Stick that in your pipe and smoke it: Hollow-core fibre for atomic clocks

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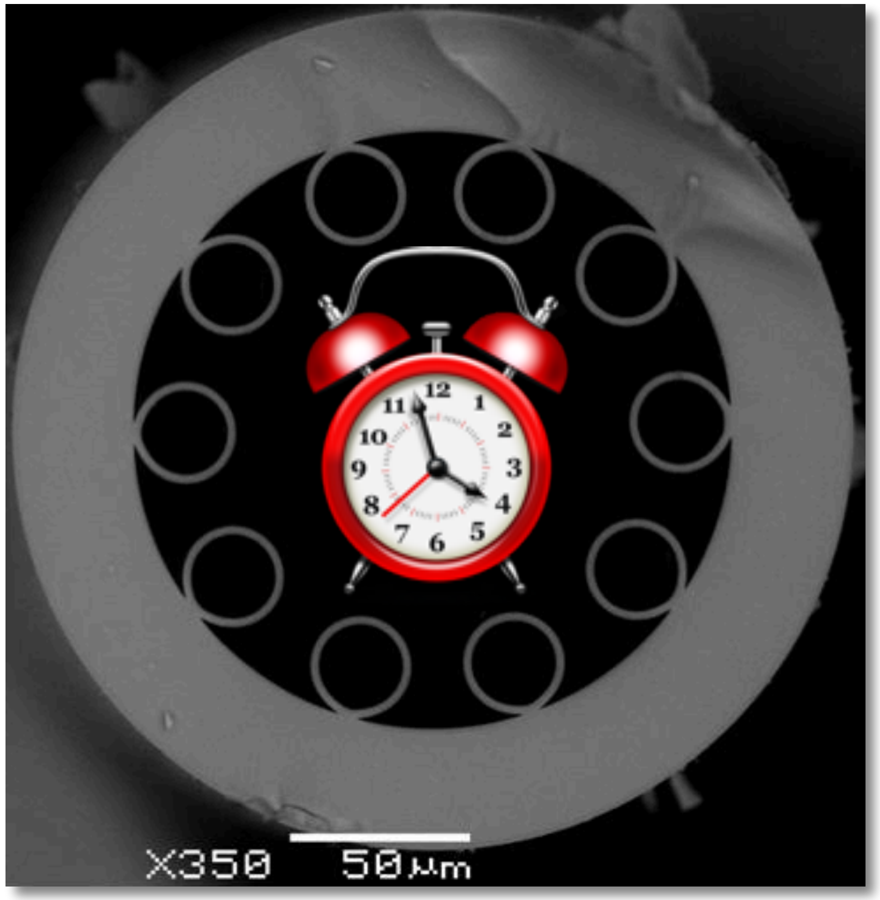
Outline

- **FEmtosecond Measurement Technology Options** (FEMTO) project overview
- **Hollow-core fibre** for light-matter interactions
- **Free-boundary** hollow-core fibre



UK Quantum Technologies programme

- **£270m investment** by UK Government in quantum technologies (QT)
- **5-year programme** to bring **QT out of the laboratory**

"Quantum technologies are considered to be those that harness quantum physics to gain a functionality or performance which is otherwise unattainable"

- 4 EPSRC **QT Hubs**:
    - Glasgow - enhanced **imaging**
    - York - quantum **communications**
    - Birmingham - **sensors** and **metrology**
    - Oxford - **networked quantum information**

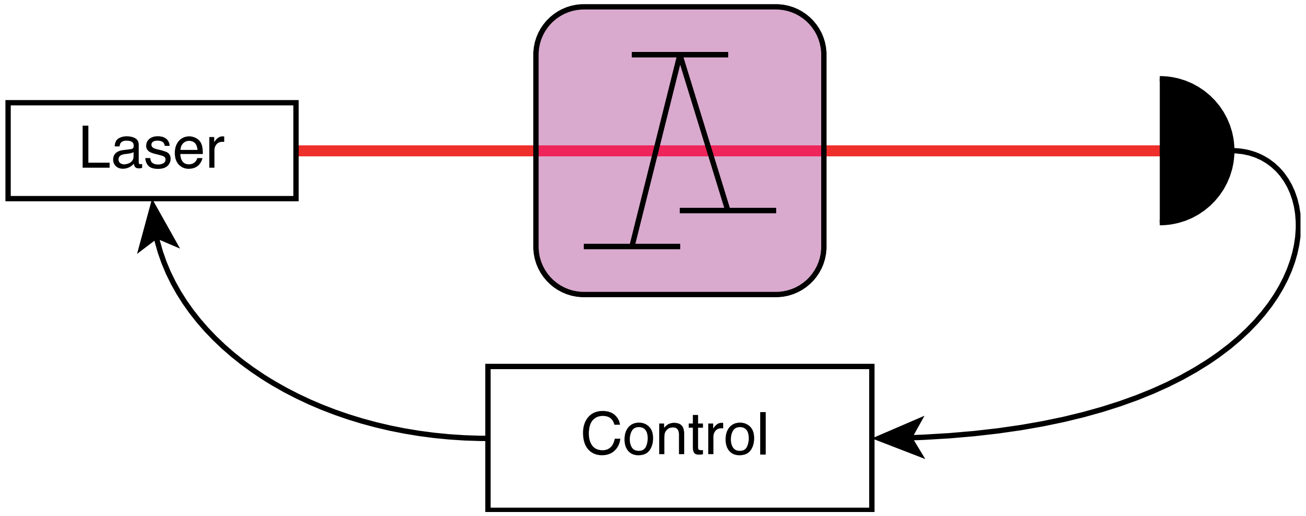
- **Innovate UK** funded projects

FEMTO project overview

- Funded by **Innovate UK**
- Early stage UK commercialisation of ***Quantum 2.0* clock technologies**
- Develop **microwave** down-conversion, **physics** package encapsulation, and time error **measurement** techniques
- Develop **transportable prototypes** of miniaturized optical clocks
- Demonstrate **prototype HCF** technology
- Develop enabling technologies for **next-generation** quantum clocks

Coherent light-matter interactions

- **Coherent population trapping** in ^{87}Rb, D1 transition wavelength 795nm
- Hyperfine splitting **6.8GHz**

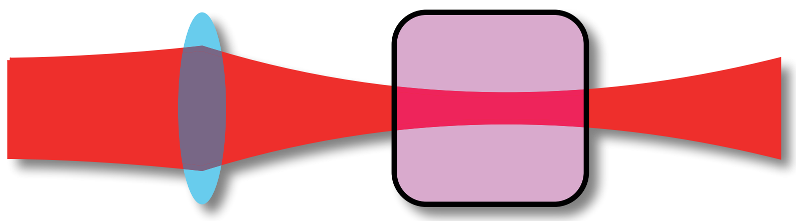


- **Coherent interaction** between modulated laser and atomic vapour
- Lock laser modulation to peak in transmission from "**dark state**"
- Optical requirements
  - **optical depth**
  - **length** of interaction region
  - **coherence** between atoms and field

Why use hollow-core fibre?

