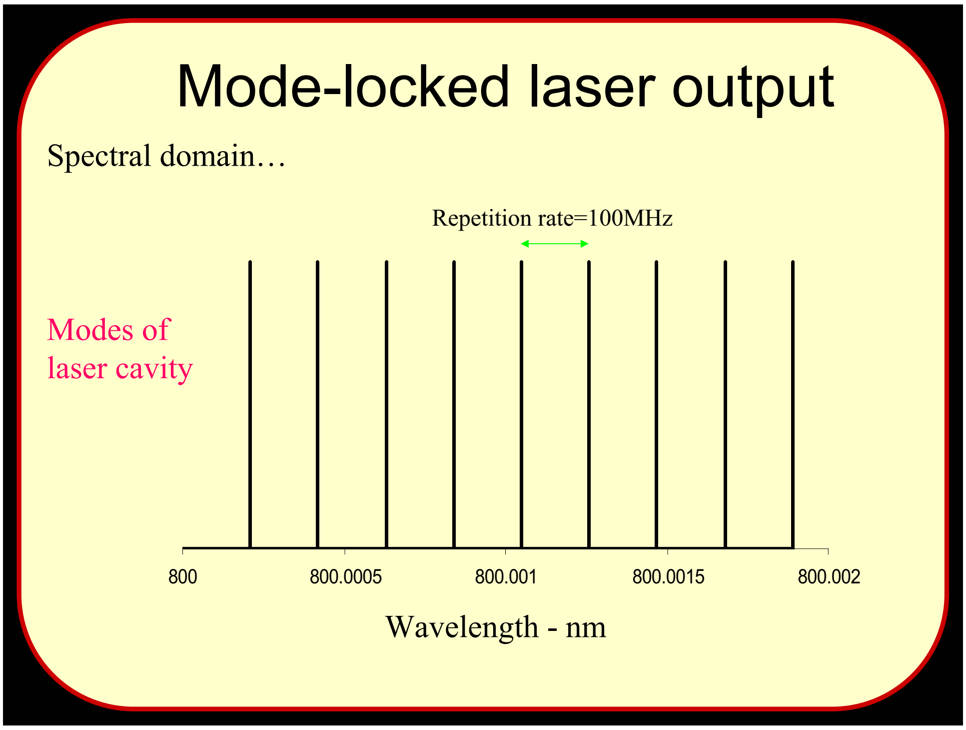
Mode-locked laser running on fifteen longitudinal modes



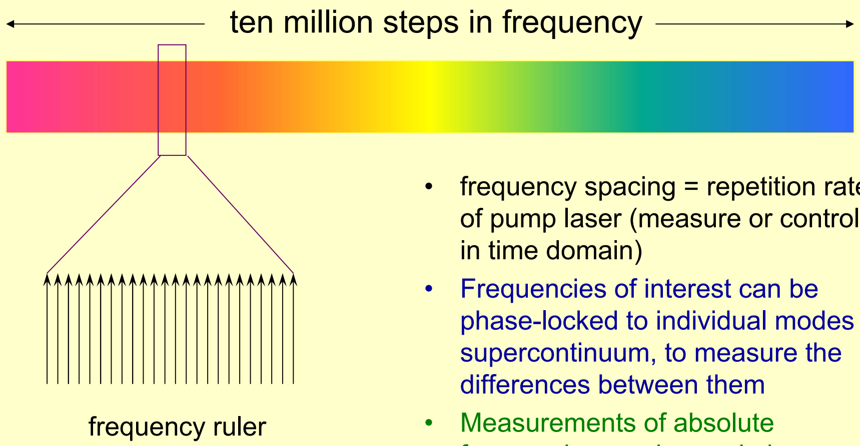
Mode-locked laser output




Mode-locked laser output
Spectral domain…
Gain profile of laser
1.2
1
0.8
0.6
0.4
0.2
0
Power
400
600
800
1000
1200
Wavelength - nm


Mode-locked laser output
Spectral domain…
Repetition rate=100MHz
Modes of
laser cavity
800
800.0005
800.001
800.0015
800.002
Wavelength - nm

Supercontinuum is a frequency ruler

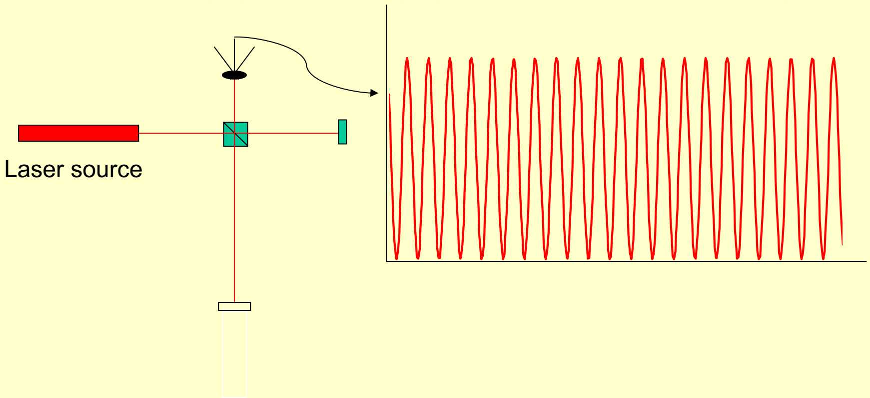


- frequency spacing = repetition rate of pump laser (measure or control in time domain)
- Frequencies of interest can be phase-locked to individual modes of supercontinuum, to measure the differences between them
- Measurements of absolute frequencies can be made by measuring 2f-f

Work done by:Ted Hänsch, MPI Garching
John Hall, JILA

Optical coherence tomography

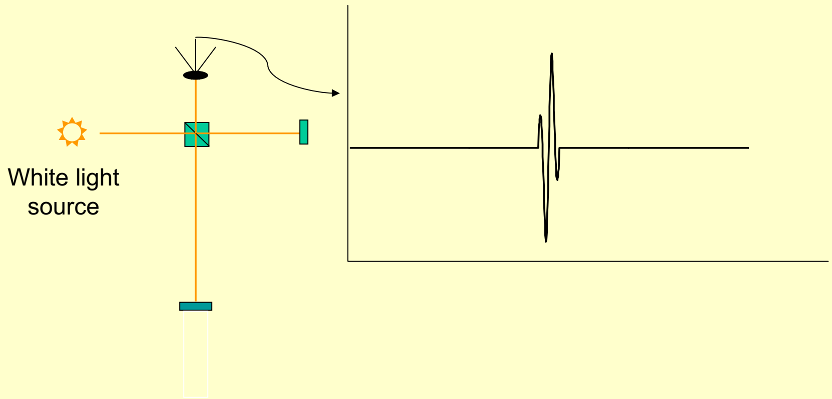
Medical imaging technique, relying on low-coherence interferometry



Remember that coherence length is inversely related to bandwidth.

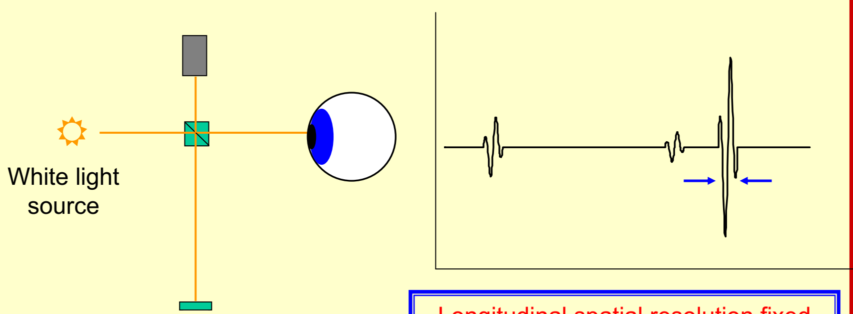
Optical coherence tomography

Medical imaging technique, relying on low-coherence interferometry



OCT

Medical imaging technique, relying on low-coherence interferometry



Longitudinal spatial resolution fixed by bandwidth of source

This is used to do a 2-dimensional scan of the eye, or even skin.

Selected reading

Reviews:
J. C. Knight, Nature, **424**, 847 (2003)
P. St. J. Russell, Science **299**, 358 (2003)

Classic papers:
Kaiser, P. & Astle, H. W., Low loss single material fibers made from pure fused silica. Bell Syst. Tech. Journ. 53 1021-1039 (1974)
Knight, J. C., Birks, T. A., Russell, P. St.J. and Atkin, D. M., All-silica single-mode optical fiber with photonic crystal cladding Opt. Lett. 21 1547-1549 (1996), errata 22 484 (1997)
Birks, T. A., Knight, J. C. and Russell, P. St.J., Endlessly single-mode photonic crystal fiber. Opt. Lett. 22 961-963 (1997)
Kumar, V. V. R. K. et al. Extruded soft glass photonic crystal fiber for ultrabroad supercontinuum generation. Opt. Express 10 1520-1525 http://www.opticsexpress.org/abstract.cfm?URI=OPEX-10-25-1520 (2002)
Ranka, J. K., Windeler, R. S. and Stentz, A. J. Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800nm. Opt. Lett. 25 25-27 (2000)
Udem, T., Holzwarth, R. and Hänsch, T. W. Optical frequency metrology. Nature 416 233-237 (2002)
Povazay, B. et al. Submicrometer axial resolution optical coherence tomography. Opt. Lett. 27 1800-1802 (2002)

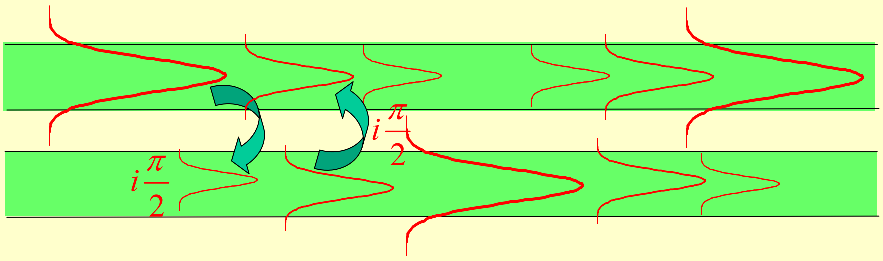
Topical work:
B. Zsigri *et al.*, Demonstration of broadcast, transmission and wavelength conversion functionalities using photonic crystal fibers. IEEE Photon. Technol. Lett. **18** 2290 (2006)
J. H. Rothwell *et al.* Photonic sensing based on variation of propagation properties of photonic crystal fibers. Optics Express **14** 12445 (2006)
H. Hasegawa *et al.* 10Gb/s transmission over 5km at 850nm using single-mode photonic crystal fiber, single-mode VCSEL and Si-APD. IEICE Electronics Express
E. F. Chilcce *et al.*, Tellurite photonic crystal fiber made by a stack-and-draw technique. Journ. Non-Crystalline Solids **352** 3423 (2006)

Bandgap fibres

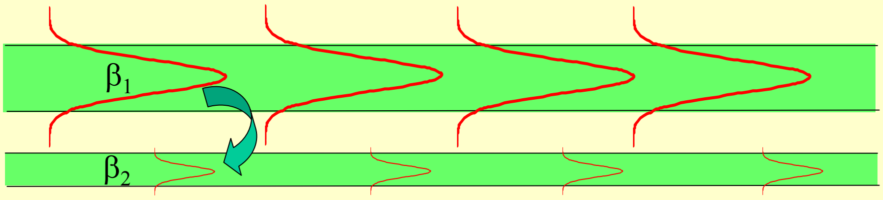
Overview of this section

- Multi-core fibres and photonic bandgaps
- Simple bandgap fibres
- Bend loss and simple bandgap fibre designs
- Hollow core photonic bandgap fibres
- Scattering and loss in HC PBGF's
- 7-cell and 19-cell designs
- HC-PBGF's for the mid-infrared

