Hollow Core Fibers: Past, Present & Future

Thomas Bradley, University of Southampton

OSA
Technical
Groups

Hollow Core Optical Fibres: Past, Present & Future

Thomas D Bradley, Gregory Jasion, Hesham Sakr, John Hayes, Kerrianne Harrington, Eric Numkam Fokoua, Ian A Davidson, Austin Taranta, Seyd Mohammad Abokamis, Yong Chen, N V Wheeler, Marco Petrovich, David J Richardson and Francesco Poletti

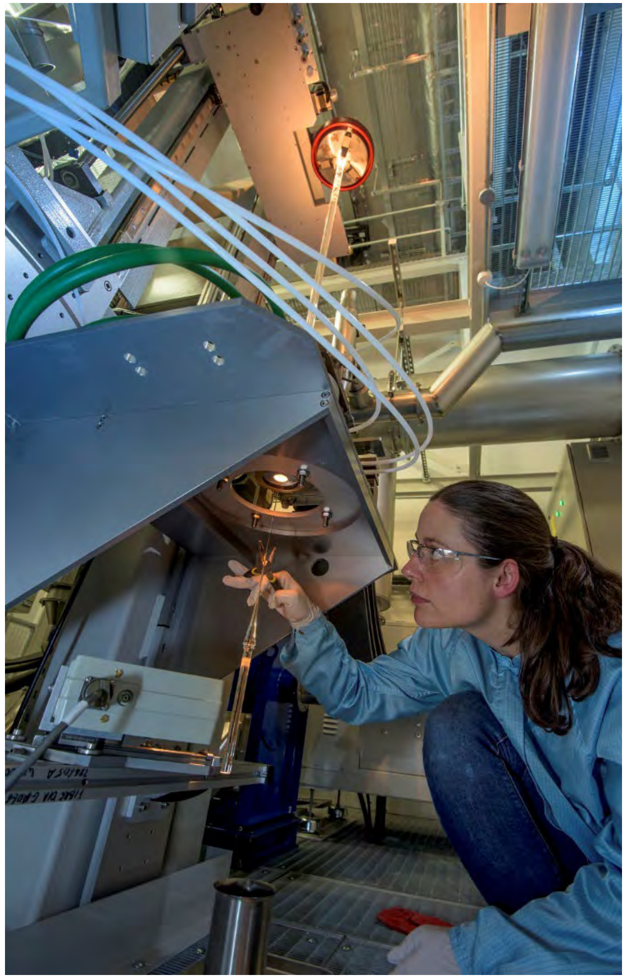
Micro-structured Optical Fibre Group, Optoelectronics Research Centre, University of Southampton

10/11/2020

OSA Webinar: Fibre Optics Technical Group

Optoelectronics Research Centre – Fibre Fabrication

- 4x Fibre Draw Towers
- 2x MCVD Lathe + 1x OVD System
- 1x Glass Working Lathe
- Dedicated ISO5 Preform Preparation Area



Micro-structured Optical Fibre Group

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- Simulations
  - Electromagnetics
  - Fluid Dynamics
- Fibre Fabrication
  - State of the Art Cleanroom Facilities
- Characterisation
  - Spatial & Spectral Imaging
  - Low Coherence Interferometry
  - Data Transmission
  - State of the art Laser Labs
- Applications
  - High Power Laser Delivery
  - Gas Sensing
  - Telecommunications
  - Nonlinear Optics

Hollow Core Fibres – the research field

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- CPPM, University of Bath, UK
- Xlim Research institute, France
- Fibre Optics Research Centre, Russia
- CREOL, University of Central Florida, USA
- Optoelectronics Research Centre, University of Southampton, UK
- Max Planck Institute for the Science of Light, Erlangen, Germany
- PhLam, University of Lille, France
- OFS Research Labs, USA
- Beijing University of Technology, China
- Danish Technical University, Denmark
- Ecole Polytechnique Fédérale de Lausanne, Switzerland
- ….

Nonlinear Optics

Molecular & Atomic Spectroscopy

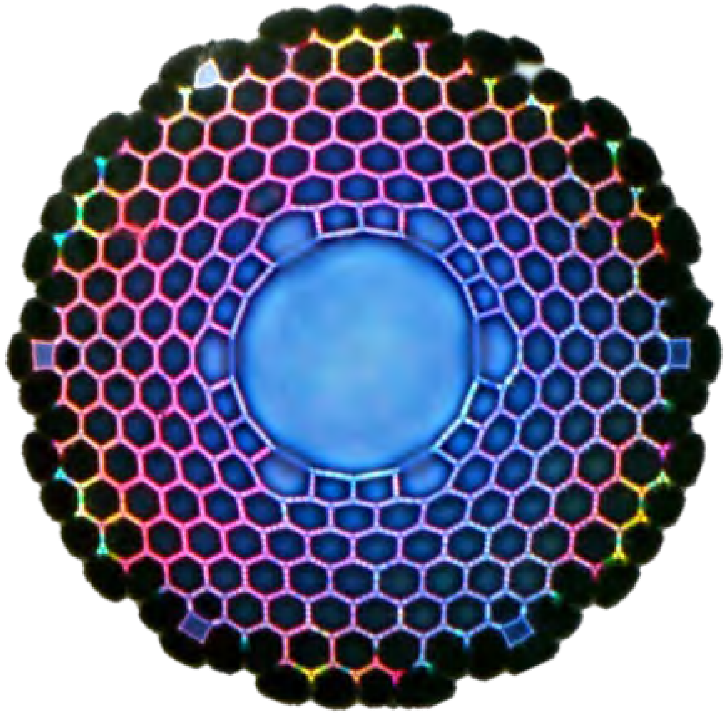
Telecommunications

Laser Power Delivery

Fibre Design & Fabrication

Fibre Optic Sensors

Overview



- Hollow Core Optical Fibres
  - What?
  - Why?
  - How?
- Hollow Core Photonic Bandgap Fibres
  - Guidance Mechanism
  - State of the Art
- Hollow Core Anti-Resonant Fibre
  - Path way to NANF
- Nested Anti-Resonant Nodeless Fibres
  - Progress
  - State of the art
- Conclusions
- Applications of Hollow Core Fibres

Hollow Core Optical Fibres – The Differences

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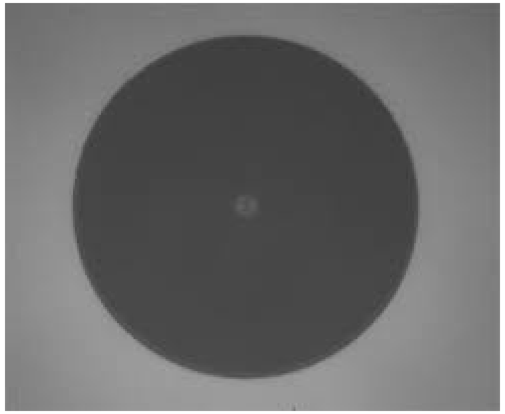
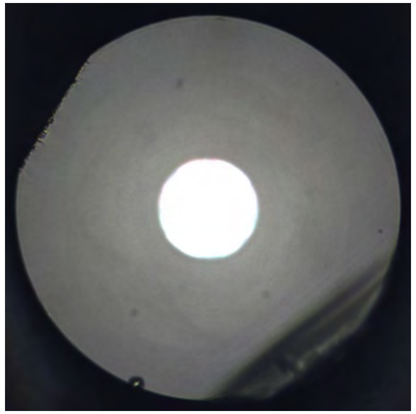
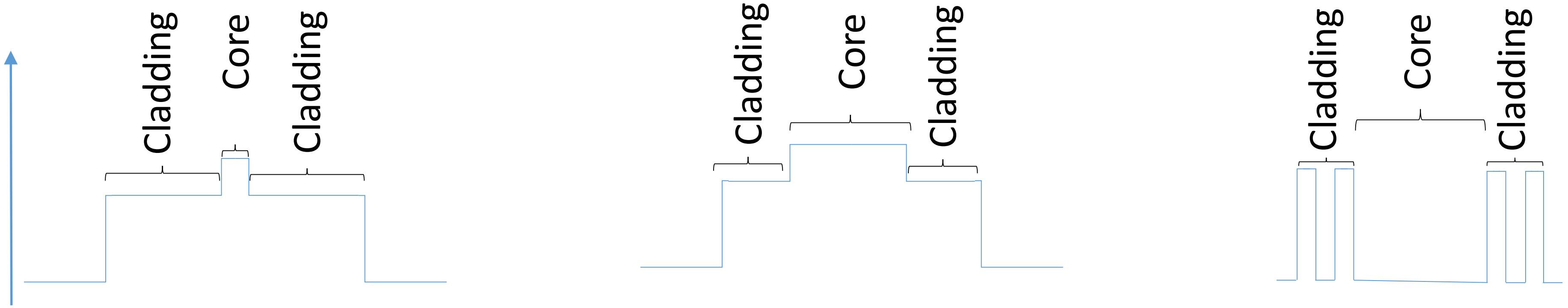
Single Mode Fibre



Multi Mode Fibre



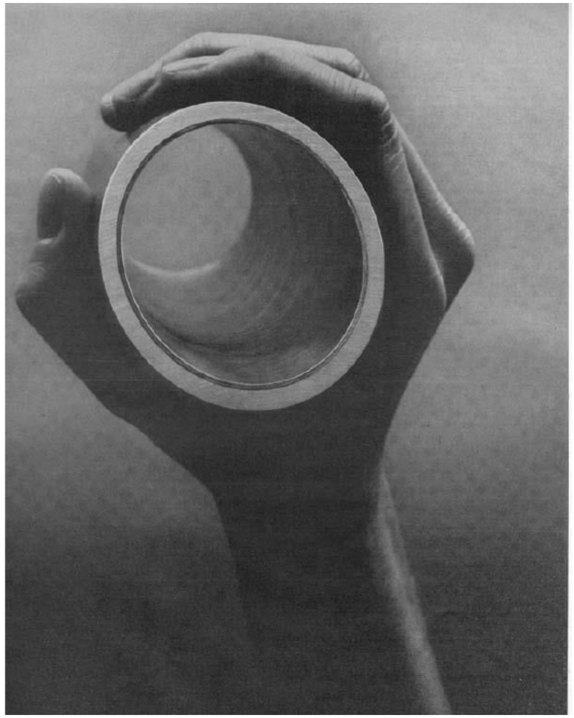
Hollow Core Fibre



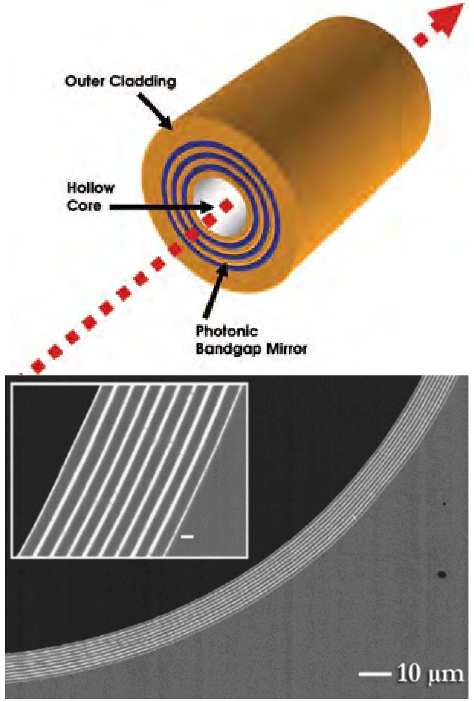
EPSRC
Engineering and Physical Sciences Research Council

UNIVERSITY OF Southampton

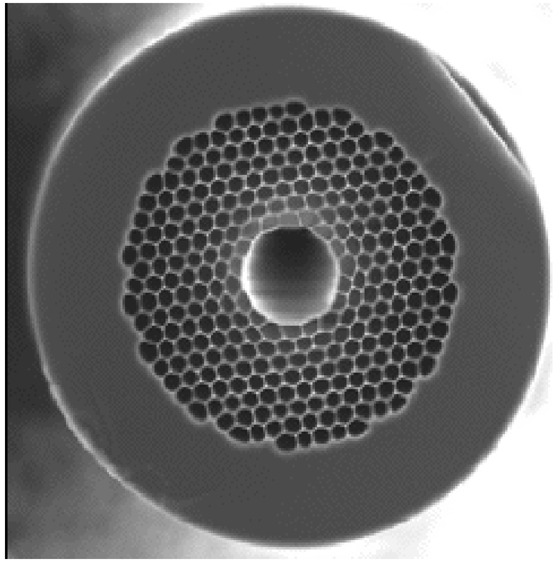
Hollow Core Fibres – what?



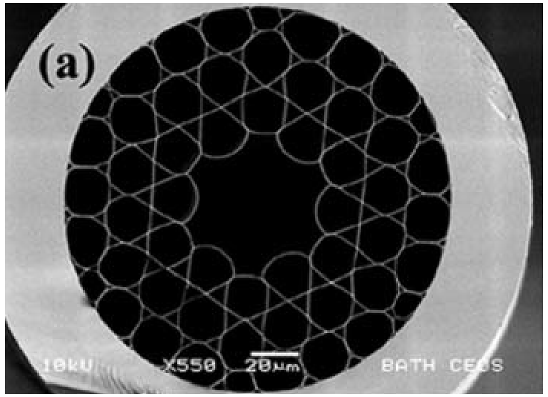
Ohmic and macrobend loss



Absorption loss



Surface scattering



Strong Resonant Losses

All few/multi moded

Hollow core fibres – why?

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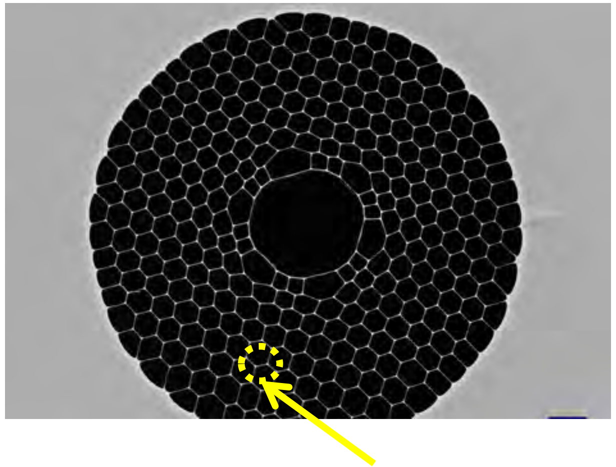
Vast topological range of fibres proposed:

- Low nonlinearity
- Low latency
- Low dispersion
- Wide enough bandwidth
- High damage threshold

Develop a waveguiding technology with all the advantages of flexible all-glass fibres without the penalties of light propagation in glass

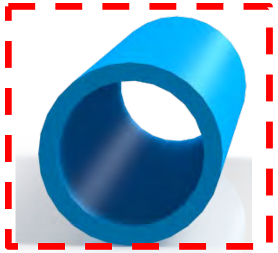
Hollow Core Fibres – how?

2 Stage Stack & Draw



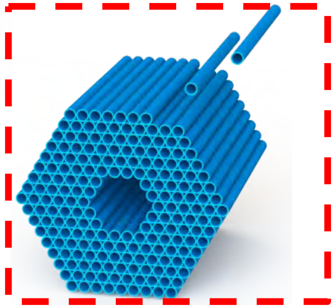
~ 100 nm scale cladding features

Glass Tube (OD ~ 20 – 30 mm)

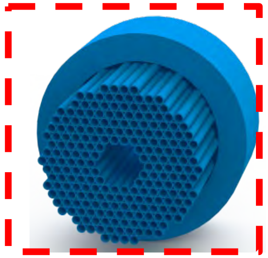


Capillary (OD ~ 1 – 2 mm)

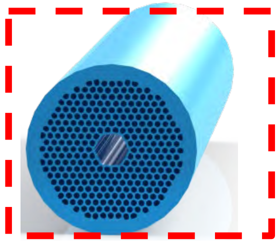
Stacking



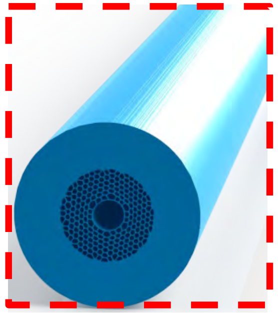
Jacketing (OD ~ 20 mm)



Caning (OD ~ 3 – 5 mm)

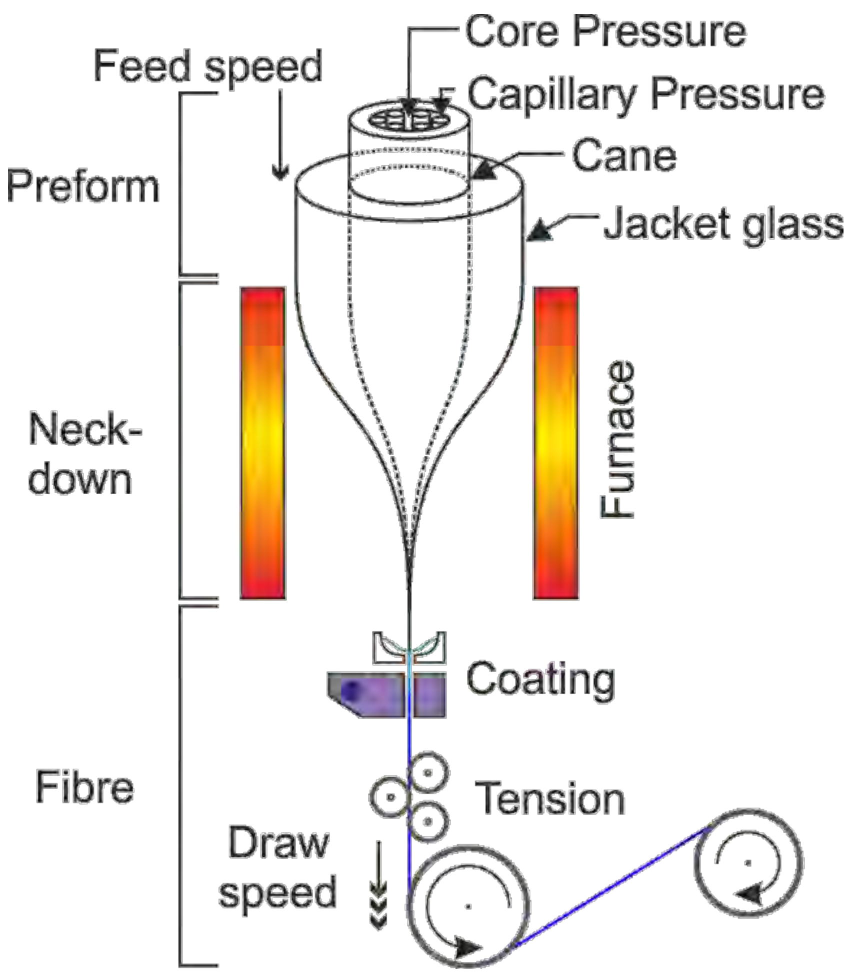


Fibre Drawing (OD ~ 150 µm)



Benabid, Phil. Trans. R. Soc. A, 2006, **364**

Virtual Draw Model



Aim: to predict the final geometry of fibre given a preform geometry and draw conditions.