$$f = \frac{L_{\mathrm{int}}\lambda}{A}$$

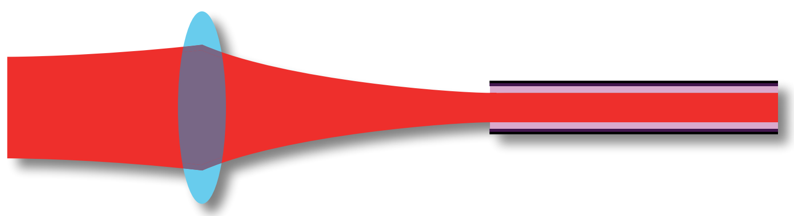
- **Vapour cell**



- Limited by Rayleigh range of focus

$$f \approx 10$$

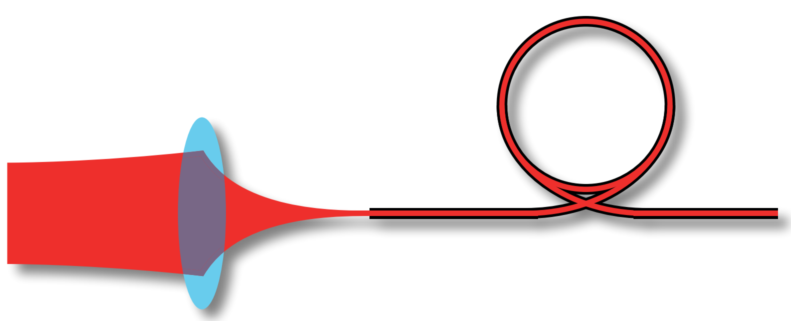
- **Capillary**



- Limited by leaky guidance

$$f \approx 100$$

- **Hollow-core fibre**



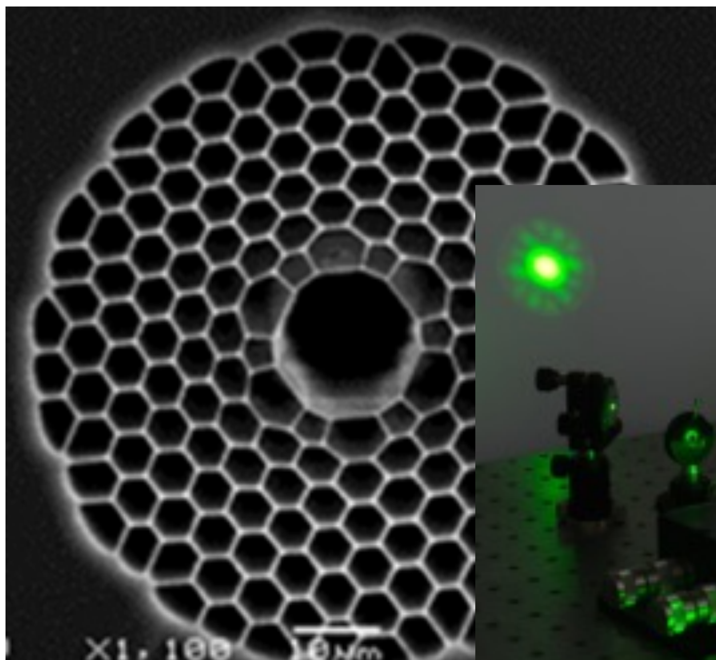
- As good as you can make the fibre!

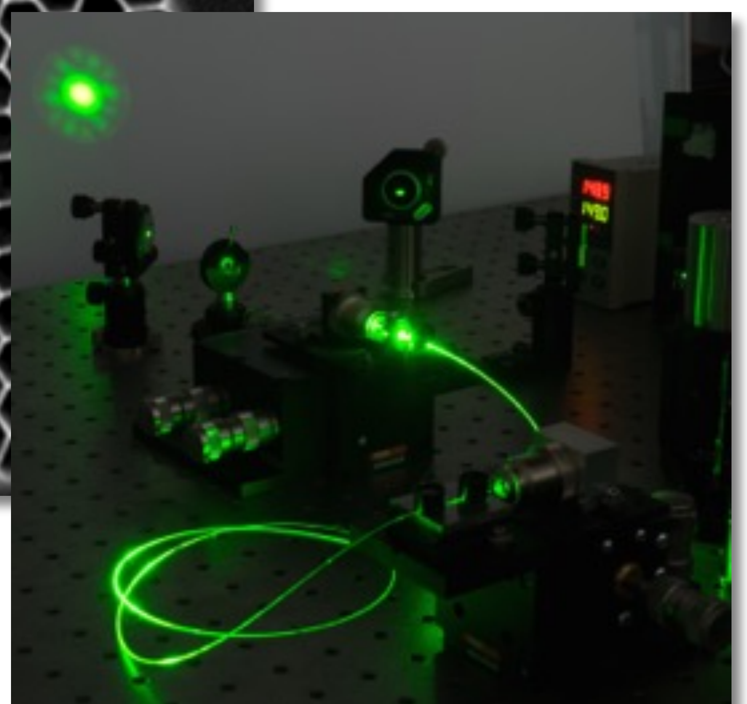
$$f > 1000$$

Benabid et al, Science **298**, 399 (2002)

Hollow-core fibre designs

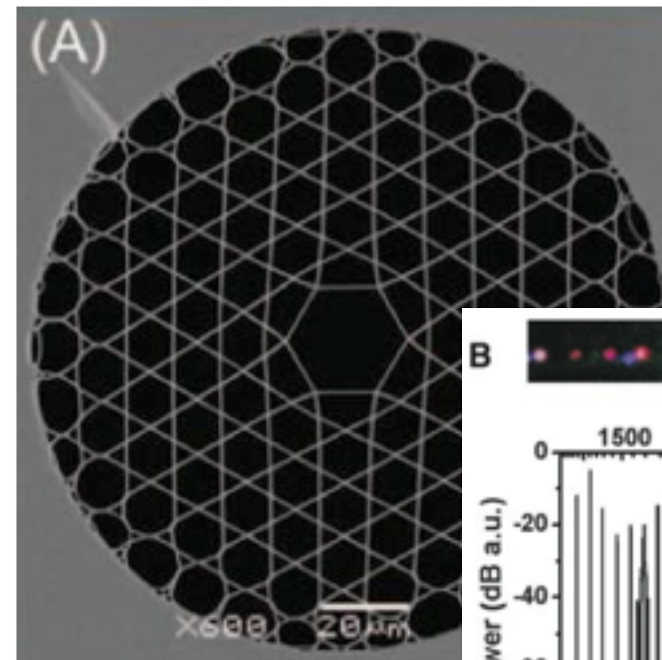
- **Photonic bandgap fibre**

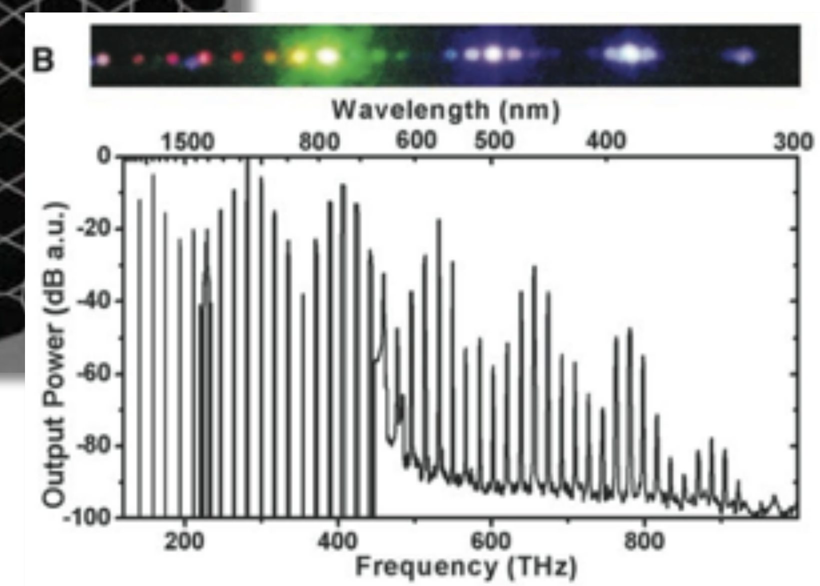




Mosley et al, Opt Lett **35**, 3589 (2010)