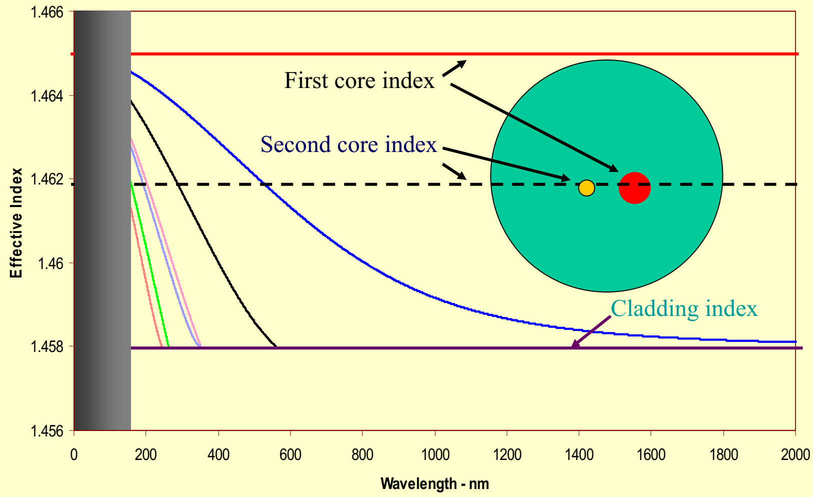
Light in identical coupled fibres

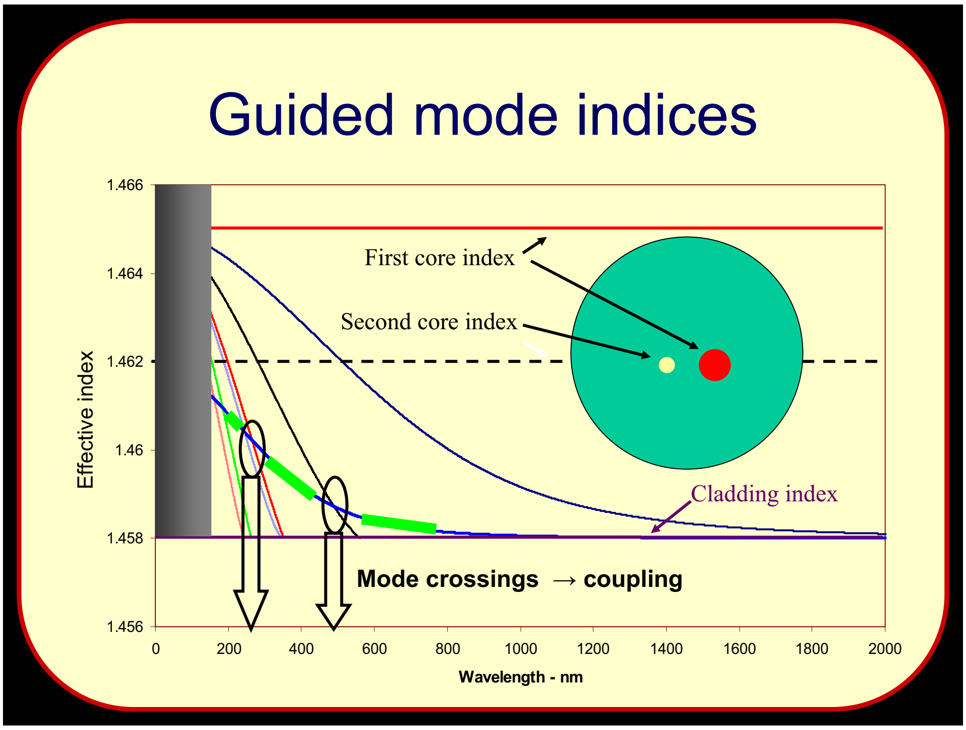


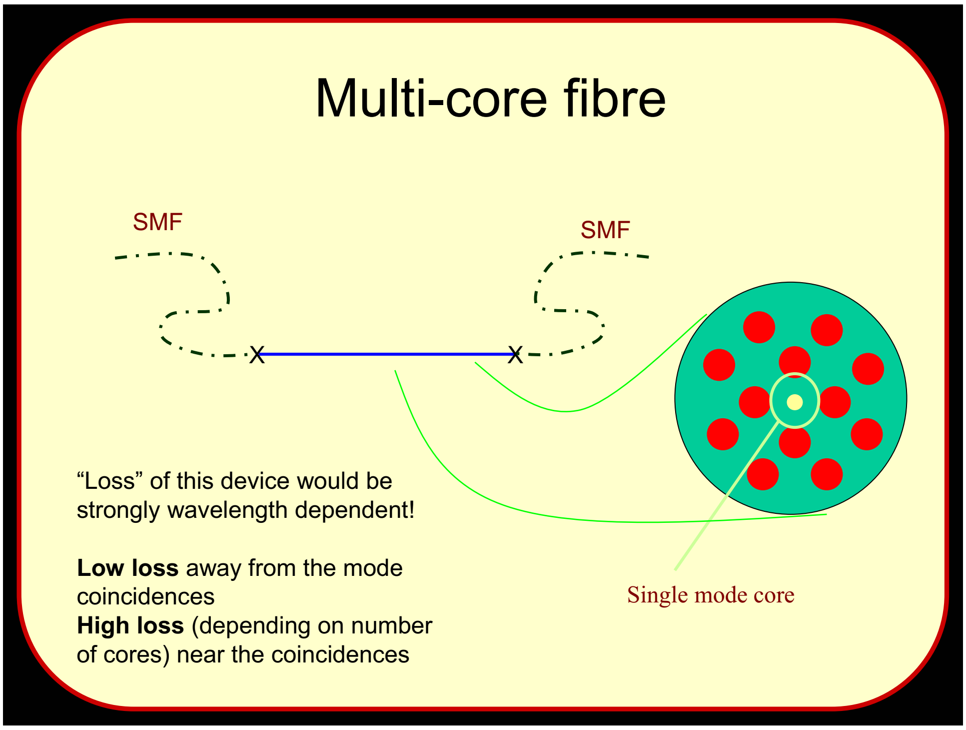
What if the fibres are different?



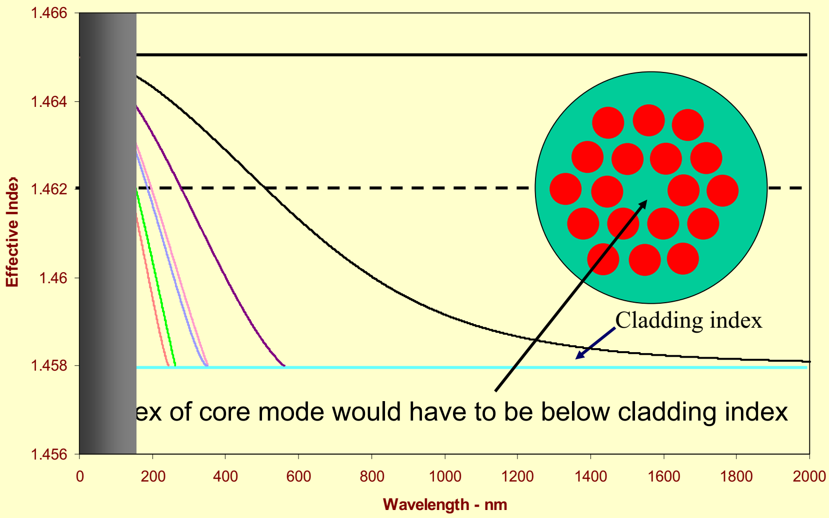
Guided mode indices



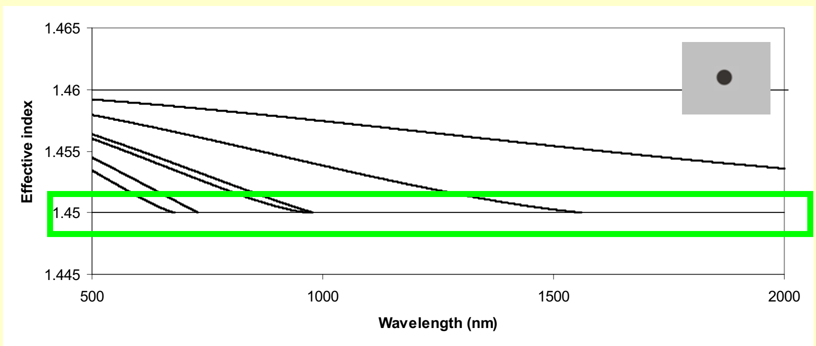

Guided mode indices
First core index
Second core index
Cladding index
Mode crossings → coupling
Effective index
1.466
1.464
1.462
1.46
1.458
1.456
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Wavelength - nm


Multi-core fibre
SMF
SMF
Single mode core
"Loss" of this device would be strongly wavelength dependent!
Low loss away from the mode coincidences
High loss (depending on number of cores) near the coincidences

Guided mode indices



Guided modes in a standard fibre

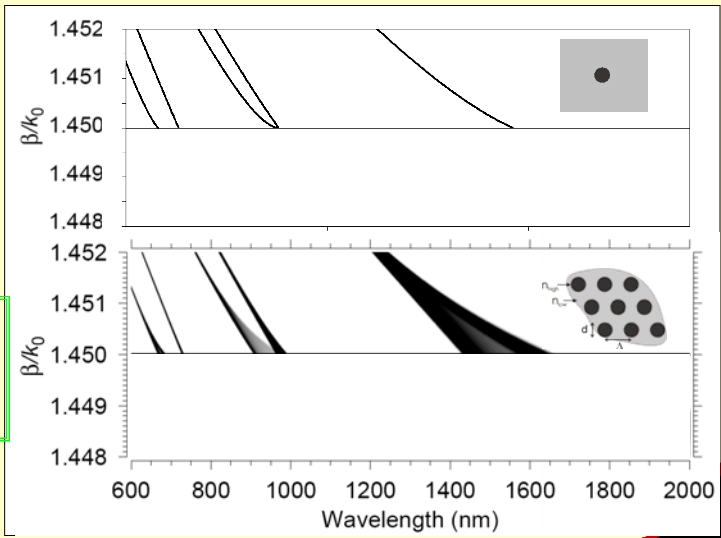


Core index 1.46
Cladding index 1.45
Core diameter 7μm

Guided modes and band gaps

Guided modes of a single core

Density of states: periodic array of cores

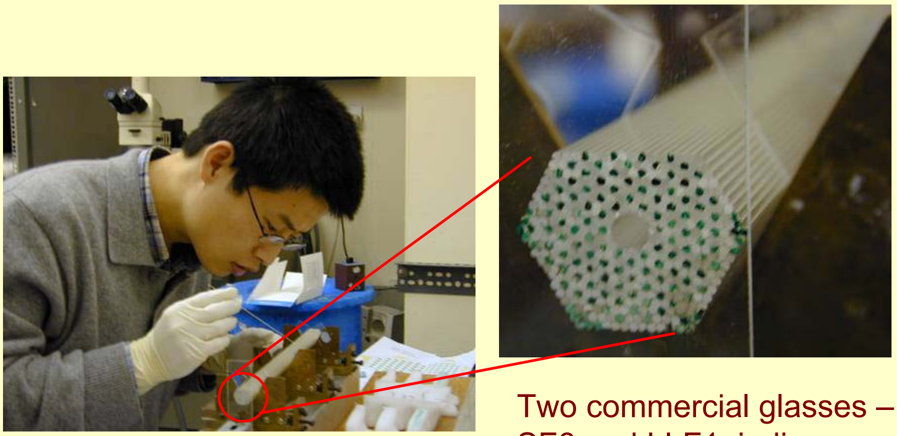


Demonstrations of “simple” bandgap fibres

- Liquid-filled holey glass fibre[1]
- Two different glasses in an all-solid fibre[2]
- Doped and undoped silica in an all-solid fibre[3]
- Liquid-crystal based PBG fibre devices[4]

1. J. Jasapara *et al* OFC 2002 519 (2002).
2. F. Luan *et al,* Opt. Lett. **29** 2369 (2004)
3. A. Argyros *et al*, Opt. Express **13** 309 (2005)
4. T. Larsen *et al,* Opt. Express **11** 2589 (2003)

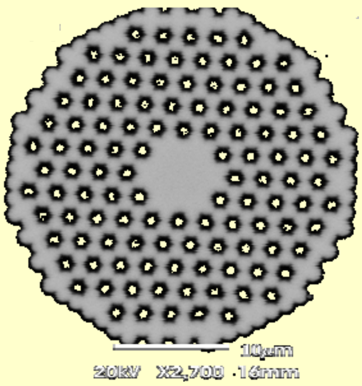
Fabricating a simple photonic bandgap fibre

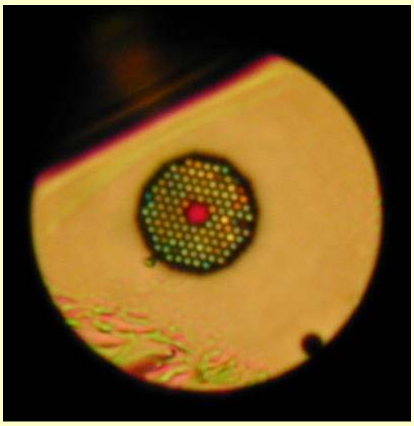


Two commercial glasses – SF6 and LLF1, indices 1.54 and 1.79

"All-solid photonic bandgap fiber", F. Luan *et al,* Opt. Lett. **29** 2369 (2004)

"Simple" bandgap fiber

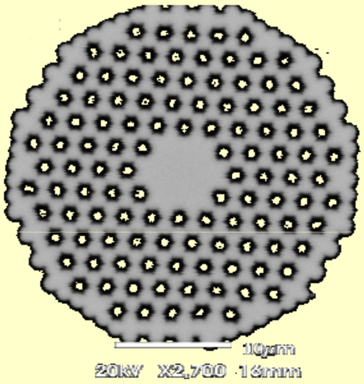


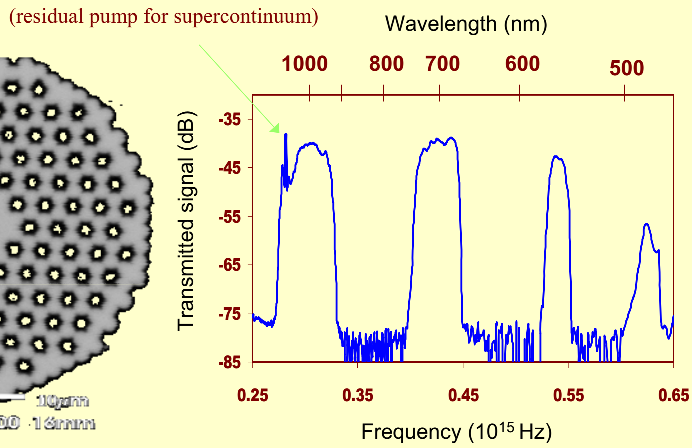


(light = high index)

"All-solid photonic bandgap fiber", F. Luan *et al,* Opt. Lett. **29** 2369 (2004)