Geometry parameters:

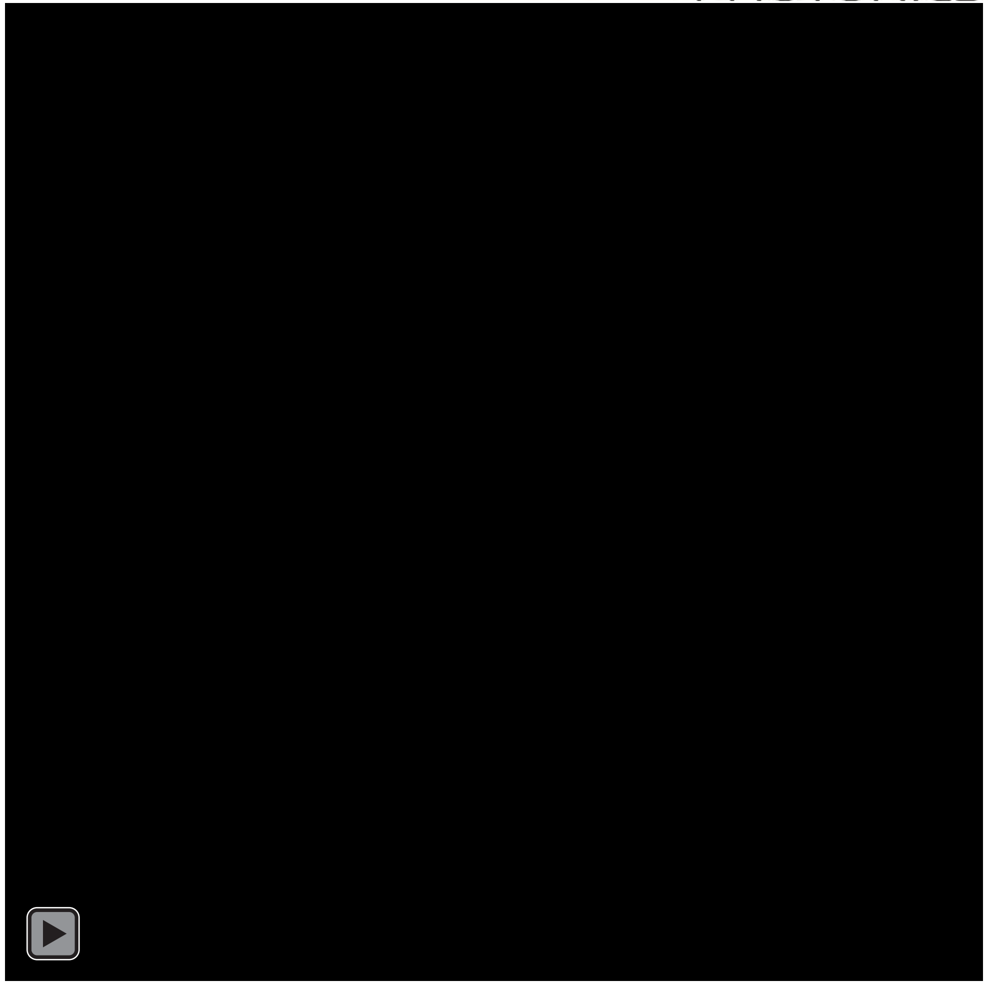
- Capillary outer / inner diameters.
- Cane and jacket tube inner/outer diameters.
- Target fibre outer and inner diameters.

Draw parameters:

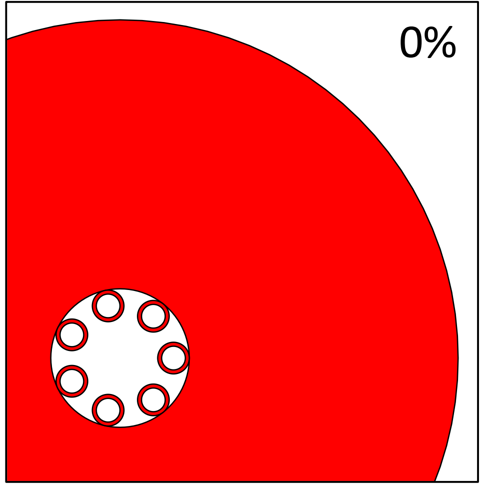
- Feed / draw speeds
- Furnace temperature and profile
- Material data: viscosity and surface tension
- Core and Capillary pressures

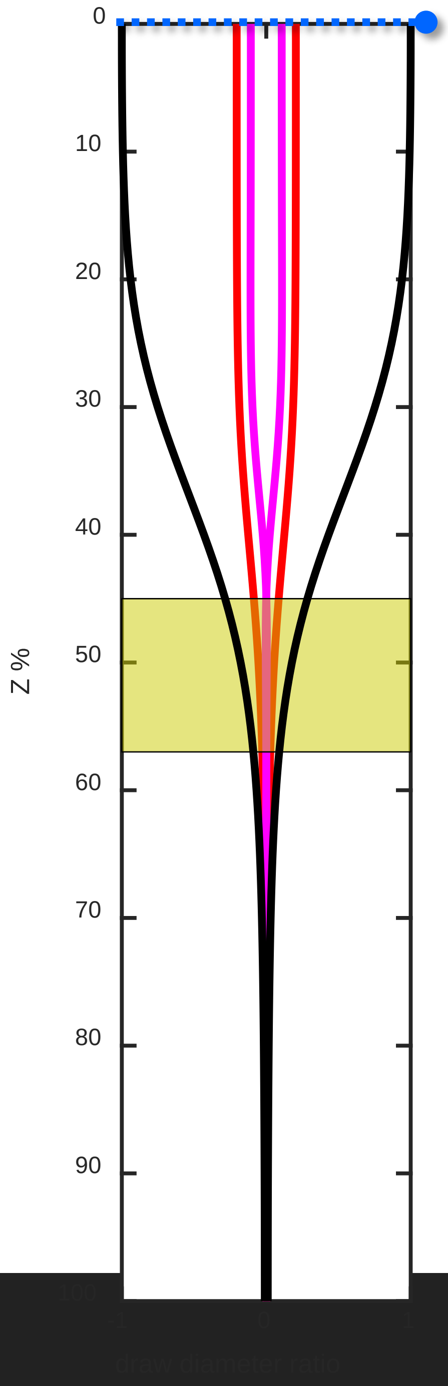
Virtual Draw Model

1. A simple capillary draw model[1] derived from the Navier-Stokes equations is used for the **outer jacket tube**.
2. The **inner capillary tubes** use the same model but are bound to the jacket tube.
3. The inner capillary solution has 2 parts:
   - axial draw down determined by the jacket tube solution.
   - The lateral dynamics are solved by the Fitt model using **gas pressures**, **surface tension** and **viscous stress**.



[1] Fitt et al, J. of Eng. Mathematics 43, no. 2-4, 201-227, (2002).
[2] Jasion et al, Opts Exp 27, 15, 20567-20582, (2019)





Draw Dynamics

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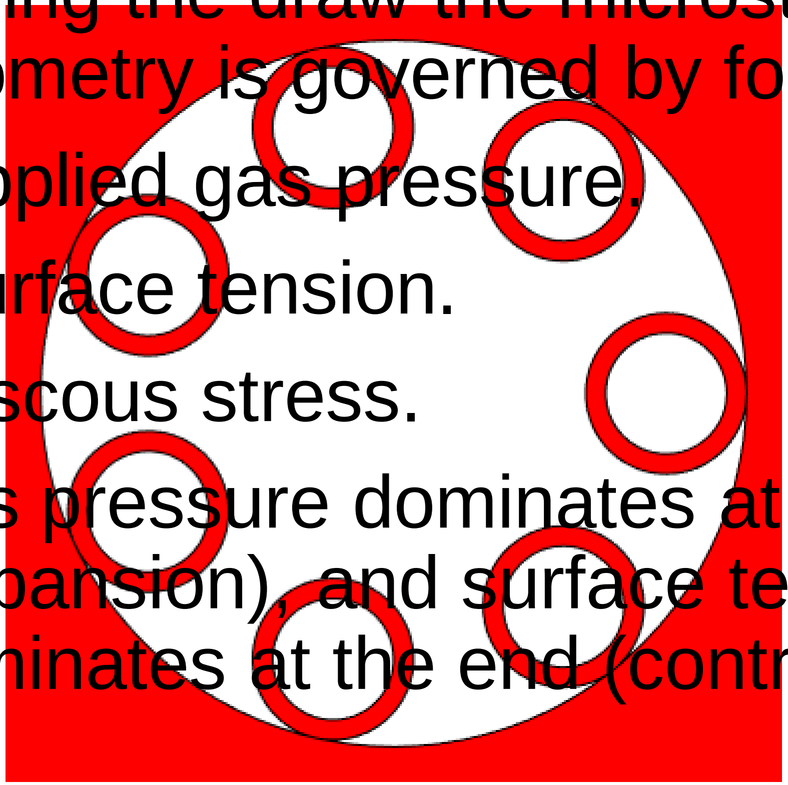
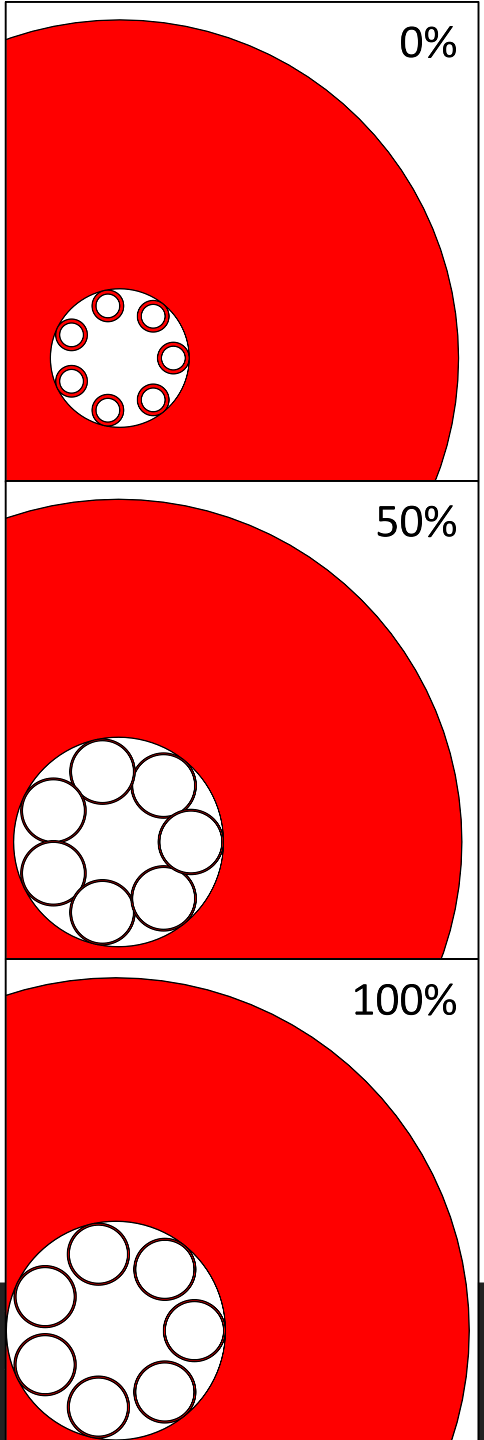


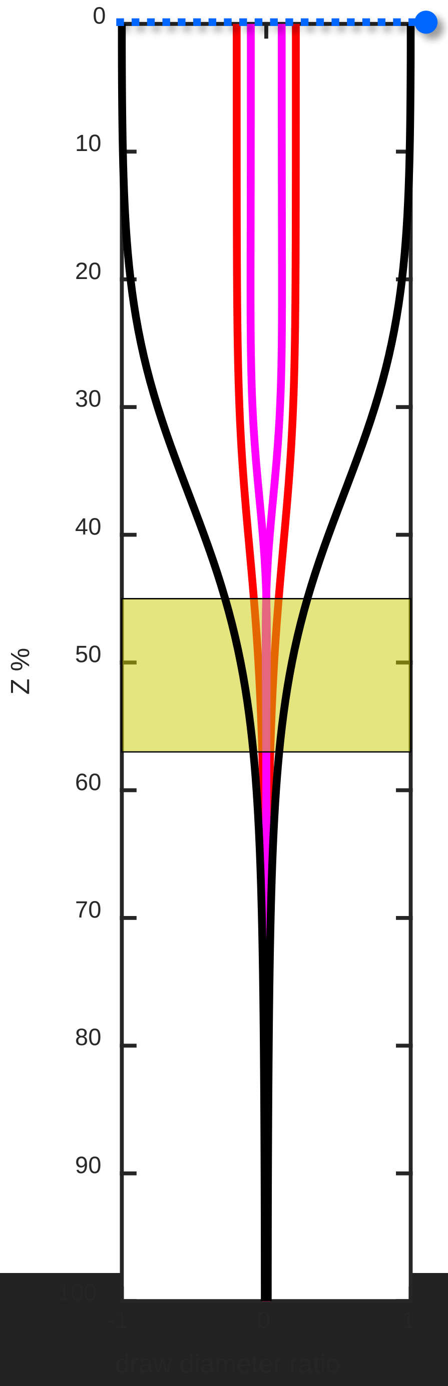
During the draw the microstructure geometry is governed by forces:

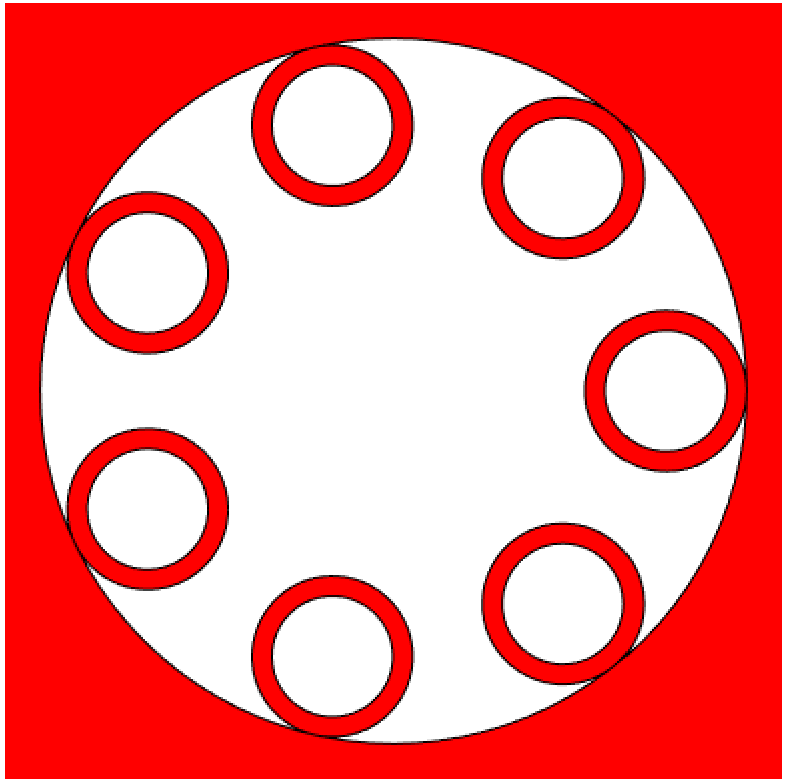
- applied gas pressure.
- surface tension.
- viscous stress.

Gas pressure dominates at the start (expansion), and surface tension dominates at the end (contraction).

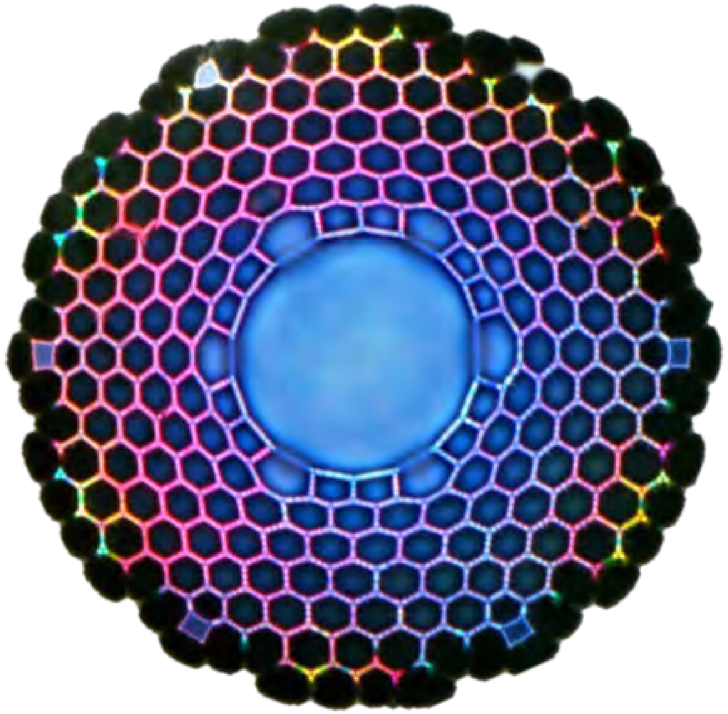
Draw Dynamics







Overview



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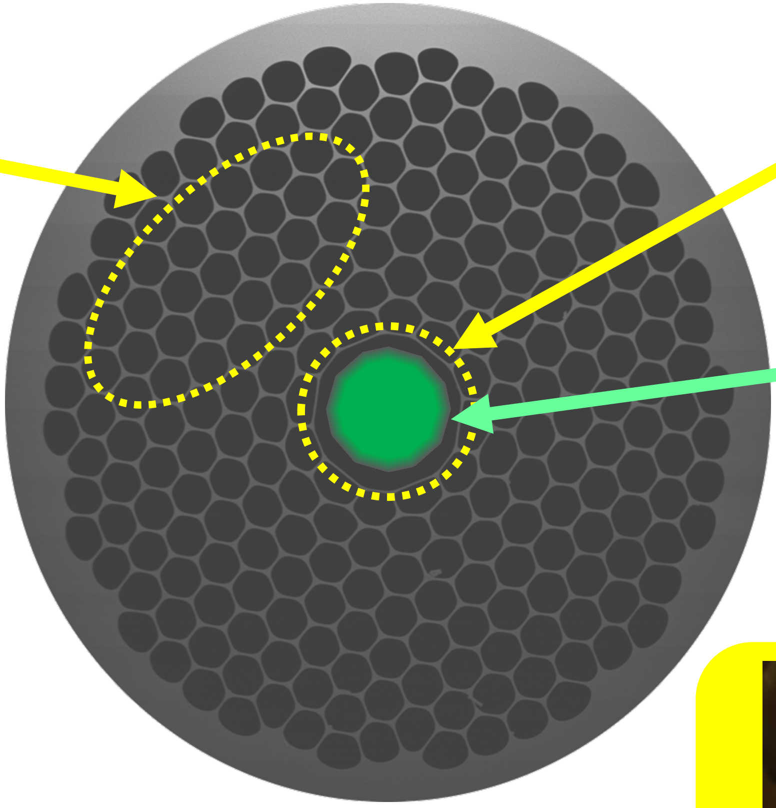
Key HC-PBGF properties

Periodic lattice of rods/holes

Determines optical bandgap
in the longitudinal direction



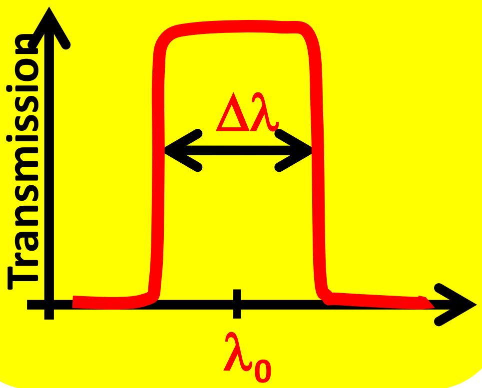
Hollow core

Obtained by removing elements at the centre
of the lattice

"Air guided modes"

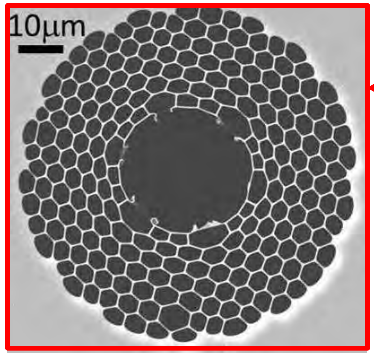
At wavelengths within the Optical Bandgap

