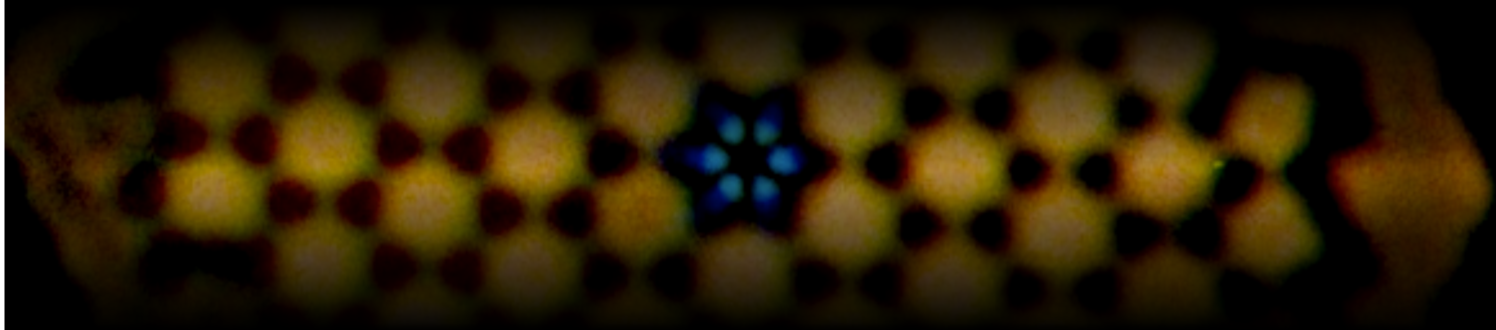
Microstructured optical fibres:

Opportunities & challenges



Philip Russell

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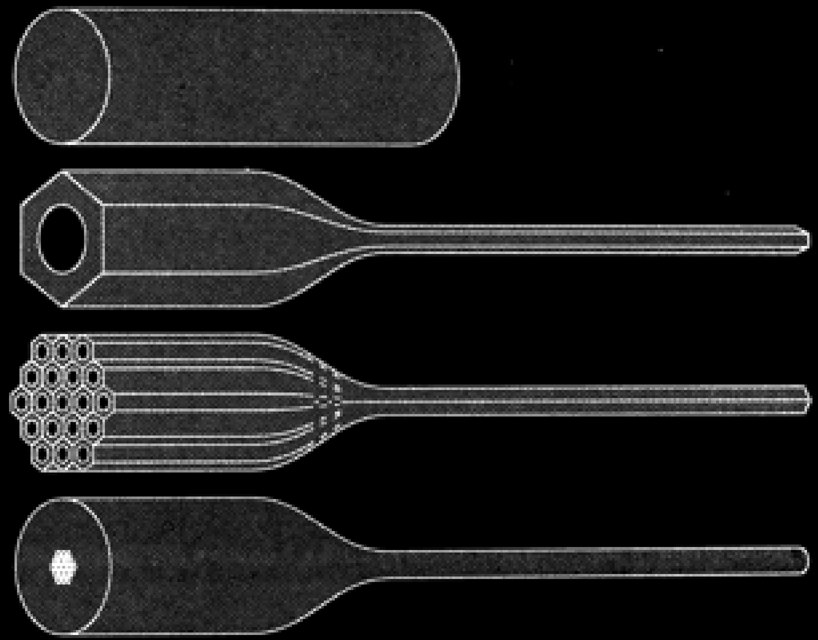
Erlangen, Germany

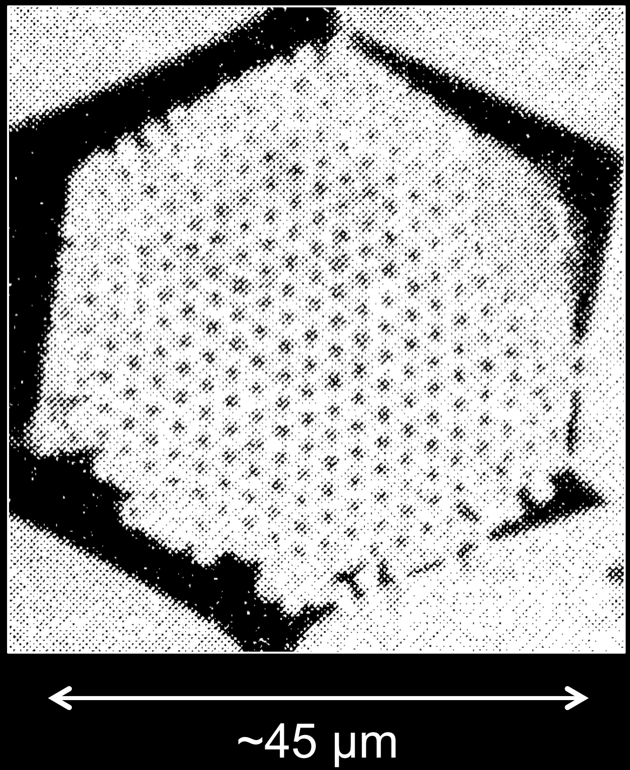
Topics

- Introduction to PCF
- Compound glass PCF
- Hybrid two-glass structures
- Optomechanicalstructures
- Twisted fibres
- Final comments

Elounda, Crete: Summer 1995

Birks et al in Photonic Band Gap Materials (Editor: C.M. Soukoulis) Kluwer 1996

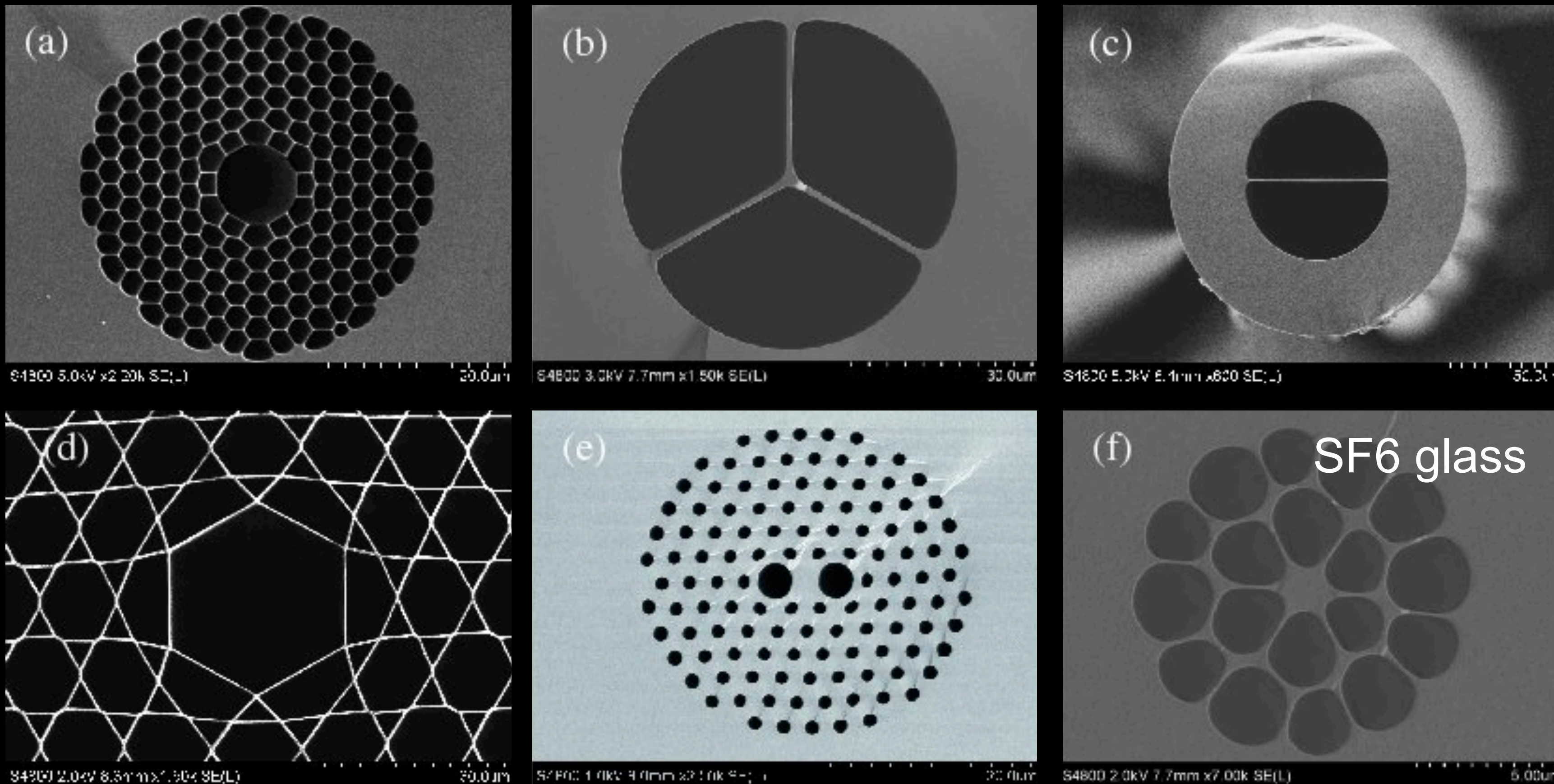




Optimistic subtitle: "Photonic bandgaps by the km"

Some of the latest structures

J. Lightwave Tech. 24, 4729–4749 (2006)



new ways to guide light

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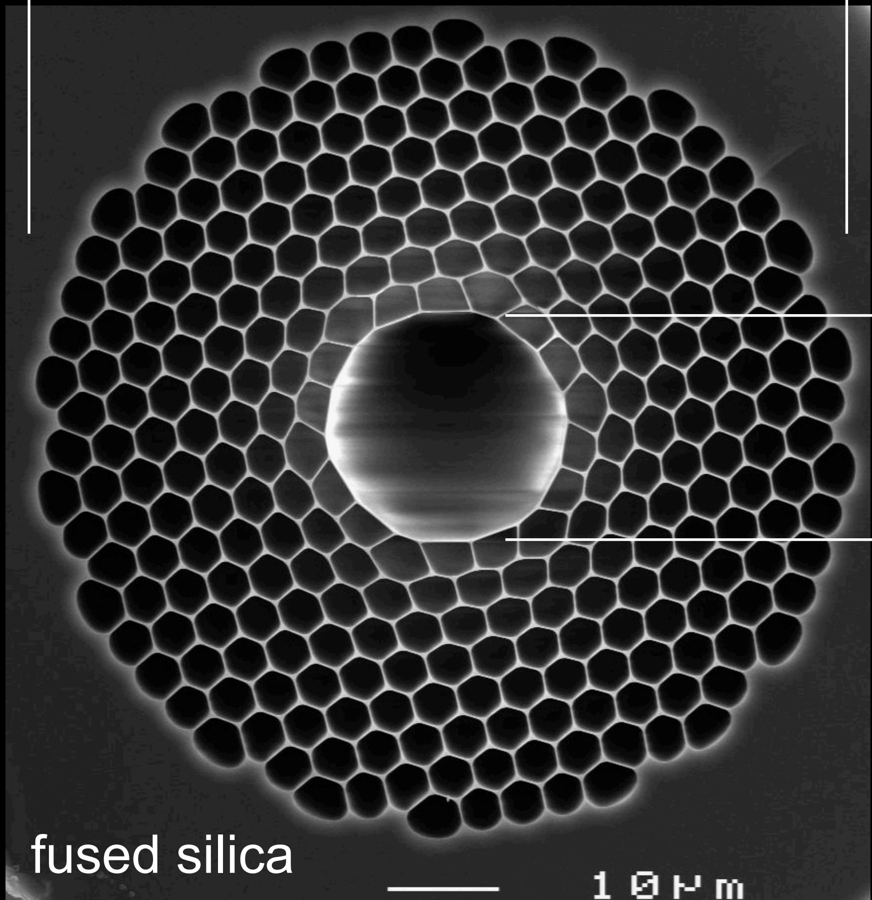
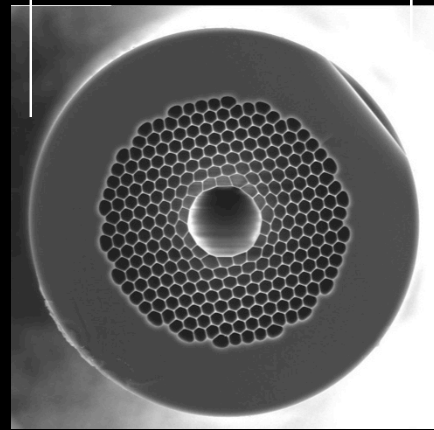
State-of-the-art hollow-core PCF (2004)

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

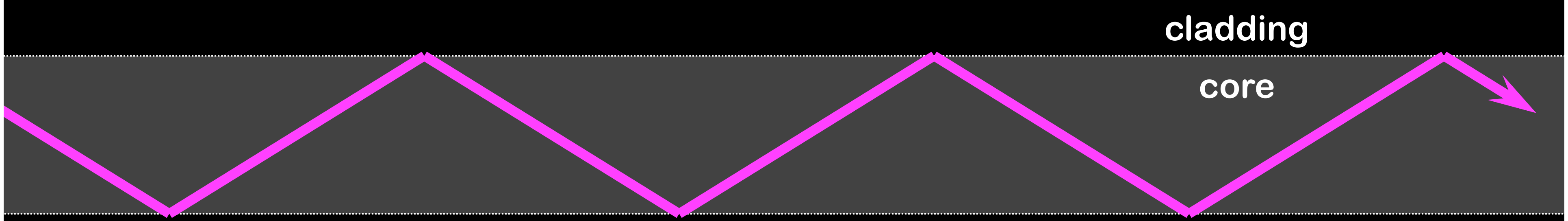
blazephotonics





1 dB/km at 1550 nm

Hollow core 1 dB/km



2.8 million bounces per km (20 µm core, 1550 nm)

0.35 µdB/bounce (reflectivity 0.99999992)

all angles, all polarisation states

new mirror every time

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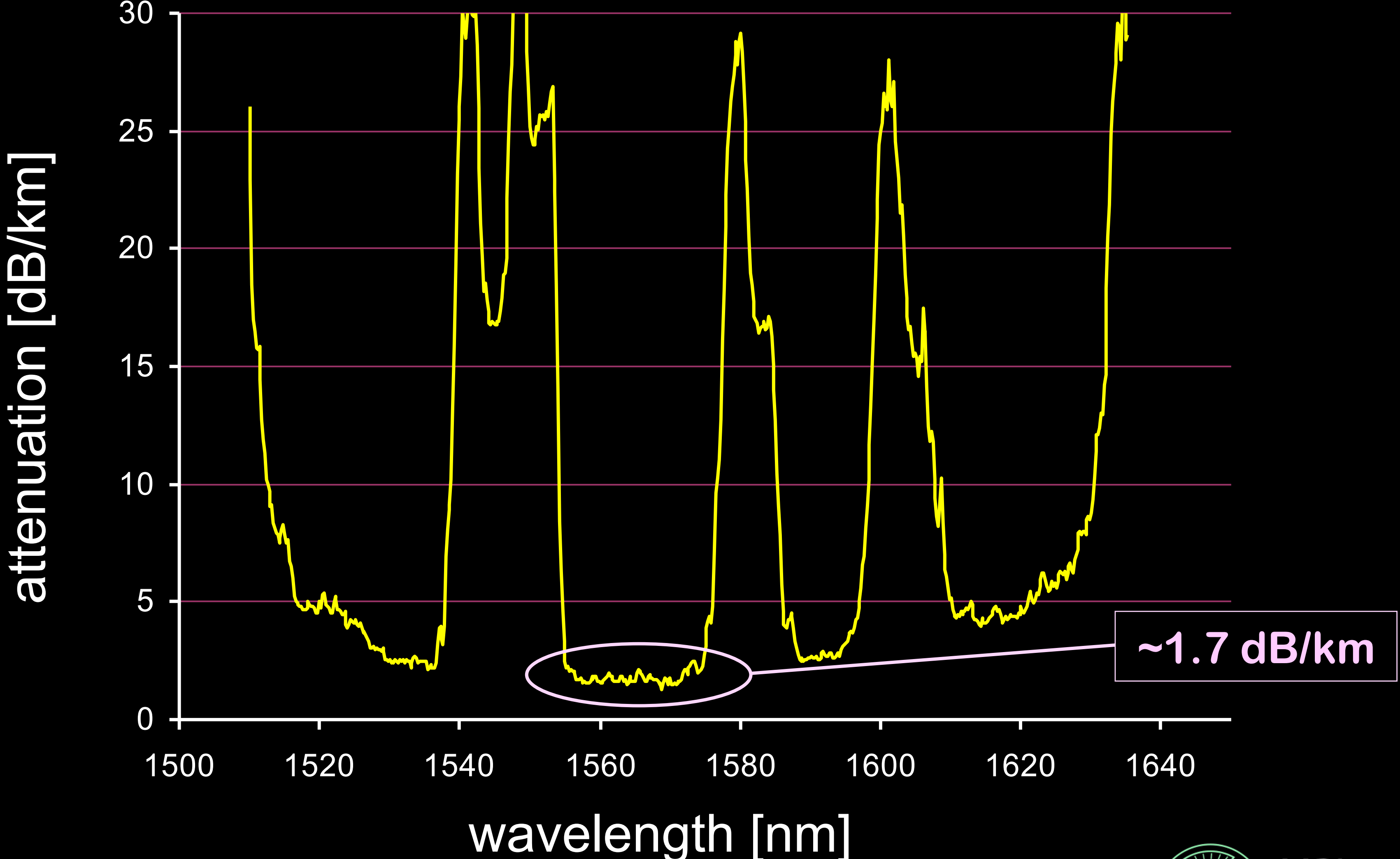
Typical attenuation spectrum