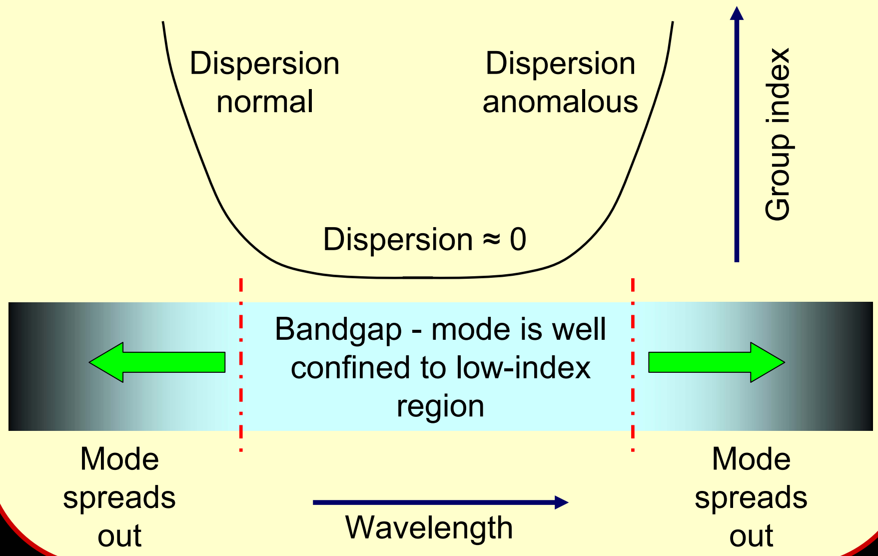
“Simple” bandgap fiber

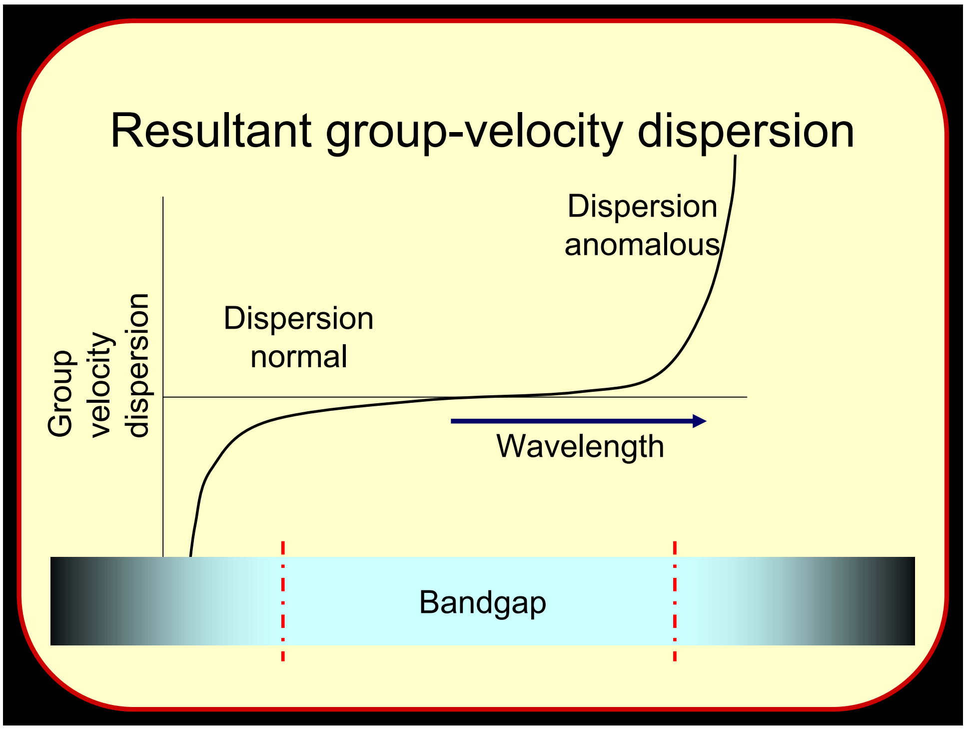


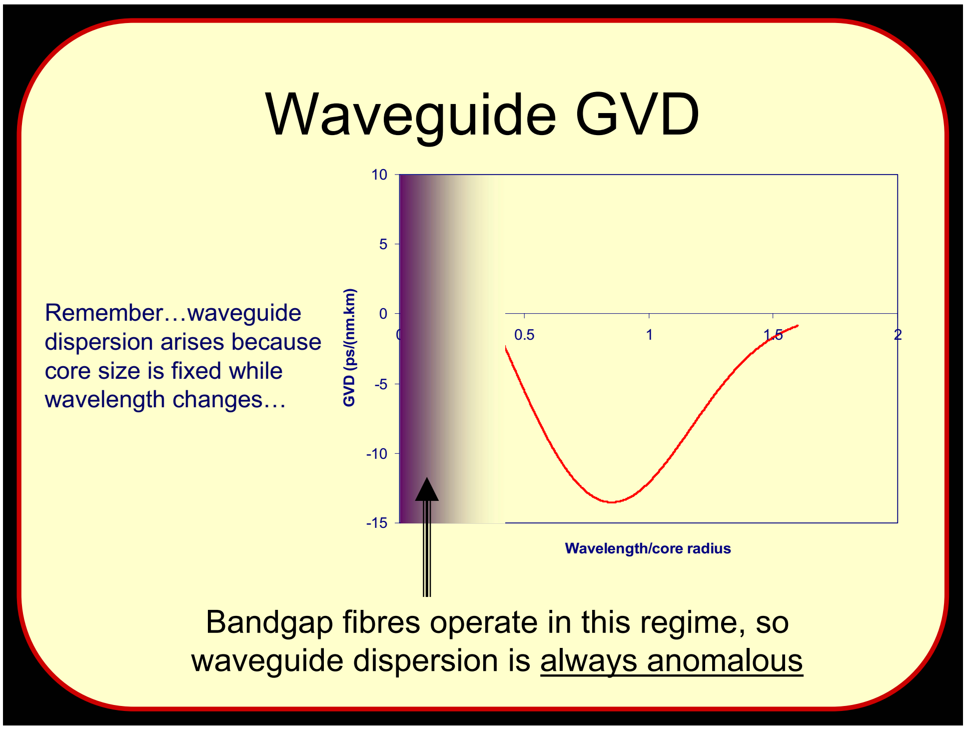


“All-solid photonic bandgap fiber”, F. Luan *et al,* Opt. Lett. **29** 2369 (2004)

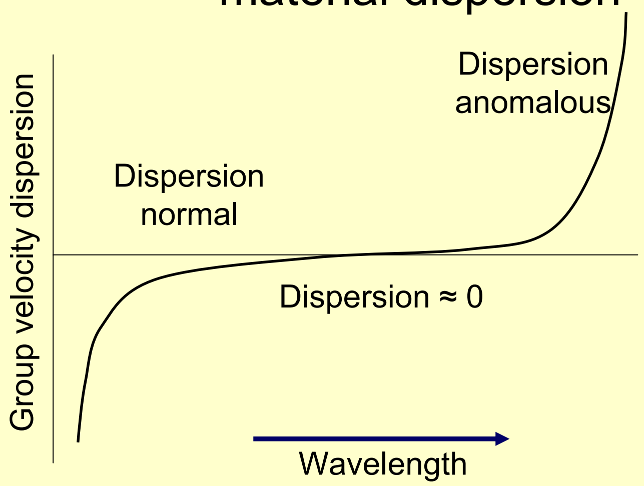
Dispersion in a PBG fibre




Resultant group-velocity dispersion
Dispersion anomalous
Dispersion normal
Group velocity dispersion
Wavelength
Bandgap

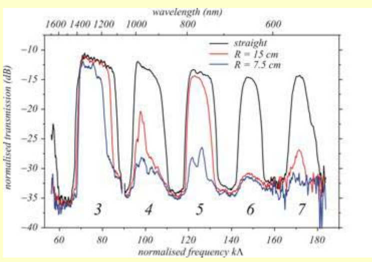

Waveguide GVD
Remember…waveguide dispersion arises because core size is fixed while wavelength changes…
10
5
0
-5
-10
-15
0.5
1
1.5
2
GVD (ps/(nm.km)
Wavelength/core radius
Bandgap fibres operate in this regime, so waveguide dispersion is always anomalous

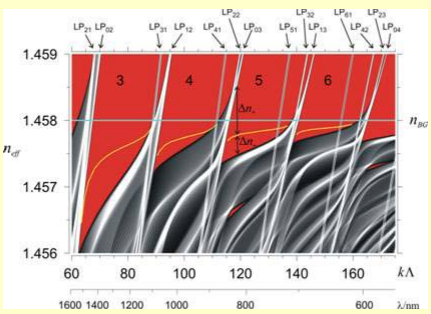
Effect of waveguide dispersion + material dispersion



Bend loss

- Even and odd bandgaps suffer different bend loss
- Varying ‘depth’ , Δn

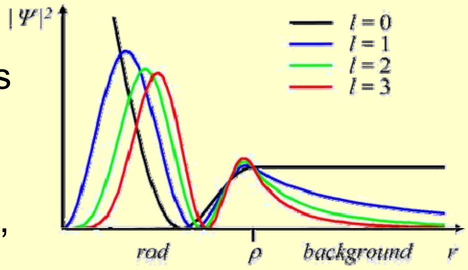




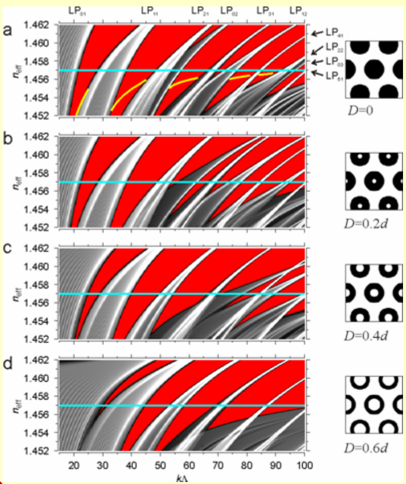
- Cladding density of states (DOS) plot
- Fundamental core guided mode shown in yellow

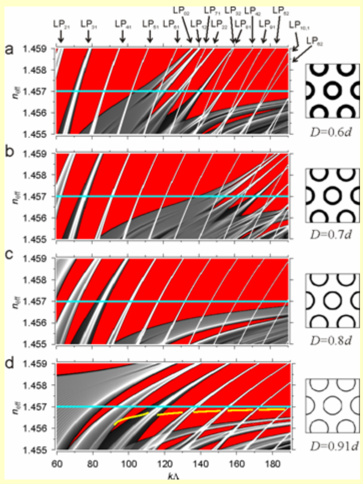
Cladding modes $LP_{l,m}$

- Decay rate determines how strongly the rod modes couple
- For l=0 modes Ψ does not decay, strongly coupled
- For l=1 Ψ does decay, weakly coupled