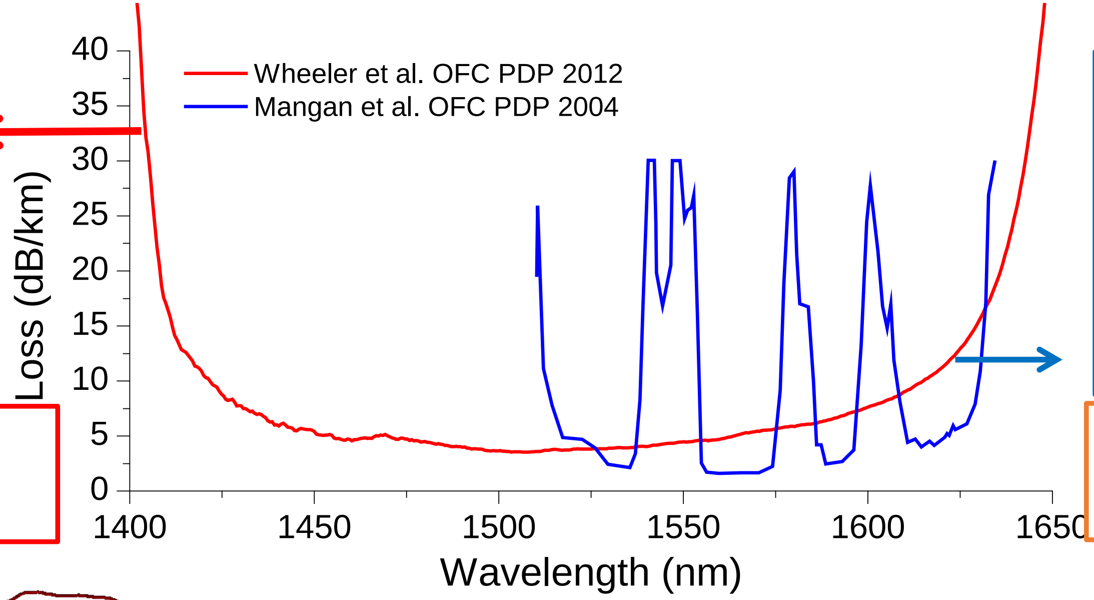
Low overlap with glass surround (0.1-0.2%)

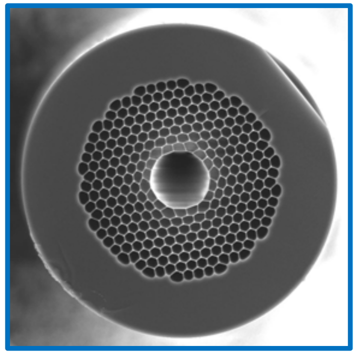


Stack First Stage Draw "Cane"

Low loss & wide bandwidth at 1.55 µm

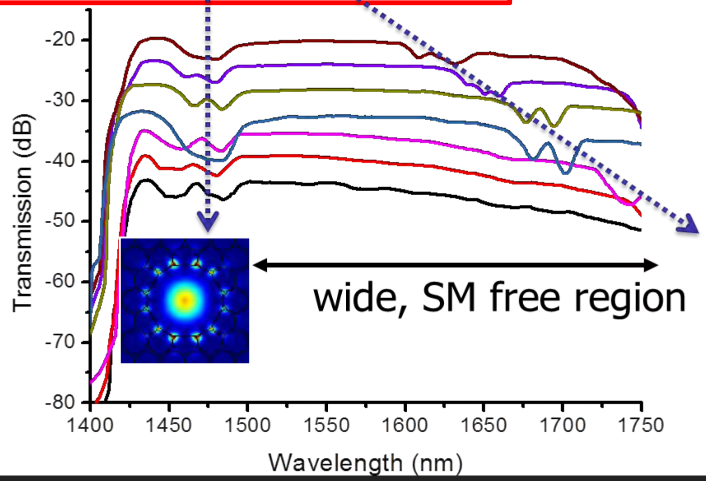






- Low loss (3.5 dB/km) combined with wide bandwidth (160 nm)

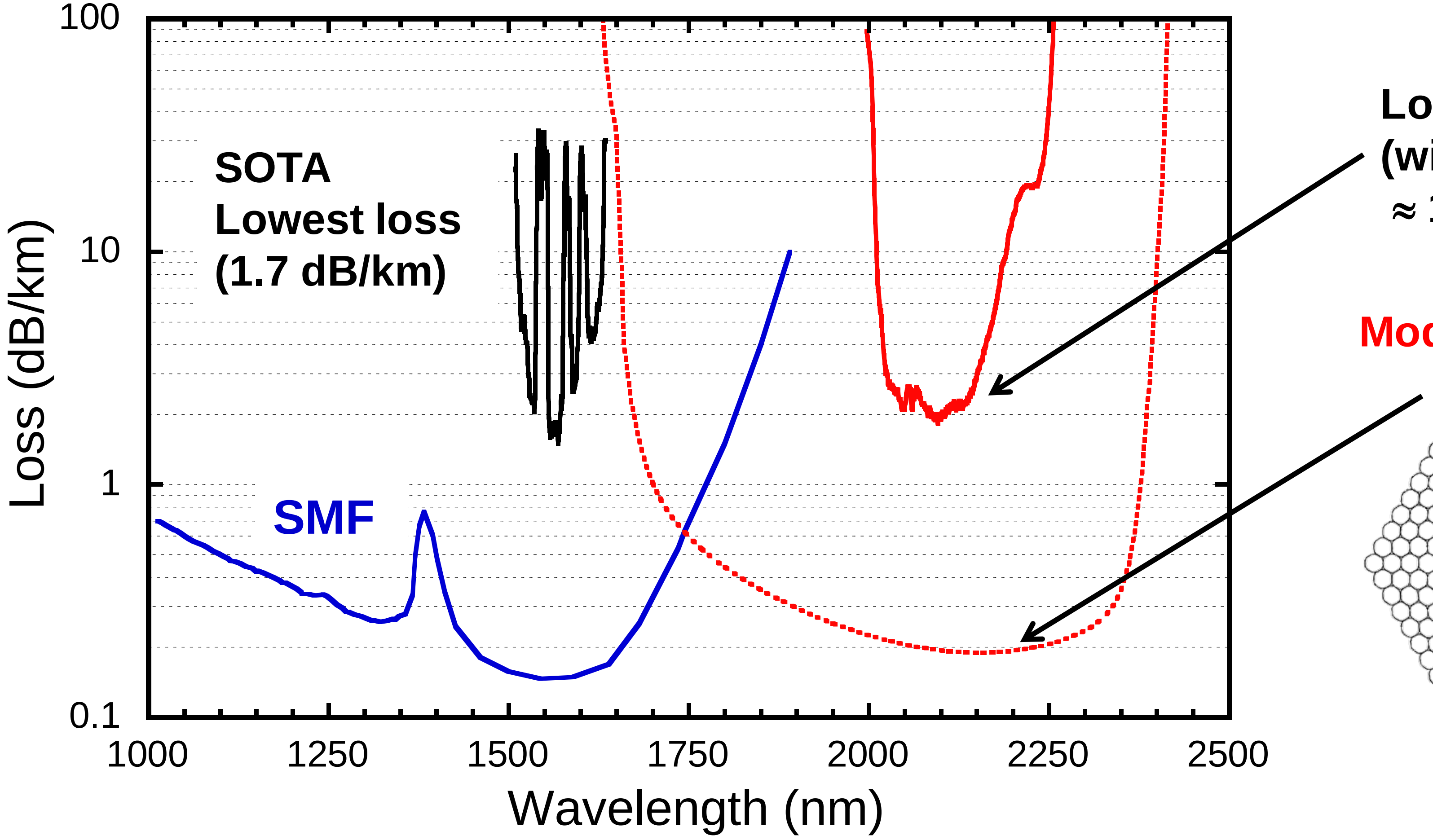
- SOTA loss (1.7 dB/km), surface mode limited bandwidth (20 nm)

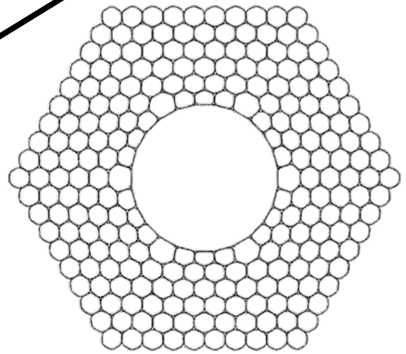


- Achieved through careful use of pressure in fabrication to control surface modes
- **Eight-fold BW improvement with just ~2x higher loss than current SOTA**

Wheeler et al., OFC PDP 2012

The promise of HC-PBGF



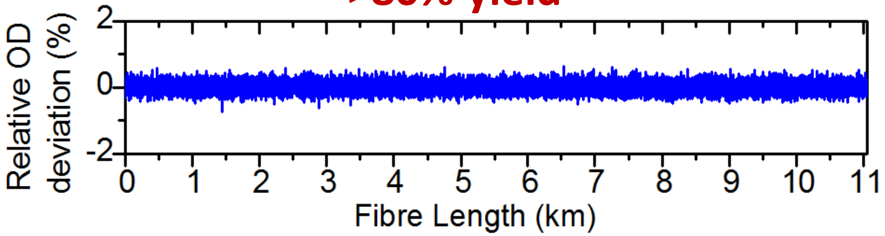


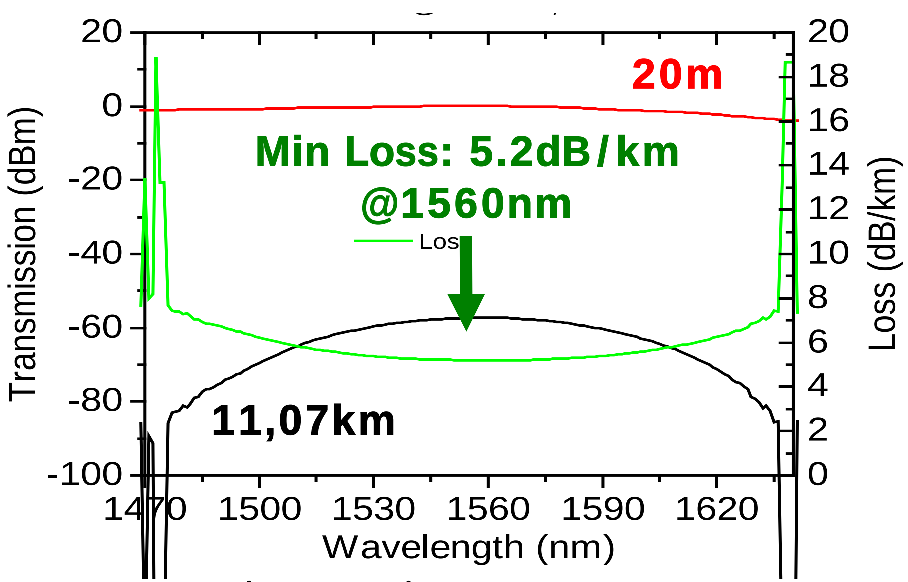
Key factor in reducing loss is achieving highly regular structures, particularly in the core region

Improving reach: New record 11km length

- **1m long preform**
- **~20mm diameter**
- **Max yield: ~14 km**

>80% yield

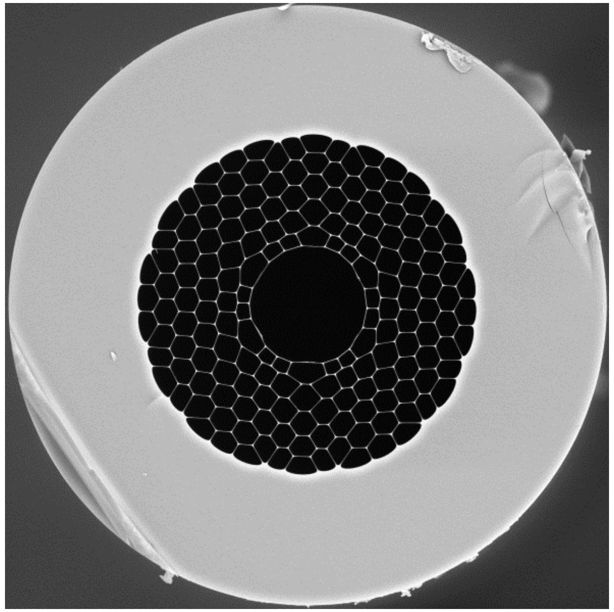




Chen et al, OFC PDP 2015

- Loss measured via long cutback (**~11km to 20m**)
- Using SC source
- Transmission BW: >160nm (subsequent measurements **≈200nm** - previous SOTA 160nm)
- Loss in the region of **5dB/km**

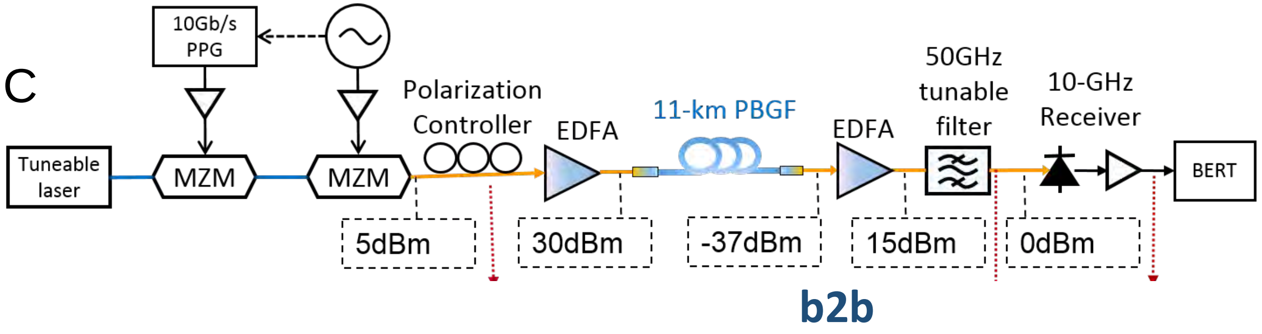
Strut t/L aspect ratio: $\sim 10^{11}$

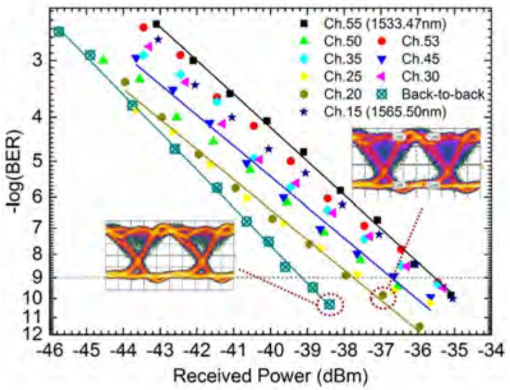


- Core diameter: $29.7 \pm 1\mu m$
- Average Pitch: $6.2 \pm 0.2\mu m$
- Average Cladding strut thickness: $48.0 \pm 10nm$
- Thinnest strut thickness : $27.5 \pm 5nm$
- Average d/Λ: 0.992
- Air-filling fraction $> 96\%$

Transmission: Low latency -11km

- Single channel, 10G RZ, scanned across C band
- Main challenge: 65-67dB loss
- Nonlinearity not a problem

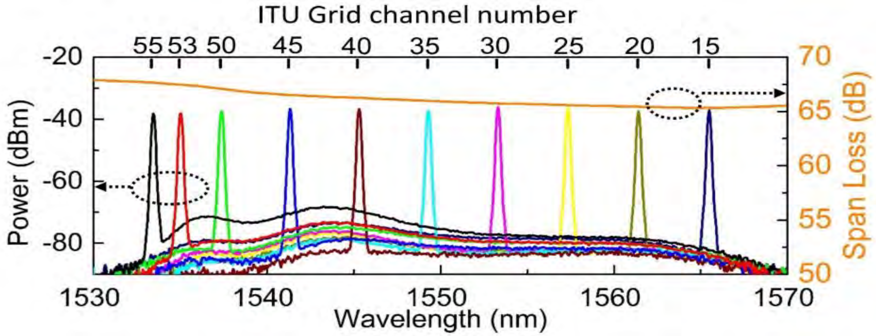




- Error free transmission, (BER<1e-9) no error floor on all tested channels
- 1.4-3.9dB power penalty likely due to OSNR limitation
- **11km transmission: 16μs latency reduction** from all-glass equivalent fibre link

\+

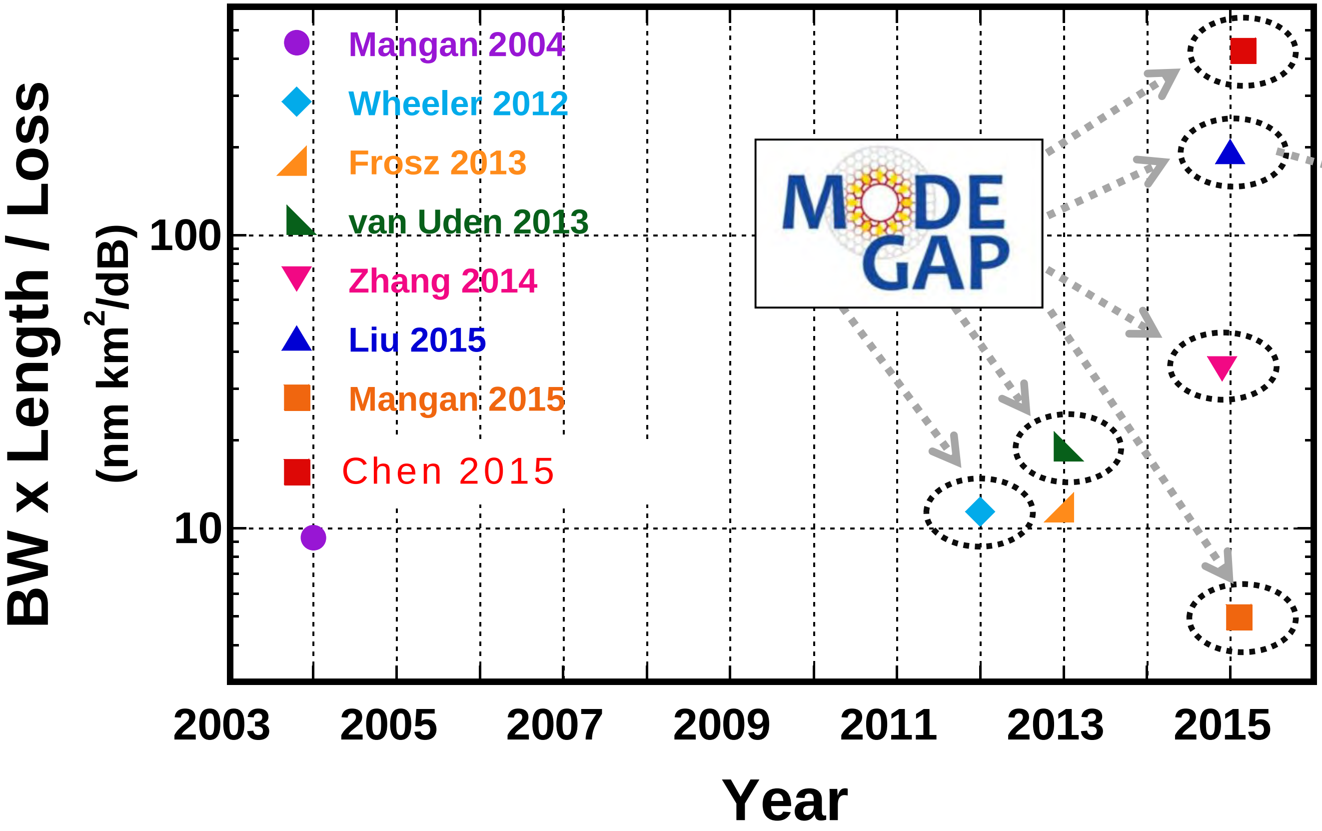
- First recirculating loop experiment with 2 sub-sections of this fibre (2.7km and 3.5km)
- Total length = 74.8km



Chen et al, OFC PDP 2015

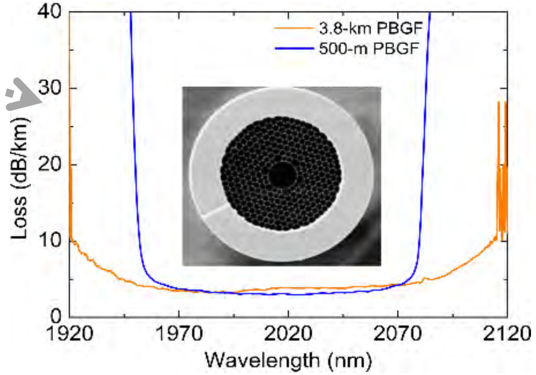
Kuschnerov et al. ECOC 2015 Th 1.2.4

SoTA long-length HC-PBGF



OFC 2015 PDP

3.85km 3dB/km

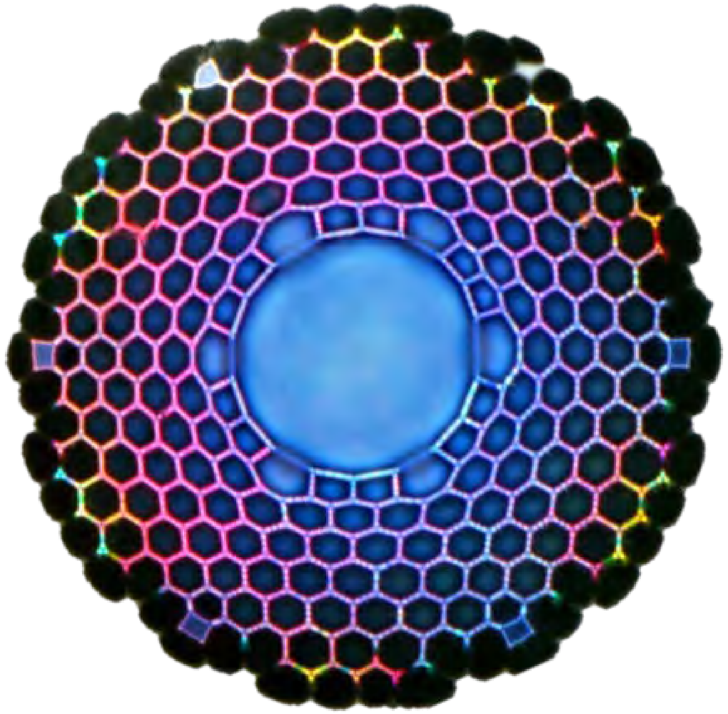


Liu et al., JLT 33,1373, 2015.