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



blazephotonics

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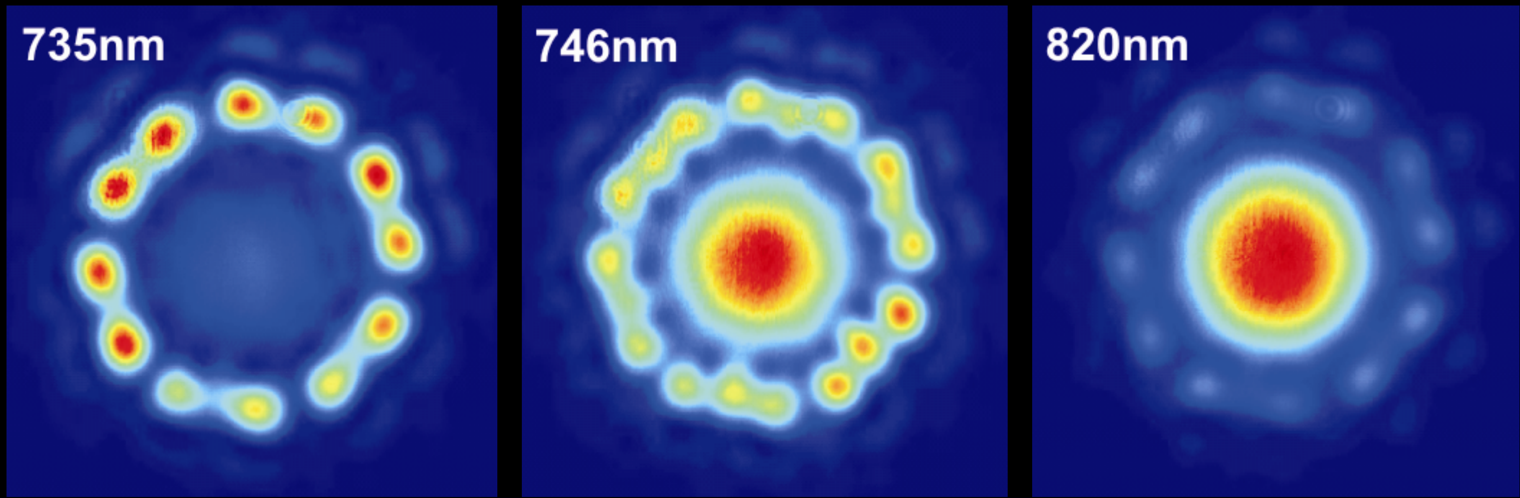
Loss peaks caused by surface states

Humbert et al, Opt. Exp. 12 1477 (2004)

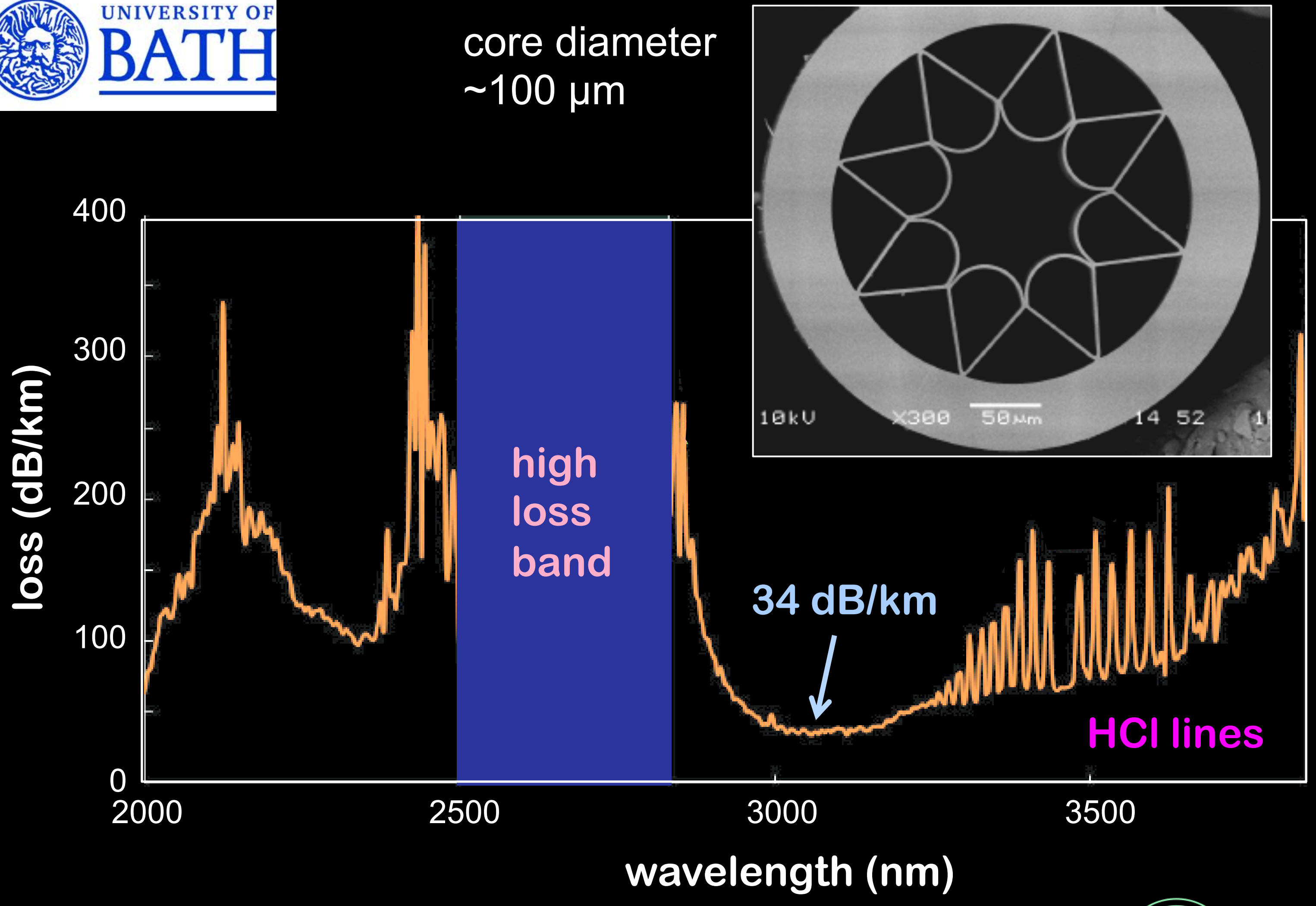


fraction of light in glass changes dramatically
with wavelength of the light

Low loss mid IR silica fibre

Yu et al: Opt. Exp. **20**, 11153 (2012)

core diameter
~100 μm



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Guidance mechanisms: summary

- Total internal reflection
  - core index must be higher than cladding index
- Photonic band gap (PBG)
  - core index not important (can be lower than cladding)
  - core resonance must coincide with PBG in the cladding
  - losses as low as 1 dB/km
- Low leakage structures (ARROW** and kagome)
  - core light anti-resonant with cladding states, i.e., not phase-matched
  - some light leaks into cladding, typical losses 1 dB/m

** anti-resonant reflection optical waveguides

Topics

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- Hybrid two-glass structures
- Optomechanicalstructures
- Twisted fibres
- Final comments

Xin Jiang

Why bother with compound glasses?

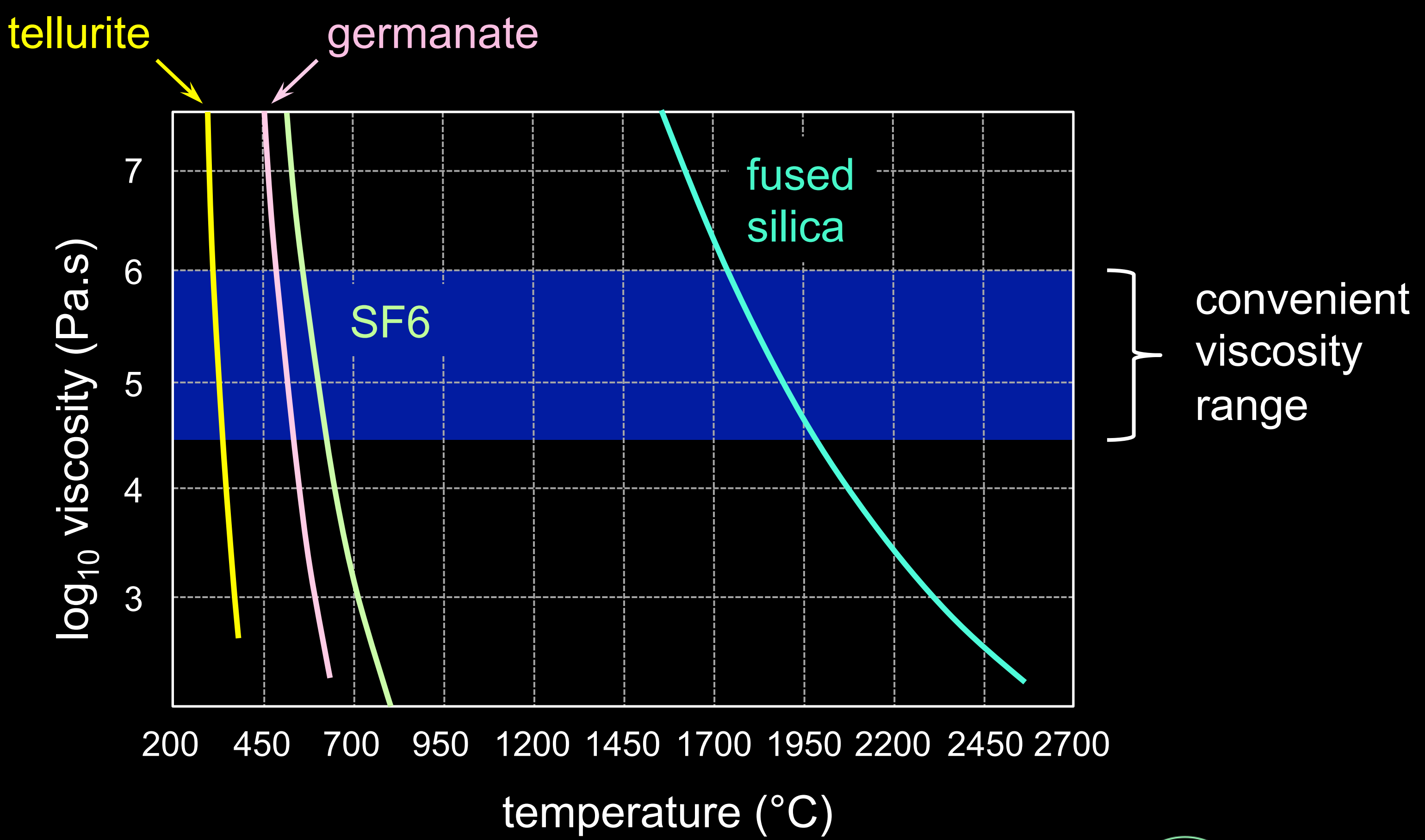
Manning et al: Opt. Mat. Exp. **2**, 140–152 (2012)

- Higher nonlinearity & refractive index
- Extended window of transparency (e.g., into the mid-IR)
- Higher rare-earth solubility

	Silica SiO_2	Chalcogenide AsGeSeTe	Tellurite TeO_2-based	Lead-silicate SF6
Glass transition temperature (°C)	1175	245	300	423
Refractive index	1.46	2.9	1.9-2.3	1.81
n_2 (m^2/W)	10^{-20}	10^{-17}	10^{-19}	10^{-19}
Window of transparency (µm)	0.2-2.3	4-11	0.4-5	0.3-2.5

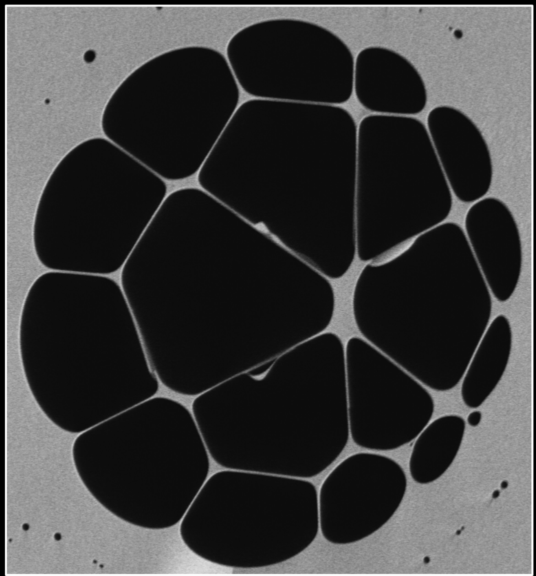
Viscosity control is key to fibre drawing

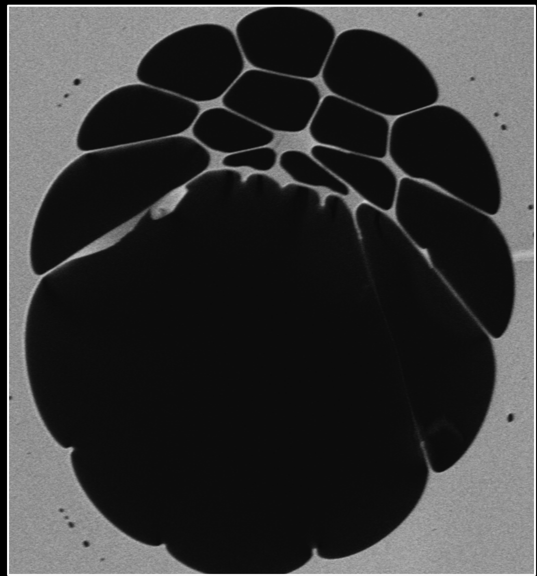
- hollow core soft-glass PCF difficult because of:
  - steep viscosity gradient with temperature
  - reactivity or thermal instability

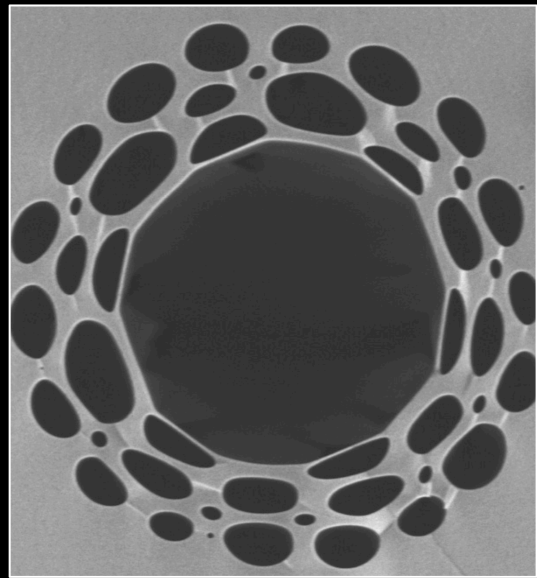


When things go wrong

Jiang et al: Opt. Exp. **19**, 15438 (2011)