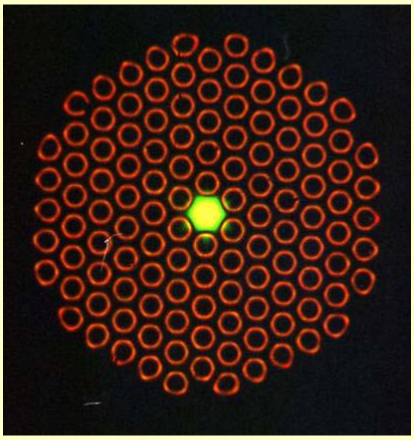


Evolution of the ring band gaps

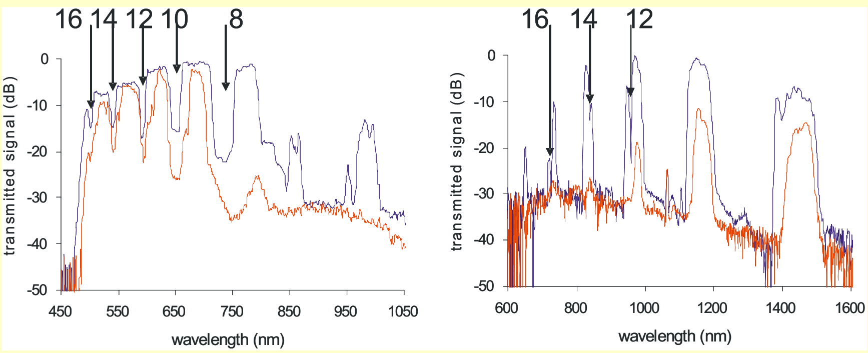




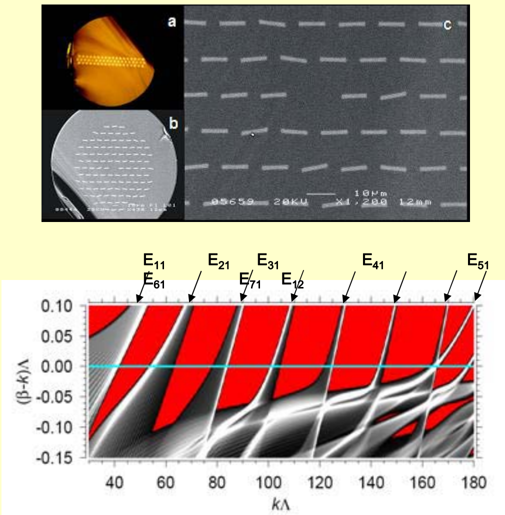
THE RING FIBRE



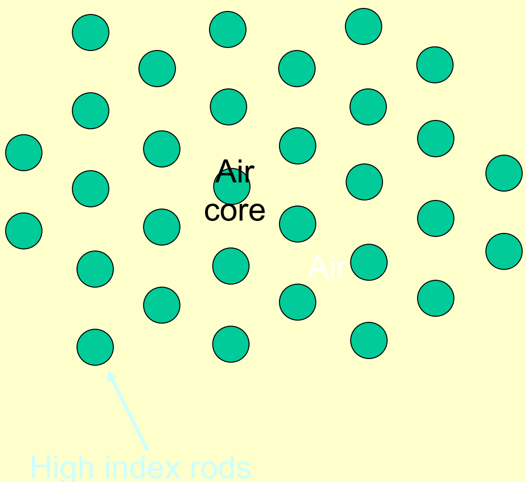
Comparison of rods and rings



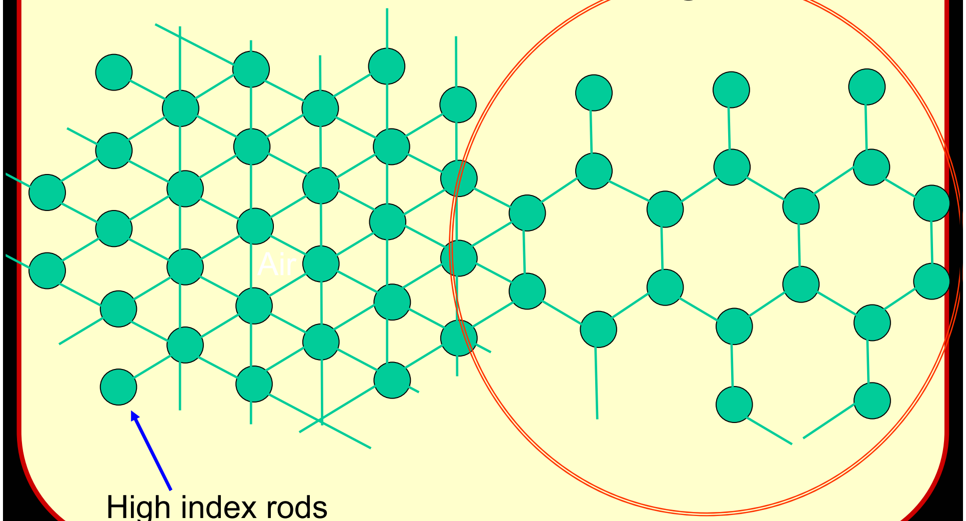
“Pencil” fibre



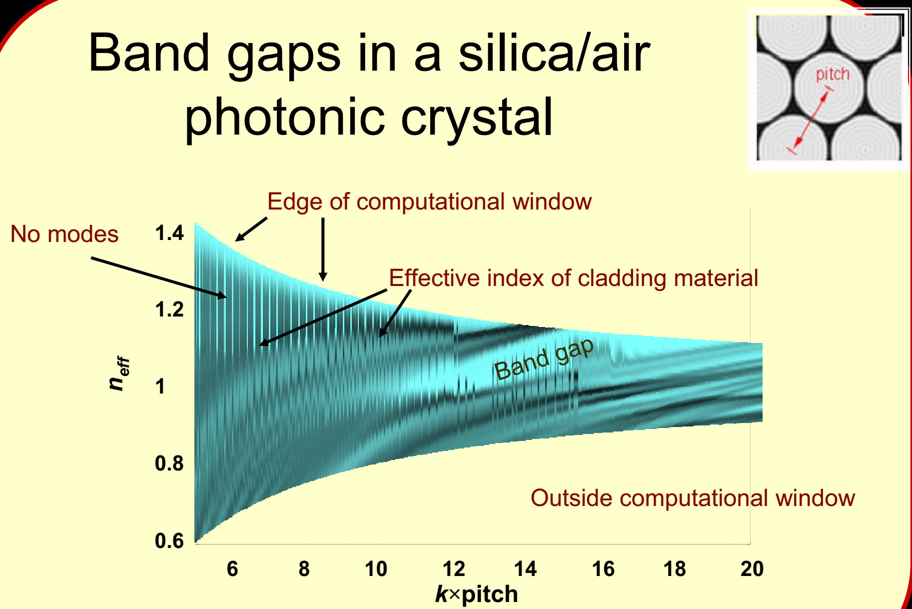
How to make an air-guide



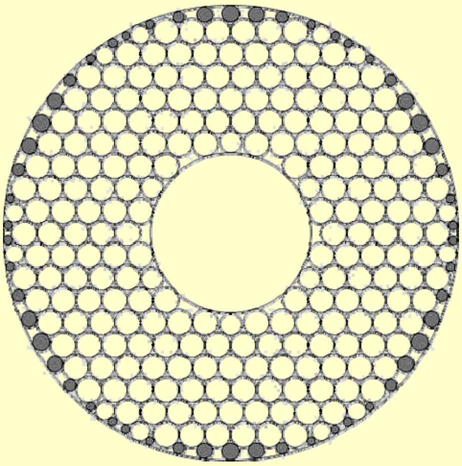
How to make an air-guide



Band gaps in a silica/air photonic crystal

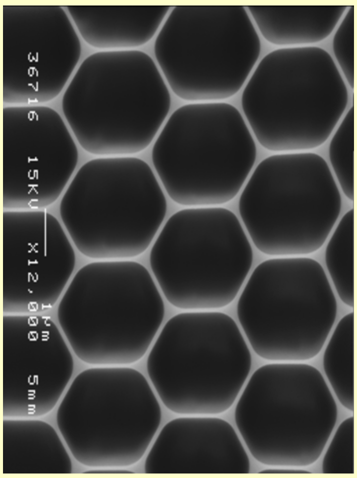


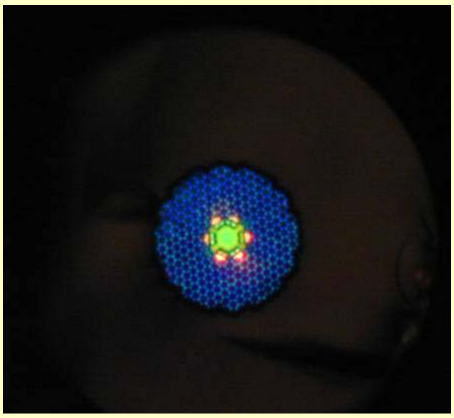
How to fabricate a hollow-core fibre



A round core can be formed by:
Omitting 1 unit cell (too small)
Omitting 7 cells
Omitting 19 cells
Omitting 37 cells…
etc.

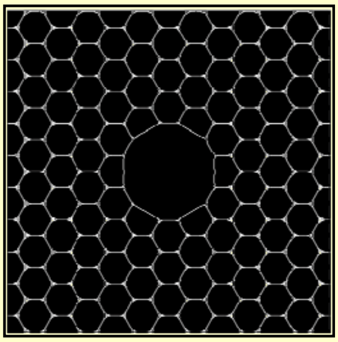
Working hollow-core fiber…



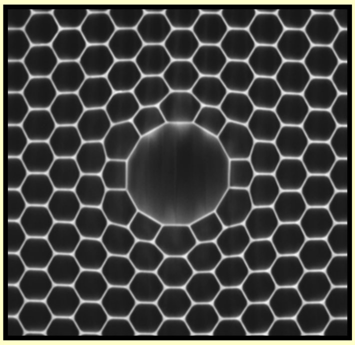


R. F. Cregan *et al,* Science **285** 1537 (1999)
C. M. Smith *et al*, Nature ***424*** 657 (2003)

Air mode guided in a band gap

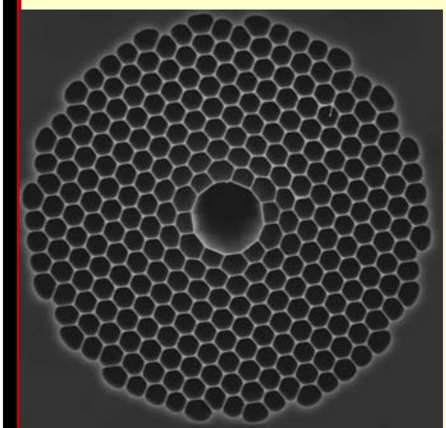


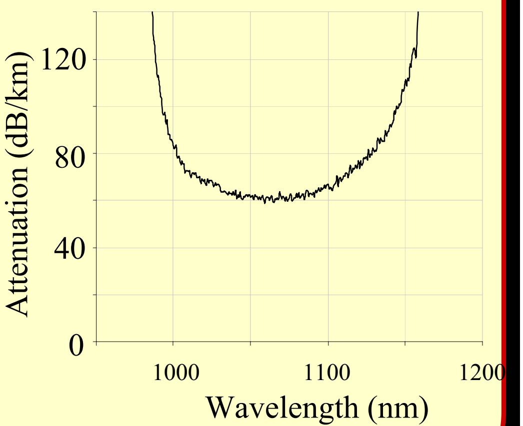
Modelled



Fabricated

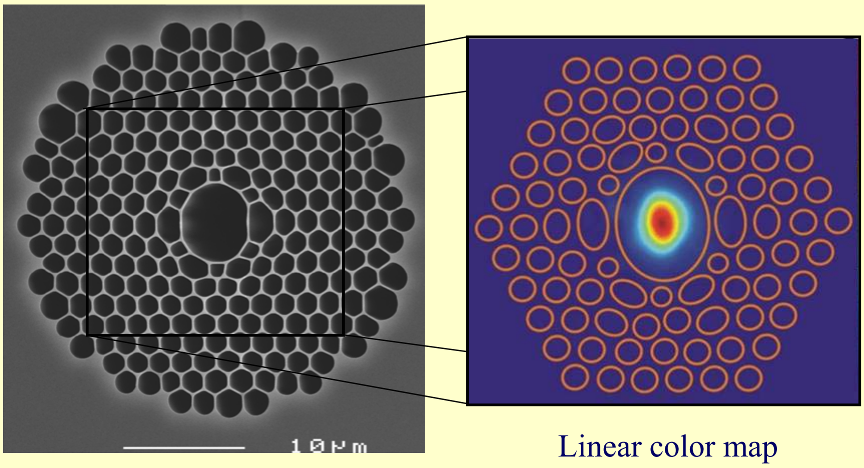
Hollow-core fiber





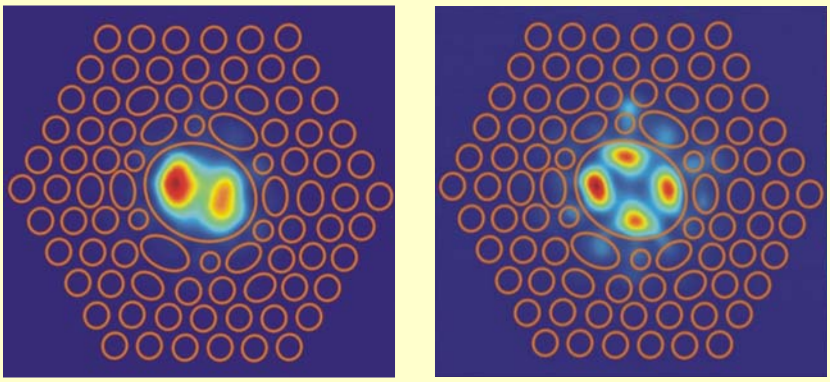
$\Lambda = 3\mu m$
FF > 90%
…with 7-cell defect

Near field patterns – 60m length



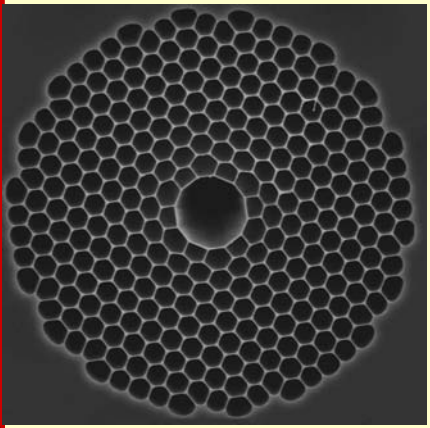
Linear color map

Higher-order modes – 1 meter length



Linear color map

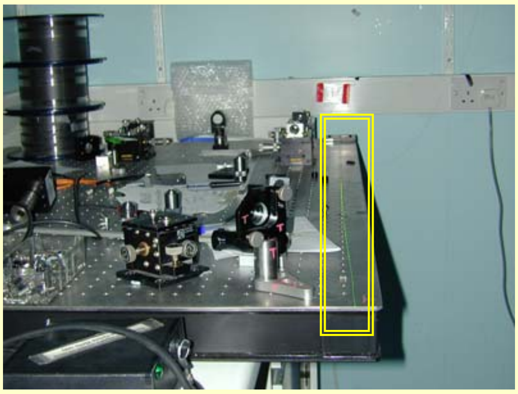
Hollow-core fiber



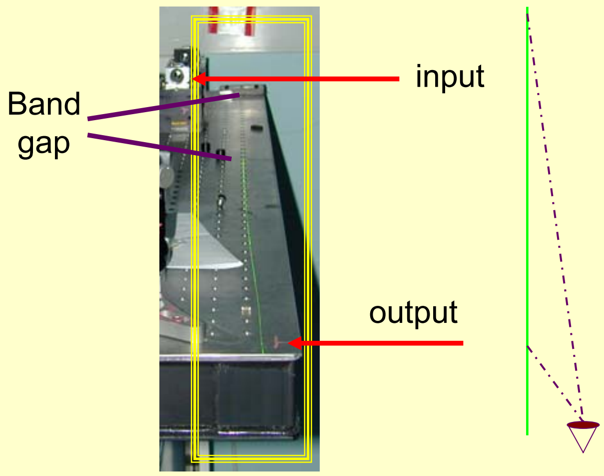
<u>What determines minimum attenuation?</u>