- **Kagomé fibre**





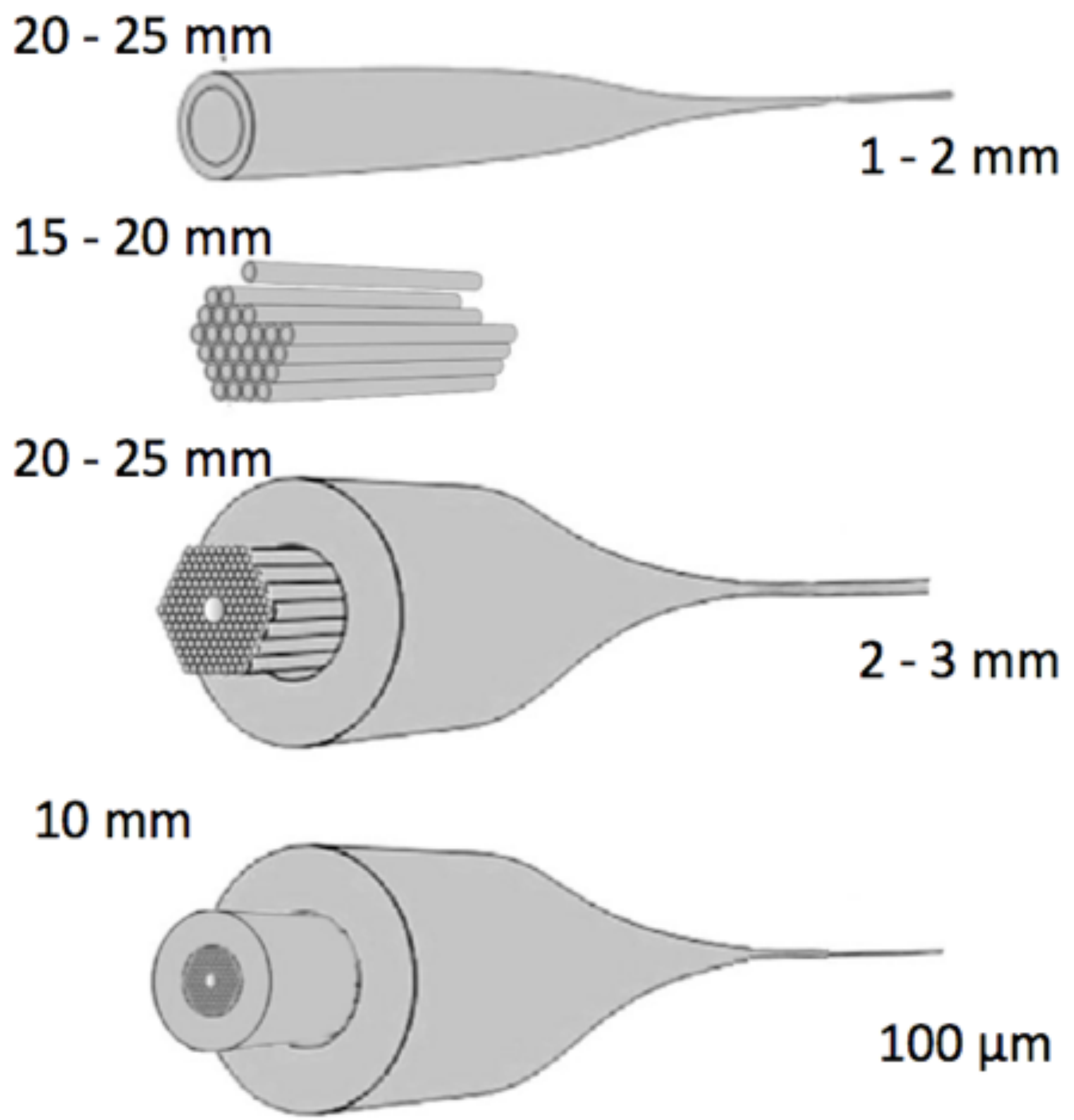
Couny et al, Science **318**, 118 (2007)

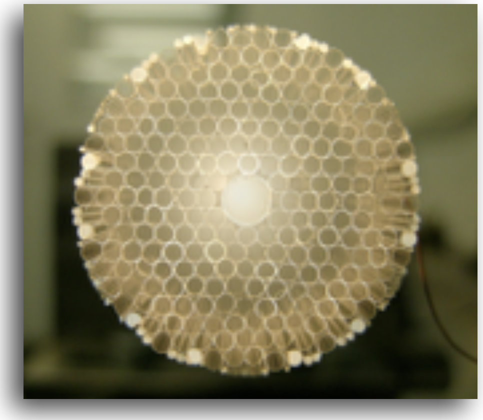
- Low-loss guidance over narrow range
- Broadband guidance, higher loss

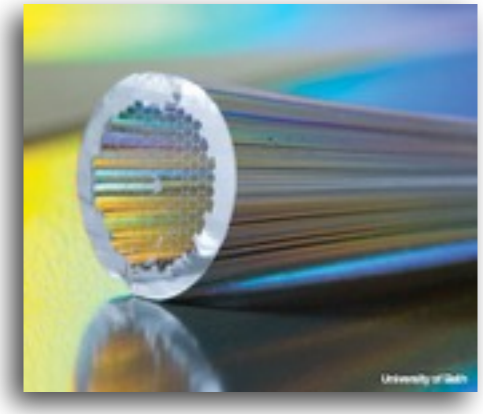
- Both have **intricate cladding**; tough to fabricate