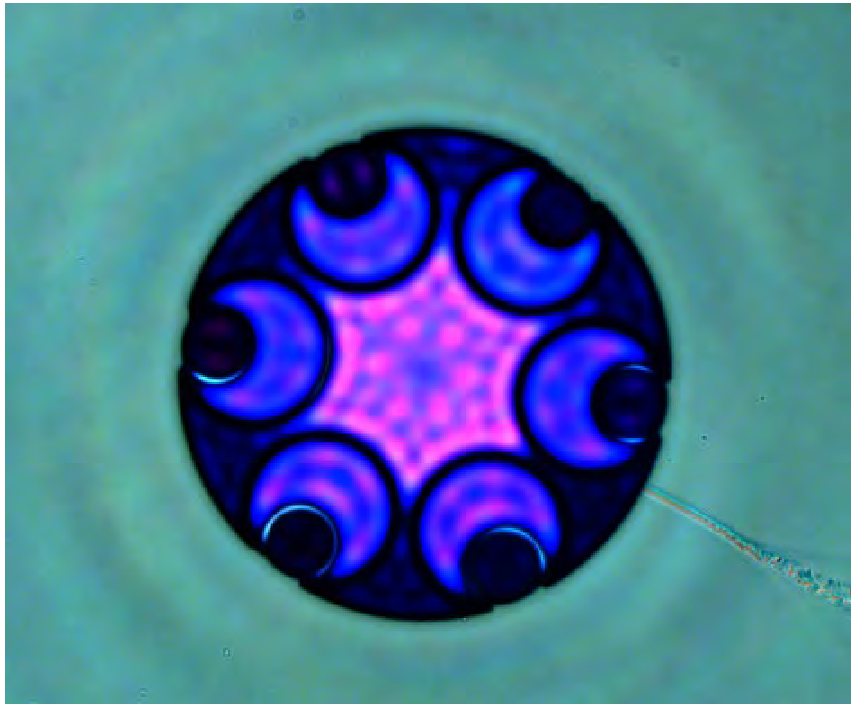
Reference		λ (nm)	Loss (dB/km)	BW (nm)	Length(km)
Mangan et al.	2004	1565	1.7	20	0.8
Wheeler et al.	2012	1510	3.5	160	0.25
Frosz et al.	2013	1530	1.8	40	0.5
van Uden et al.	2013	1510	8	160	0.95
Zhang et al.	2014	1990	2.8	85	1.15
Liu et al.	2015	2010	3.2	160	3.85
Mangan et al.	2015	1540	6.5	12	2.75
Chen et al.	2015	1560	5.2	200	11.07

Transition from HC-PBGF to Antiresonant Fibre

HC-PBGF



NANF



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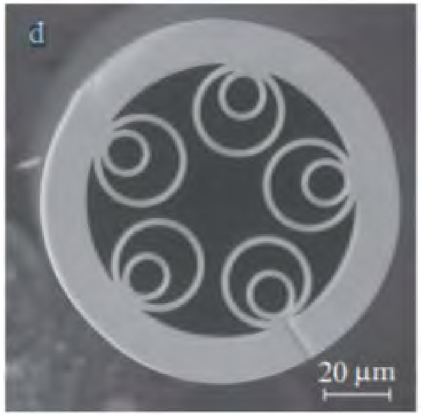
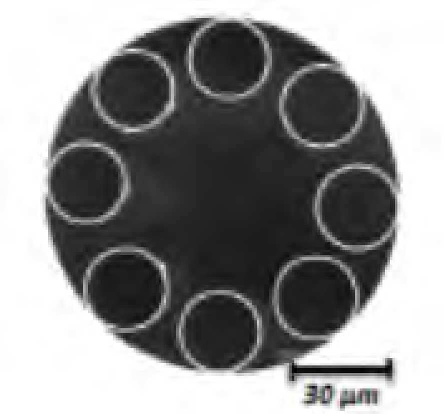
Hollow Core Antiresonant Fibres

- Pioneering work from
- Bath
- Limoges
- FORC Moscow
- Erlangen
- ORC
- …

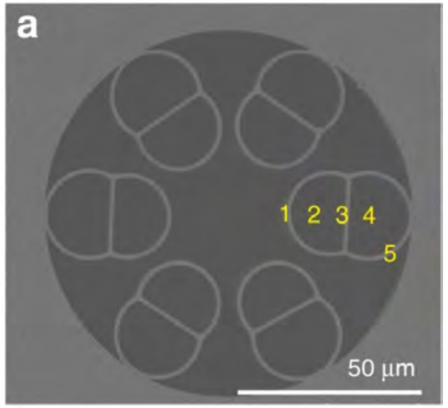
2016 FORC



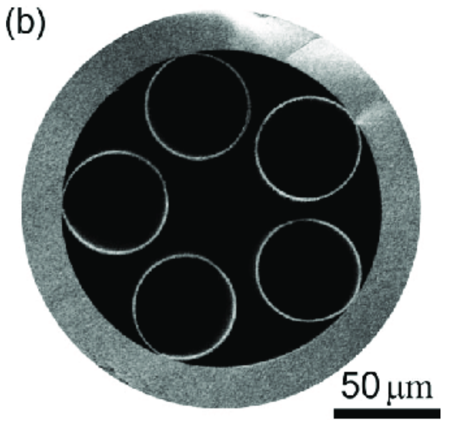
2017 Xlim



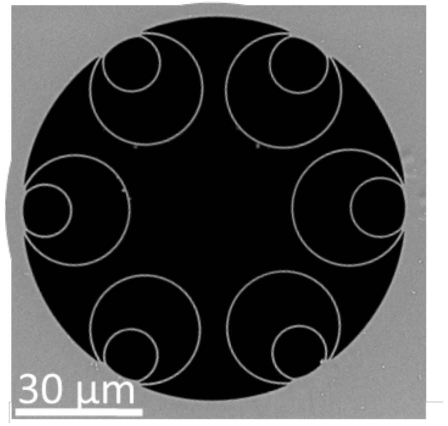
2018 BUT



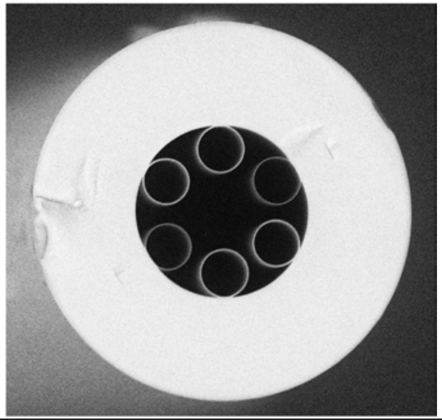
2018 Max Planck, Erlangen



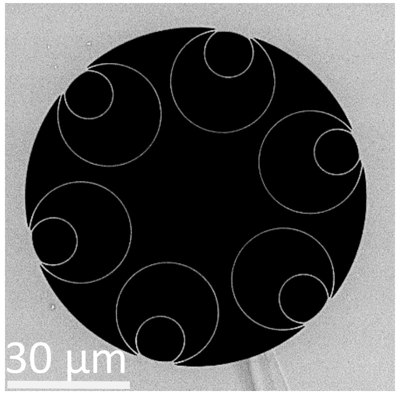
2019 ORC



2020 University of Bath

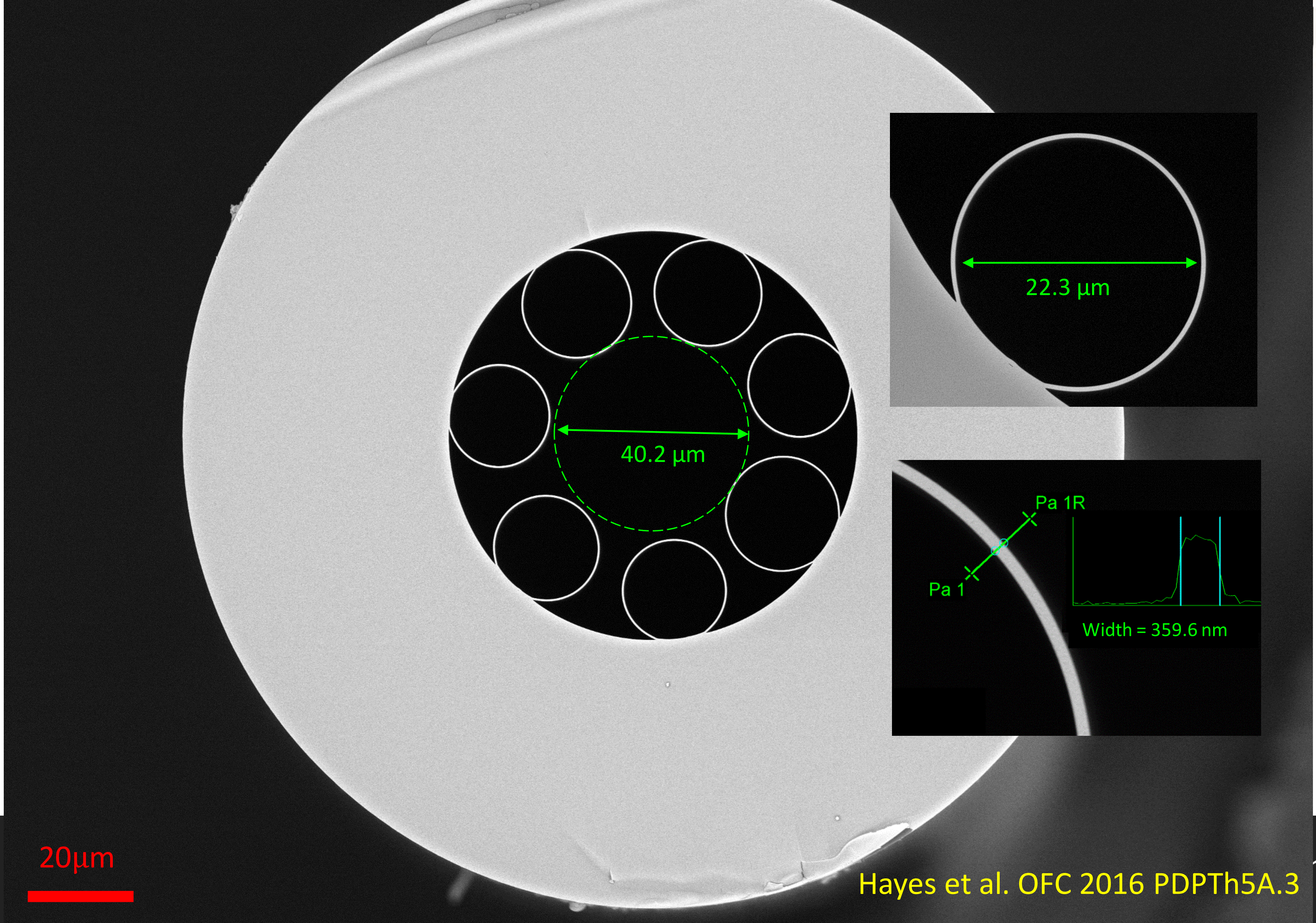


2020 ORC

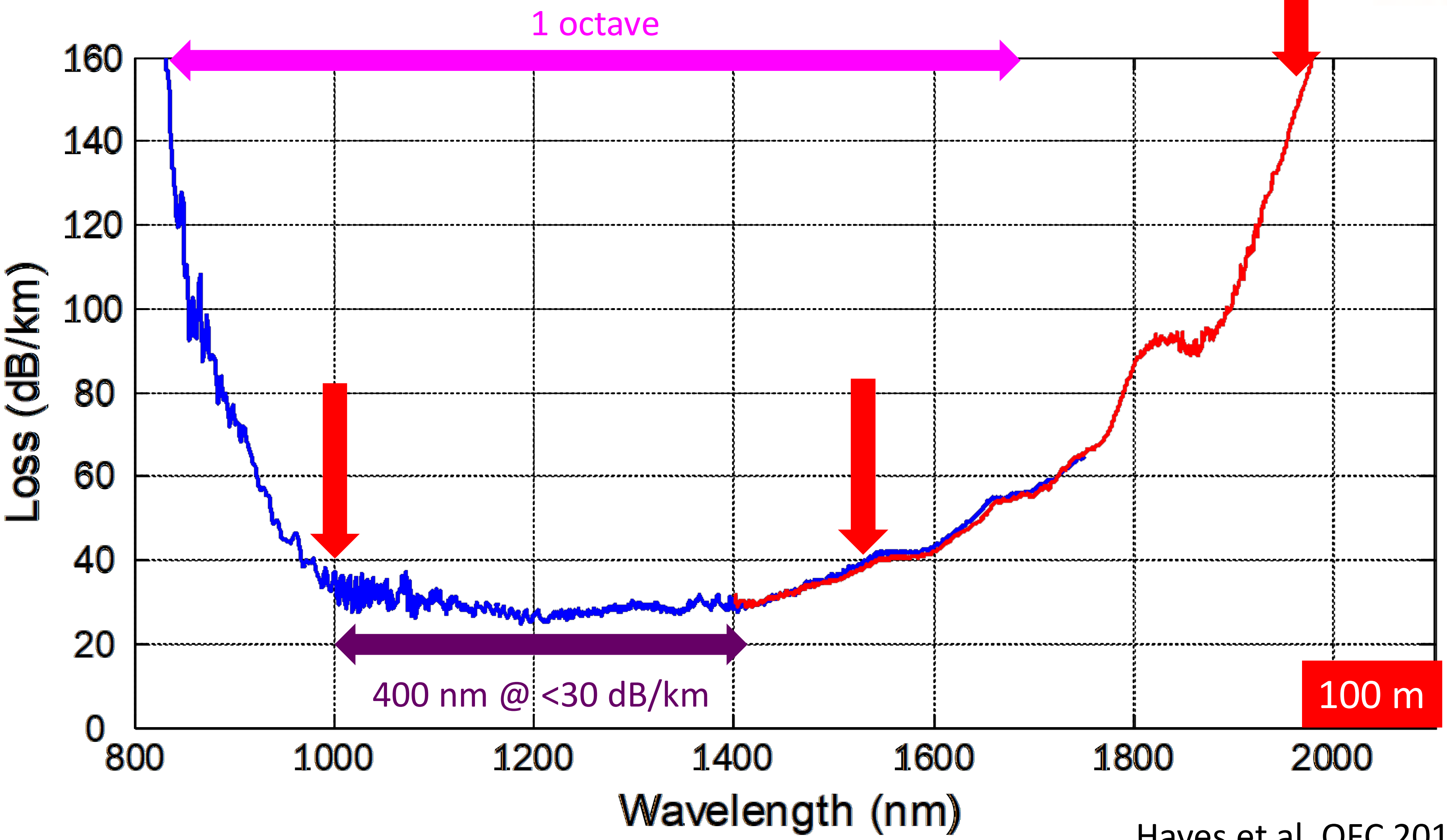


1) Kosolapov et al, Qnt Elec 46 (3), 2016, 2) Debord et al, Optica 4 (2), 2017, 3) Gao et al, Nat Comms (9), 2018, 4) Roth et al, Optica 5 (10), 2018 , 5)Yerolatsitis et al, JLT 38 (18) 2020