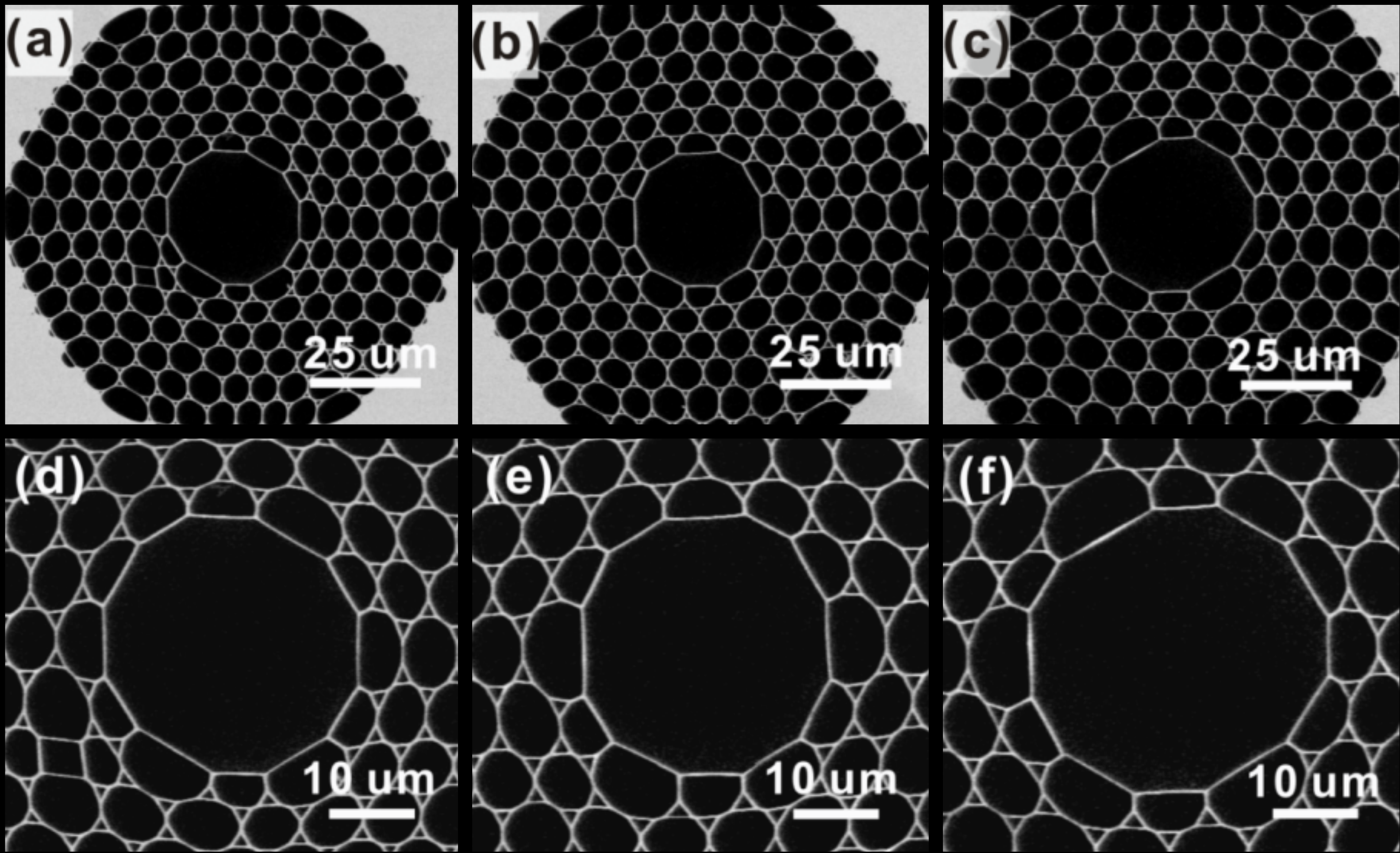




Serious structural distortion in hollow-core SF6 PCF

When things go better

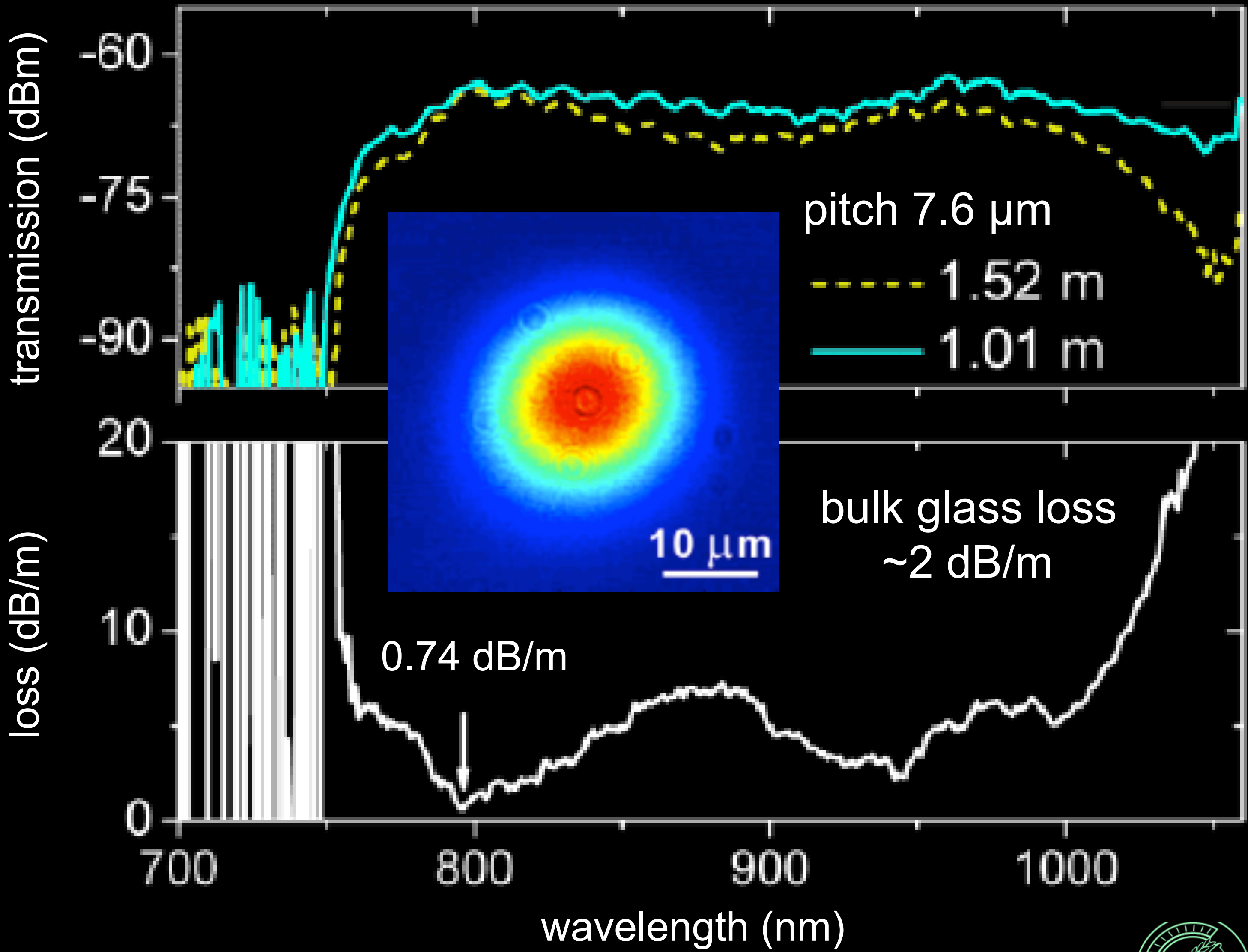
Jiang et al: Opt. Exp. **19**, 15438 (2011)



increasing internal pressure during drawing

Transmission losses

Jiang et al: Opt. Exp. **19**, 15438 (2011)



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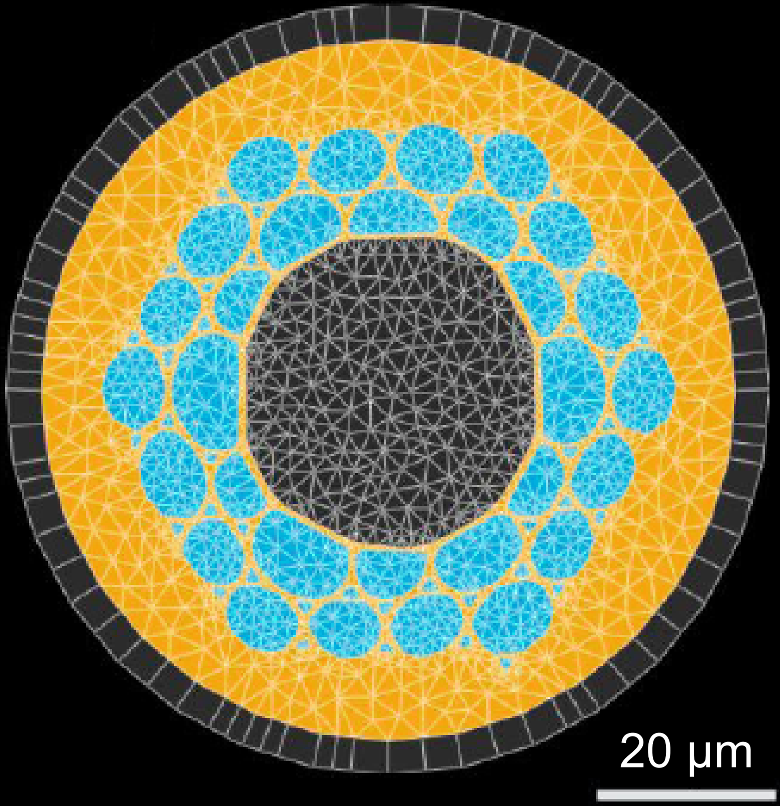
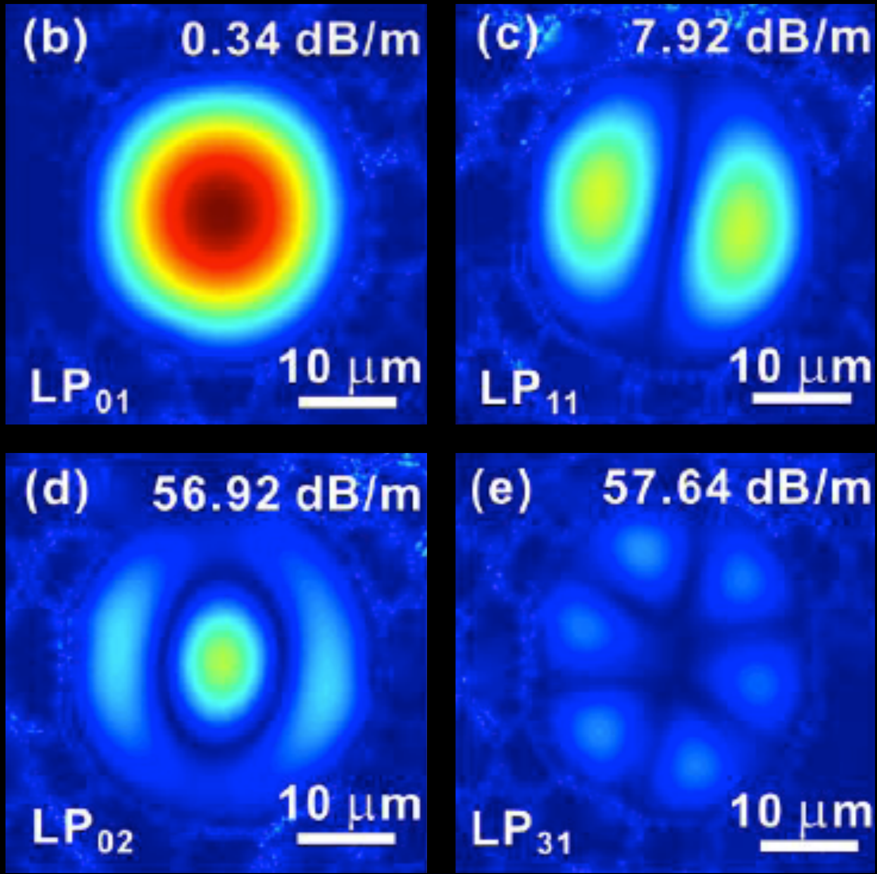
Finite element modelling

Jiang et al: Opt. Exp. **19**, 15438 (2011)





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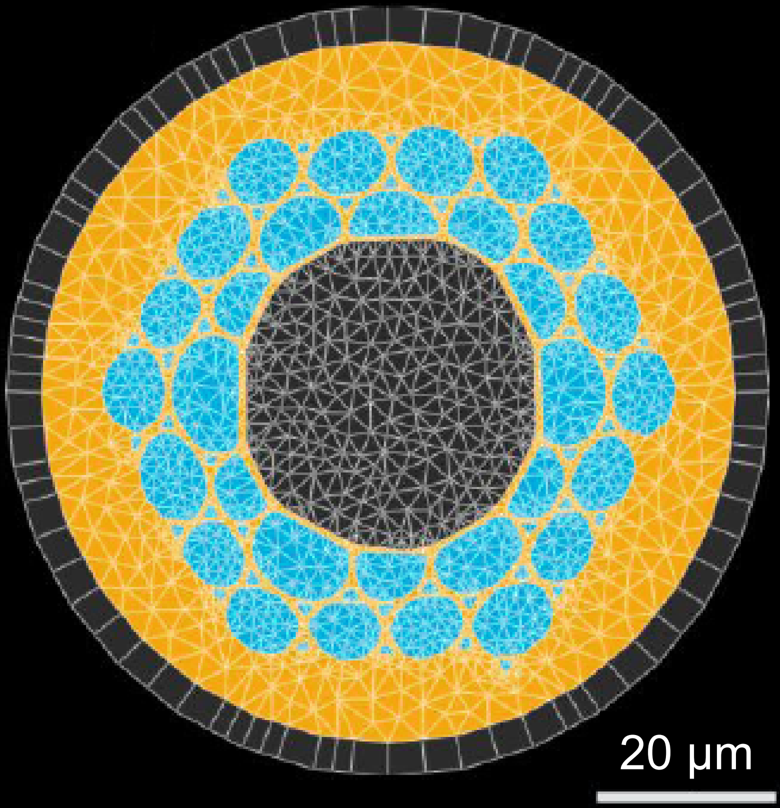

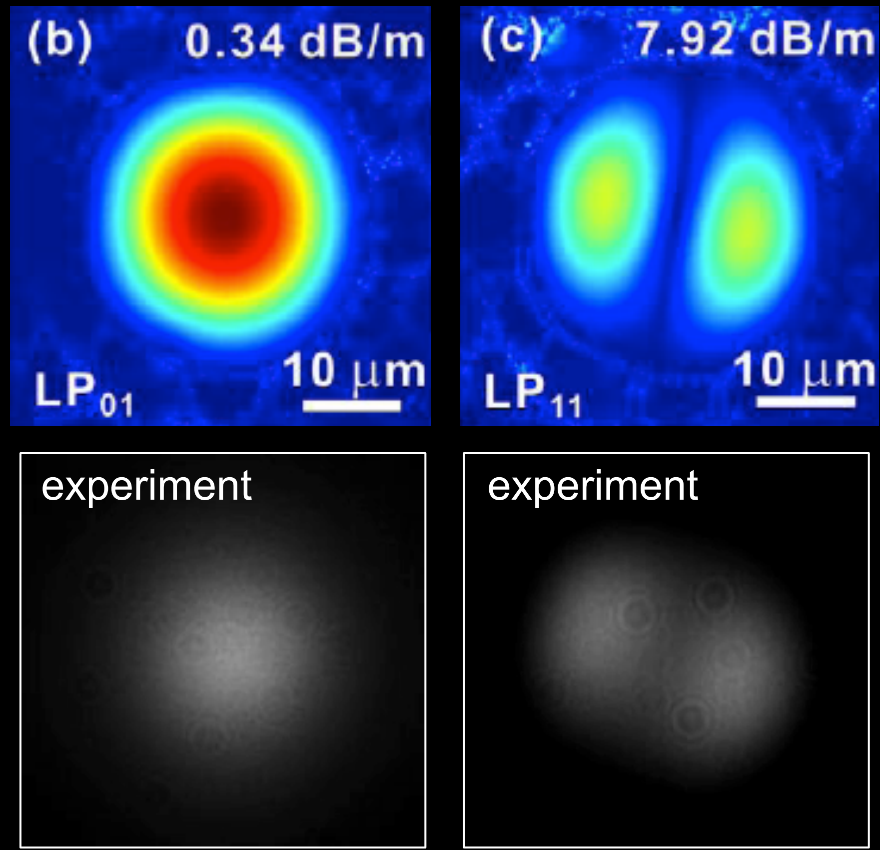

- 20 cm length
- launch LP_{11} mode

Topics

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- **Hybrid two-glass structures**
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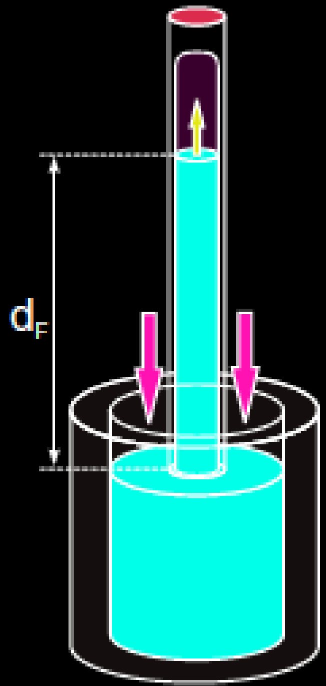
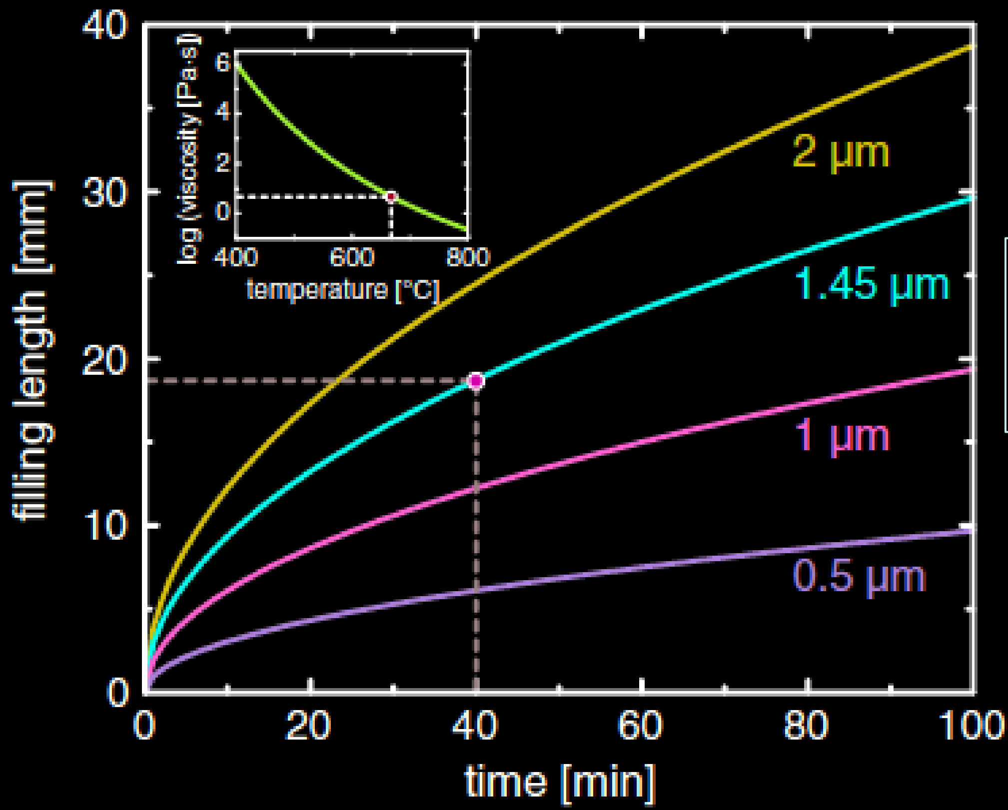
Hybrid glass-glass structures

- **Pressure-assisted melt-filling technique:**
  - **low-melting-point glasses in a fused silica host matrix**
  - **strand diameters as narrow as 200 nm**





viscosity 5 Pa.s
temperature 665°C
pressure 50 bar

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Hybrid glass-glass structures

- Pressure-assisted melt-filling technique:
  - low-melting-point glasses in a fused silica host matrix
  - strand diameters as narrow as 200 nm
- Overcomes viscosity and process incompatibility of silica and non-silicate optical glasses
- Unique waveguiding devices with:
  - high core-cladding index-contrast
  - high optical non-linearity
  - wide transparency windows into the mid infrared
- Very small quantities of filling material required:
  - protected from environmental contact
  - ultra-high cooling rates possible
  - difficult-to-handle or reactive optical glasses can be used