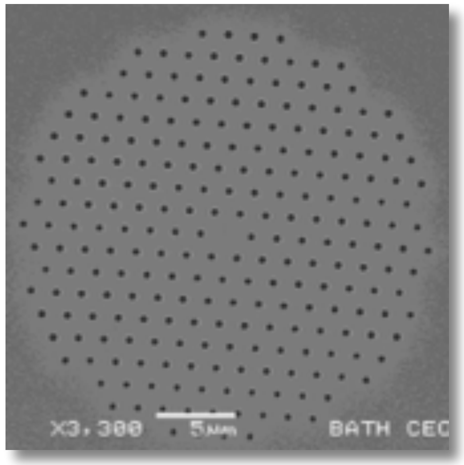
Fabrication - stack and draw

- Silica capillaries
- Stack
- Cane
- Fibre



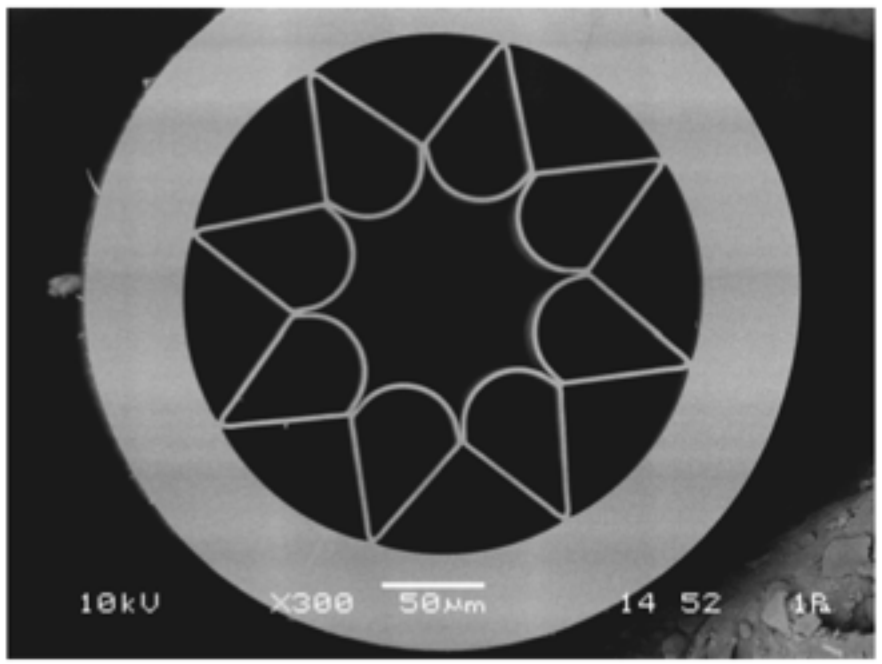




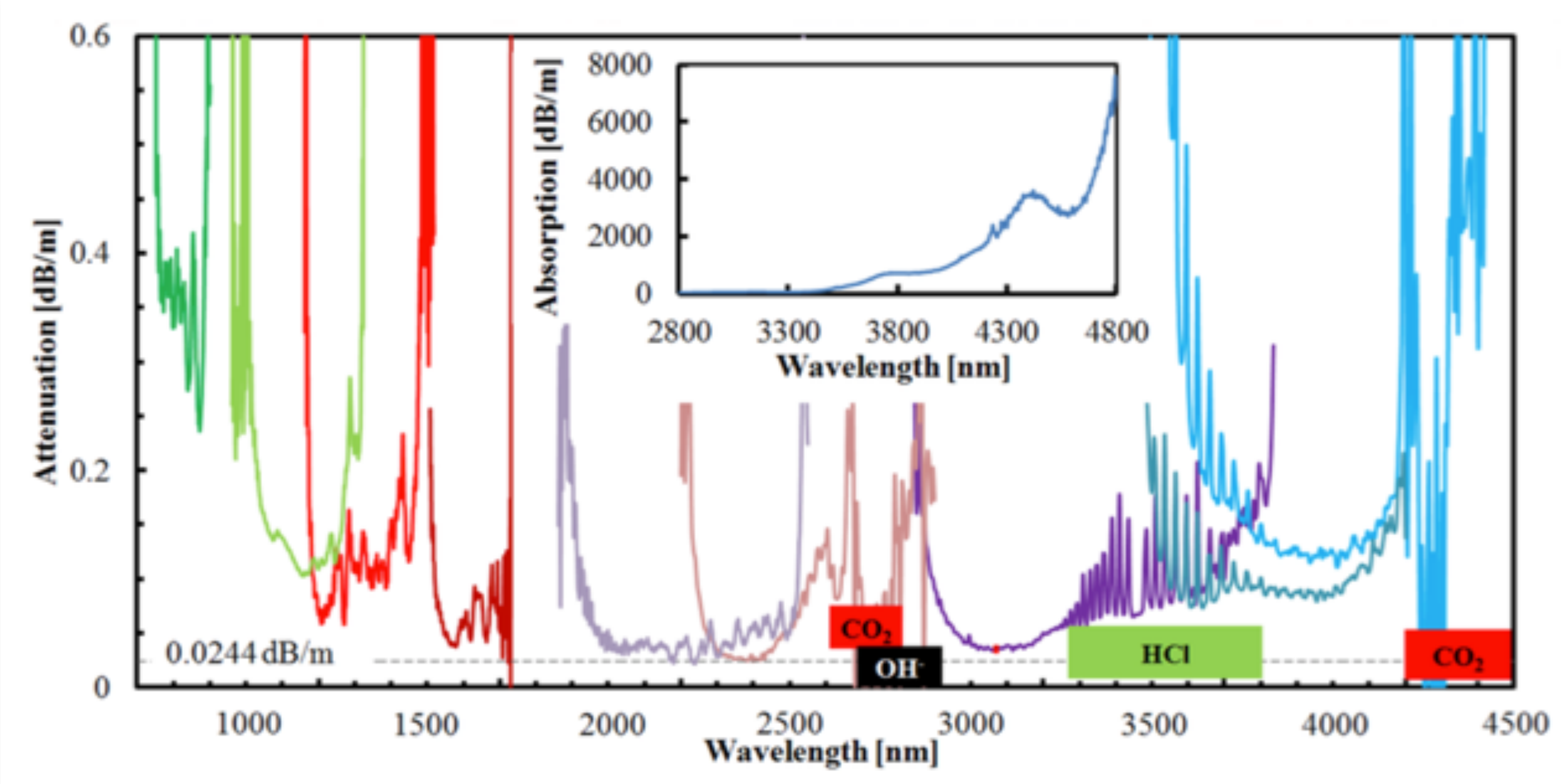


Negative curvature hollow-core fibre

- **Simplified structure** - single ring of capillaries around core
- "Negative curvature" of core wall



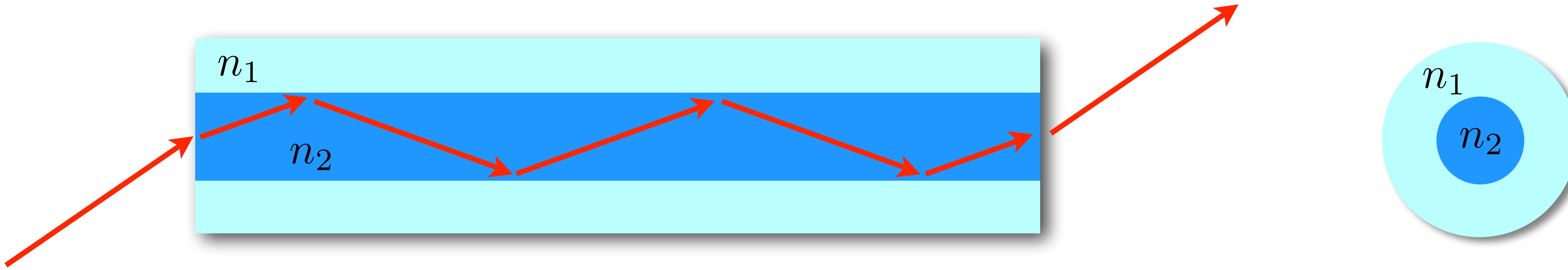
Yu and Knight, Opt Express **21**, 21466 (2013)



- **Susceptible to bend loss** due to nodes in cladding

How does the hollow-core fibre work?

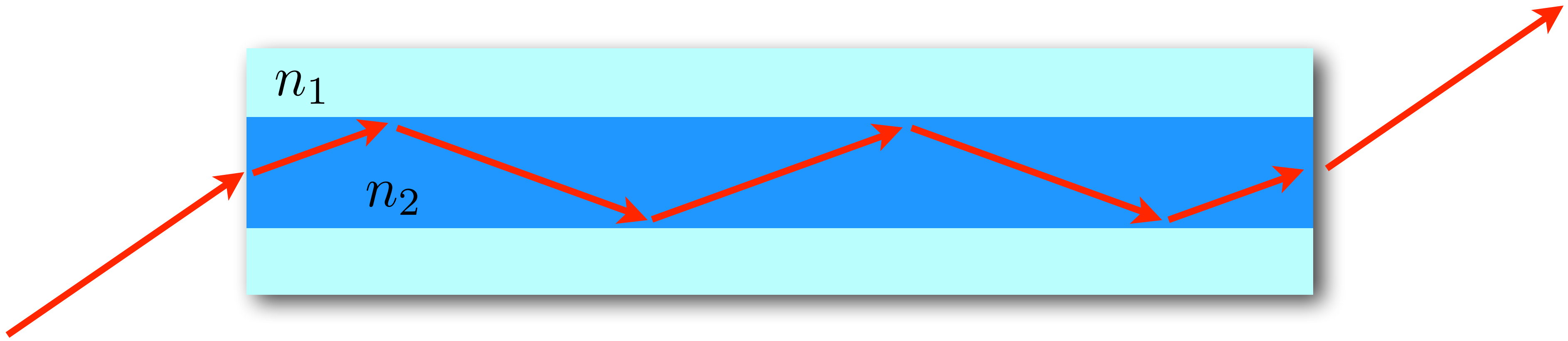
- **Conventional fibre**

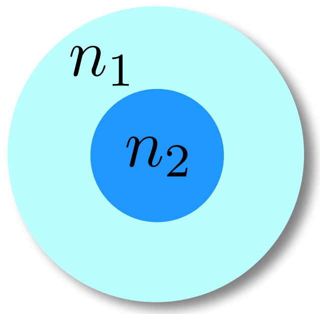


$n_2 > n_1$

How does the hollow-core fibre work?