First Data-transmitting ARF

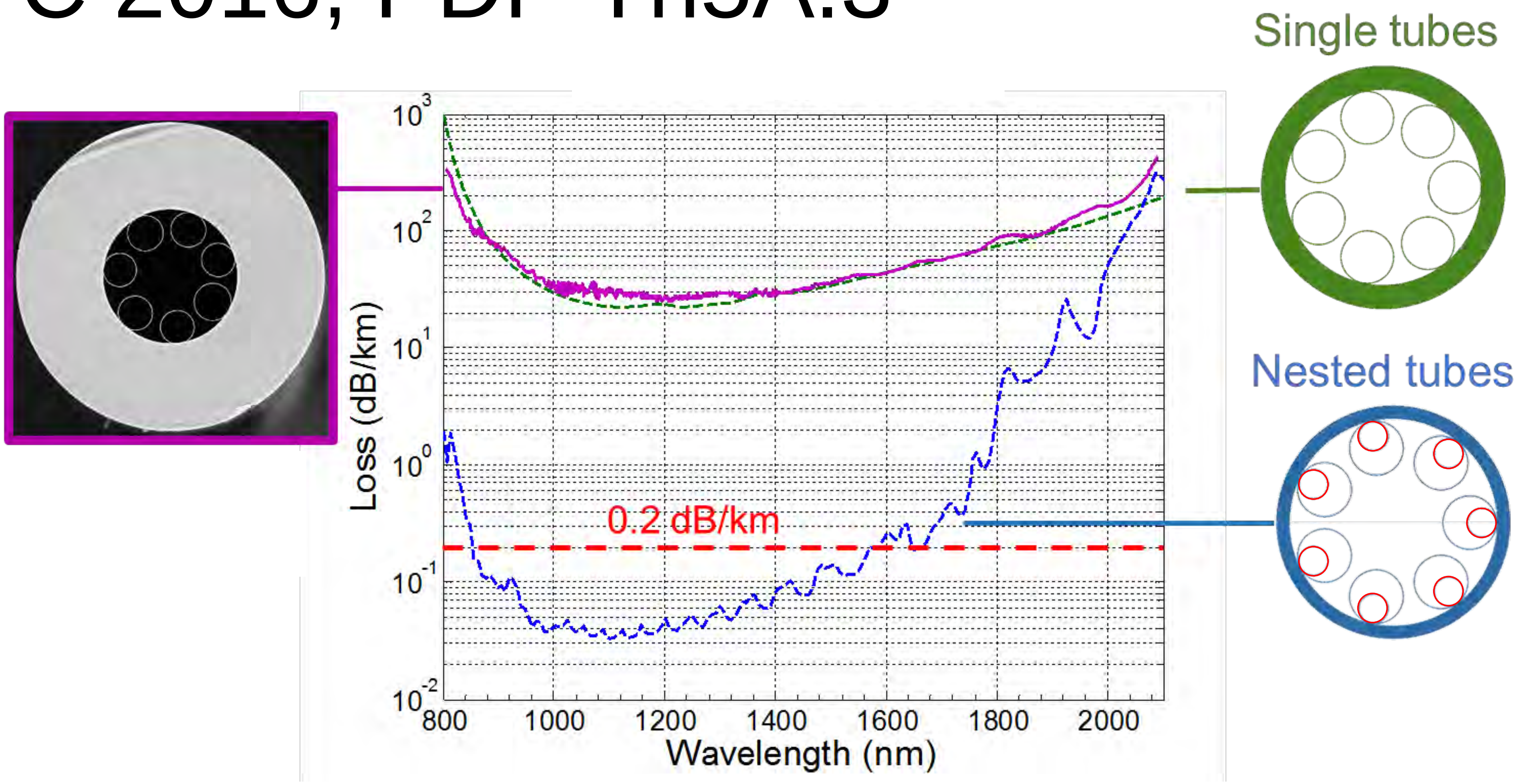


Hayes et al. OFC 2016 PDPTh5A.3



Hayes et al. OFC 2016 PDPTh5A.3

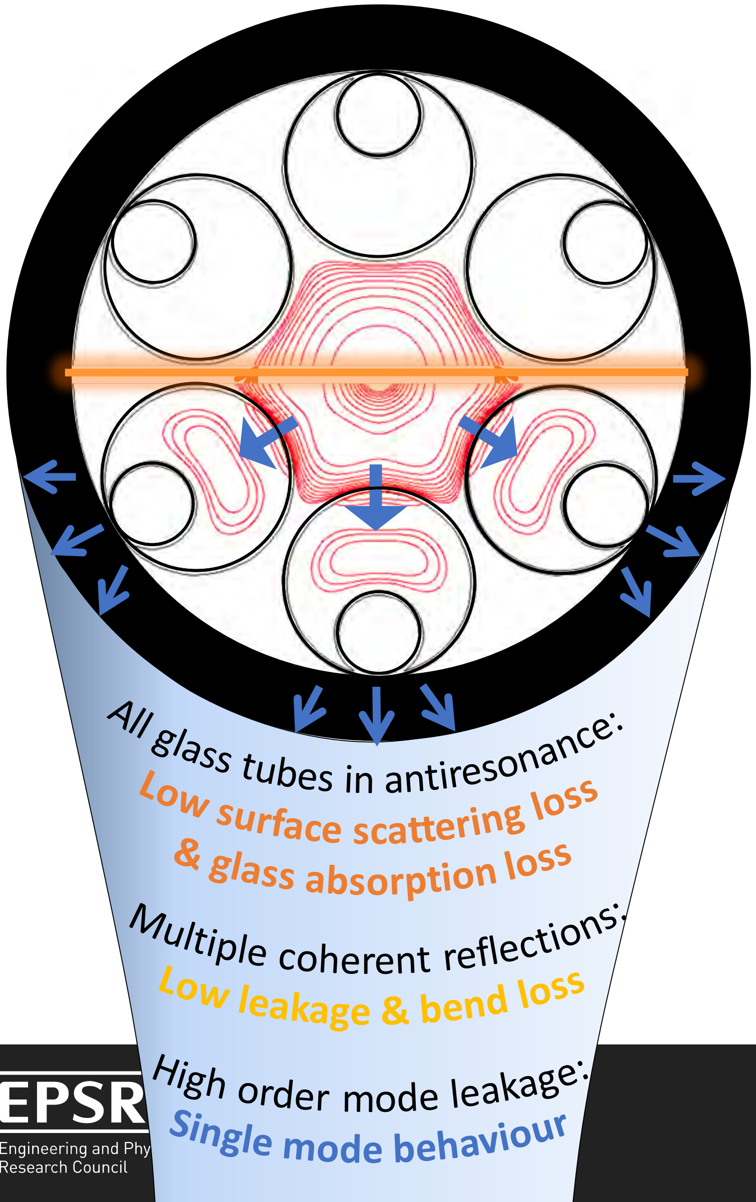
OFC 2016, PDP Th5A.3



Nested Antiresonant Nodeless Fibre (NANF)

F. Poletti, Opt Express **22**, 23807 (2014)

Guidance Mechanism - NANF



Core struts act as Fabry-Perot resonators– transmission windows open between resonances given by:

$$\lambda_j = \frac{2t}{j}\left(n_g^2 - 1\right)^{\frac{1}{2}} \quad j = 1,2,3..\,,\ t = \text{thickness}$$

n_g = glass refractive index

Pros:

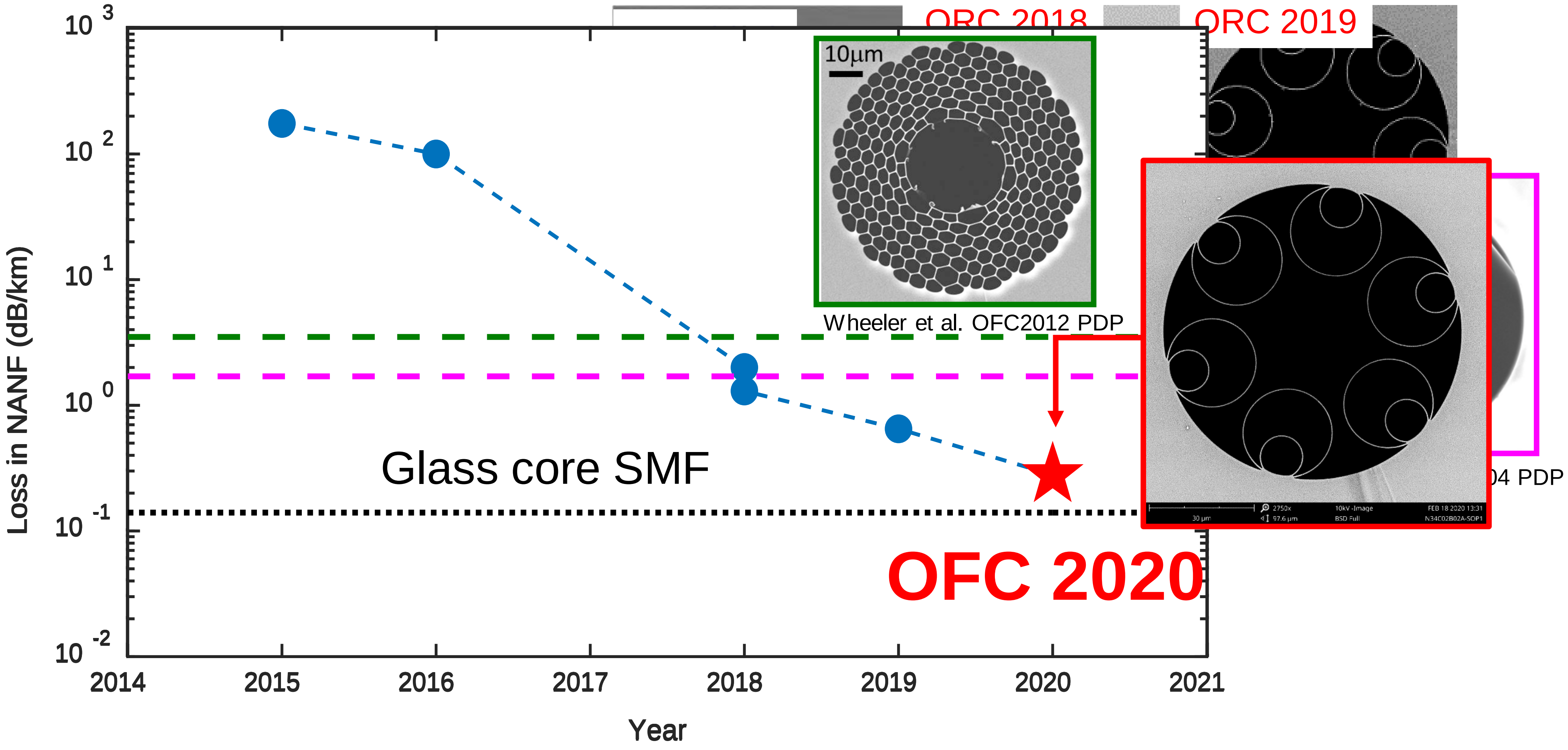
- Lower mode overlap with glass, 10^{-5}
- Larger mode field diameter
- Huge bandwidth
- Large range of core sizes

Cons:

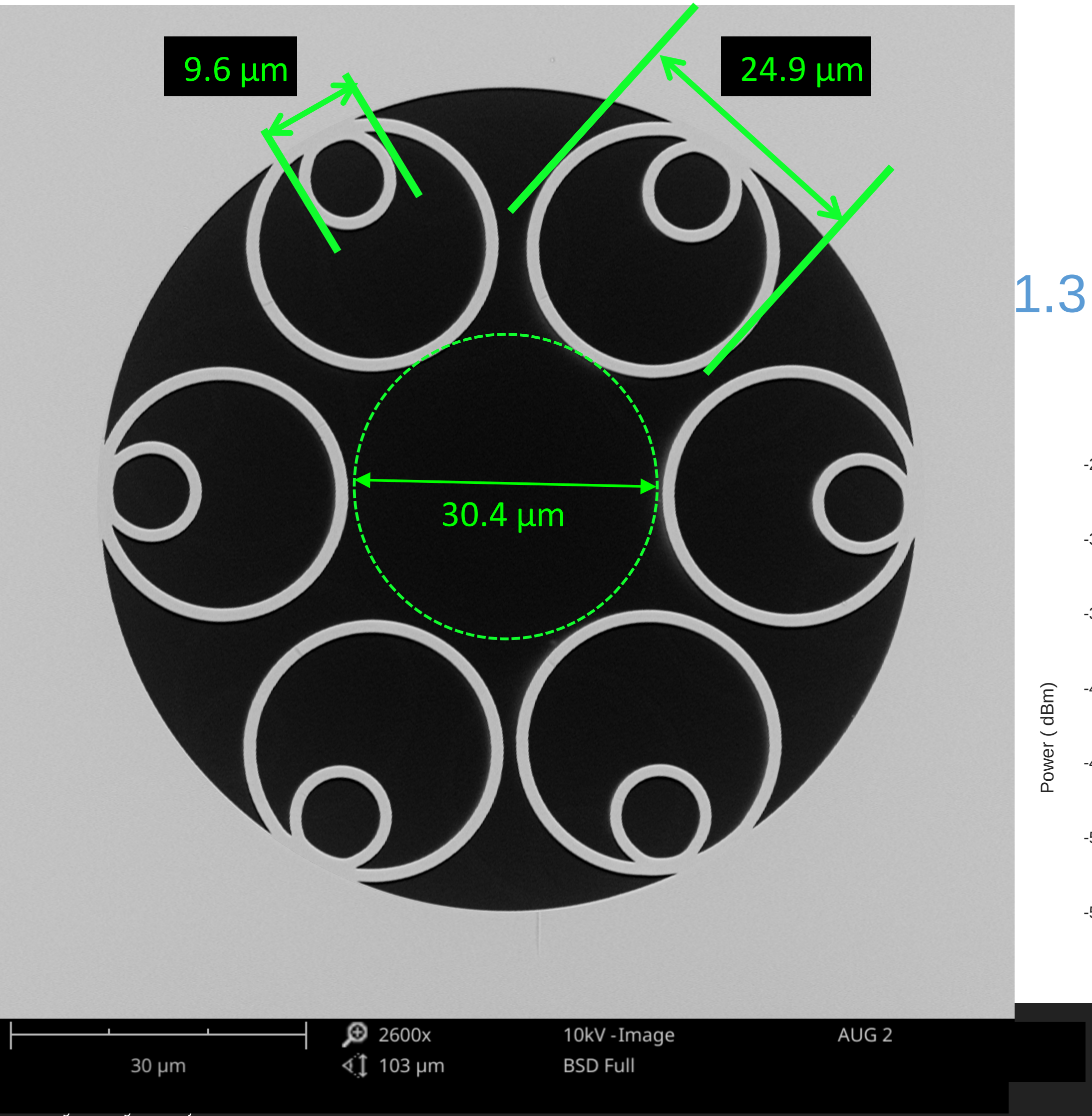
- Higher loss (so far)
- Higher bend sensitivity