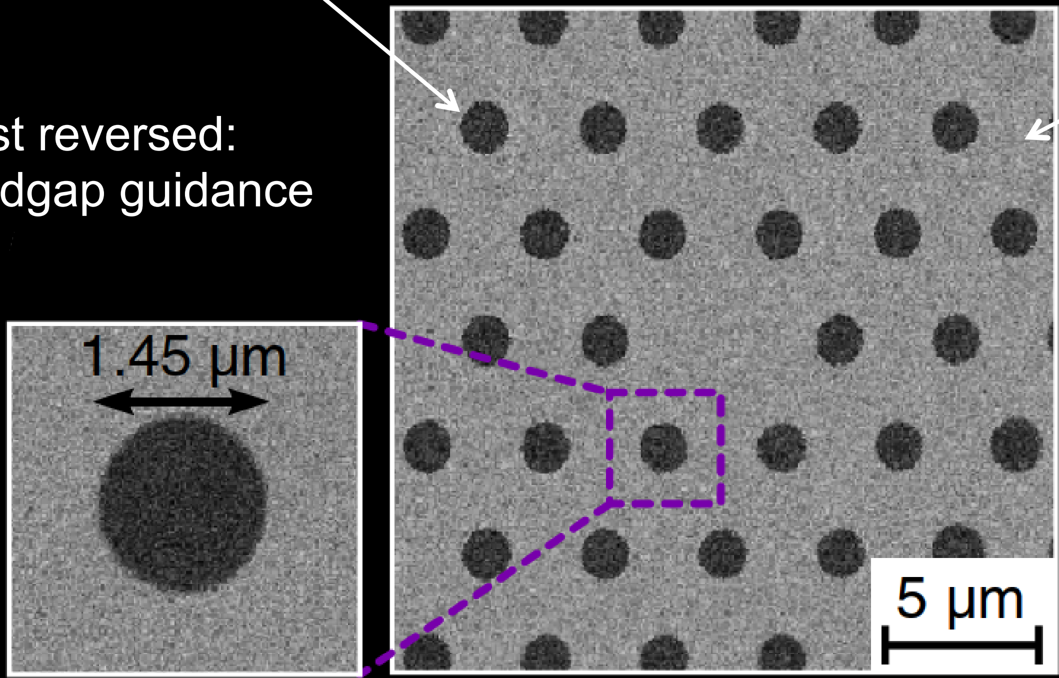
Hybrid chalcogenide-silica fibre

Granzow et al: Opt. Lett. **36**, 2432–2434 (2011)

chalcogenide glass $Ga_4Ge_{21}Sb_{10}S_{65}$
(unsuitable for fibre drawing)

silica host

- index contrast reversed: photonic bandgap guidance



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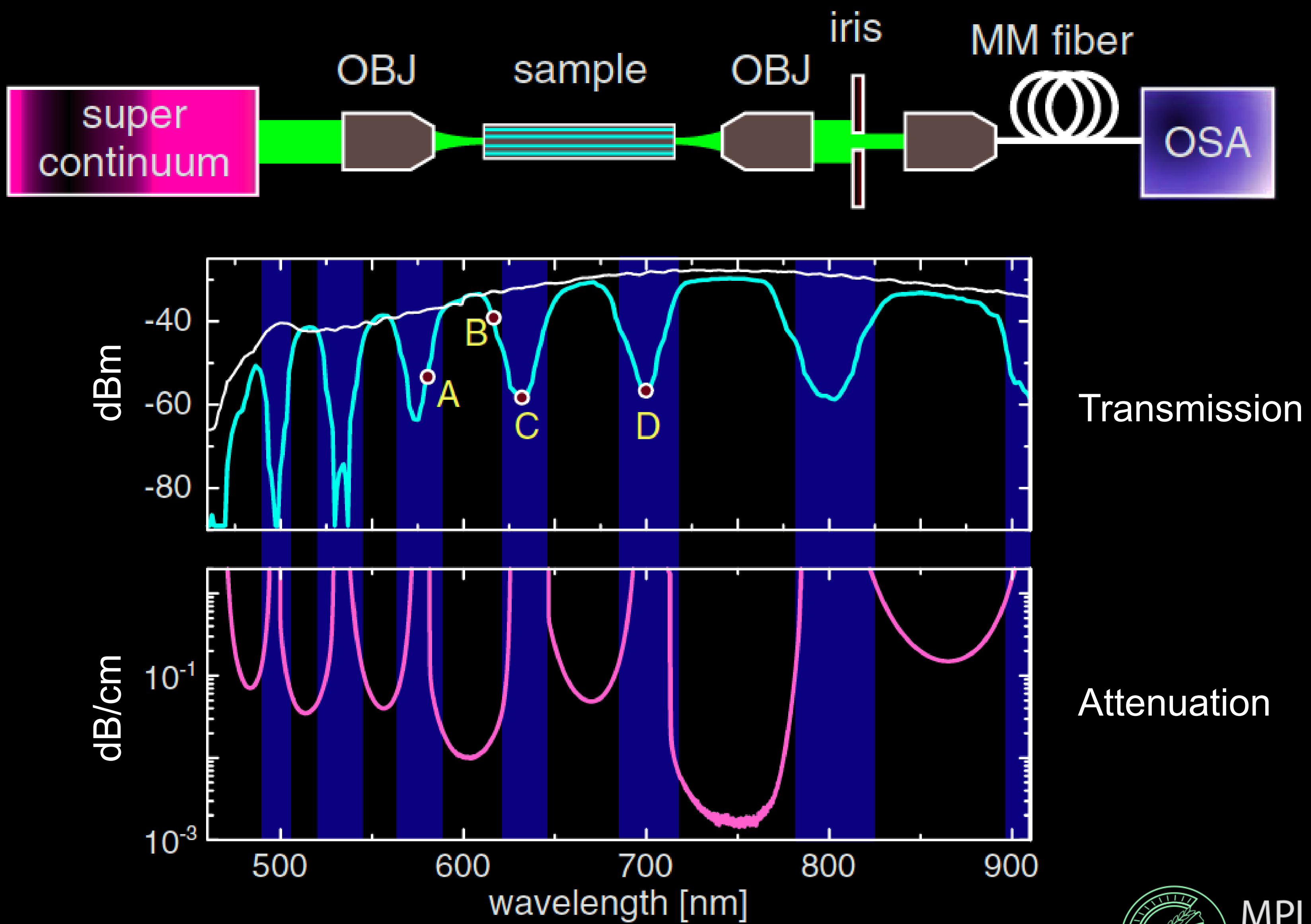
Transmission spectrum



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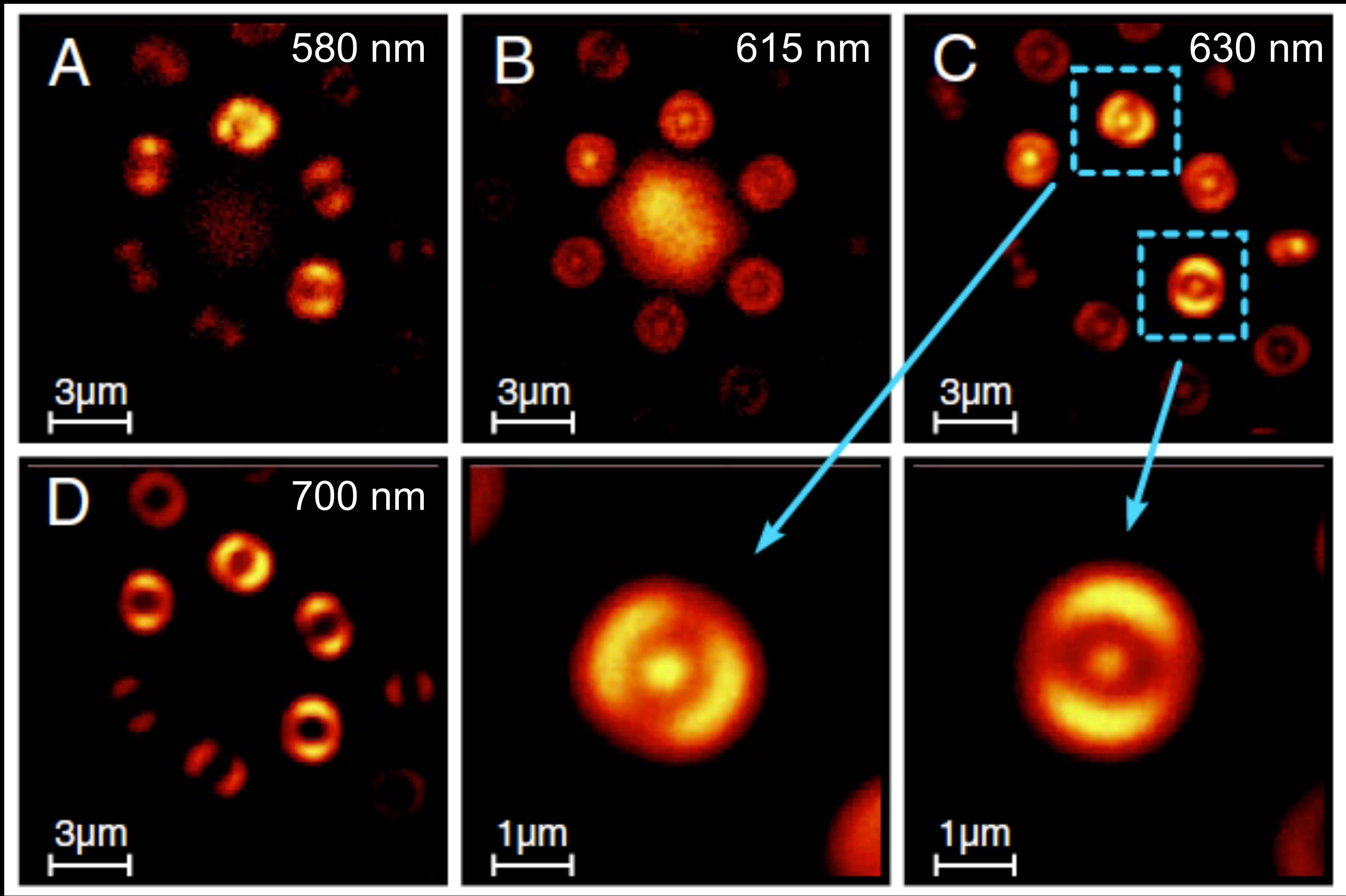
Modes in chalcogenide strands

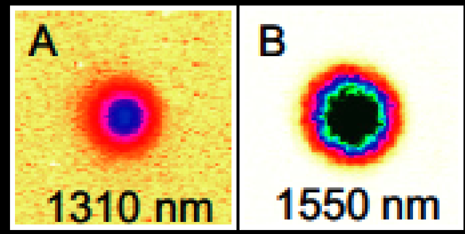
Granzow et al: Opt. Lett. **36**, 2432–2434 (2011)

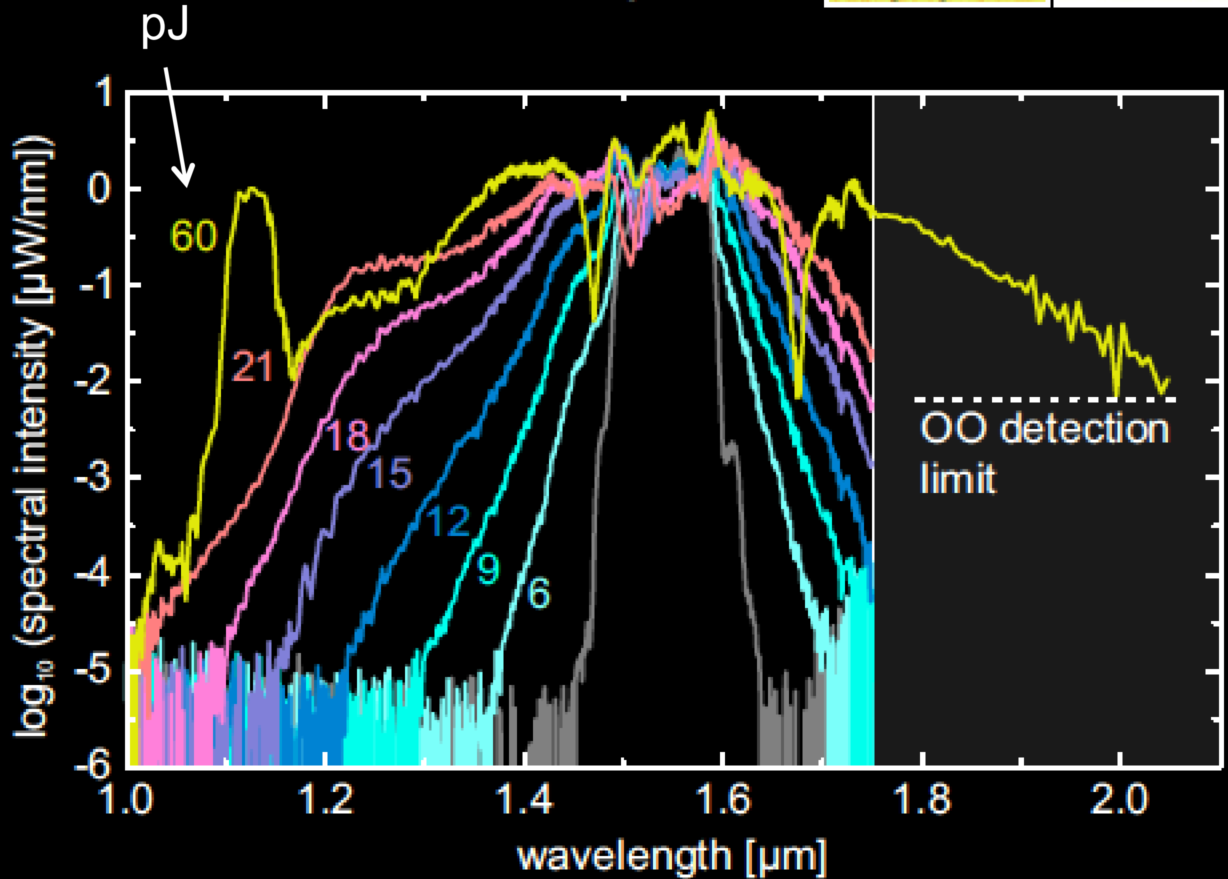


confocal microscope

Supercontinuum in $Ga_4Ge_{21}Sb_{10}S_{65}$ core

Granzow et al: Opt. Exp. **19**, 21003 (2011)





- **$Ga_4Ge_{21}Sb_{10}S_{65}$ strand:**
  - diameter 1.6 µm
  - length ~10 mm
  - ZDW 1500 nm
- **Er fibre laser**
  - 1550 nm
  - 100 MHz
  - 60 fs

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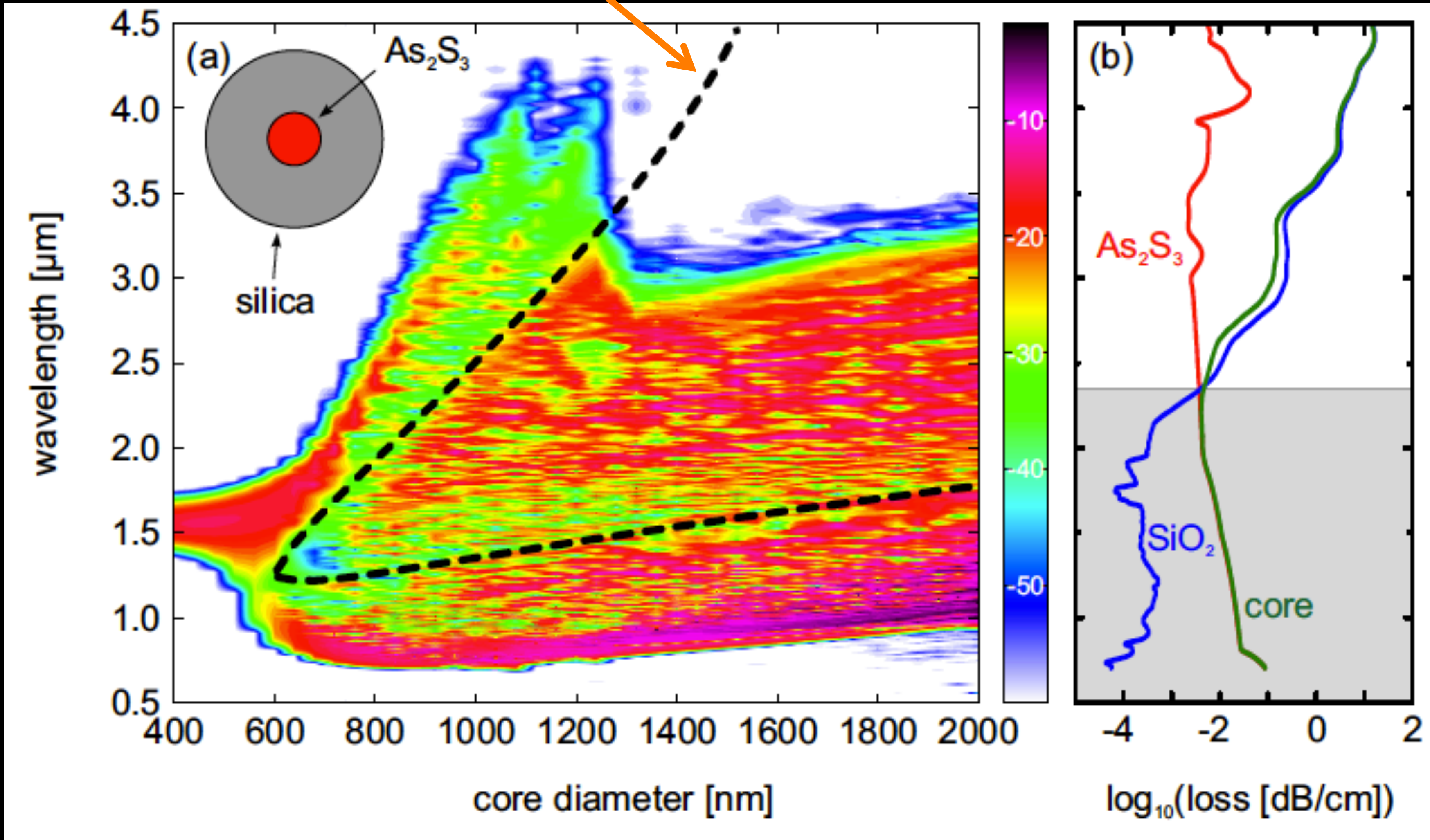
Numerical modelling: As_2S_3 strand

zero dispersion wavelength

Granzow et al: Opt. Exp. **19**, 21003 (2011)