- Light is scattered out of fundamental mode, into (core-) guided or (cladding-) propagating modes
- Scattering is due to small-scale irregularities/roughness on glass surface

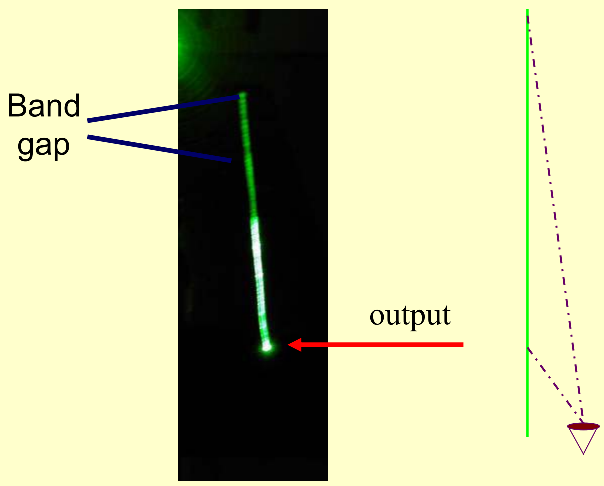
Hollow-core fiber guiding green light



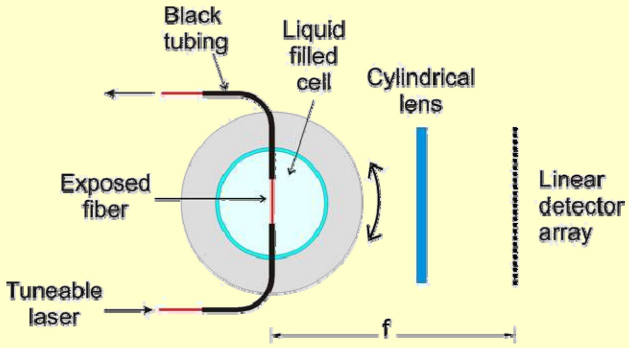
Band gap is visible!



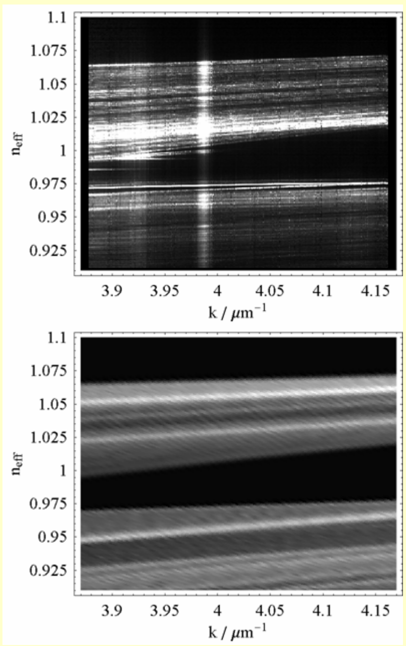
Band gap is visible!



Measure the scattering as a function of β

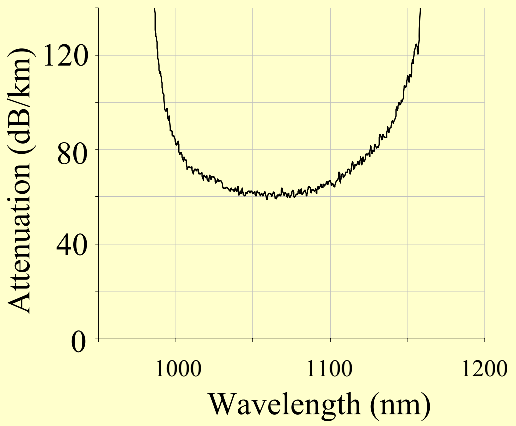


Computed and observed bandgaps



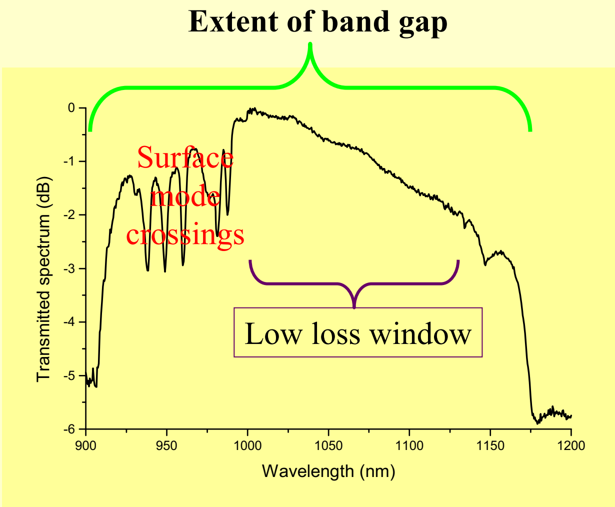
F. Couny et al, Opt. Express, **13** 558 (2005)

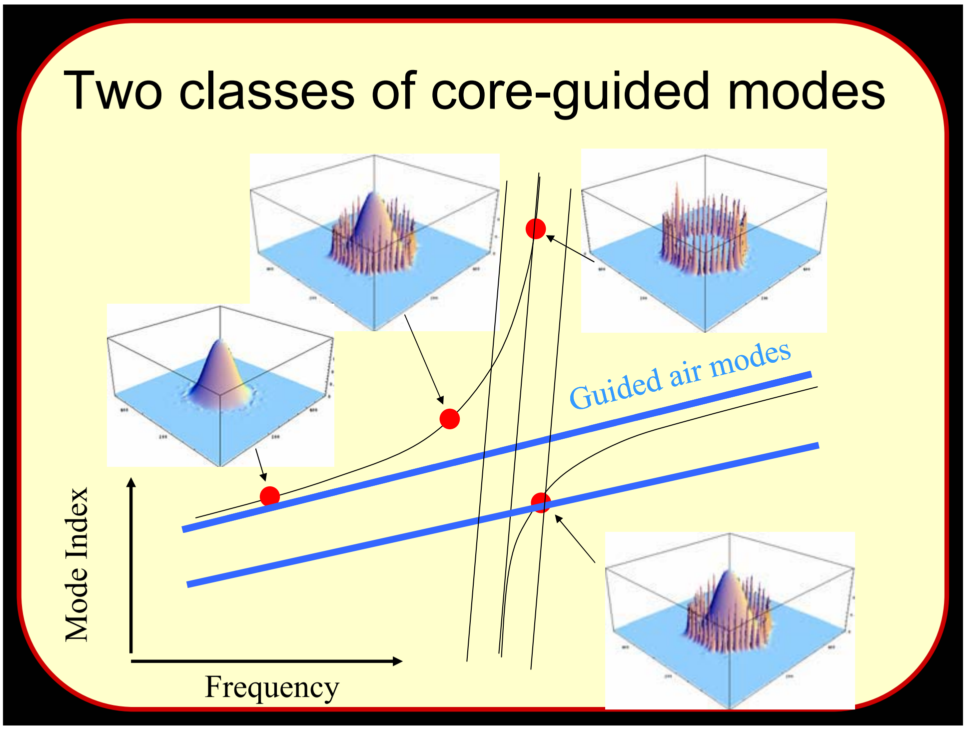
Hollow-core fiber

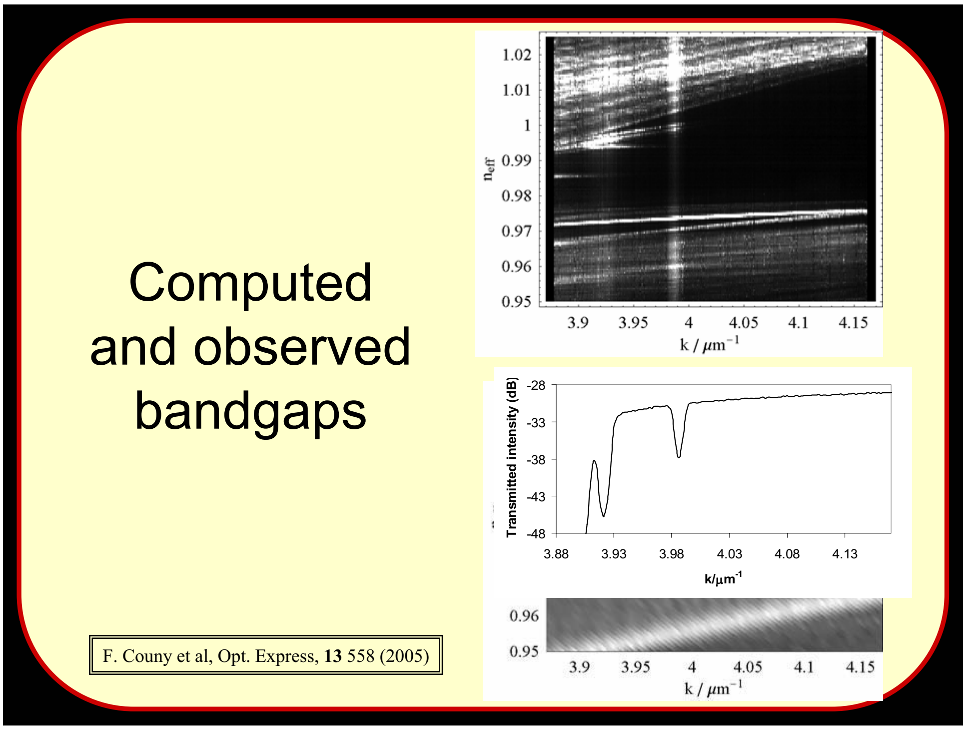


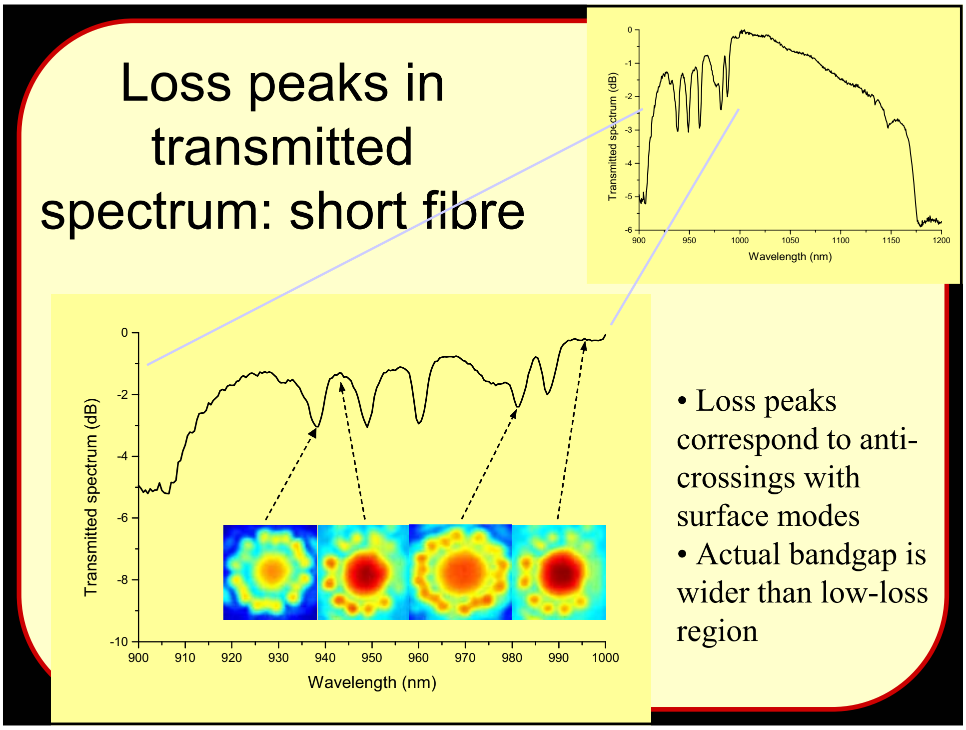
$\Lambda = 3\mu m$
FF > 90%
…with 7-cell defect