F. Poletti, Opt Express **22**, 23807 (2014

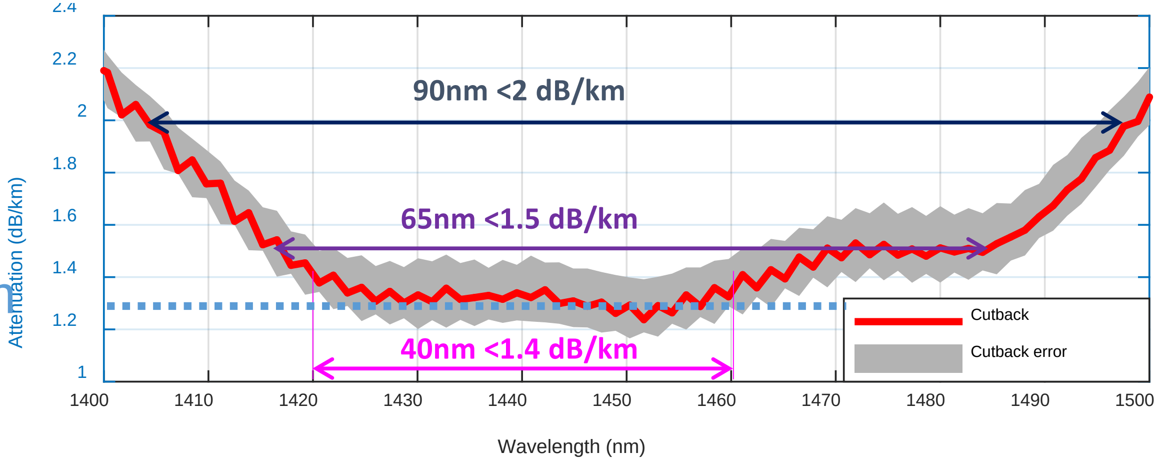
Loss in NANF Over Past 5 Years

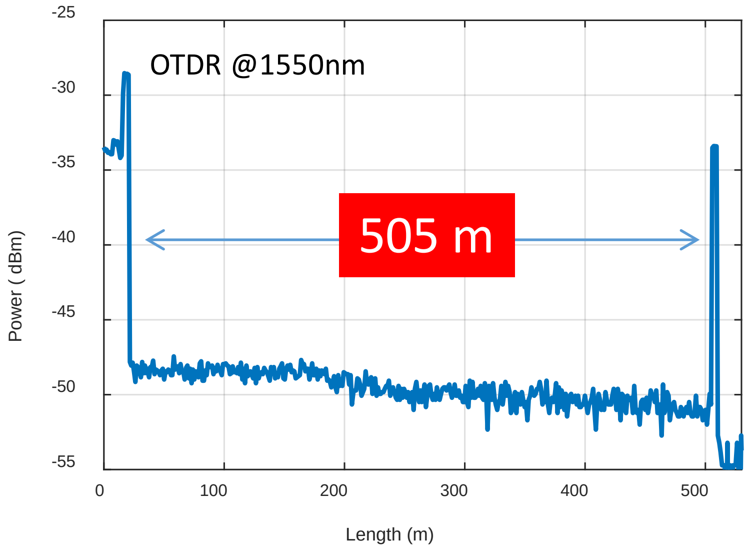


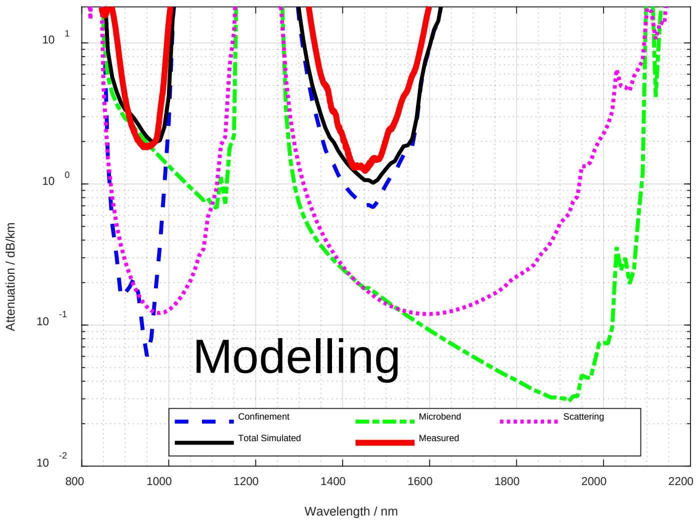
NANF Beating HC-PBGF



1.3 ± 0.1 dB/km







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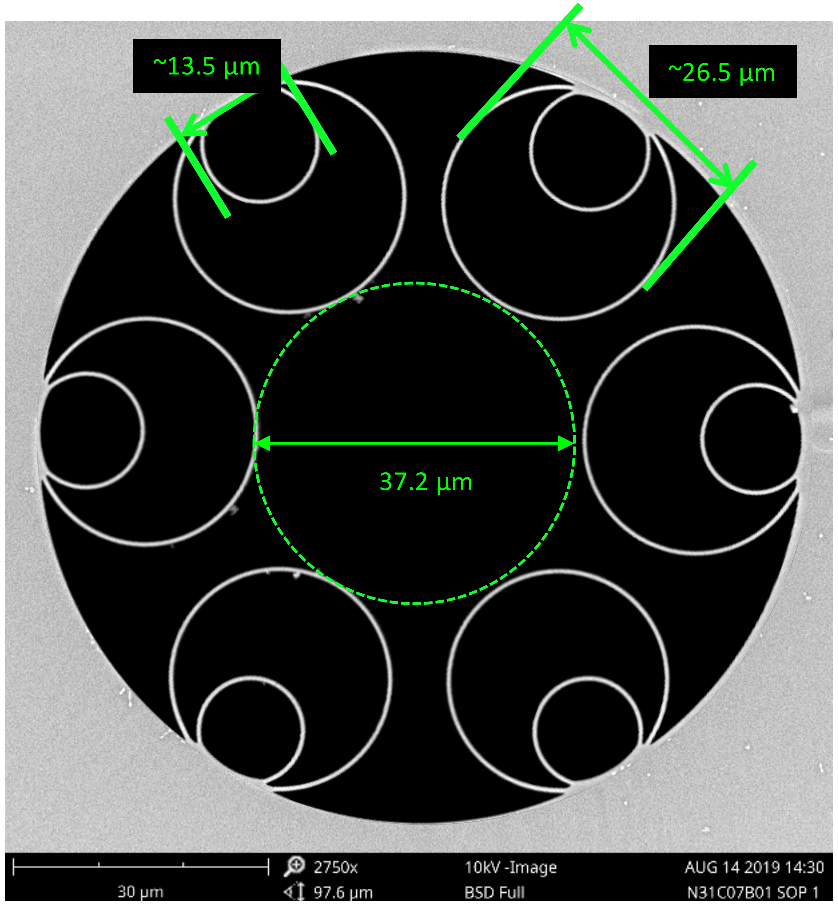
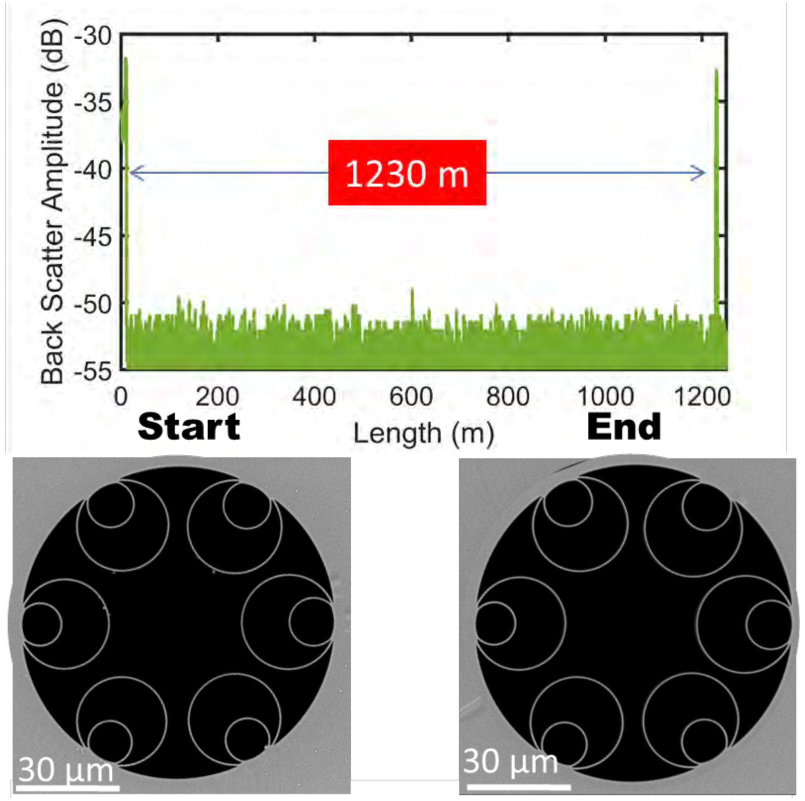
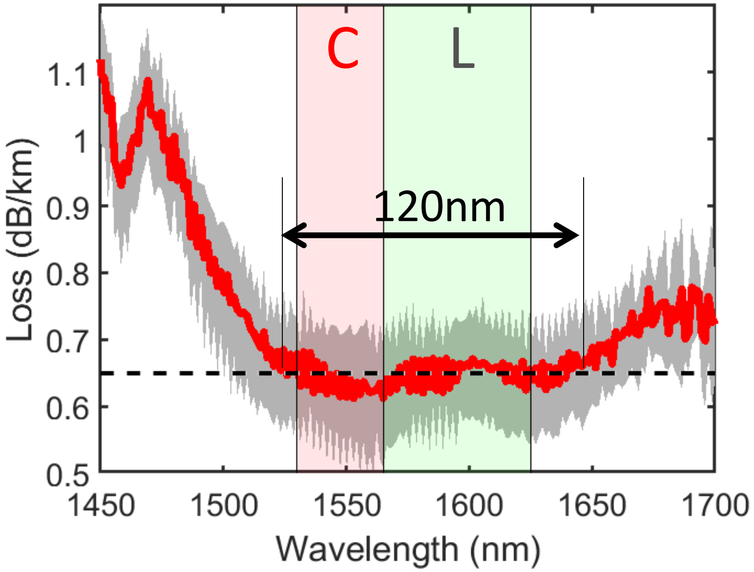
NANF – Below 1 dB/km



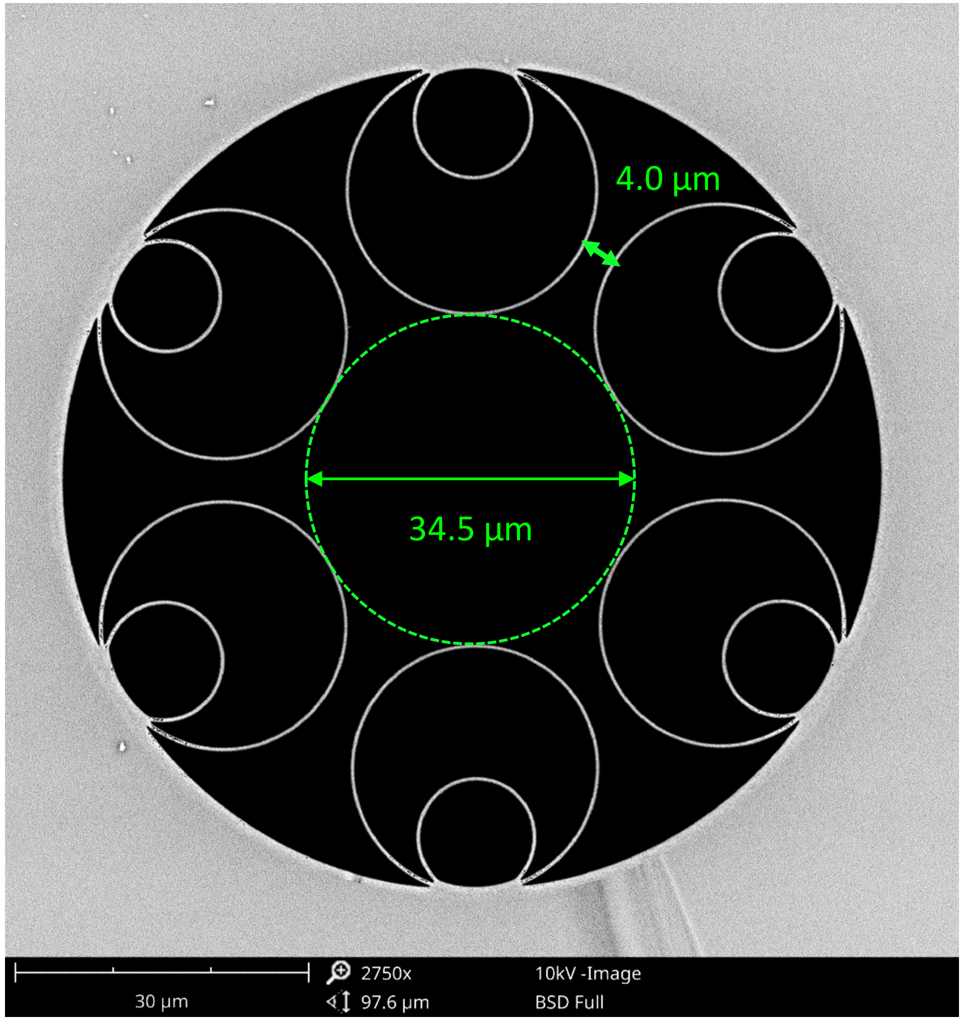




First sub 1dB/km HCF

0.65 dB/km +/- 0.08 dB/km between 1520 and 1640nm

State of the art developments

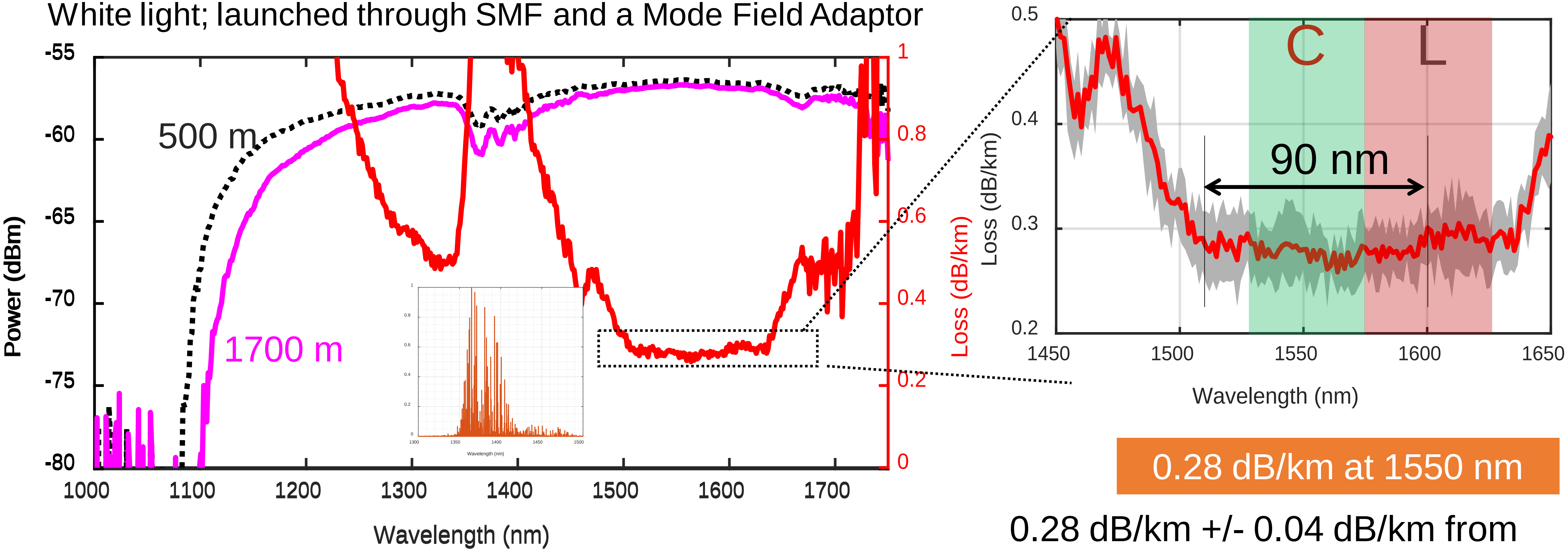


We have:

1. Improved the fabrication process and reduced asymmetries in the stacked preform
2. Reduced core size to 34.5 µm to reduce microbending
3. Reduced average azimuthal gap to 4 µm to maintain low leakage loss

Record Low Loss NANF

White light; launched through SMF and a Mode Field Adaptor

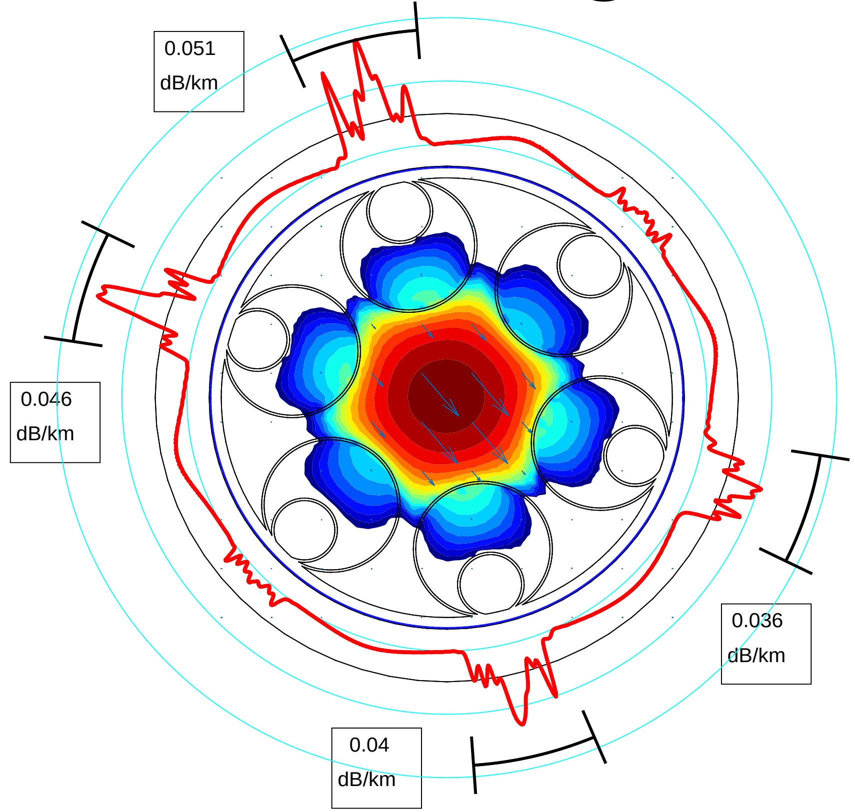


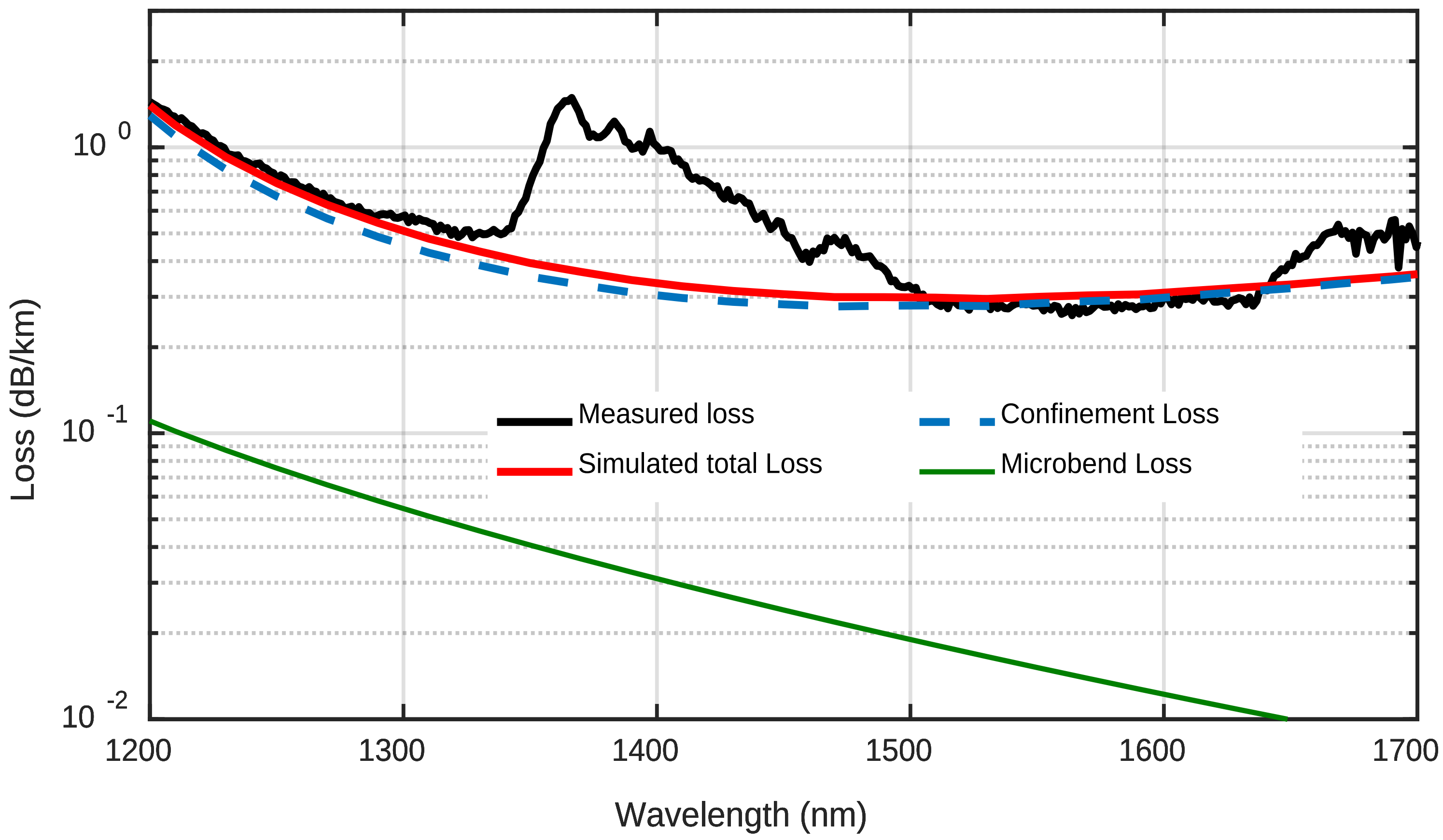
0.28 dB/km at 1550 nm

0.28 dB/km +/- 0.04 dB/km from 1510 nm to 1600 nm

≤0.3 dB/km in C and L bands

Modelling



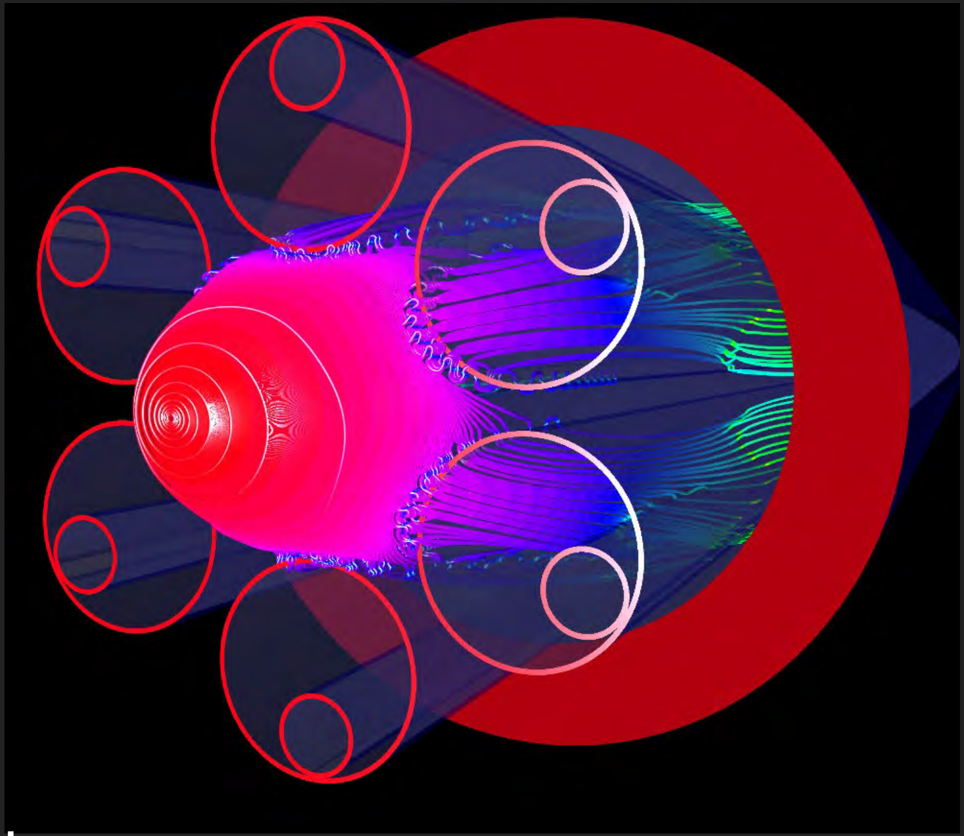


- Small and uniform gaps prevent leakage
- Leakage alone accounts for 0.26 dB/km

Surface scattering limit may be lower than previously thought!