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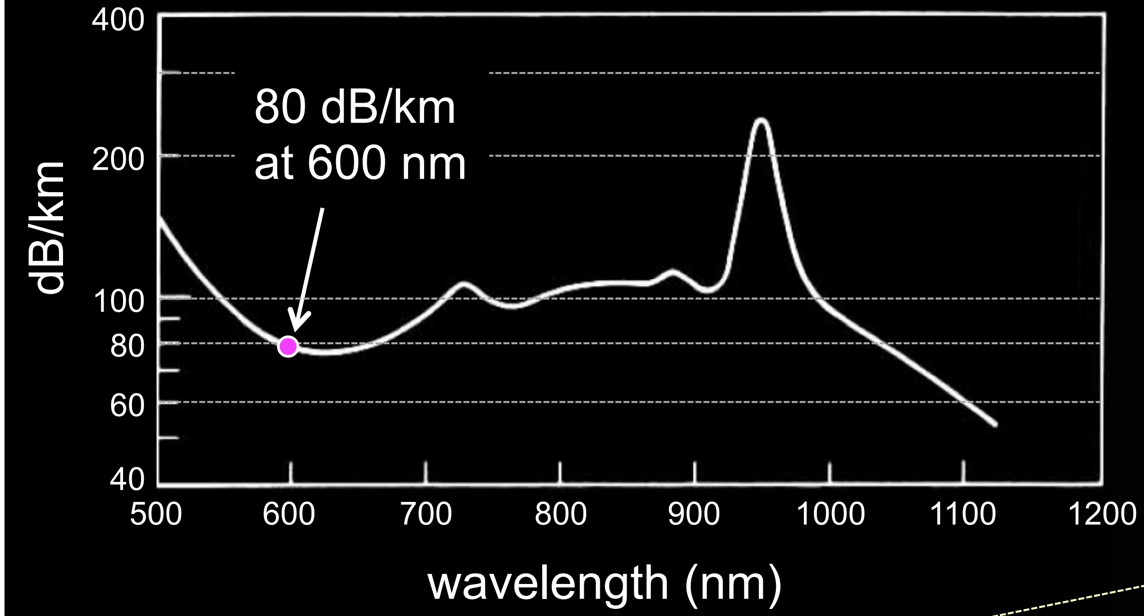
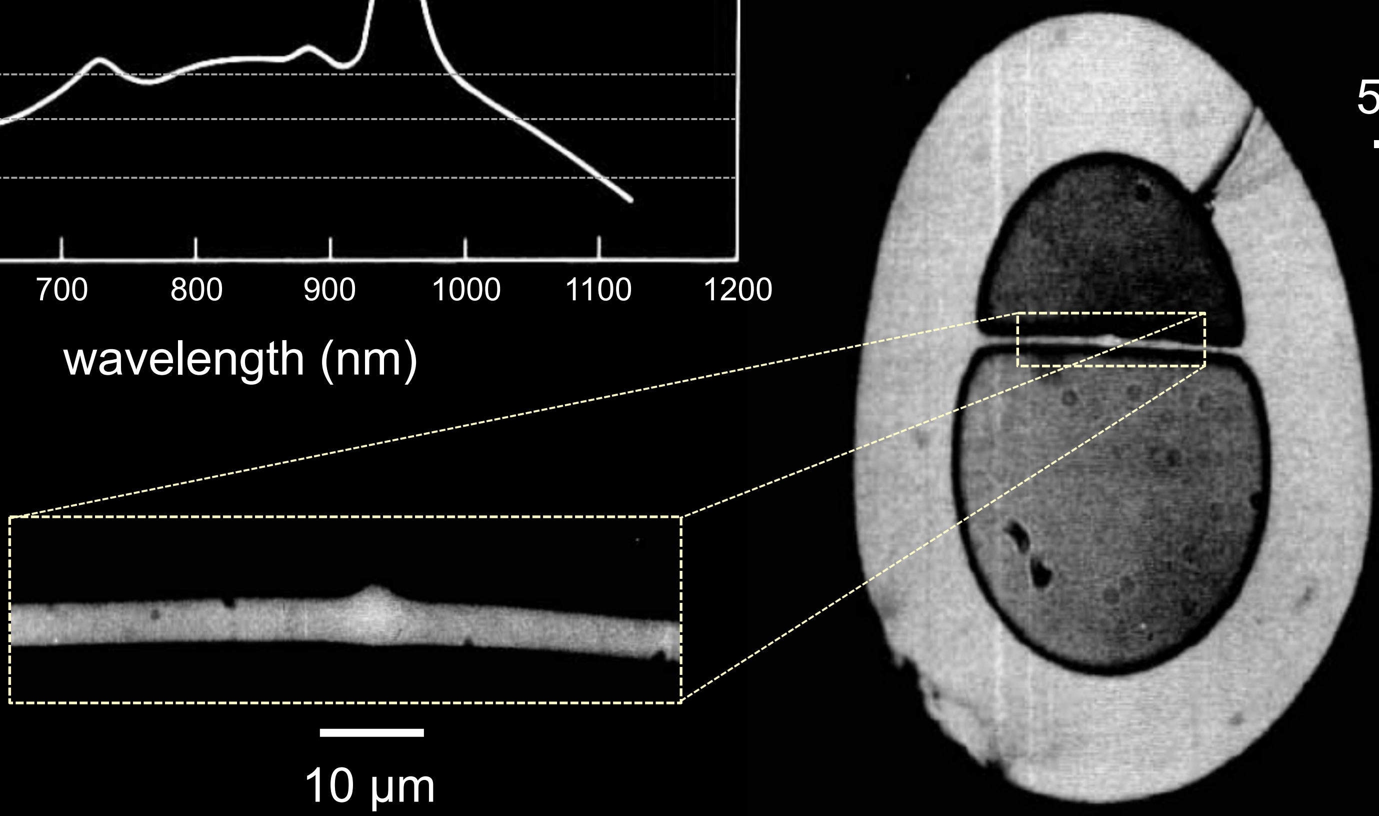
Stripe waveguide in fibre: 1974

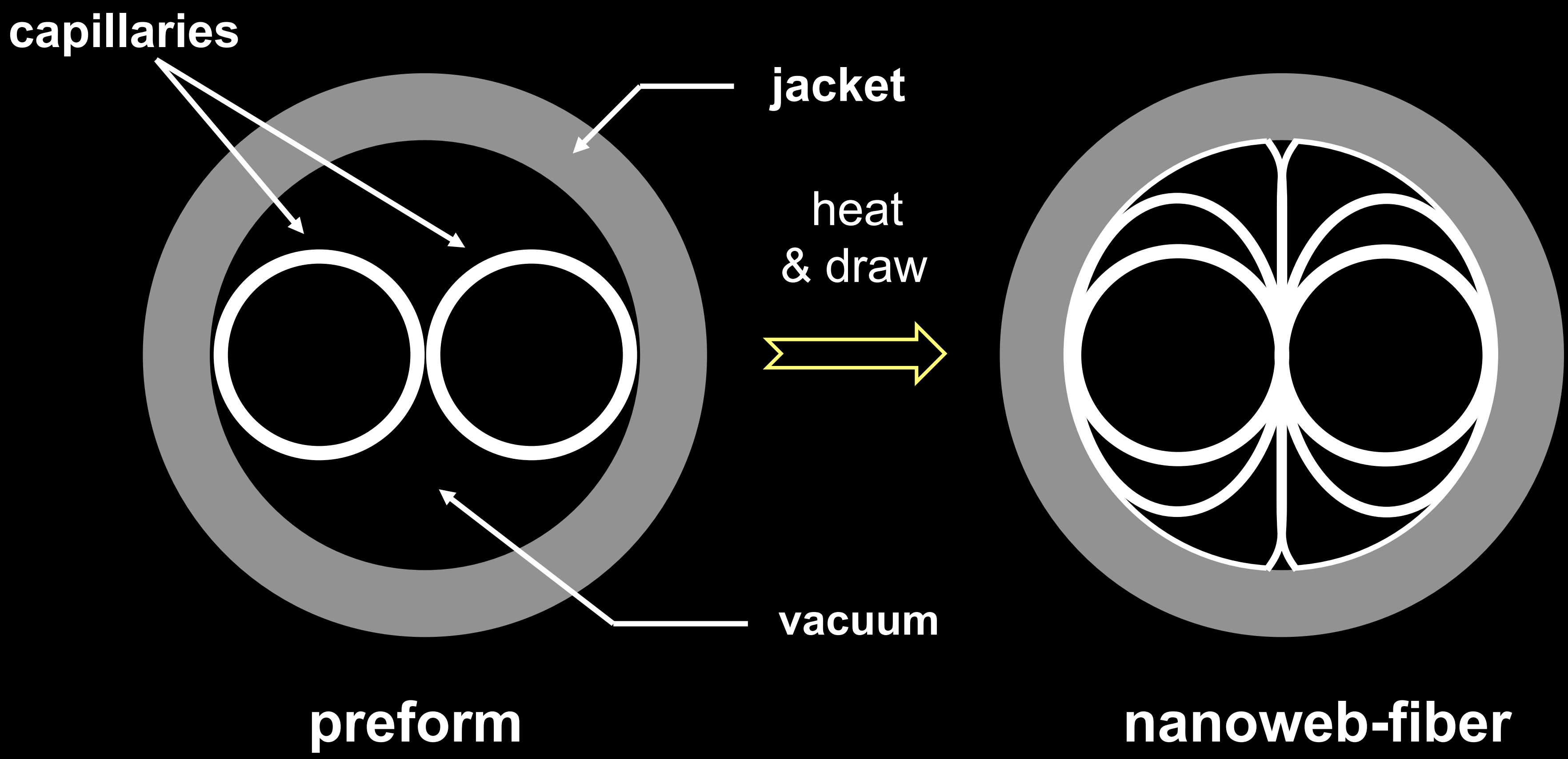
P. V. Kaiser and H. W. Astle:
Bell Syst. Tech. J. 53, 1021 (1974)





Fabricating nanowebs

Joly et al: Opt. Lett. 30, 2469 (2005)



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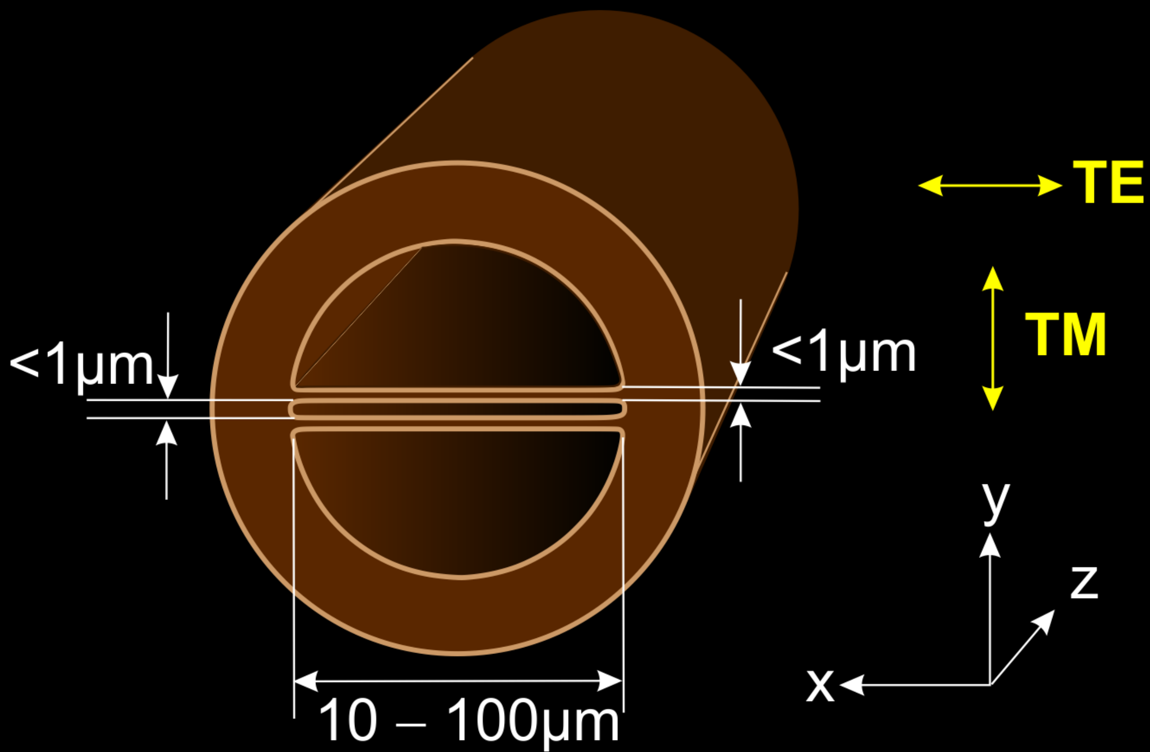
Dual nano-web fibre

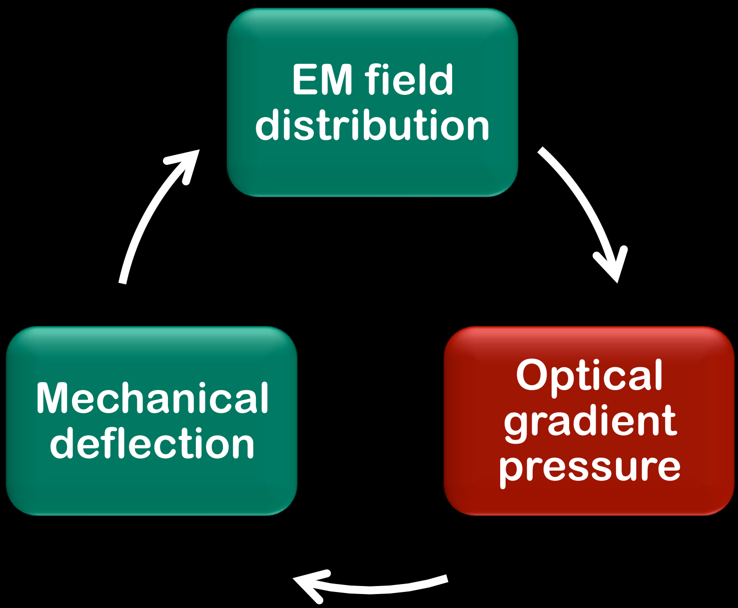
Butsch et al: Phys. Rev. Lett. **108**, 093903 (2012)
Conti et al., Phys. Rev. A **86**, 013830 (2012)

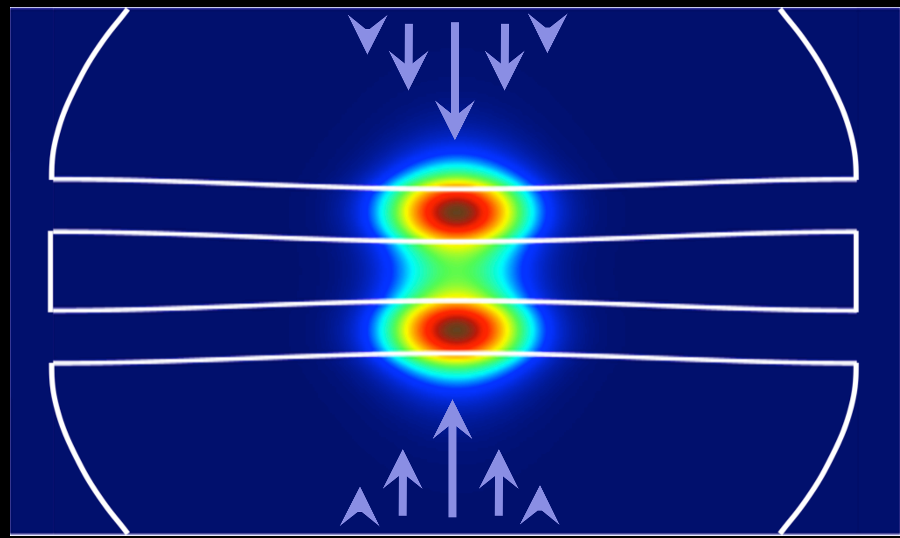


- **two suspended air-clad silica nanowebs**
- **long optomechanical interaction length**

Optomechanical self-channelling

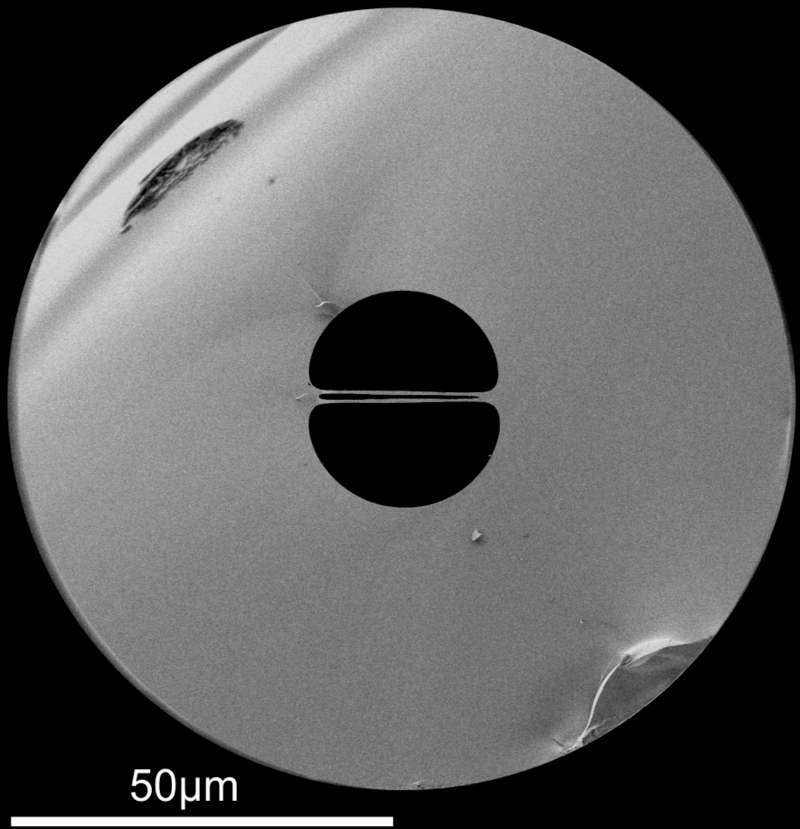
Butsch et al: Phys. Rev. Lett. **108**, 093903 (2012)
Conti et al., Phys. Rev. A **86**, 013830 (2012)