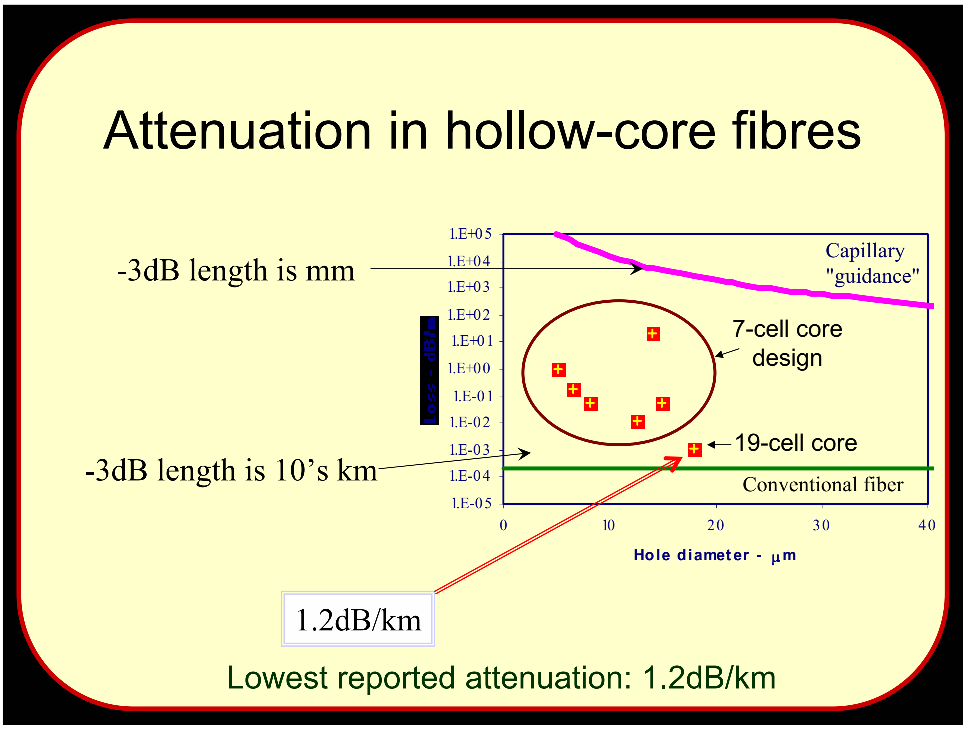
Loss peaks in transmitted spectrum



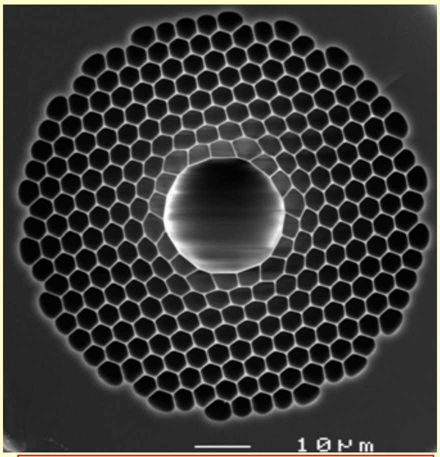

Two classes of core-guided modes
Guided air modes
Mode Index
Frequency


Computed and observed bandgaps
F. Couny et al, Opt. Express, **13** 558 (2005)
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
n_{eff}
3.9 3.95 4 4.05 4.1 4.15
$k / \mu m^{-1}$
Transmitted intensity (dB)
-28
-33
-38
-43
-48
3.88 3.93 3.98 4.03 4.08 4.13
$k/\mu m^{-1}$
0.96
0.95
3.9 3.95 4 4.05 4.1 4.15
$k / \mu m^{-1}$


Loss peaks in transmitted spectrum: short fibre
Transmitted spectrum (dB)
Wavelength (nm)
• Loss peaks correspond to anti-crossings with surface modes
• Actual bandgap is wider than low-loss region


Attenuation in hollow-core fibres
-3dB length is mm
-3dB length is 10's km
Capillary "guidance"
7-cell core design
19-cell core
Conventional fiber
Hole diameter - μm
1.2dB/km
Lowest reported attenuation: 1.2dB/km

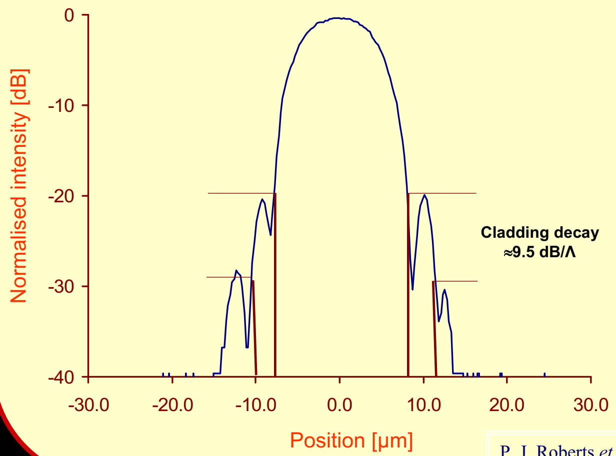
Low-loss fibres: larger core

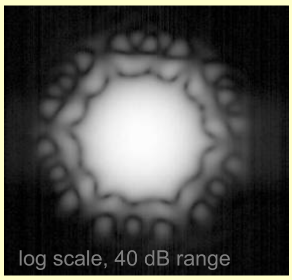


Fiber with 19-cell hollow core

- 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 carefully chosen

Mode profile in a 19-cell hollow core



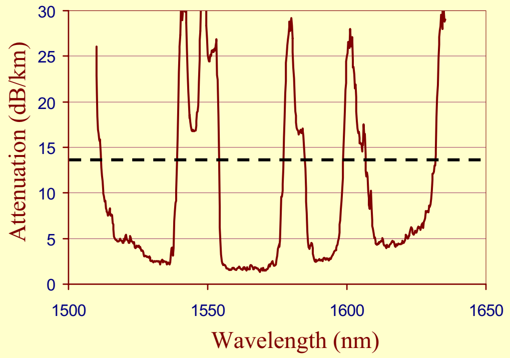


Fraction of light in

core	: 98.4%
cladding holes	: 1%
glass	: 0.6%

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

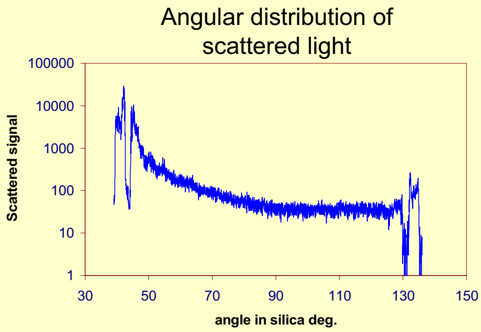
Attenuation in a large-core fibre



- 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…

What limits the attenuation?

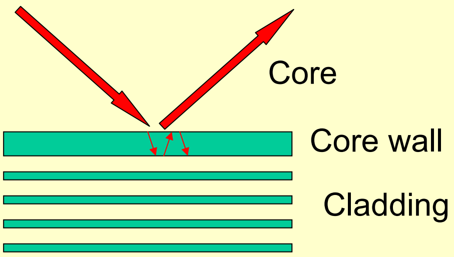
- Scattering by roughness at the silica/air surfaces is very strong, because of the massive dipole moment
- Such roughness is probably intrinsic, due to frozen-in and thermally-excited capillary waves. These result in the observed scattering



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

What can be done to reduce scattering?

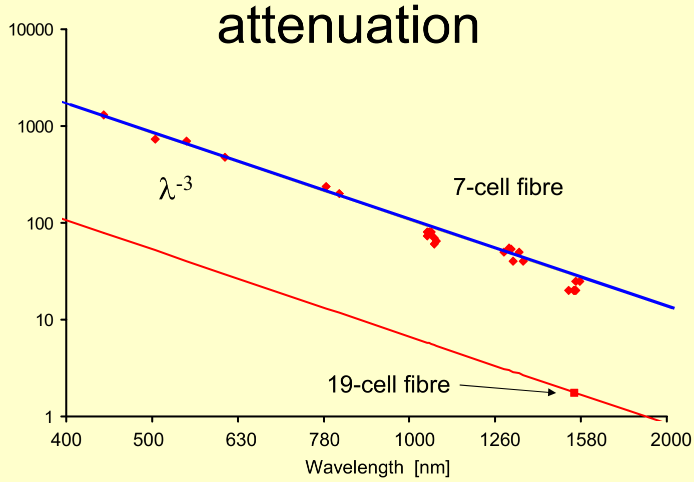
- Obvious – reduce overlap of the guided mode with the core walls!!



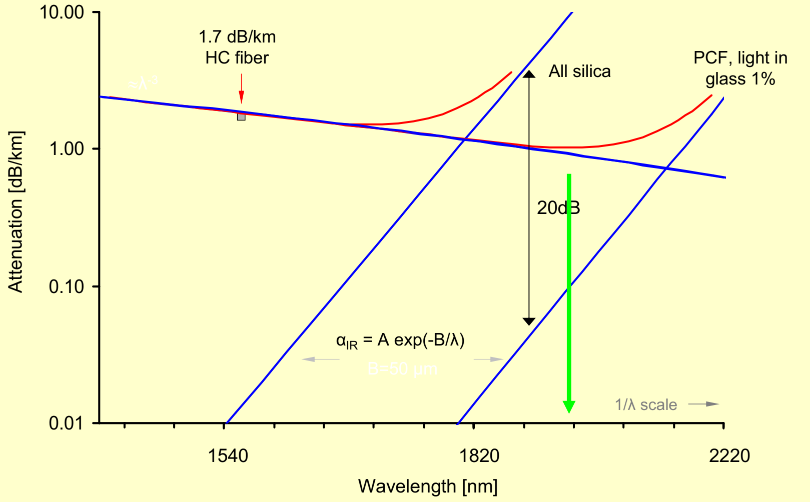
Core wall must be made anti-resonant as well!

Core wall thickness must be $t = \dfrac{\lambda}{4\sqrt{n^2 - 1}}$

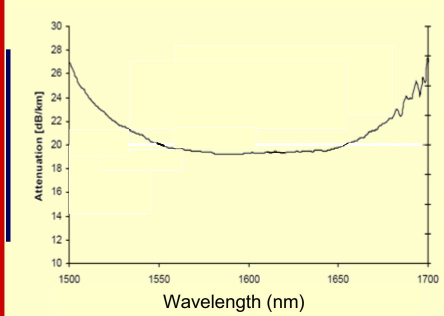
Wavelength dependence of attenuation

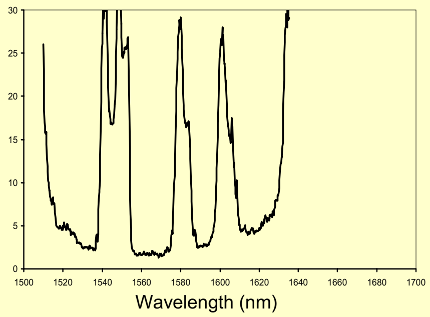


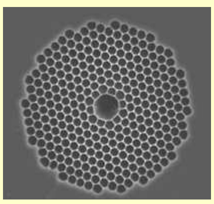
MINIMUM ATTENUATION WAVELENGTH

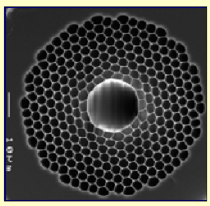


Comparison of 7-cell and 19-cell HC designs

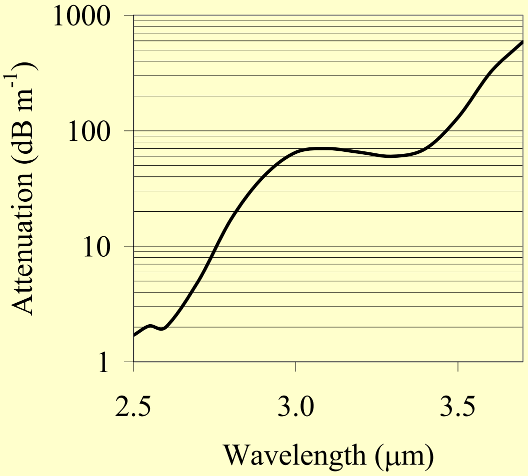




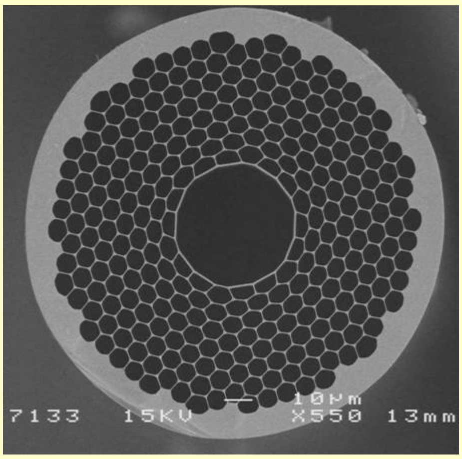




Attenuation of bulk silica

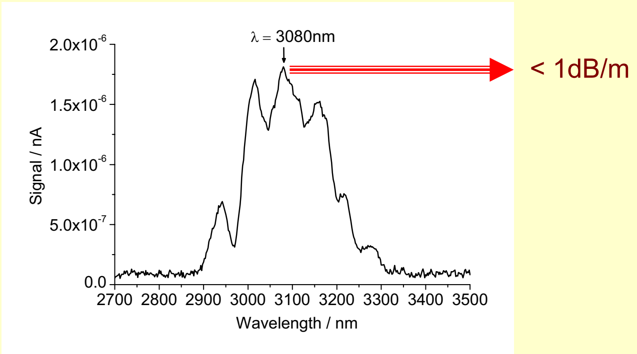


Mid-Infrared beam delivery using a silica fibre



- Hollow-core fibre for the mid-IR
- 43 µm core, 8 µm pitch, 160µm OD

Mid-Infrared beam delivery using a silica fibre



Silica-based fibre with just 1/50th the attenuation of bulk silica

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

Selected background reading

Reviews:

J. C. Knight, Nature, **424**, 847 (2003)
P. St. J. Russell, Science **299**, 358 (2003)

Classic papers:

J. C. Knight *et al.* "Photonic bandgap guidance in optical fibers" Science **282,** 1476 (1998)
R. F. Cregan *et al.* "Single-mode photonic bandgap guidance of light in air", Science **285,** 1537 (1999)
N. M. Litchinitser *et al.*, "Antiresonant reflecting photonic crystal optical waveguides," Opt. Lett. 27, 1592 (2002).
D. G. Ouzounov *et al.* "Generation of megawatt optical solitons in hollow-core photonic bandgap fibers" Science **301,** 1702 (2003)

Topical work:

R. Amezcua-Correa *et al.* "Optimizing the usable bandwidth and loss through core design in realistic hollow-core photonic bandgap fibers" Opt. Express **14,** 7974 (2006)
J. Atai *et al.* "Stability and collisions of gap solitons in a model of a hollow optical fiber" Opt. Commun. **265,** 342 (2006)
C. K. Nielsen *et al.* "A 158 fs 5.3 nJ fiber-laser system at 1 μm using photonic bandgap fibers for dispersion control and pulse compression" Opt. Express **14,** 6063 (2006)
J. M. Stone *et al.*, "An improved photonic bandgap fiber based on an array of rings" Opt. Express **14,** 6291 (2006)
C. Peucheret, "Demodulation of DPSK signals up to 40 Gb/s using a highly birefringent photonic bandgap fiber" IEEE Photon. Technol. Lett. **18** 1392 (2006)
A. Wang *et al.* "Three-level neodymium fiber laser incorporating photonic bandgap fiber" Opt. Lett. **31** 1388 (2006)
G. Bouwmans et al. "Fabrication and characterization of an all-solid 2D photonic bandgap fiber with a low-loss region (< 20 dB/km) around 1550 nm" Opt. Express **13** 8452-8459 (2005)

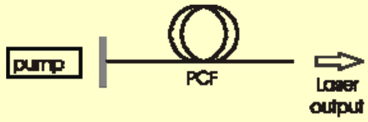
Photonic crystal fibres: The third part

More applications

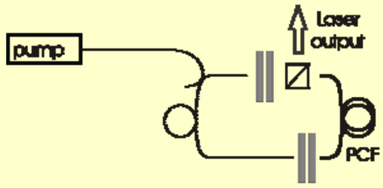
Things to do with photonic crystal fibres …

- High power lasers
- Modelocked lasers
- Pulse and beam delivery and manipulation
- Others

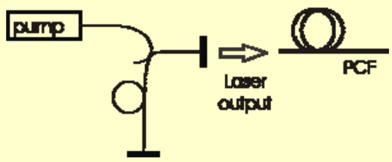
PCF fibre laser



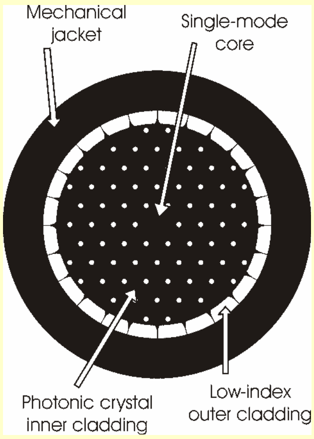
PCF in a fibre laser



PCF with a fibre laser

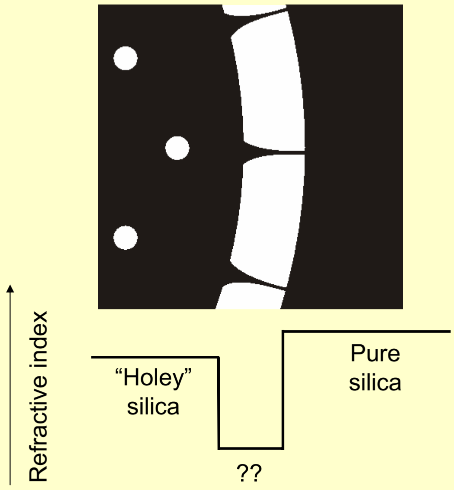


PCF fibre laser

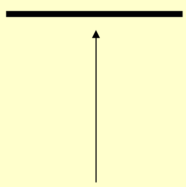


- Very high numerical aperture for cladding
- Leads to relatively small inner cladding diameters
- As a result, large ratio core/cladding
- …and short pump absorption length

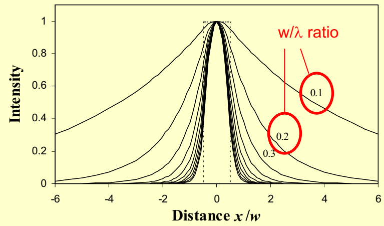
Inner cladding NA

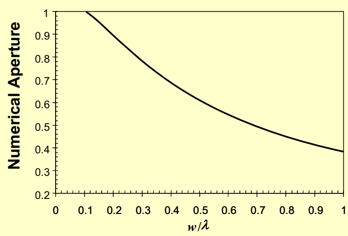


Outer cladding is made of slab waveguides



Effective index is just $n_{eff} = \beta / k$
of slab waveguide modes

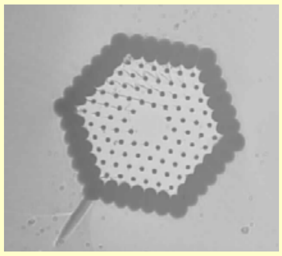


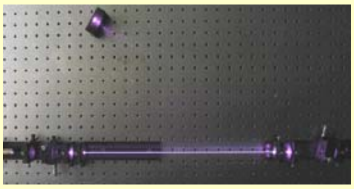


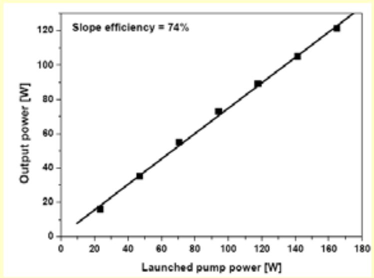
Example: Limpert *et al*

- Yb^{3+}-doped core diameter 35 μm
- Inner cladding diameter 120 μm
- Numerical aperture 0.6
- Fibre length 48 cm

- Pumped from one end
- Output power up to 120W
- 74% slope efficiency







J. Limpert *et al,* Opt. Express **13** 1055 (2005)

PCF in a fibre laser…

- Want to make use of some special property of the fibre, without completely replacing existing gain medium
- Examples are dispersion characteristics, spectral transmission

Mode-locked fibre lasers

- For mode-locked operation, want total round-trip dispersion to be close to zero. This is usually achieved by having opposite signs of dispersion in different parts of the cavity loop
- Mode-locking mechanisms are many, but some of the most popular are nonlinear polarisation evolution, SESAM

Reminder about GVD

In plain silica: GVD is anomalous at wavelengths longer than 1300nm, and normal at shorter wavelengths

In conventional fibres: GVD is <u>always normal</u> at wavelengths shorter than 1300nm. It can be normal at longer wavelengths too through fibre design. However, it is usually anomalous at wavelengths around 1550nm

In solid-core PCF: GVD can be anomalous at any wavelength longer than about 500nm, through fibre design.

In photonic bandgap fibres: GVD is normal on the short-wavelength side of each transmission window, and anomalous on the long-wavelength side

Example: modelocked fibre lasers

#1 – solid core fibre

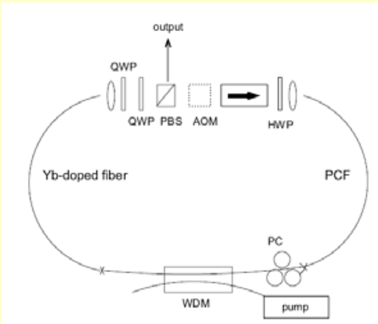
• Yb-based soliton fiber laser

• Uses PCF for anomalous dispersion around 1μm wavelength

• Yb-doped fibre allows nonlinear polarisation evolution, PCF in principle maintains polarisation

• Mode-locking initiated by AOM, but runs stably thereafter

• Still some excitation of perpendicular fibre mode, limits performance



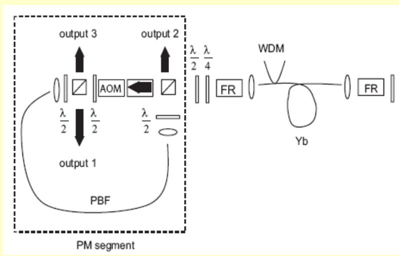
H. Lim et al, Optics Express **10** 1497 (2002)

Example: modelocked fibre lasers

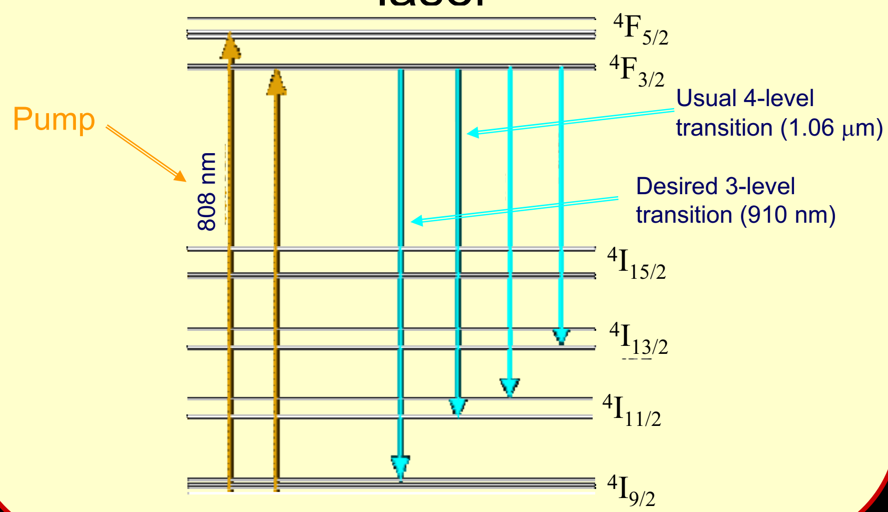
#2 – hollow core fibre

• Sigma-type cavity

• Consists of a PM loop and a linear part for NPE



Intracavity filter for 3-level fibre laser



Neodymium energy levels

Intra-cavity filter for 3-level laser

Need: strong suppression at 1.06 μm
Low attenuation at 808 nm
Low attenuation at 910 nm

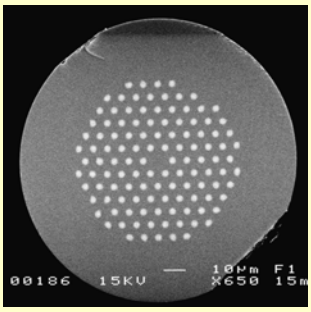
low-loss splices to gain fibre

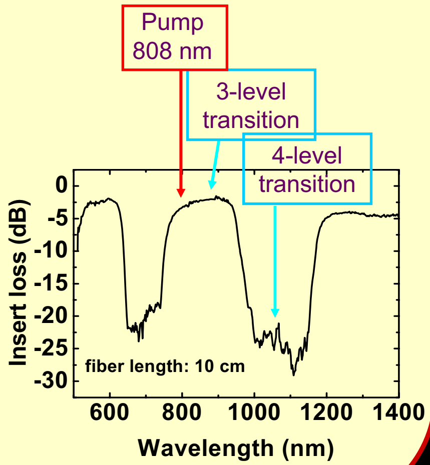
One widely-used solution: use a W-index fiber (which has a fundamental-mode cut-off).
Works reasonably well, but cannot provide a strong and sharp discrimination.

Intra-cavity filter for 3-level laser

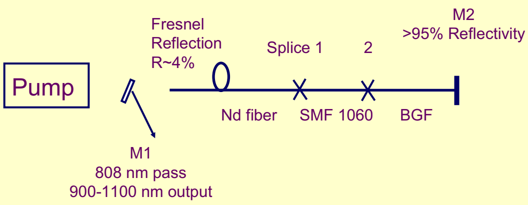
Need: strong suppression at 1.06 μm
Low attenuation at 808 nm
Low attenuation at 910 nm

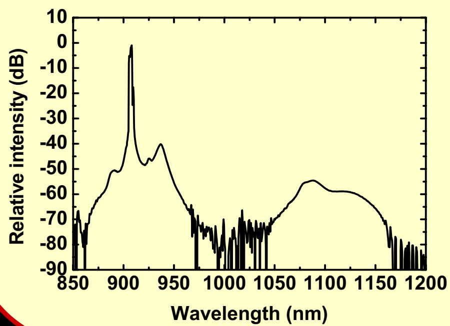
low-loss splices to gain fibre

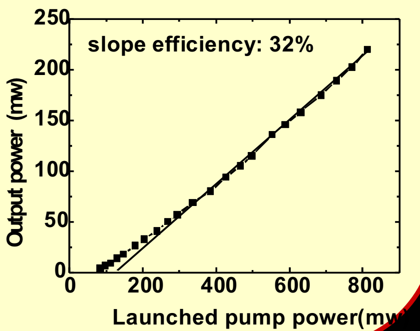




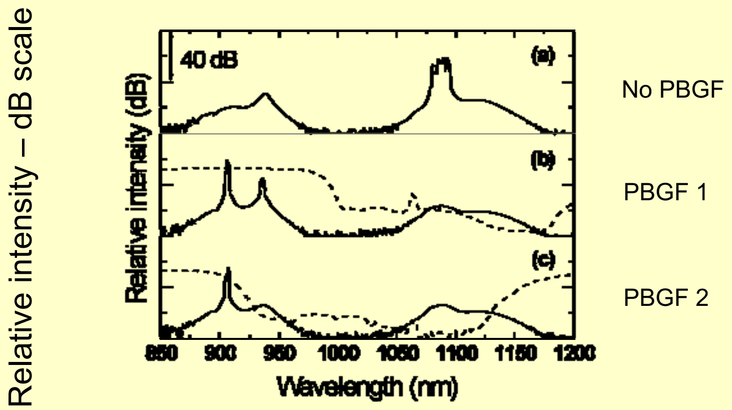
3-level neodymium fiber laser







Effect of intra-cavity PBGF



Wavelength (nm)