Fibre Fabrication Overview

- Hollow Core Photonic Bandgap Fibre developed over a number of years.
- From 2018 to 2020 NANF loss has been reduced from 1.3 dB/km to 0.28 dB/km
- Loss in NANF is now only 2x higher than pure silica SMF



Further developments are within sight

Applications of HCFs

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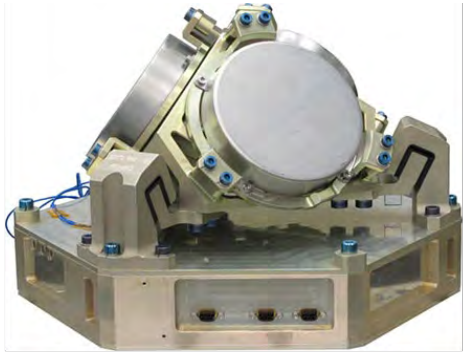
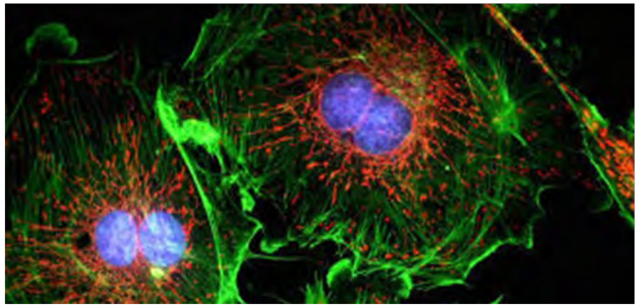
Telecoms

Fibre Optics Sensors

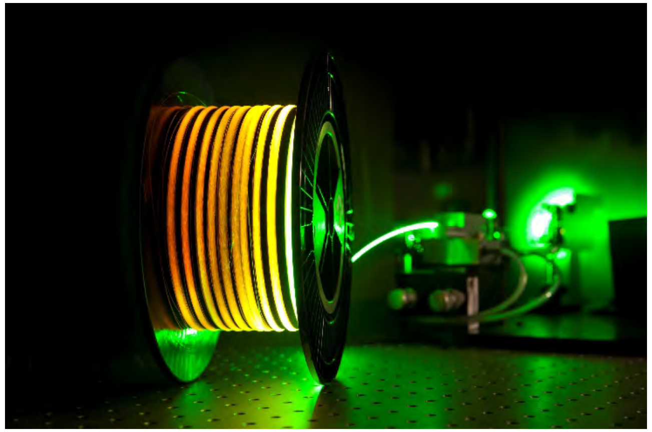


High Power Lasers

Medical Imaging

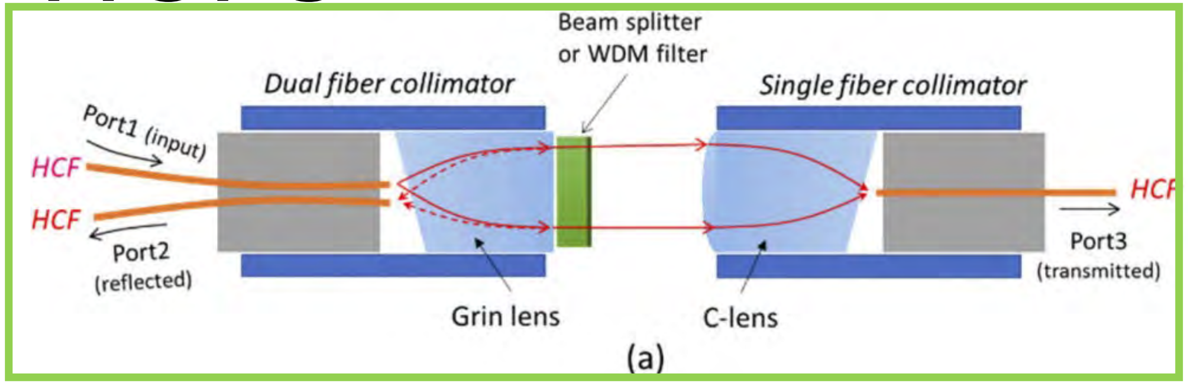


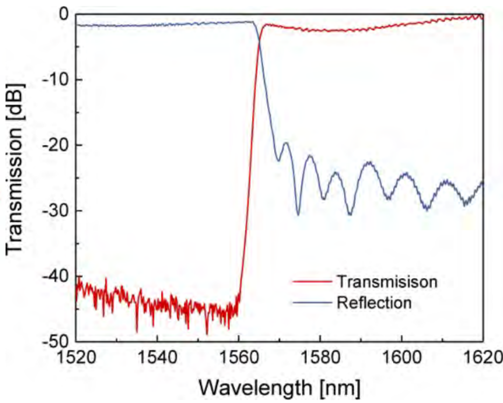
Nonlinear Optics



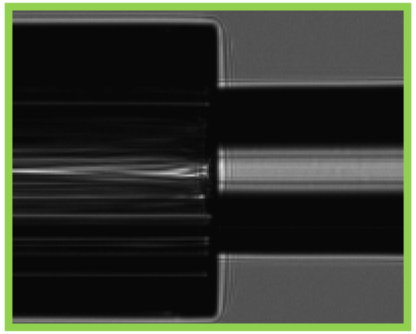
Integration of HCFs

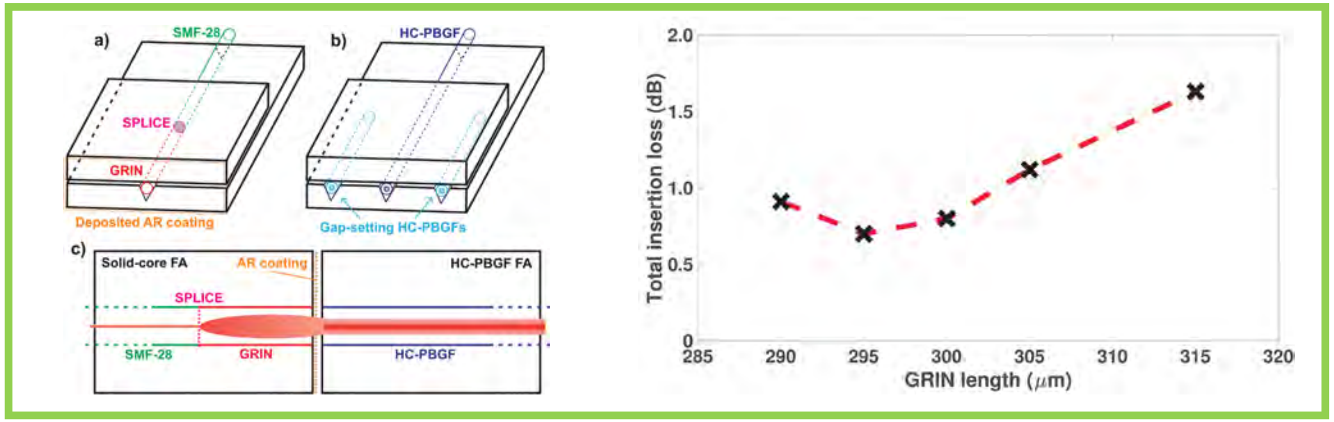
- Fusion Splicing
  - Hermetic Seal
- Packaged Micro Optics
  - Can create functional devices
- Photonic Lightwave Circuits
  - Extremely low loss
  - Not hermetically sealed
  - Complex Alignment





Yongmin Jung, Hyuntai Kim, Yong Chen, Thomas D. Bradley, Ian A. Davidson, John R. Hayes, Gregory Jasion, Hesham Sakr, Shuichiro Rikimi, Francesco Poletti, and David J. Richardson, "Compact micro-optic based components for hollow core fibers," Opt. Express 28, 1518-1525 (2020)

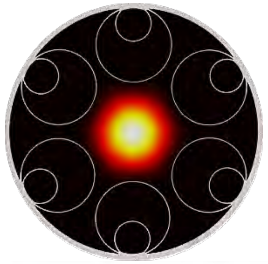




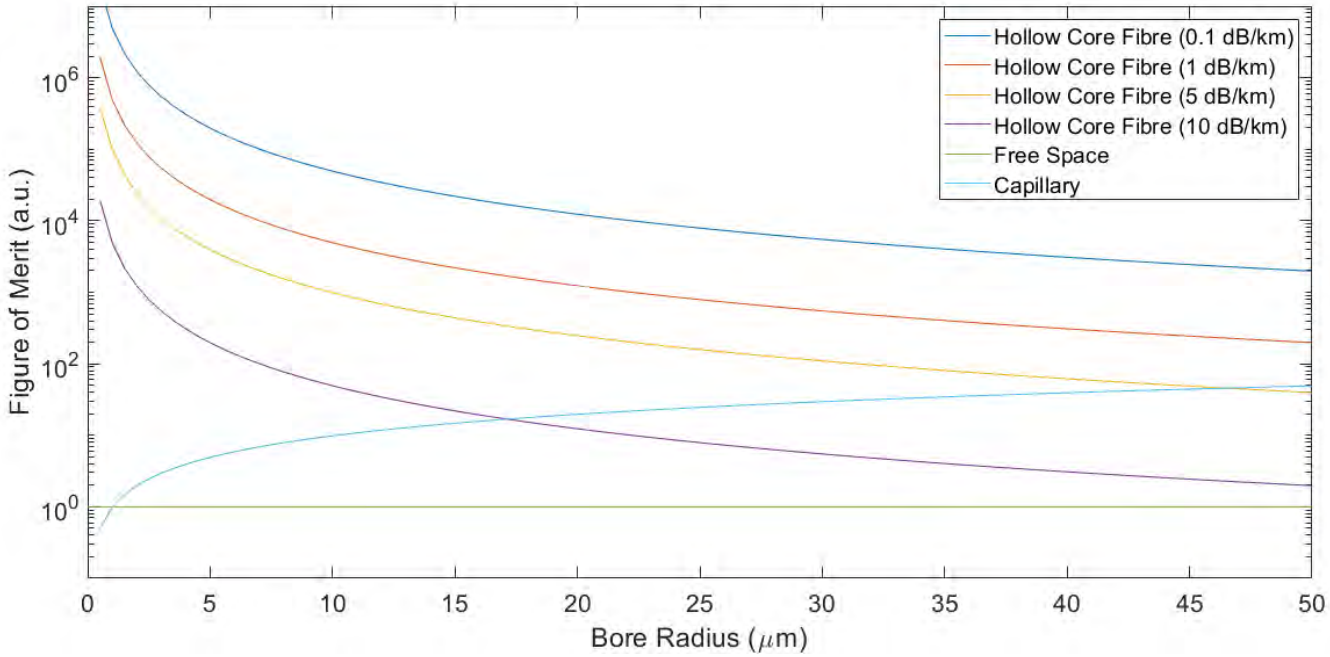
1) D. Suslov, M. Komanec, S. Zvánovec, T. Bradley, F. Poletti, D. J. Richardson, and R. Slavík, "Highly-efficient and low return-loss coupling of standard and antiresonant hollow-core fibers," in *Frontiers in Optics + Laser Science APS/DLS*, OSA Technical Digest (Optical Society of America, 2019), paper FW5B.2

2) M. Komanec *et al.*, "Low-Loss and Low-Back-Reflection Hollow-Core to Standard Fiber Interconnection," in *IEEE Photonics Technology Letters*, vol. 31, no. 10, pp. 723-726, 15 May15, 2019, doi: 10.1109/LPT.2019.2902635.

Nonlinear Optics in HCFs

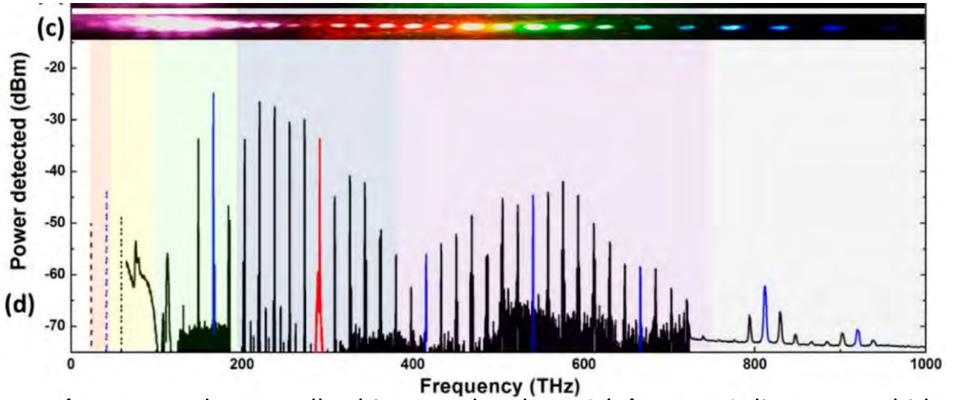


- Tight Mode Confinement
- Long Interaction Length
- Strong Light Matter Interaction



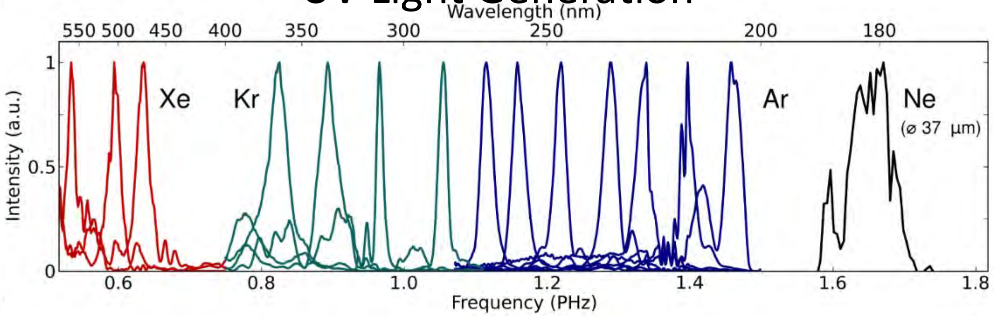
F. BENABID, J. C. KNIGHT, G. ANTONOPOULOS, P. ST. J. RUSSELL, " Stimulated Raman Scattering in Hydrogen-Filled Hollow-Core Photonic Crystal Fiber", SCIENCE11 OCT 2002 : 399-402

Raman Side Band Generation



Benoît, A.; Beaudou, B.; Alharbi, M.; Debord, B.; Gérôme, F.; Salin, F.; Benabid, F. Over-five octaves wide Raman combs in high-power picosecond-laser pumped H_2-filled inhibited coupling Kagome fiber. *Opt. Express* **2015**, *23*, 14002–14009

UV Light Generation



Ka Fai Mak, John C. Travers, Philipp Hölzer, Nicolas Y. Joly, and Philip St. J. Russell, "Tunable vacuum-UV to visible ultrafast pulse source based on gas-filled Kagome-PCF," Opt. Express 21, 10942-10953 (2013)

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EPSRC Engineering and Physical Sciences Research Council

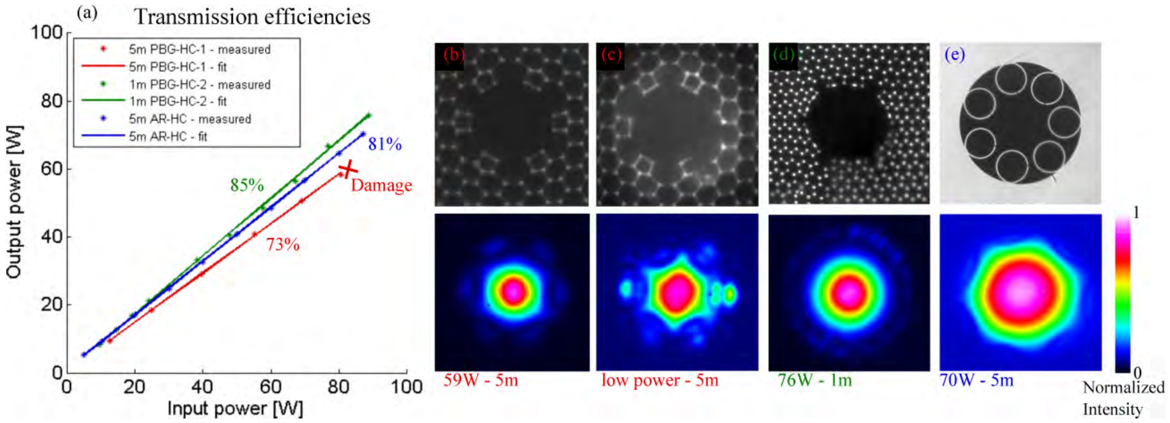
UNIVERSITY OF Southampton

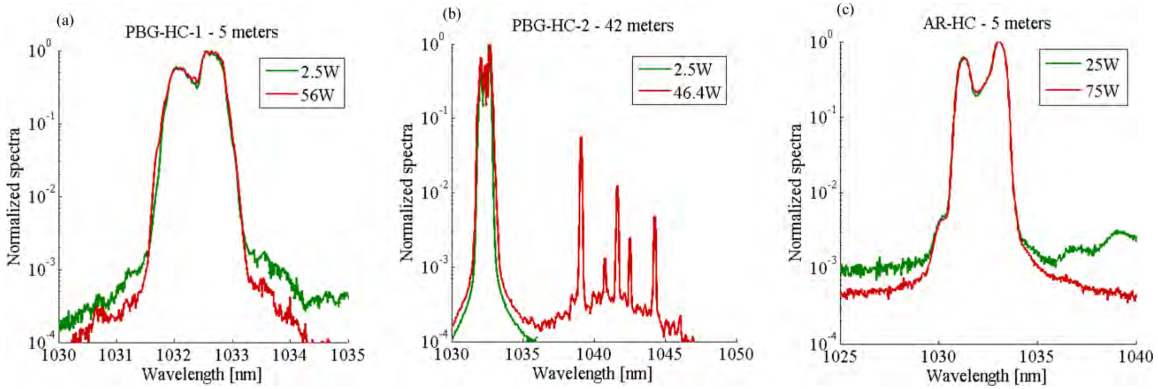
Laser Power Delivery

- Cutting/Engraving/Machining/Additive Manufacturing
  - Automated
  - Precise
  - Repeatable
  - Tailorable

https://www.spilasers.com/application-cutting/fiber-laser-cutting-of-stents/

CW Laser Delivery

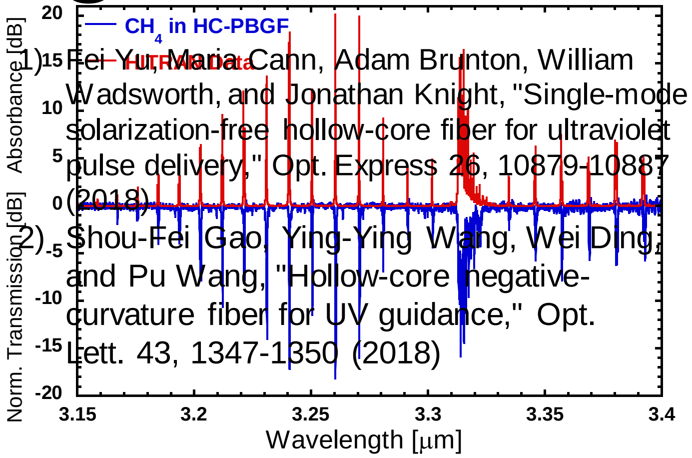




M. Michieletto, J. Lyngsø, C. Jakobsen, J. Lægsgaard, O. Bang, and T. Alkeskjold, "Hollow-core fibers for high power pulse delivery," Opt. Express 24, 7103-7119 (2016).