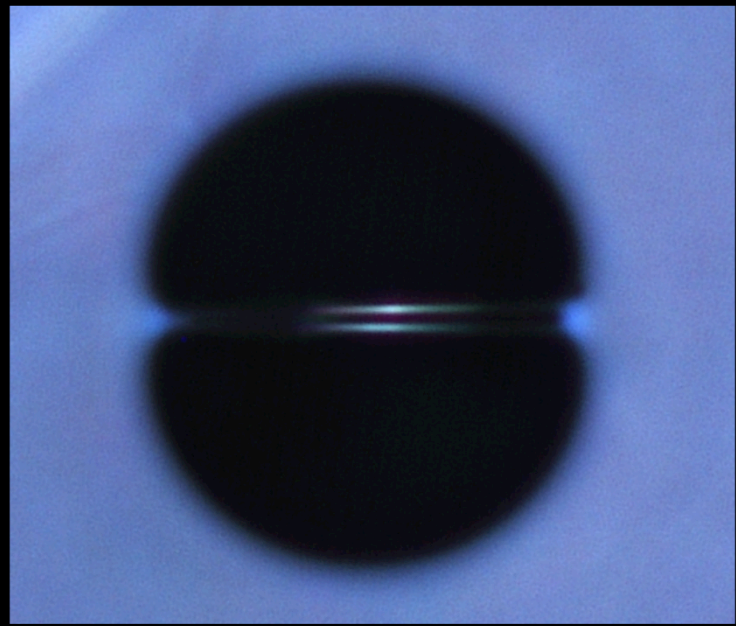


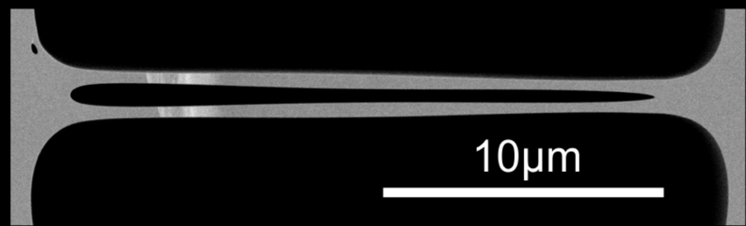


- optomechanical nonlinear refractive index
- formation of self-channeled guided beams
- highly non-local nonlinearity

Guiding dual-nanoweb fiber







- fabricated by stack-and-draw technique
- web thickness 440 nm, spacing 550 nm, width 22 µm
- slightly convex thickness profile

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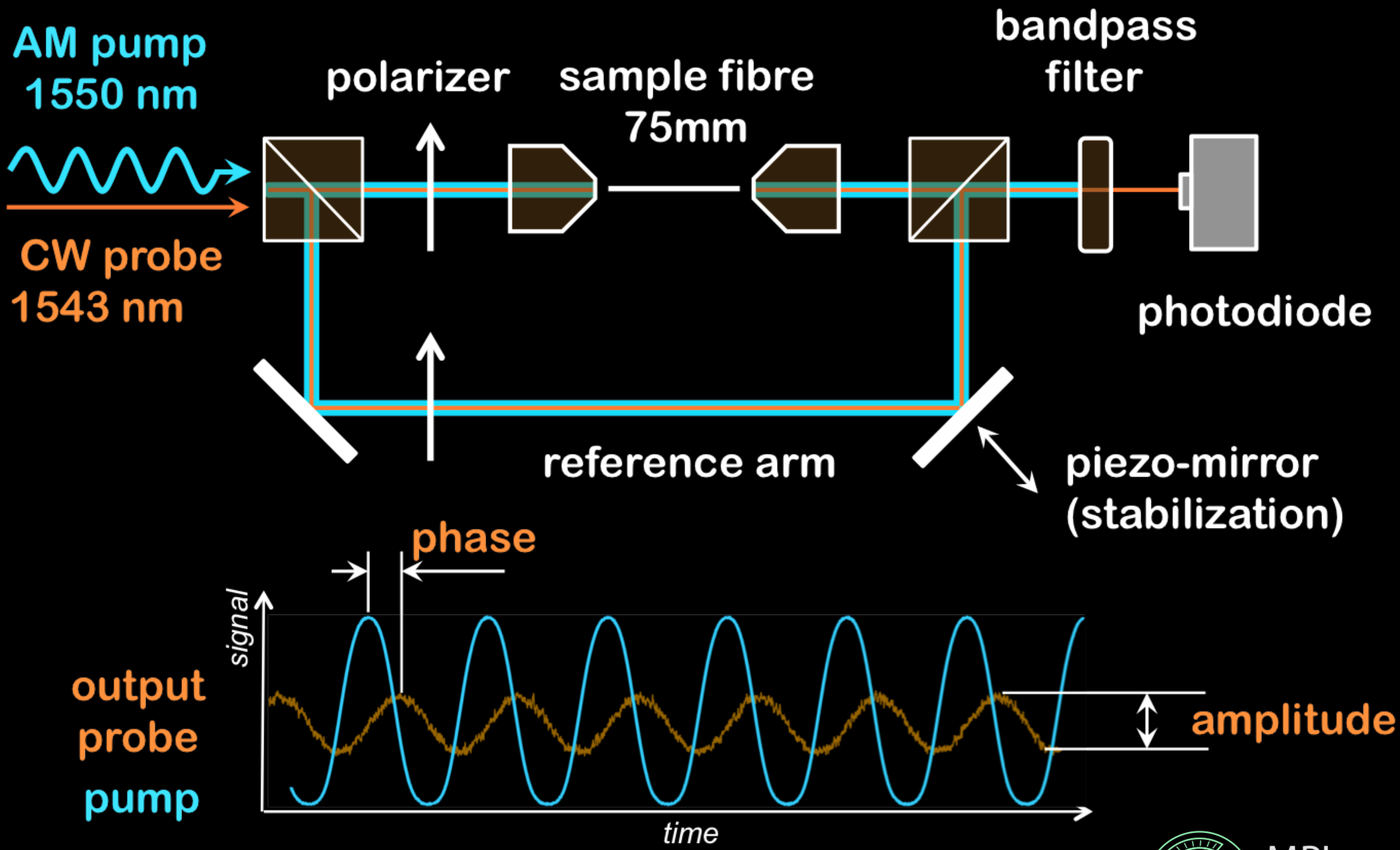
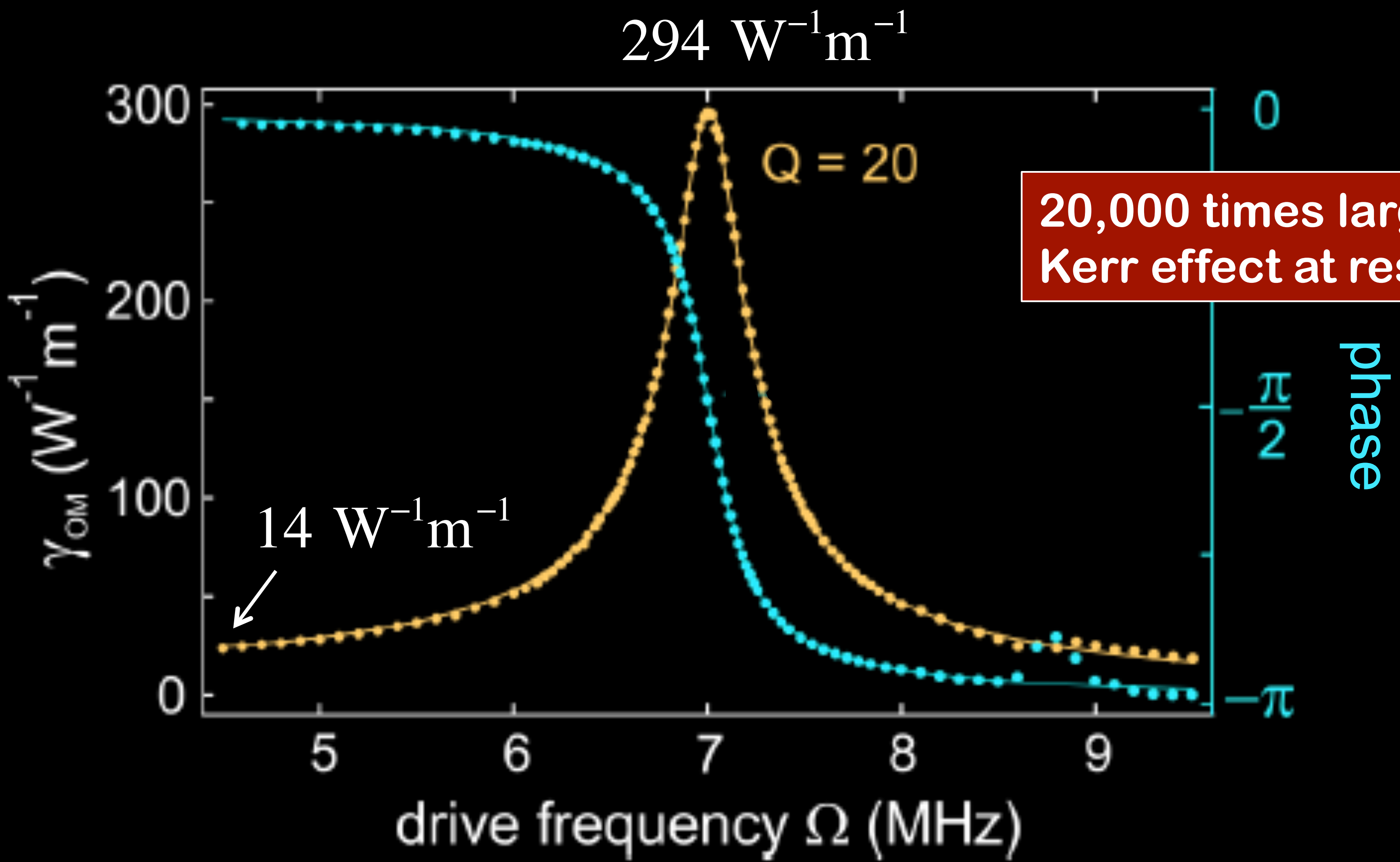
Interferometric set-up

Butsch et al: Phys. Rev. Lett. **109**, 183904 (2012)



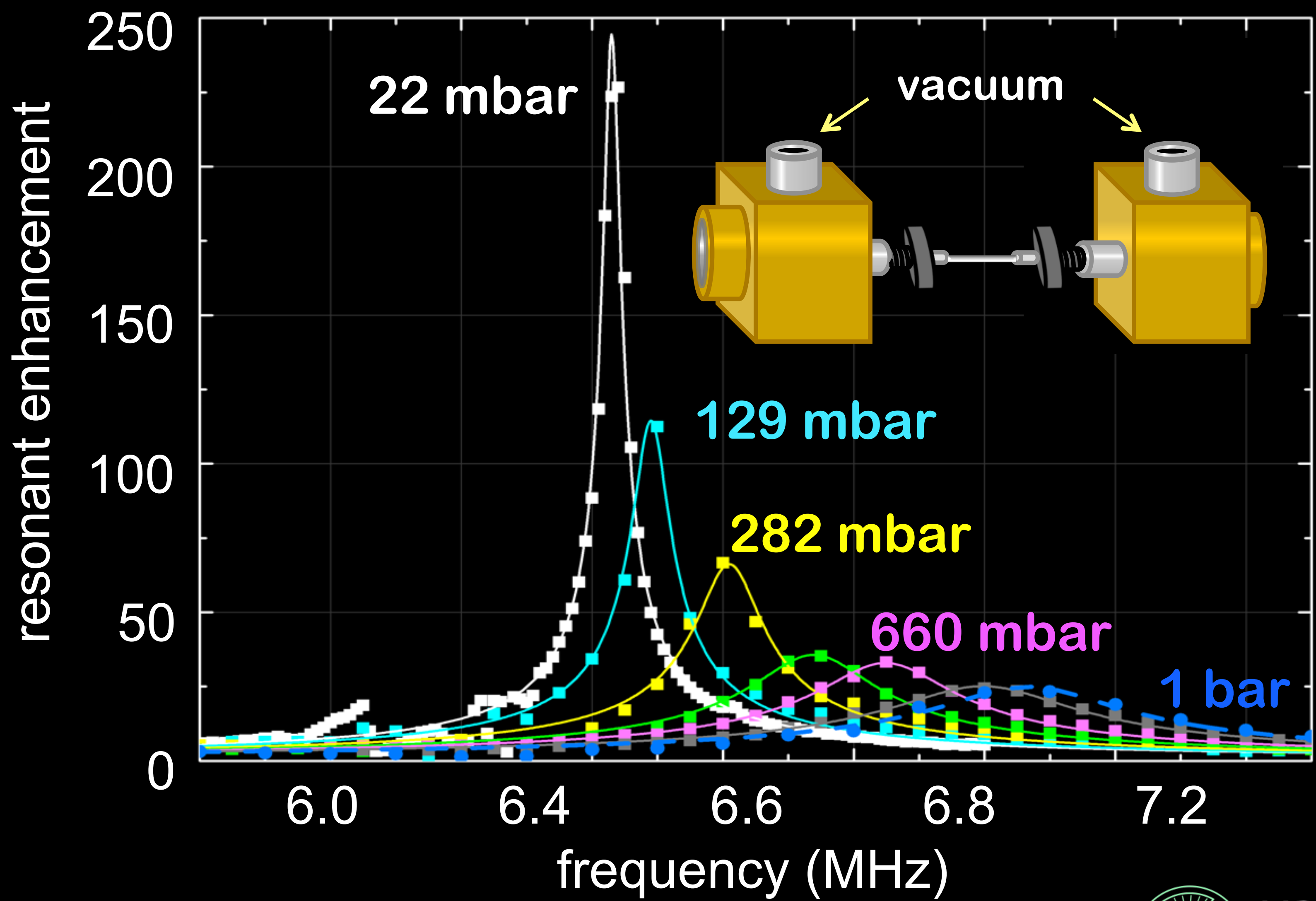
Lorentzian response

Butsch et al: Phys. Rev. Lett. **109**, 183904 (2012)



Measurements at different pressures

Butsch et al: Frontiers in Optics, paper FM3H.2 (2012)



Dual nanoweb structure

- Higher optomechanical nonlinearity possible by thinner and longer webs
- Dynamic nonlinearities > 20,000 times greater than Kerr effect
- Gas stiffness & damping affect resonances
- Q factor enhancement in evacuated fiber
- Possible applications as a highly sensitive static or dynamic fiber pressure sensor
- Ultimate goal: self-channelling

Topics

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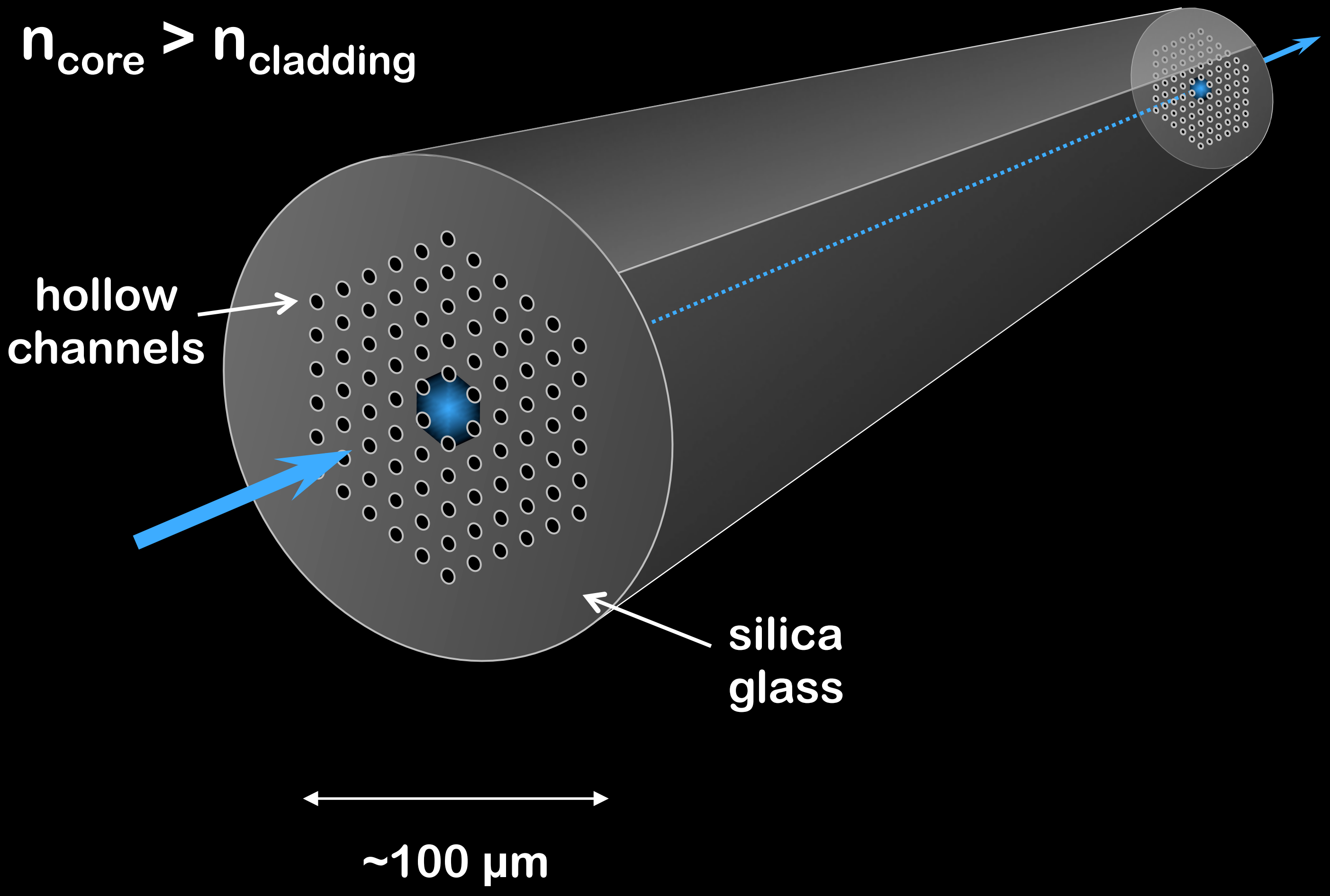
Solid core PCF (1995)

Knight et al., Opt. Lett. **21**, 1547 (1996)