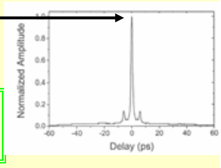
PCF with a fibre laser

- Either for beam delivery, or for beam transformations
  - Examples: high-power femtosecond pulse delivery, high power transmission, pulse compression, supercontinuum generation…

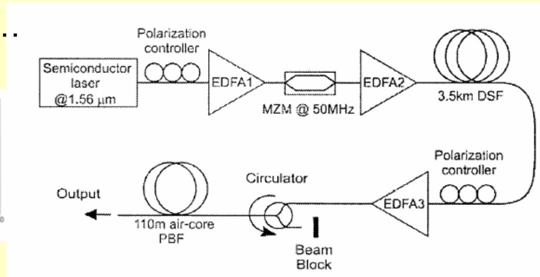
Linear use of HC dispersion…

For CPA recompression…

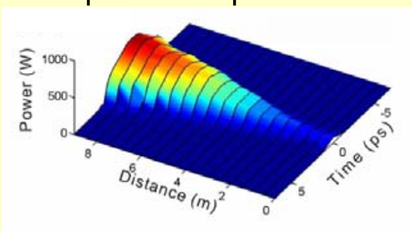
20kW peak power

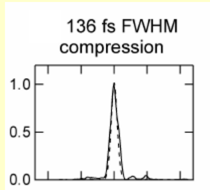


C.J.S. de Matos *et al.*, Opt. Lett., **30** 436 (2005)



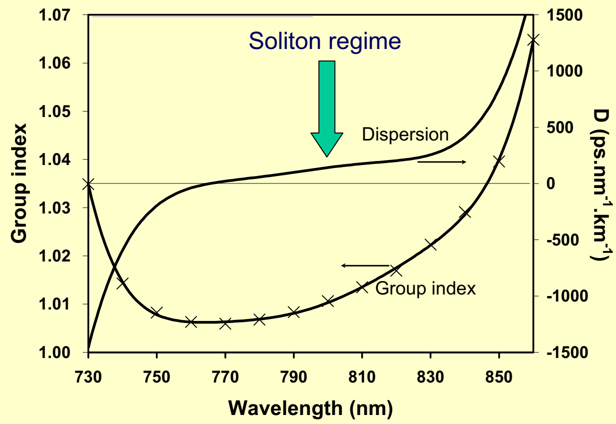
and parabolic pulse compression…



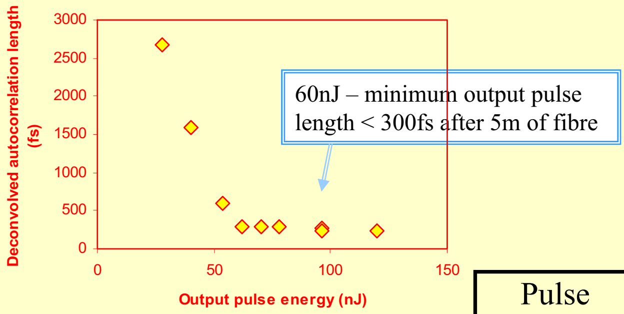


C. Billet et al., Optics Express, **13** 3236 (2005)

Group velocity dispersion at 800nm wavelength

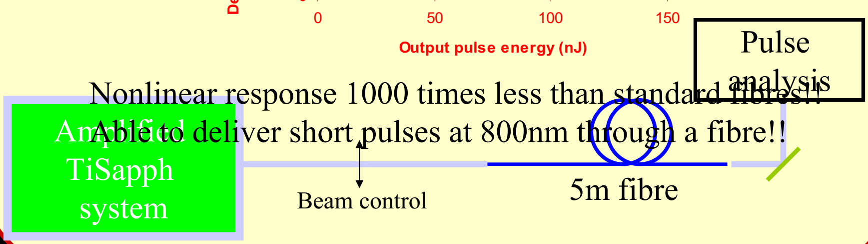


Delivering short pulses at 800nm wavelength

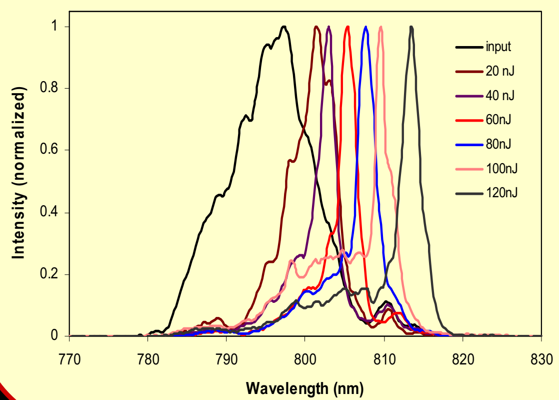


Nonlinear response 1000 times less than standard fibres!!

Able to deliver short pulses at 800nm through a fibre!!



Soliton self-frequency shift in hollow-core

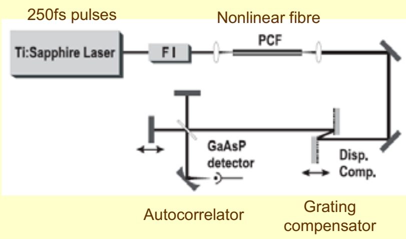


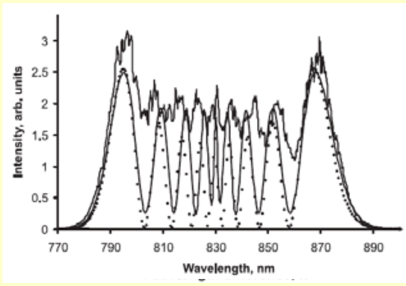
Origin of SSFS is Raman response of gas in core, with lower and much narrower gain than in silica.

(See D. G. Ouzounov *et al.*, Science **301** 1702 (2003))

Pulse compression

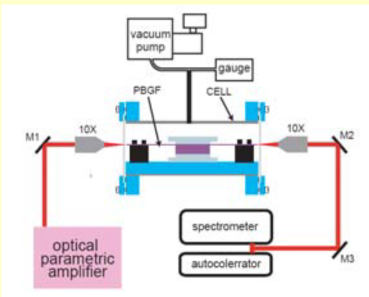
- In the normal dispersion regime, femtosecond pulse propagation is dominated by self-phase modulation
- This can be used to compress pulses…

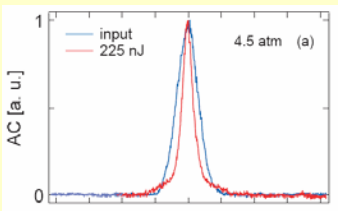




McConnell *et al.,* Appl. Phys. B **78** 557 (2004). See also Schenkel et al, JOSA B **22** 687 (2005)

Pulse compression in hollow-core fibre

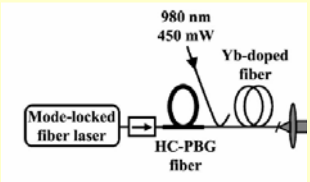


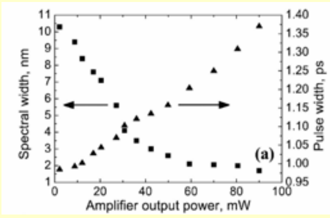


- Use Xe to avoid SSFS (no Raman)
- Use elevated pressures to increase n_2
- Use high powers to be well above fundamental soliton energy
- Peak power is several MW
- Using 120fs pulses, compression is limited by higher-order dispersion
- Using ps input pulses, much higher compression ratios would be possible

D. Ouzounov *et al.* Opt. Express **13,** 6153 (2005)

Spectral compression





- Nonlinear spectral compression uses self phase modulation to compress pulses
- Remember, in a Kerr medium with positive n_2, the leading edge of the pulse is red-shifted. So a chirped pulse with blue components at the front and red components at the back will be spectrally compressed
- This can lead to transform-limited longer pulses

M. Rusu *et al.*, Appl. Phys. Lett. **89**, 091118 (2006)

"Adiabatic" soliton compression

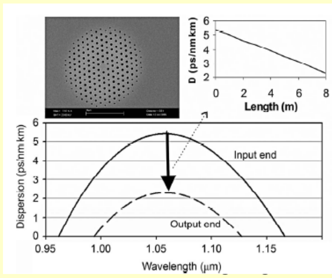
Dispersion

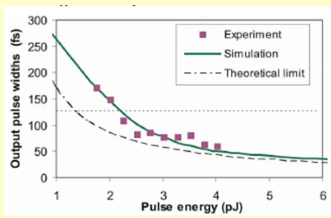
Nonlinear effective area

$$\tau_0 = 1.76\frac{\lambda^3 D A_{eff}}{2\pi^2 c n_2 E_{sol}}$$

Soliton length

Soliton energy

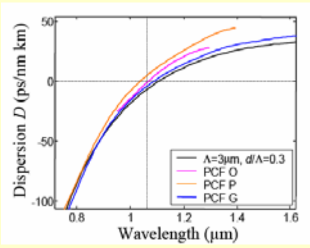




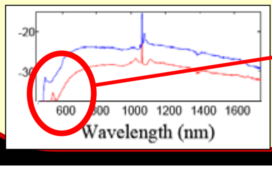
Tse *et al.*,Opt. Lett. **31** 3504 (2006)

Tapered fibre supercontinuum generation

"Conventional" PCF-based supercontinuum generation…



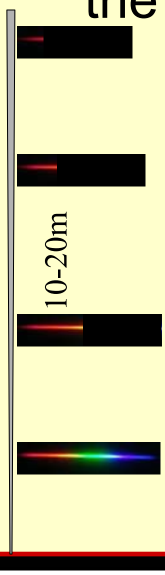
W. J. Wadsworth *et al.* Opt. Express **12** 299 (2004)



- Pump at or close to the zero-GVD wavelength (in this example, 1.06μm)
- Supercontinuum spreads through sequential processes to longer and shorter wavelengths
- Blue/uv extent is limited by phase matching, group index matching etc.

Solution: let the fibre evolve with the spectrum…

D = 5μm

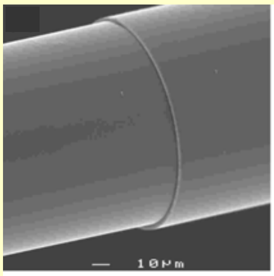


D = 1μm

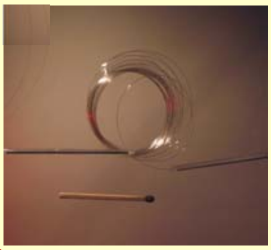
- Fibre is tapered so that zero-GVD wavelength changes along the length
- At input end, chosen to match to pump wavelength,
- As higher frequencies are generated along the fibre length, the zero-gvd wavelength evolves to continue efficient nonlinear generation
- Taper length depends on pump source and attenuation

A. Kudlinski et al., Opt. Express **14**, 5715-5722 (2006)

Gas-phase fibre optics

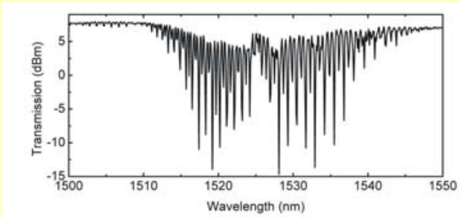


HC-smf splice



All-fibre gas cell

Suitable for absorption-based frequency standards, Raman convertors, laser-atom interactions, gas-based lasers?…



F. Benabid et al, Nature **434** 488 (2005)

Selected background reading

Current work:

D. Ouzounov *et al.* “Soliton pulse compression in photonic bandgap fibers” Opt. Express **13,** 6153 (2005)

G. McConnell *et al.,* “Ultra-short pulse compression using photonic crystal fibre” Appl. Phys. B **78** 557 (2004).

B. Schenkel *et al.* “Pulse compression with supercontinuum generation in microstructure fibers“ JOSA B **22,** 687 (2005)

A. Wang et al., “ "Three-level neodymium fiber laser incorporating photonic bandgap fiber," Opt. Lett. **31**, 1388-1390 (2006)

Tse *et al.*, “Pulse compression at 1.06μm in dispersion-decreasing holey fibers” Opt. Lett. **31** 3504 (2006)

F. Benabid *et al.,*

M. Rusu *et al.*, "All-fiber picosecond laser source based on nonlinear spectral compression," Appl. Phys. Lett. **89**, 091118 (2006).

J. Limpert *et al.*, "High-power picosecond fiber amplifier based on nonlinear spectral compression," Opt. Lett. **30**, 714-716 (2005).

C.J.S. de Matos *et al.*, “20-kW peak power all-fiber 1.57-μm source based on compression in air-core photonic bandgap fiber, its frequency doubling, and broadband generation from 430 to 1450 nm” Opt. Lett., 30 436 (2005)

C. Billet et al., “Intermediate asymptotic evolution and photonic bandgap fiber compression of optical similaritons around 1550 nm ” Optics Express, **13** 3236 (2005)

F. Benabid et al, Nature **434** 488 (2005)

A. Kudlinski et al., Opt. Express **14**, 5715-5722 (2006)