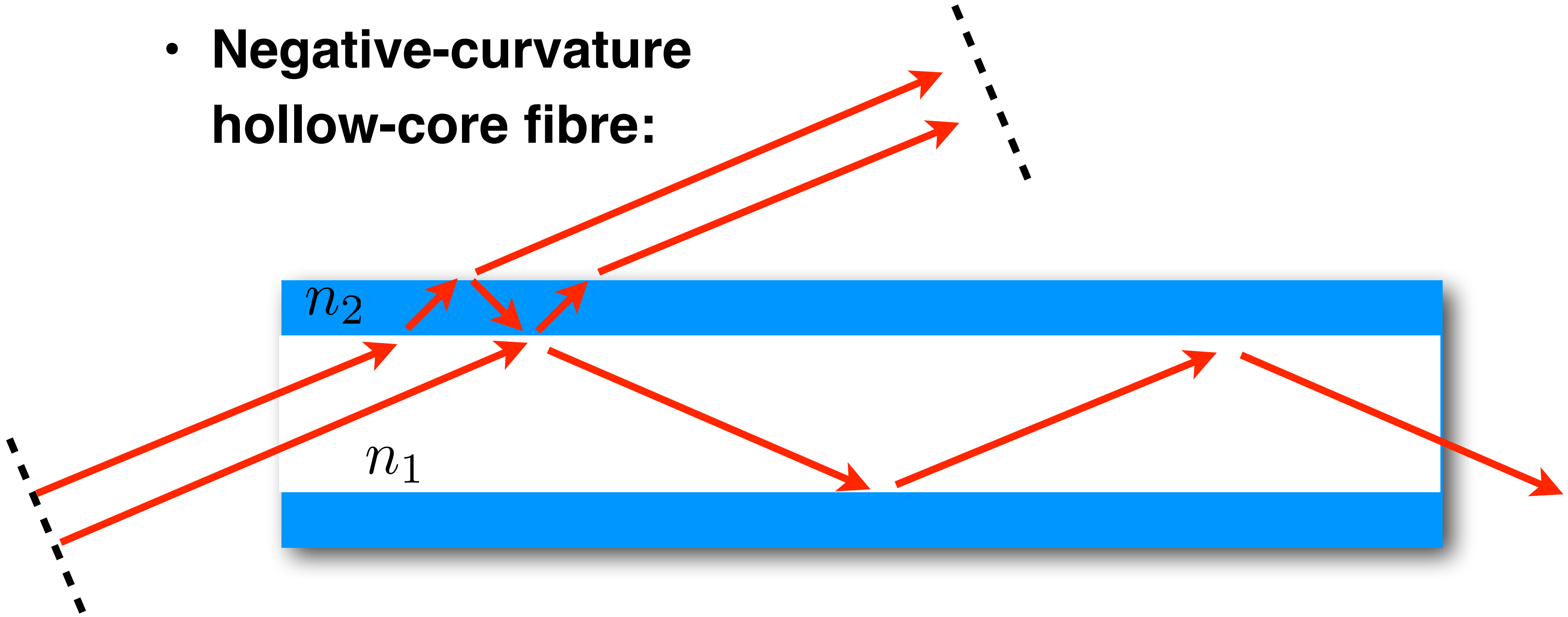
- **Conventional fibre**

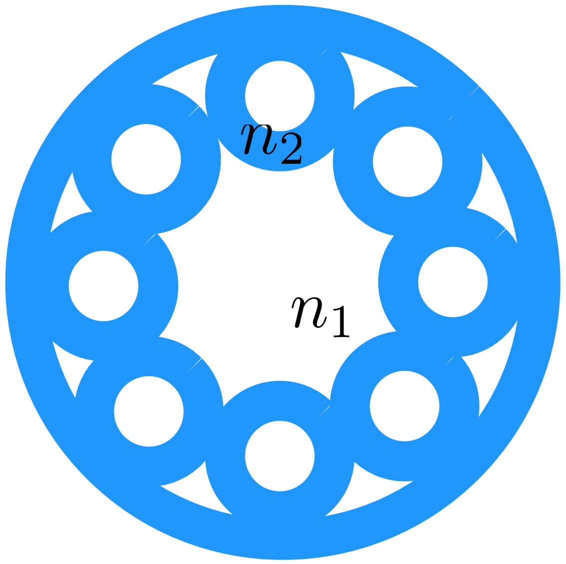




$n_2 > n_1$

- **Negative-curvature hollow-core fibre:**





ARROW model

1592 OPTICS LETTERS / Vol. 27, No. 18 / September 15, 2002

Antiresonant reflecting photonic crystal optical waveguides

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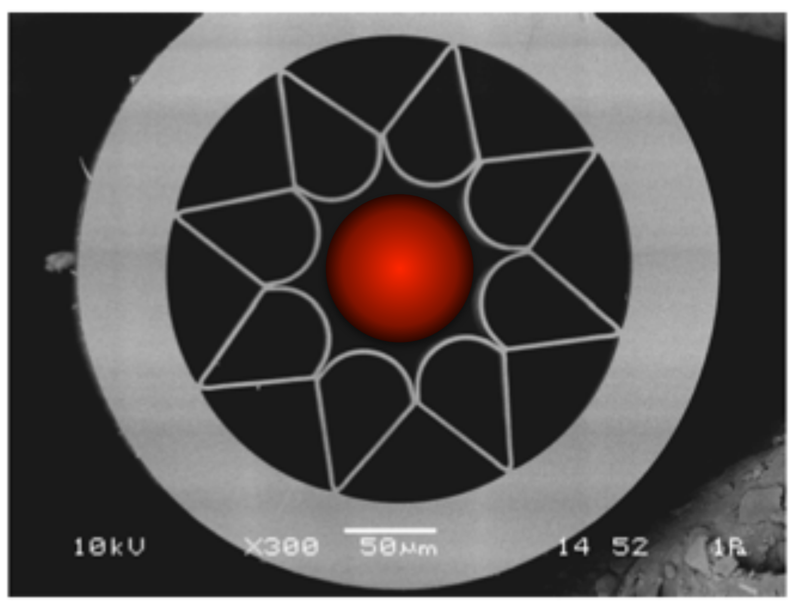
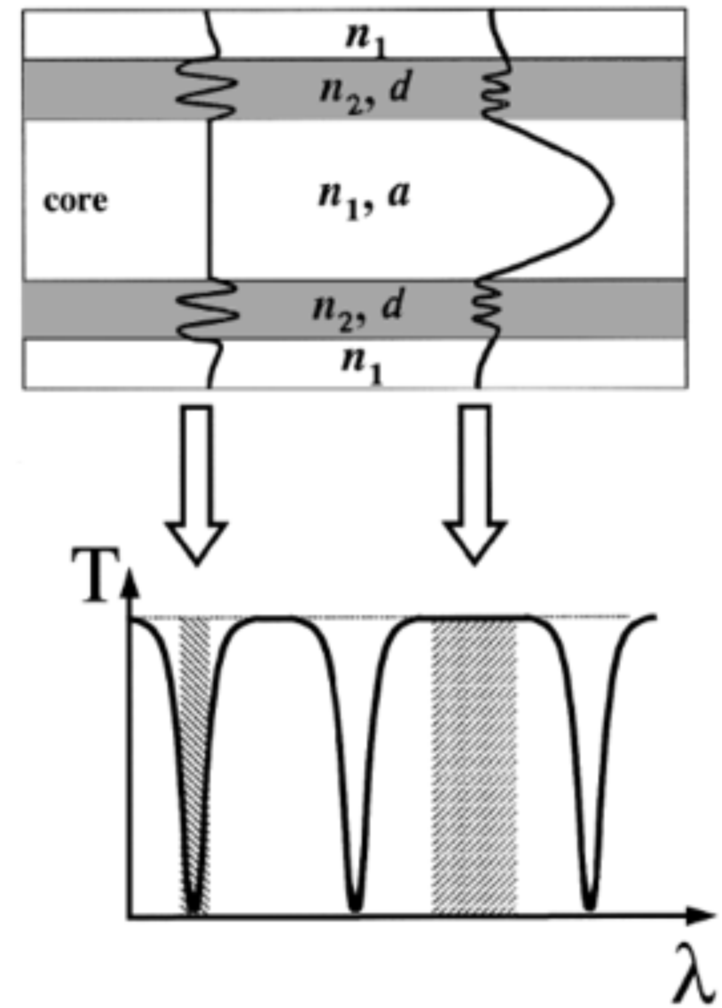
$$\lambda_l = \frac{4n_1 d}{(2l+1)}[(n_2/n_1)^2 - 1]^{1/2}, \quad l = 0, 1, 2, \ldots .$$