$n_{core} > n_{cladding}$

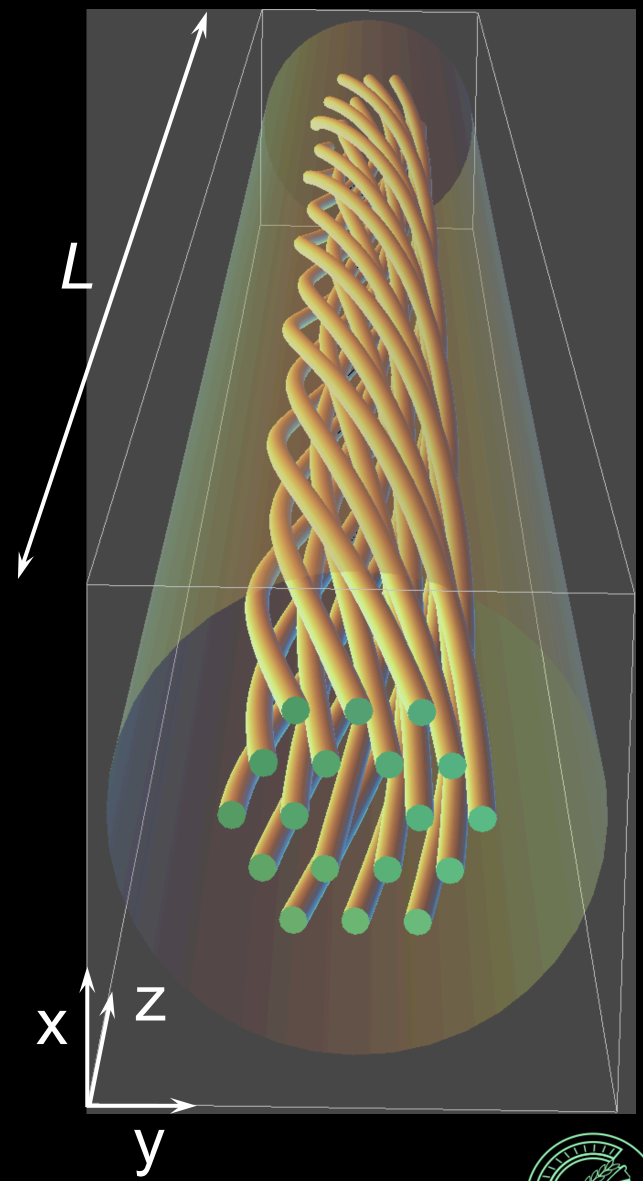


Twisted solid-core PCF

- twist rate

$$\alpha = 2\pi / L$$

- pitch *L* is much greater than inter-hole spacing
- angle between hollow channels and axis increases with radius



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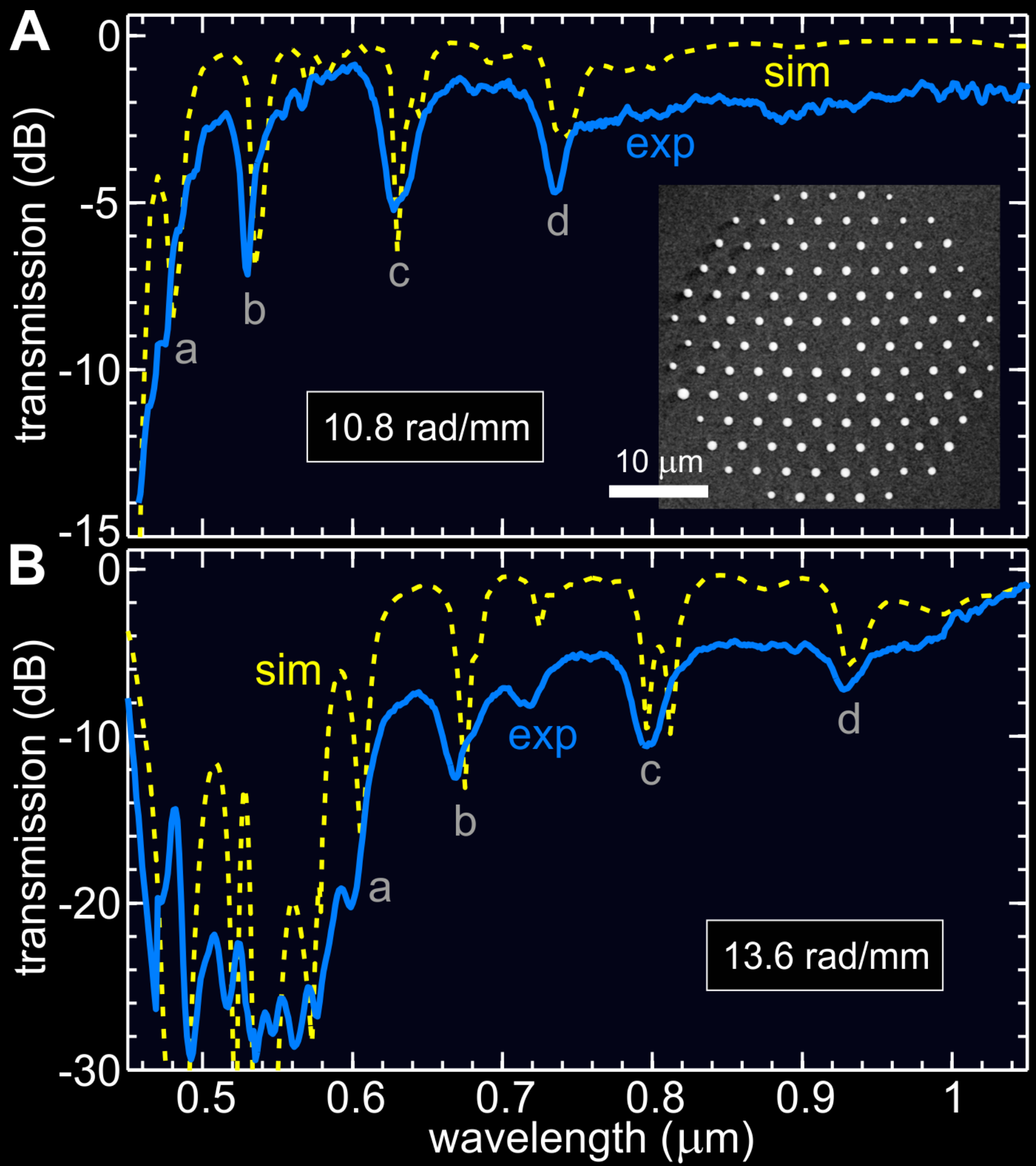
Transmission spectra

Wong et al: Science **337**, 446 (2012)



L = 581 µm

inter-hole spacing ~3 µm

L = 462 µm

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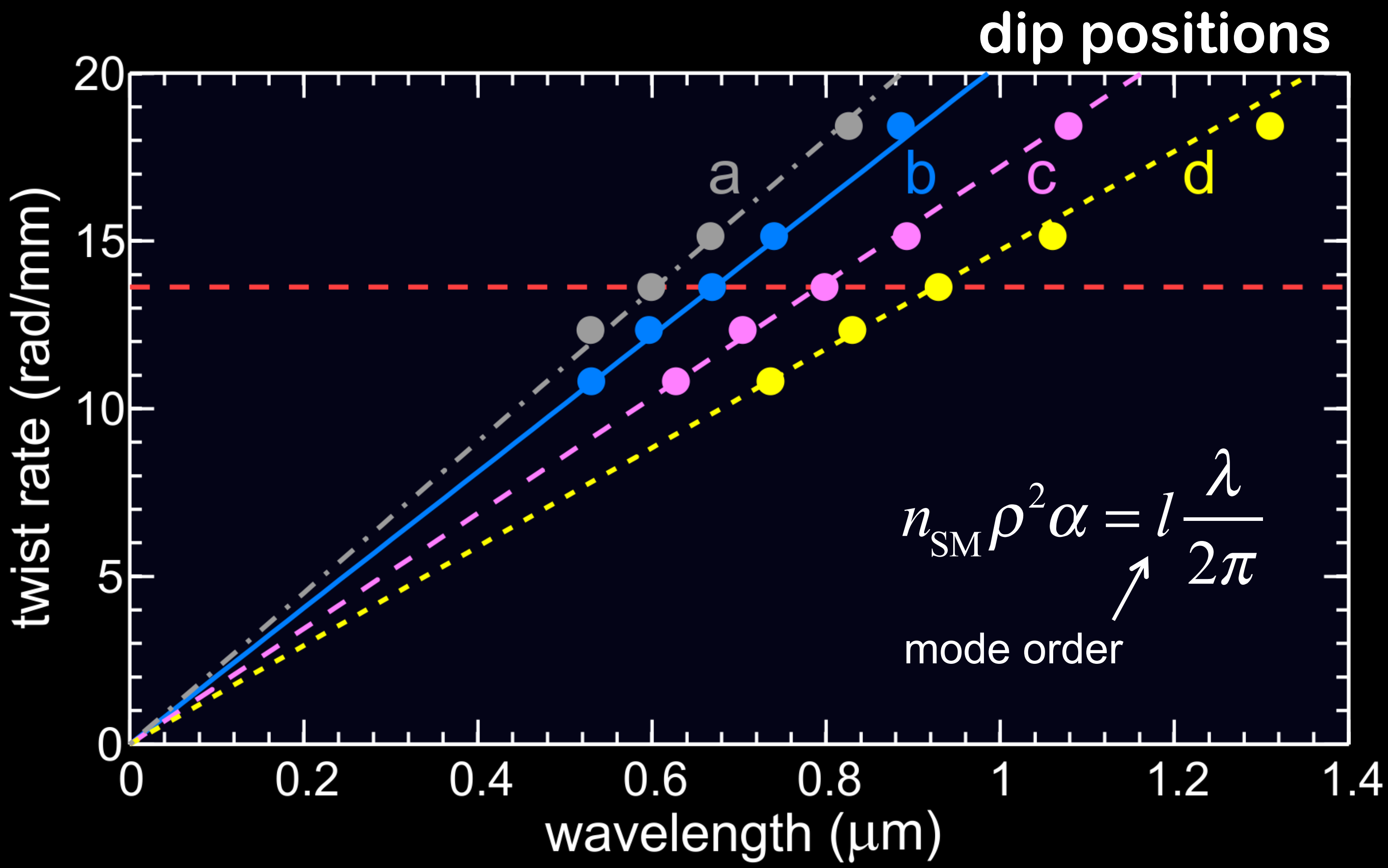
Twist rate versus resonant wavelength

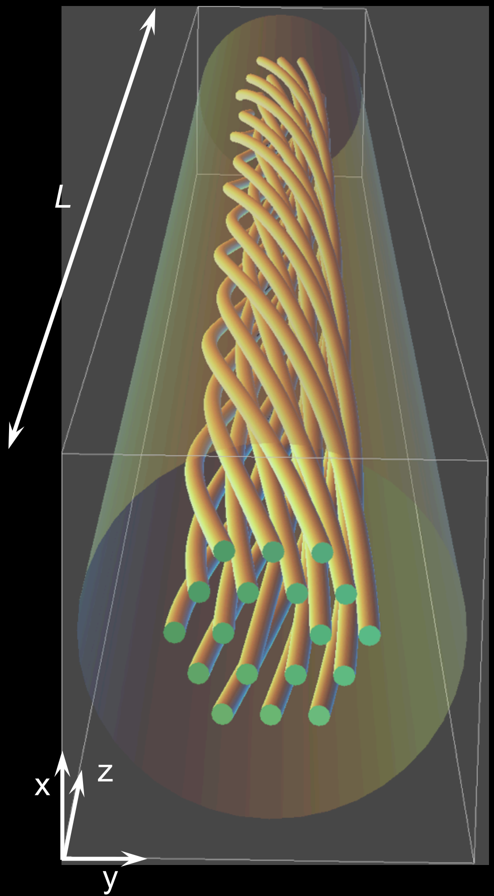
Wong et al: Science **337**, 446 (2012)



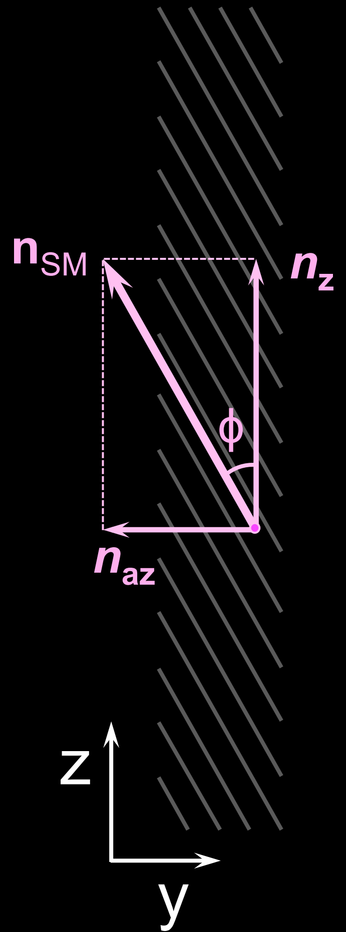
Twisted solid-core PCF

Wong et al: Science **337**, 446 (2012)

twist rate
$\alpha = 2\pi / L$



top-view



radius

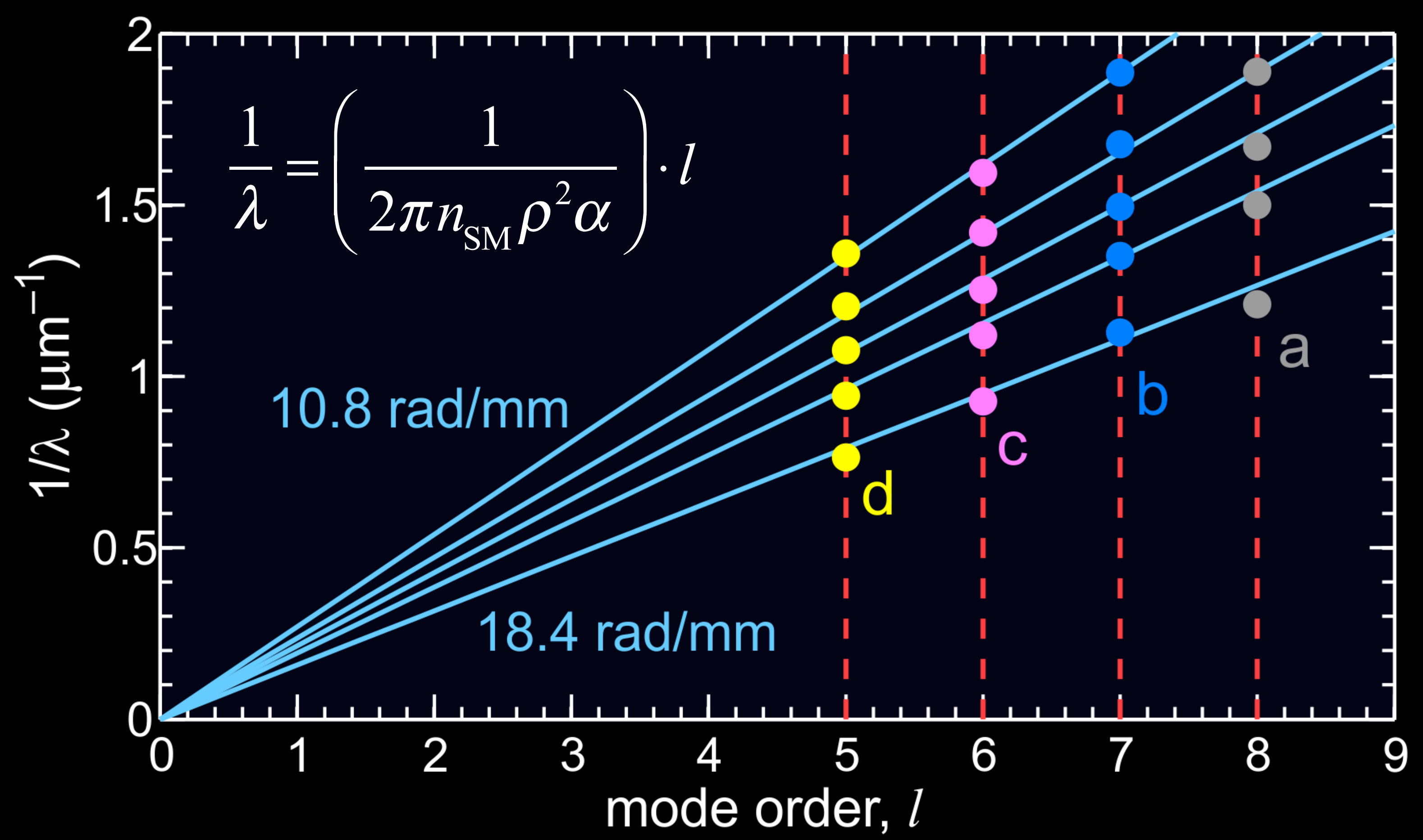
$$\sin\phi = \frac{\rho\alpha}{\sqrt{1+(\rho\alpha)^2}} \approx \rho\alpha$$

$$\Rightarrow \quad n_{\mathrm{SM}}\rho^2\alpha = l\,\frac{\lambda}{2\pi}$$

mode order

Consistent mode orders

Wong et al: Science **337**, 446 (2012)



Fits obtained for $n_{SM} \rho^2 = 54.6$ μm²

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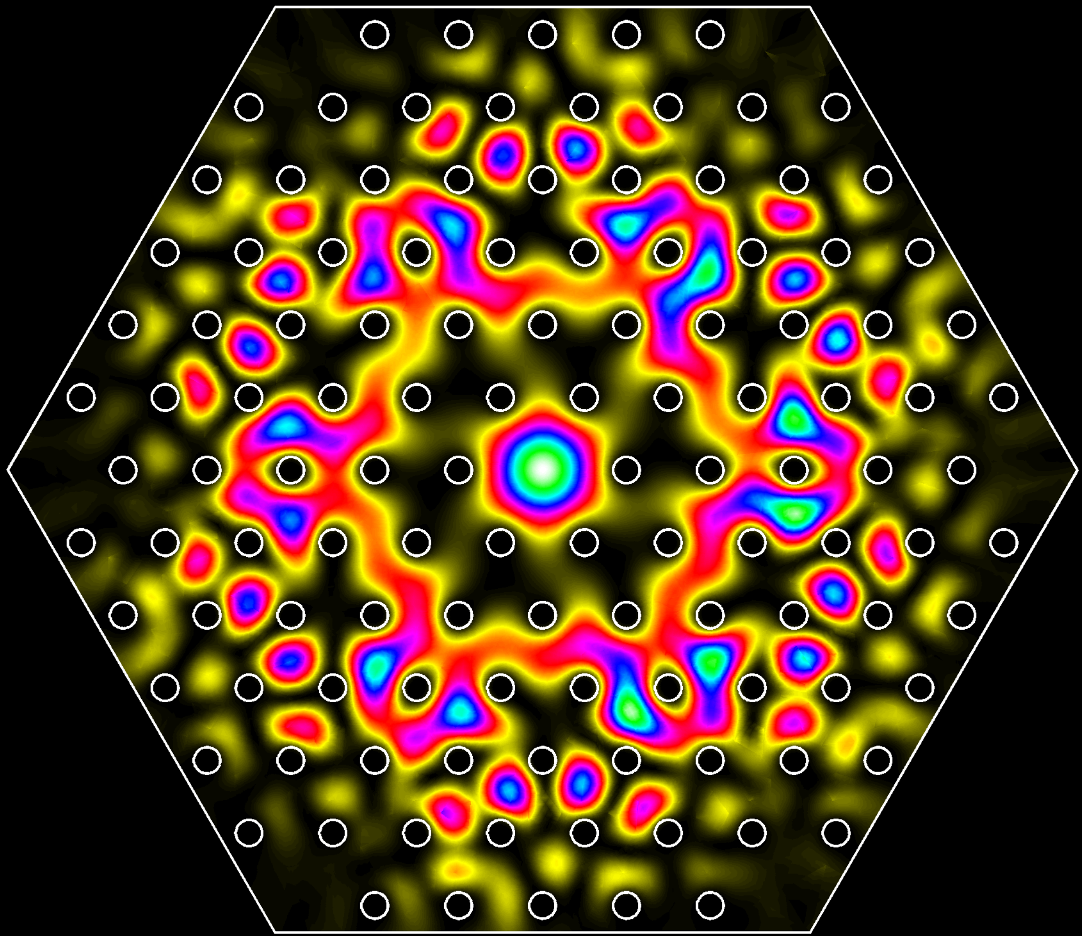
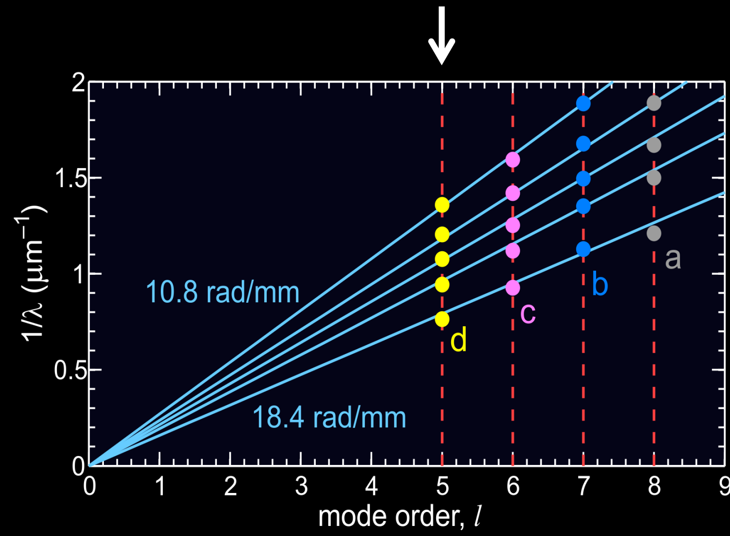
FE Modelling: Axial Poynting vector

pitch 461 µm





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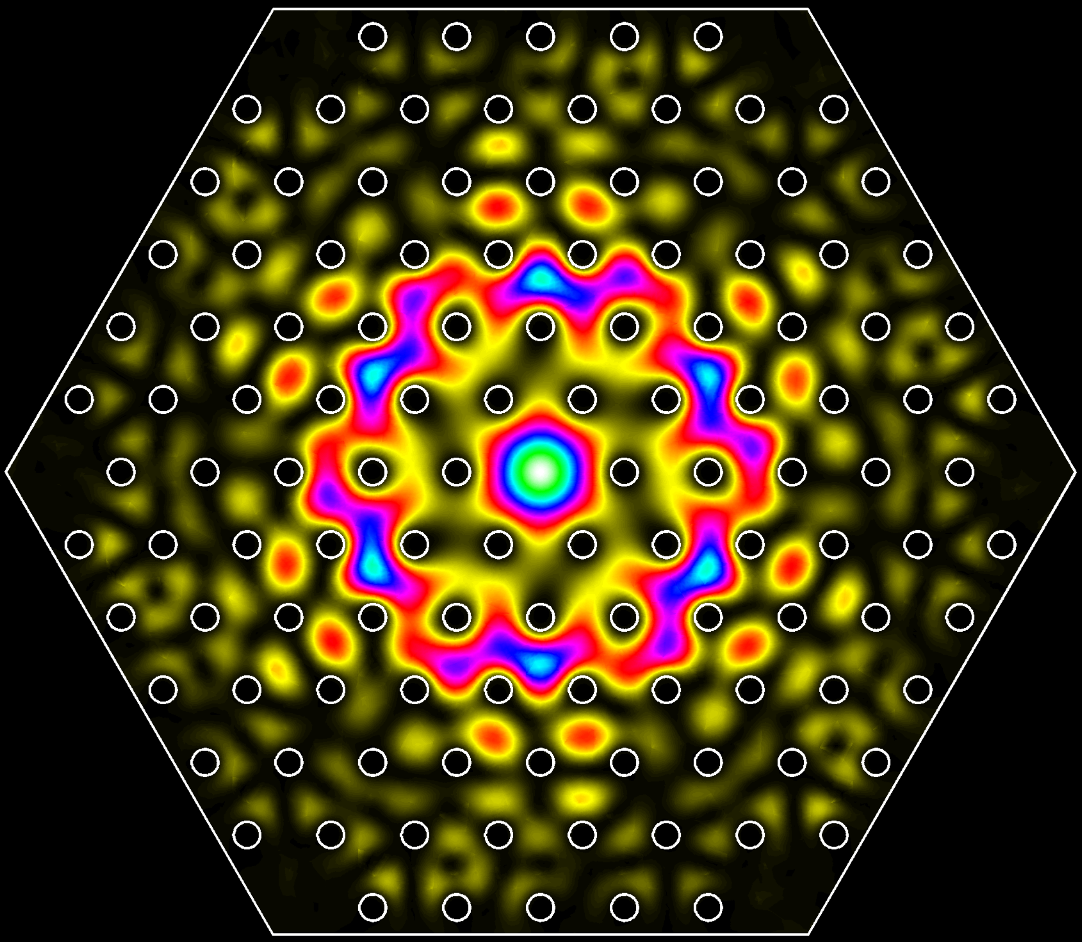

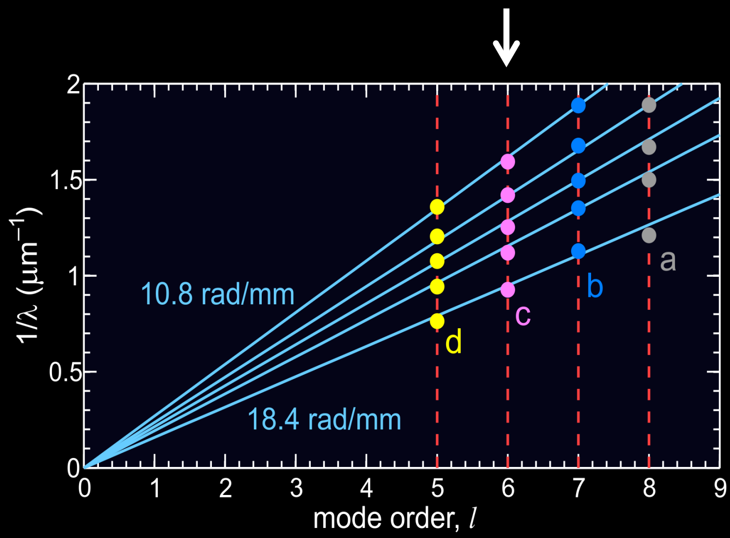

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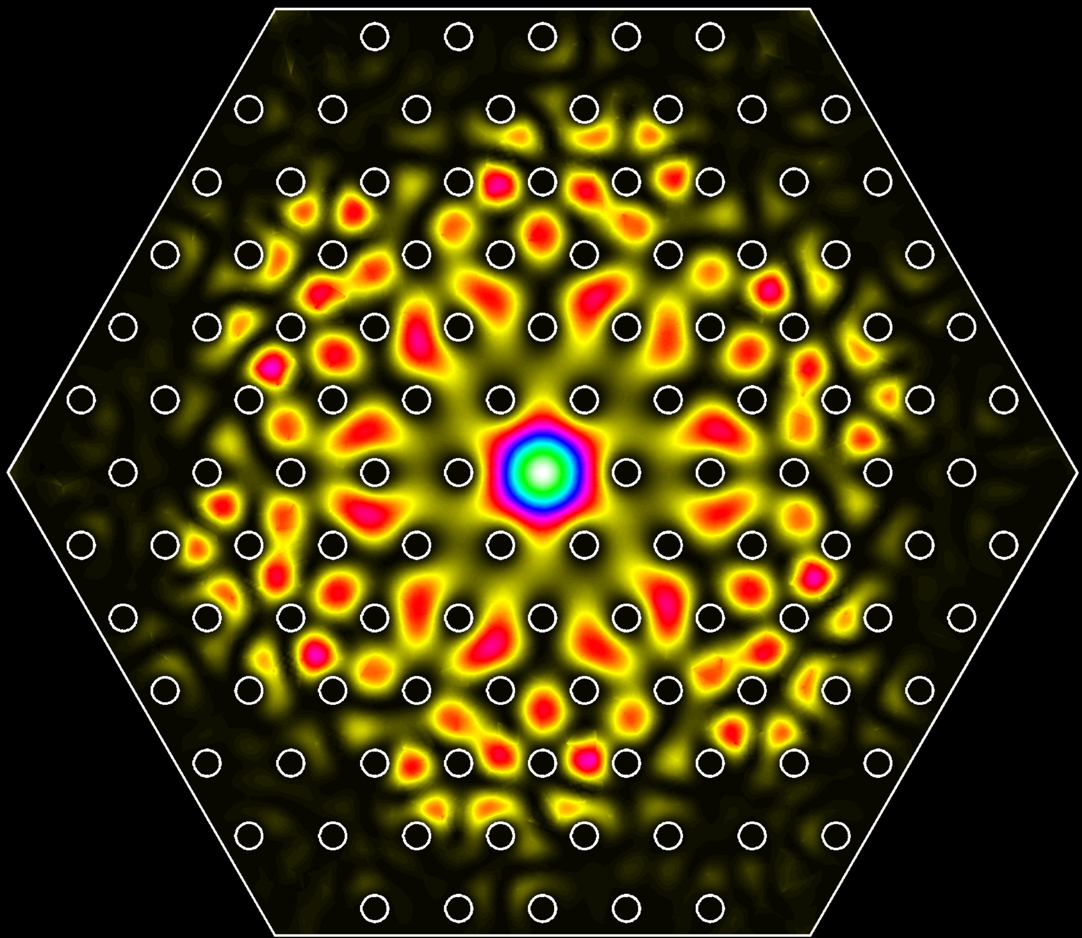
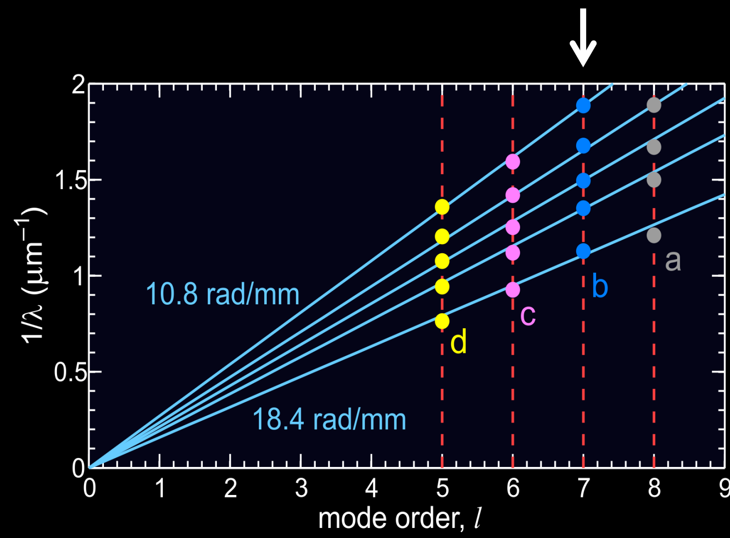
pitch 461 µm





FAU

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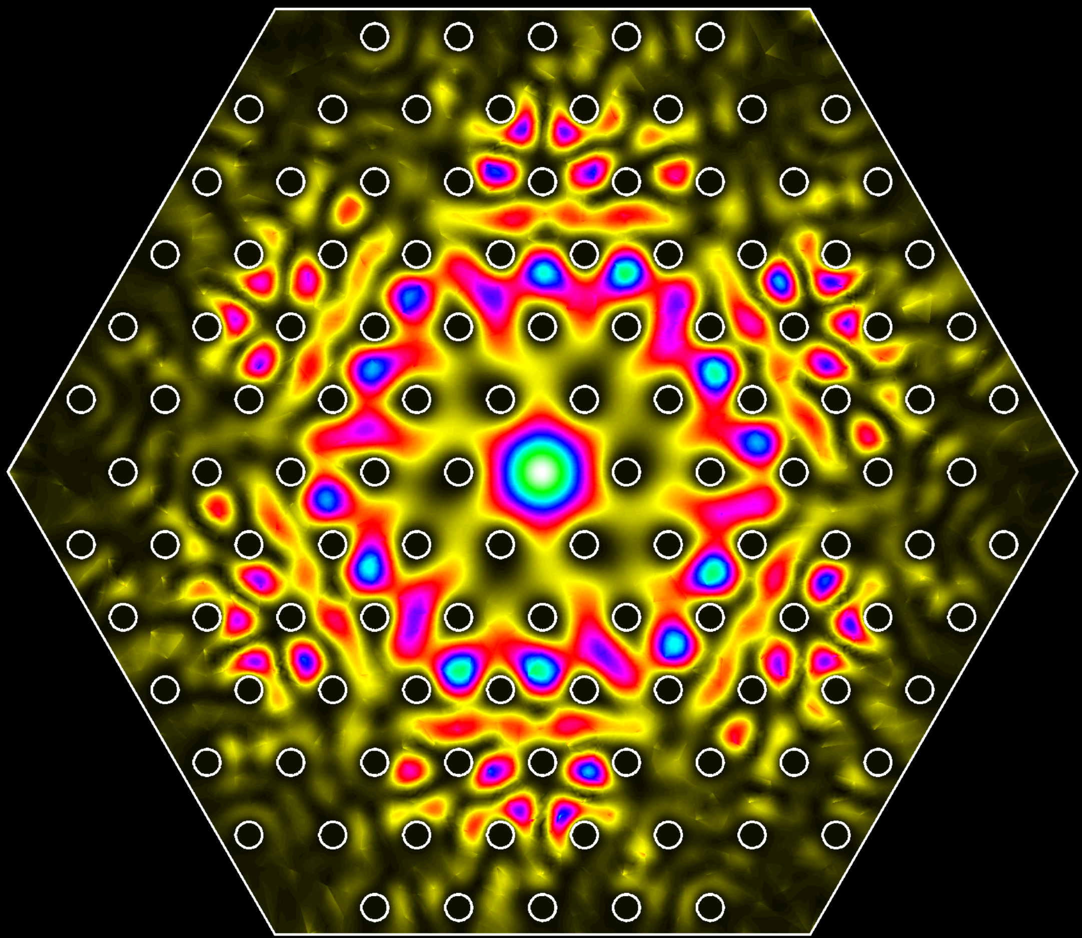
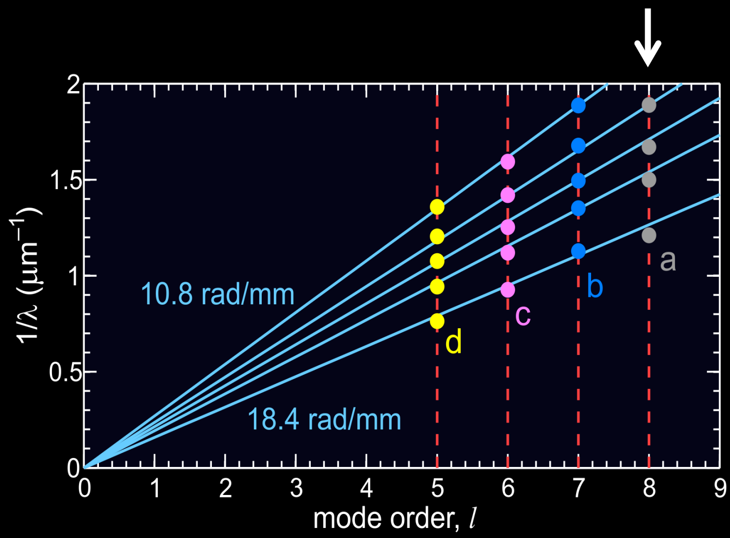
FE Modelling: Axial Poynting vector

pitch 461 µm





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Twisted fibres

- Leaky ring-shaped resonances form in the twisted cladding of helical photonic crystal fibre
- Complex filtering characteristics possible by varying the pitch along the fibre
- Twisting during fibre drawing allows extremely long lengths to be produced

Topics

- Introduction to PCF
- Compound glass PCF
- Hybrid two-glass structures
- Optomechanical structures
- Twisted fibres
- Final comments

Final comments

Requirements

- Hollow core PCF made from "soft" glasses needs more development:
  - high power delivery of IR radiation, e.g. 10 microns, not yet available
  - losses can be orders of magnitude lower than the bulk glass
- New techniques for producing nano-scale glass fibre structures
  - flow-focusing?
  - new kinds of extrusion?
- Optical glasses with other properties, e.g., magneto-optical, UV transparent, are highly desirable

Applications

- Lab-in fibre:
  - (photo)chemistry using PCF as a microfluidic channel that guides light
- Optomechanics
  - hollow core PCF for laser manipulation of particles & cells
  - intense nonlinear optoacoustic modulation driven by light
- Nonlinear optical devices
  - exquisite control of ultrafast nonlinear optics in gases (e.g., tunable deep UV light)
  - supercontinuum generation from compact pump lasers
- Nanowire plasmonics
  - devices based on metallic nanowire arrays