Free-boundary hollow-core fibre

Hollow antiresonant fibers with low bending loss

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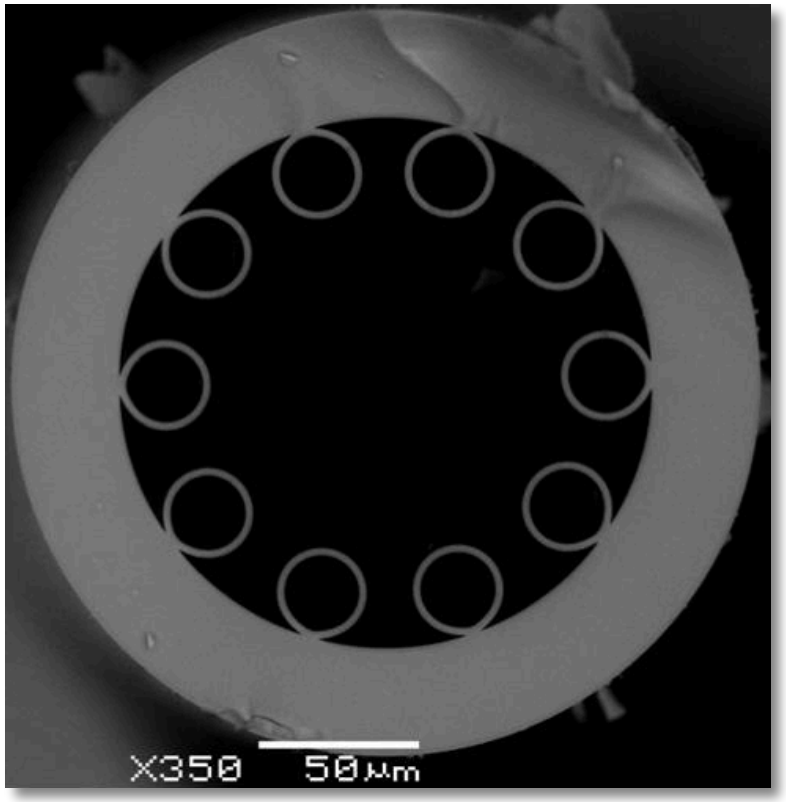
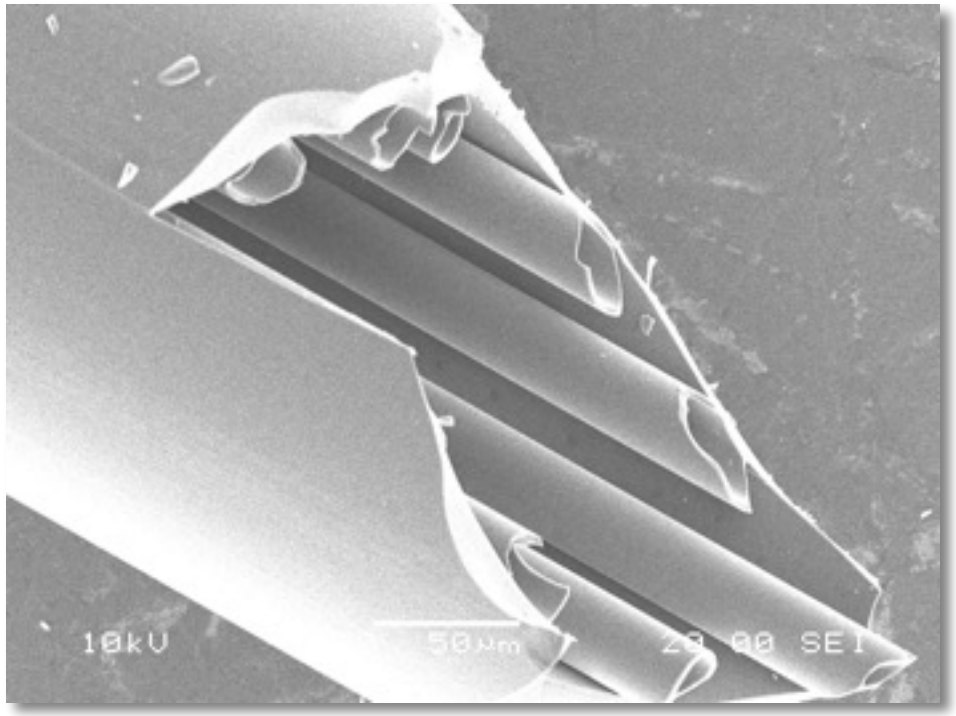
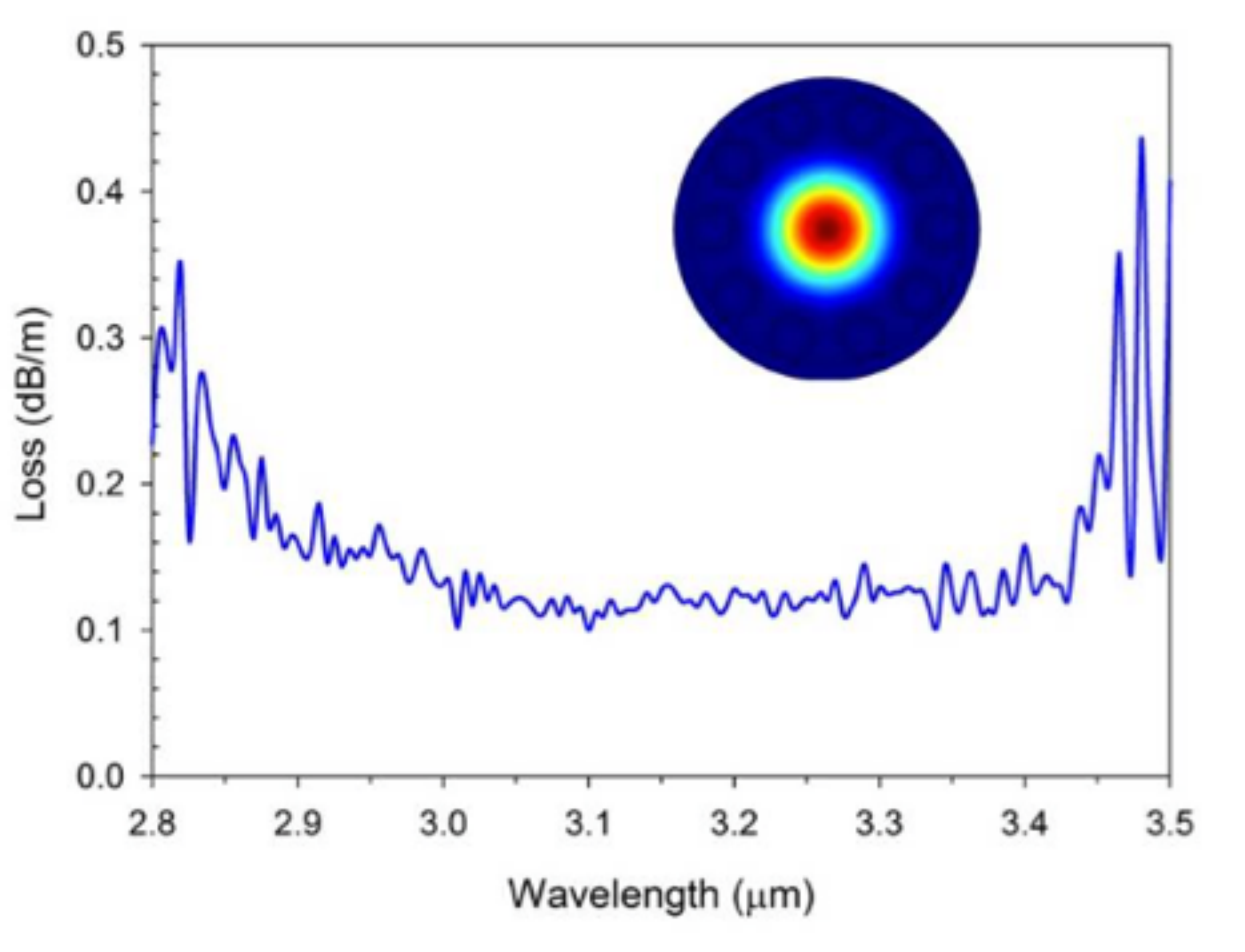
Abstract: We first use numerical simulations to show that bending losses of hollow antiresonant fibers are a strong function of their geometrical structure. We then demonstrate this by fabricating a hollow antiresonant fiber which presents a bending loss as low as 0.25dB/turn at a wavelength of 3.35μm and a bend radius of 2.5cm. This fiber has a relatively low attenuation (<200dB/km) over 600nm mid-infrared spectral range.



Belardi and Knight, Optics Express **22**, 10091 (2014)

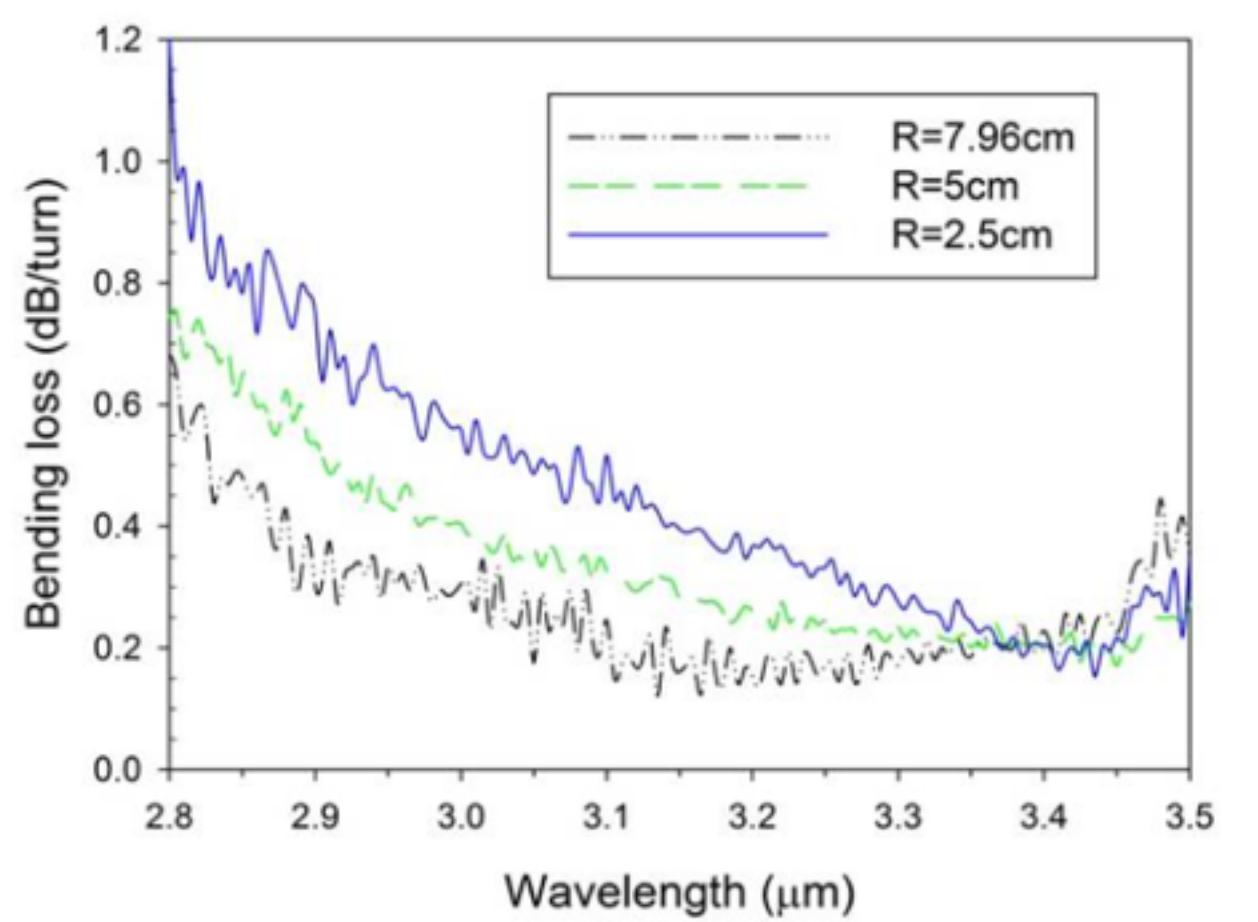


FBF long-wavelength performance

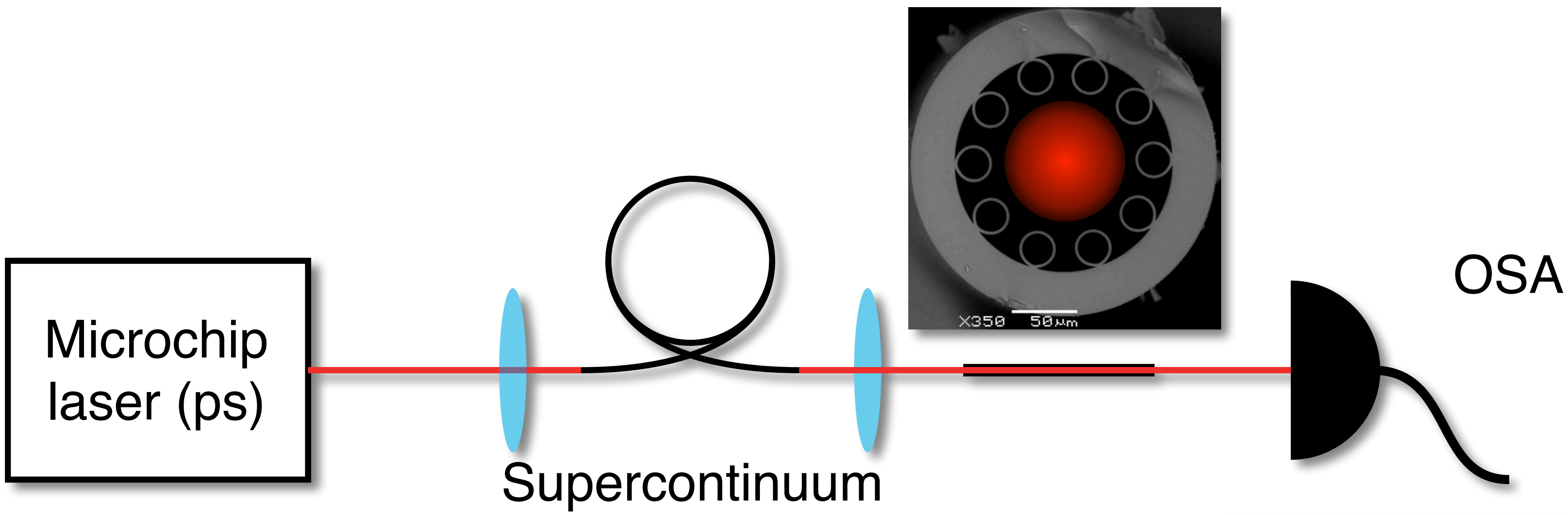


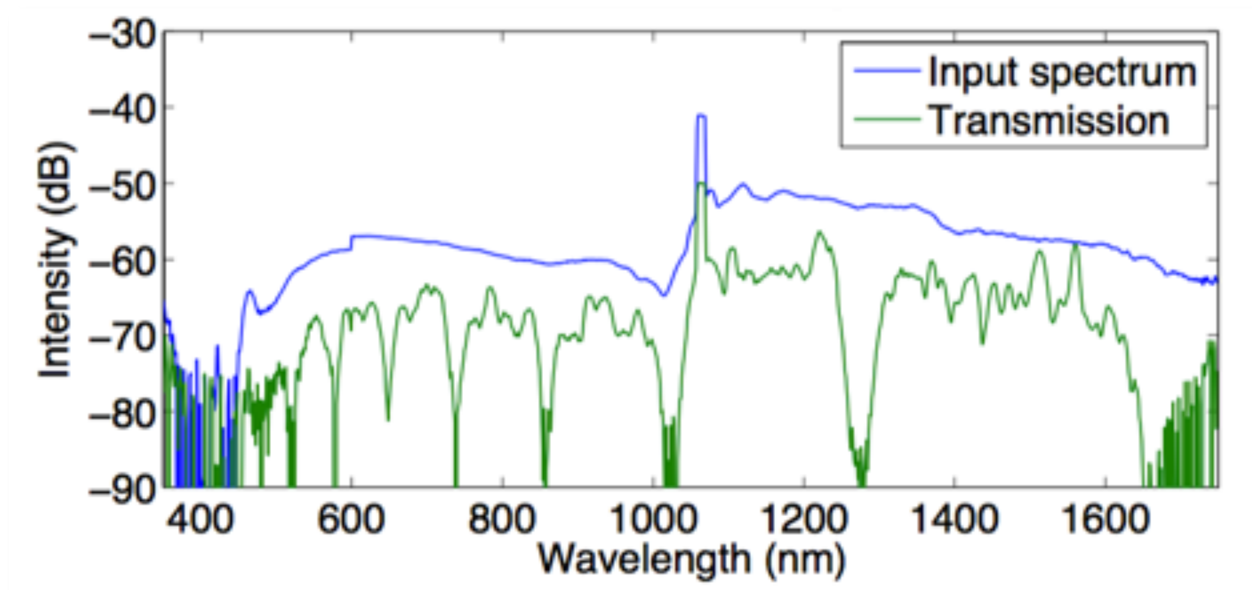
Belardi and Knight, Optics Express **22**, 10091 (2014)

- **No nodes** in cladding
- **Reduced bend loss**



FBF short-wavelength guidance

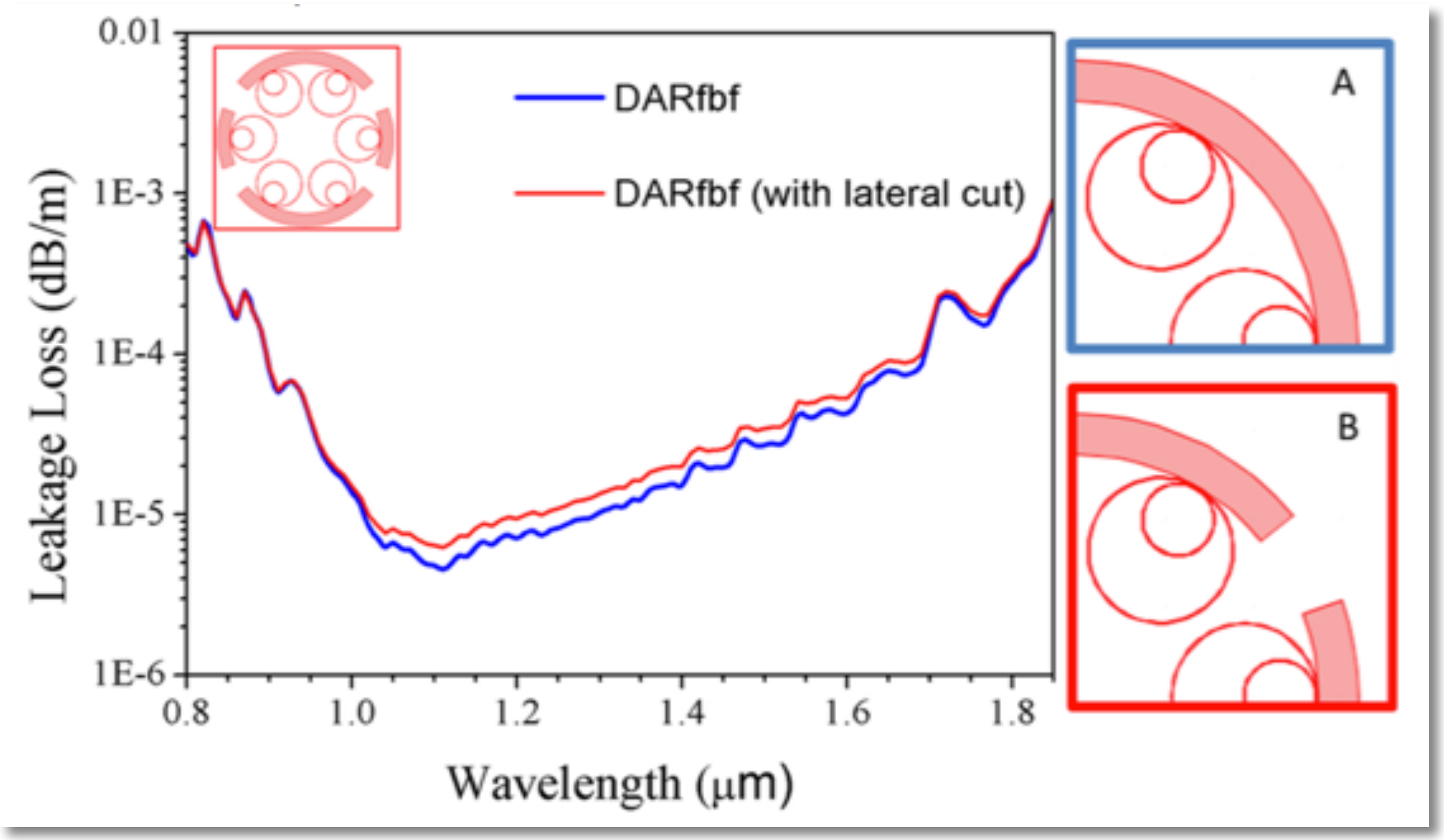


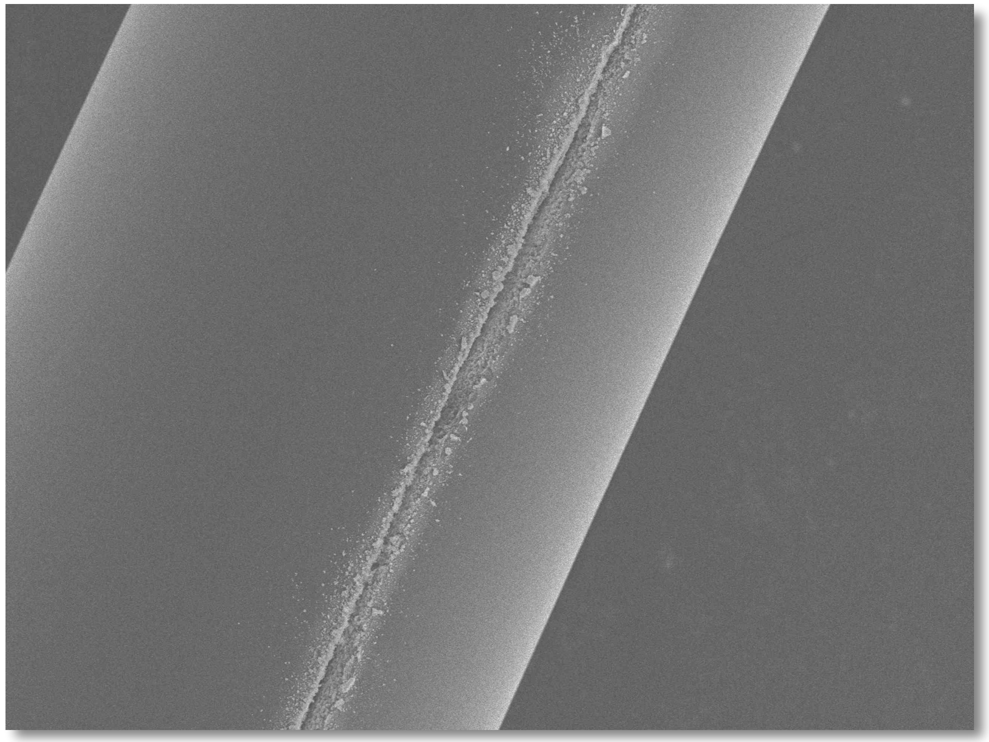


- **Short-wavelength transmission** in high-orders of cladding anti-resonance

FBF machining

- FBF design permits **access to core** without impacting guidance

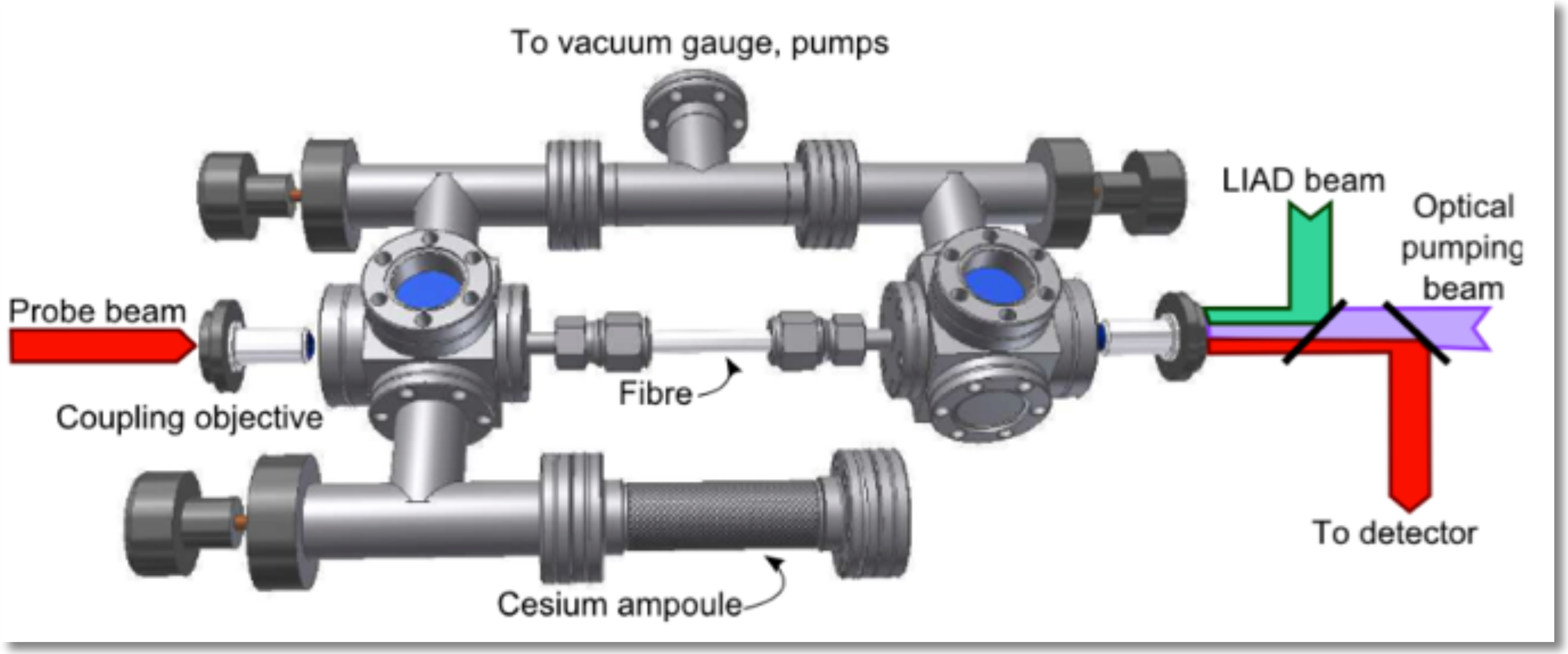




Belardi, J. Lightwave Technol. **33**, 4497 (2015)

Filling FBF with Rb and encapsulation

- Variety of possibilities for **end-filling** fibre with Rb…



Sprague et al, New J Phys **15**, 055013 (2013)

- Preliminary **splicing** of FBF to solid fibre under way…

Summary

- FEMTO project - developing technology for **miniature atomic clocks** and next-generation quantum clocks
- **Hollow-core fibre** provides opportunity for low size/weight/power packages
- New **negative-curvature fibre** designs offer simplified fabrication and high performance

Innovate UK
Technology Strategy Board