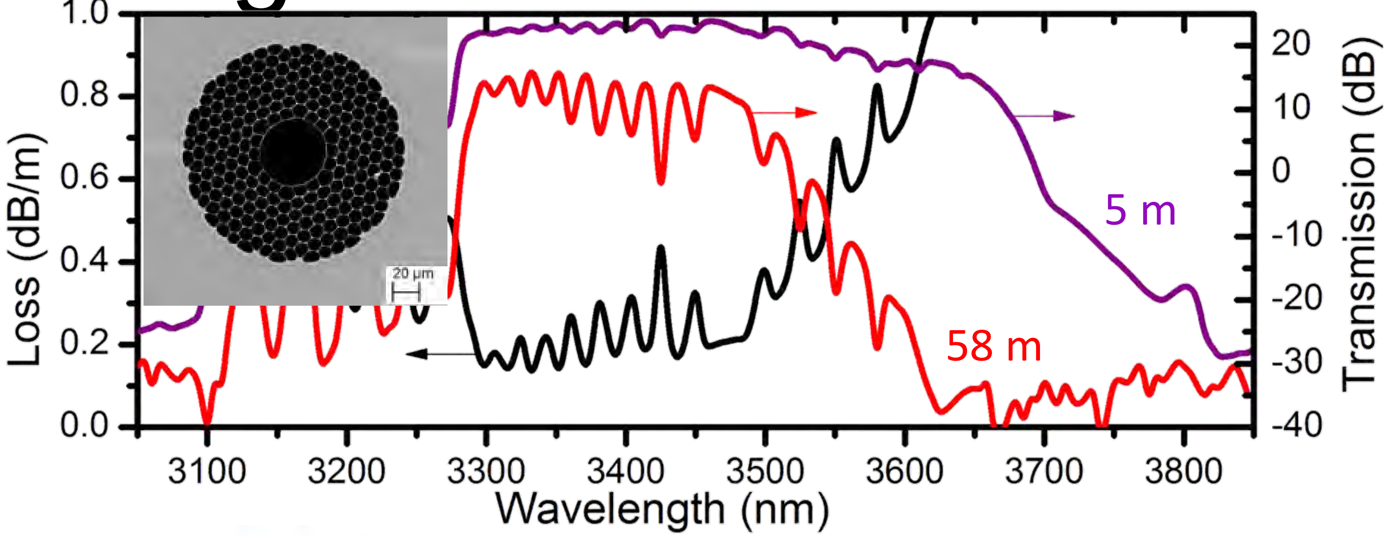
Guiding UV & Mid IR Light

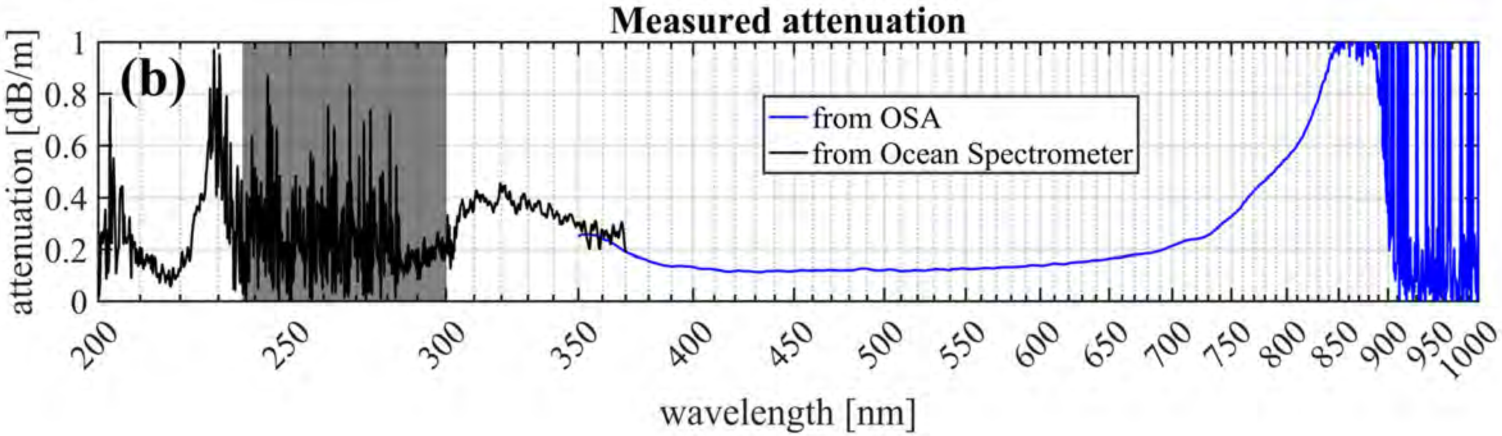
- Silica Low Loss Transmission ~ 200 – 2000nm

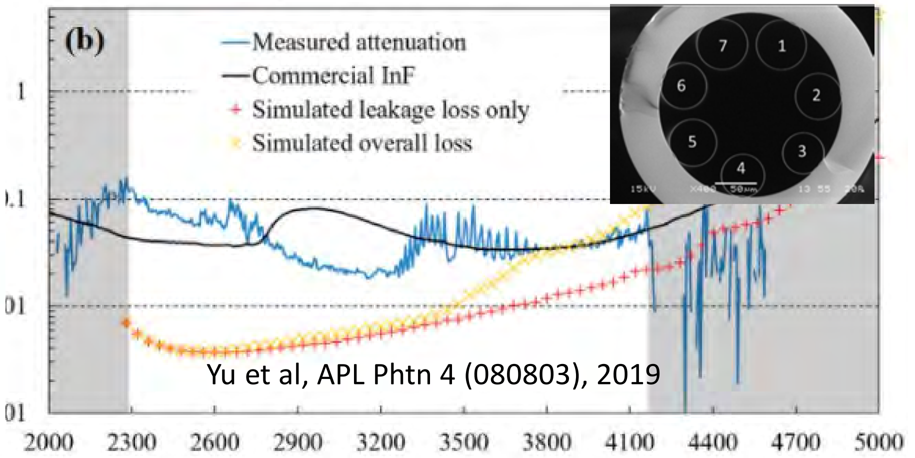


1) Fei Yu, Maria Cann, Adam Brunton, William Wadsworth, and Jonathan Knight, "Single-mode solarization-free hollow-core fiber for ultraviolet pulse delivery," Opt. Express 26, 10879-10887 (2018).

2) Shou-Fei Gao, Ying-Ying Wang, Wei Ding, and Pu Wang, "Hollow-core negative-curvature fiber for UV guidance," Opt. Lett. 43, 1347-1350 (2018)



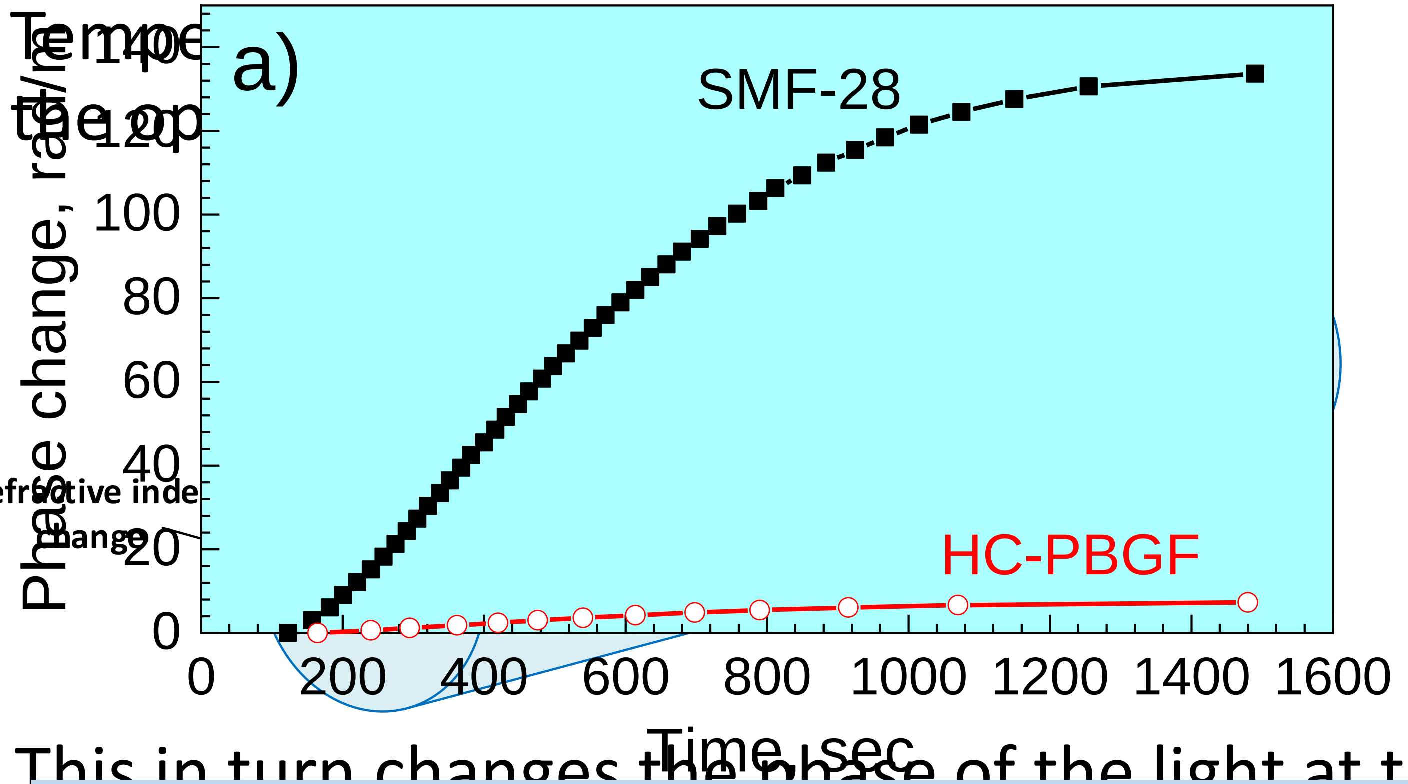




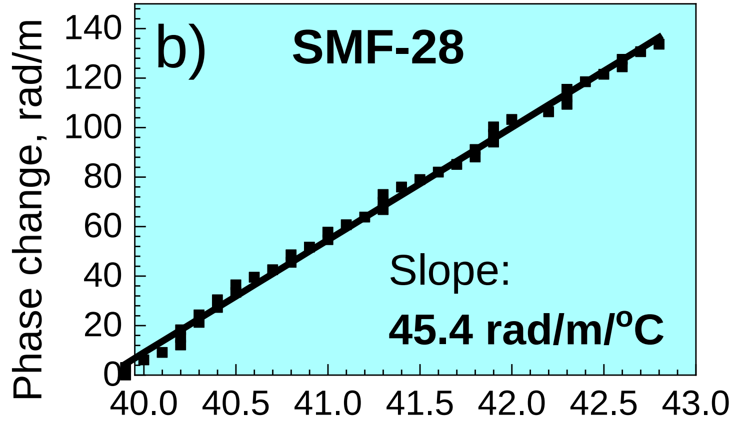
Yu et al, APL Phtn 4 (080803), 2019

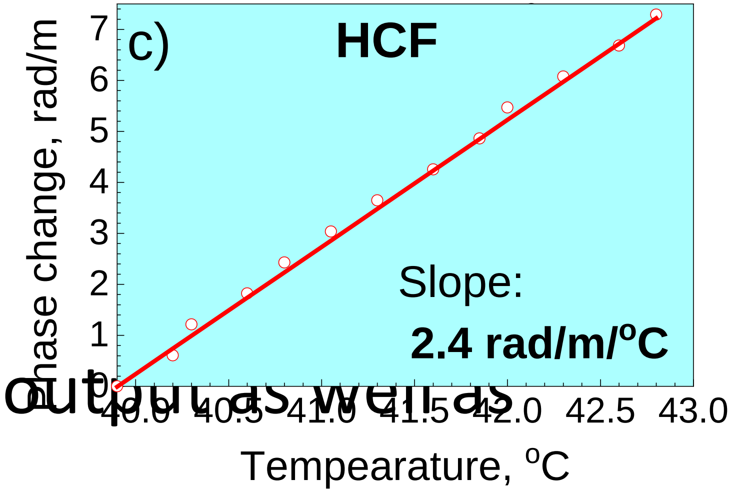
Thermal Sensitivity of HCFs

Measured data



Processed data





- Tempe... the op...

Refractive index change

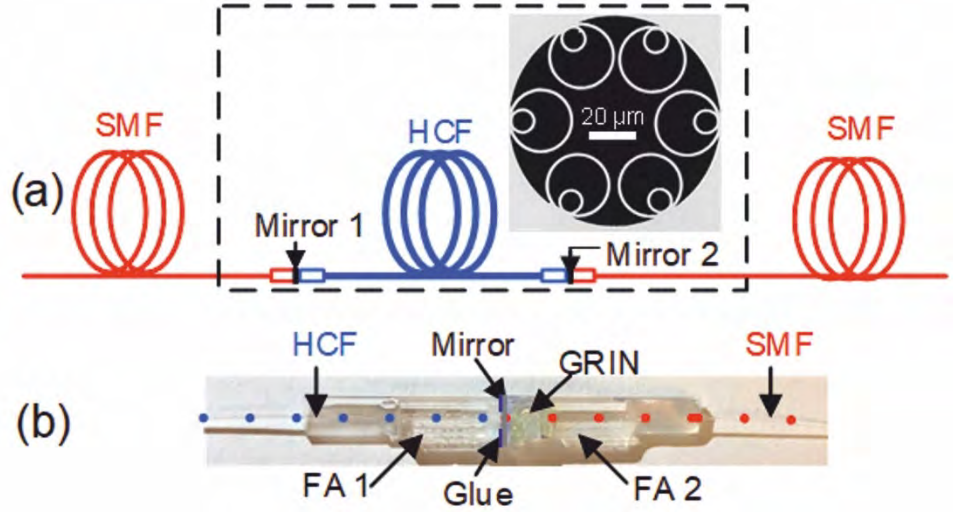
- This in turn changes the phase of the light at the fibre output as well as its arrival time.

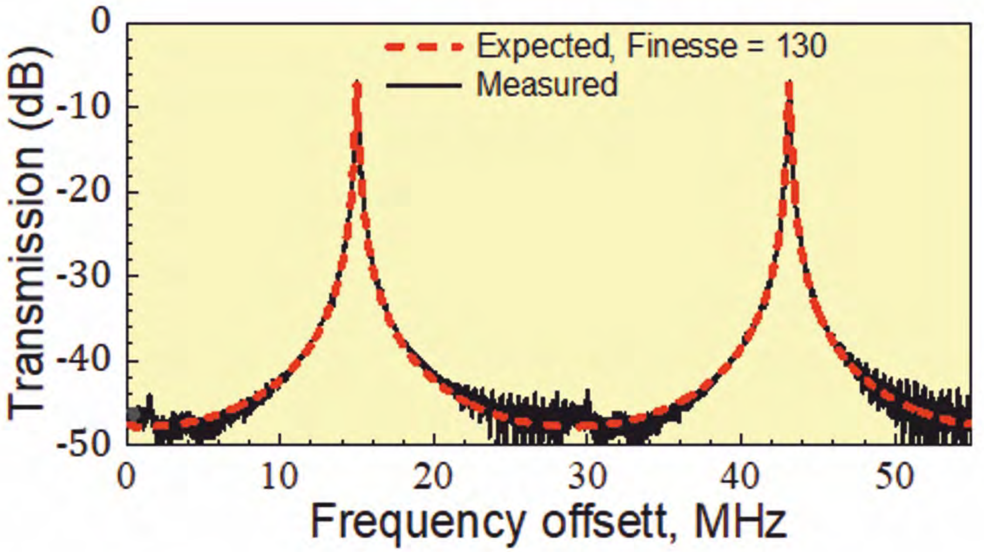
HCF has a sensitivity 18.5 times smaller than SMF-28

Slavík et al., *Scientific reports* 5, 15447, 2015.

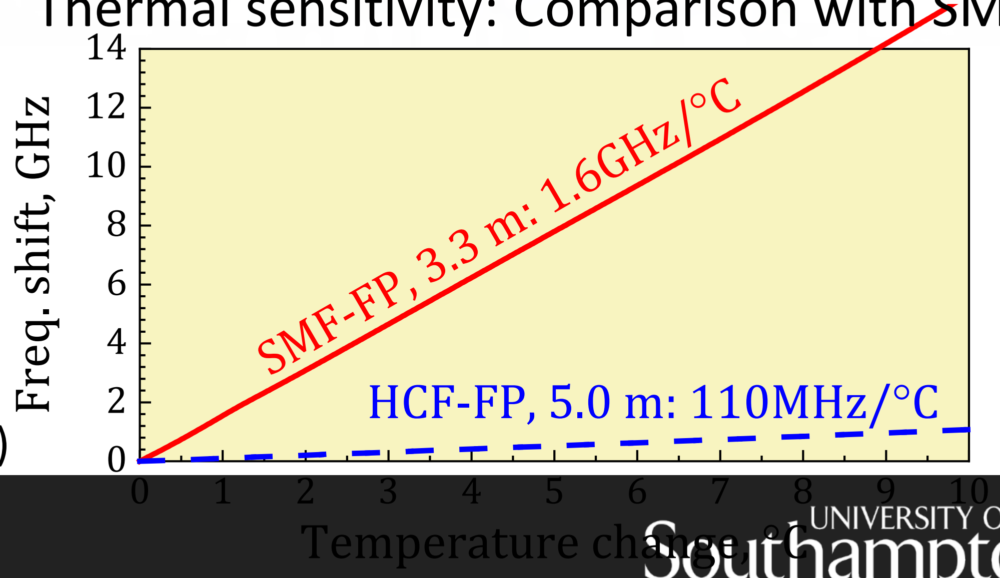
Anti-resonant HCF sensitivity & Fabry Perot etalon

5-m long, 0.9-dB/km, NANF (ARF) fibre FP





Thermal sensitivity: Comparison with SMF

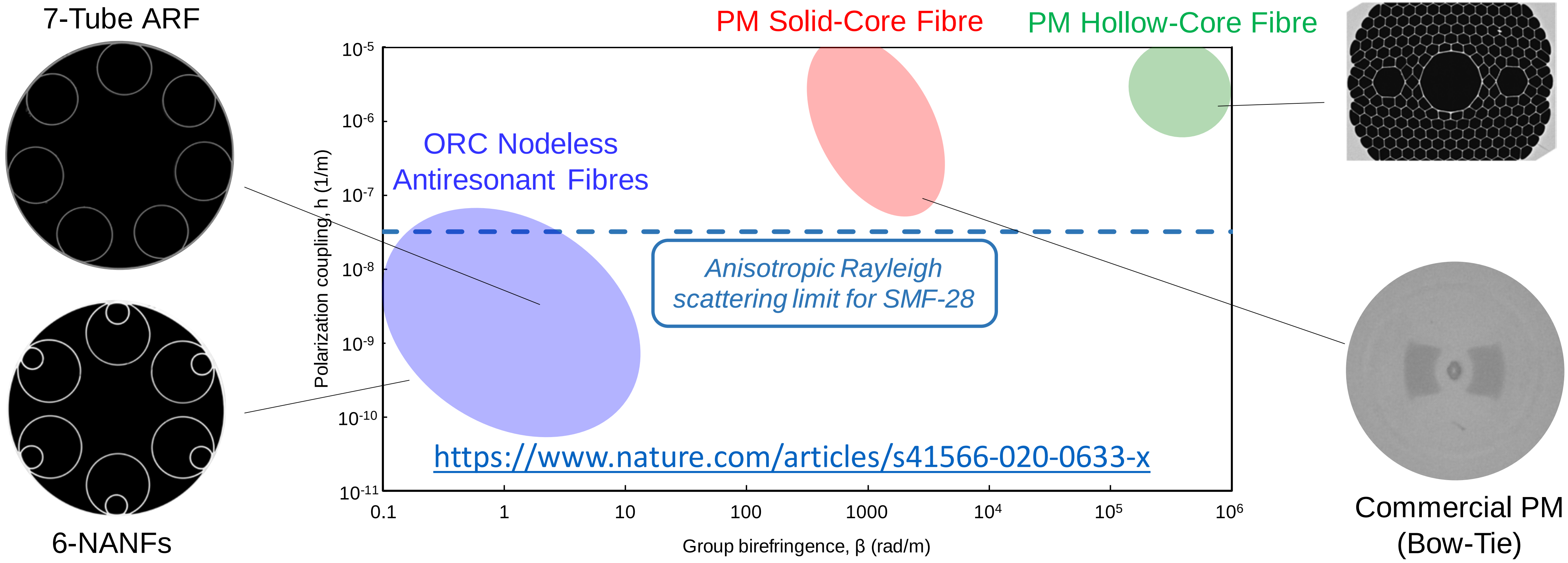


- Two FPs (HCF & SMF) with similar Free Spectral Range (FSR): 5 m HCF & 3.3 m SMF28
- HCF FP: Finesse of 130
- **NANF (ARF-type) 21 times less thermally sensitive than SMF** (per unit length; corresponding to 14.5 times per unit delay/ FSR).

M. Ding et al., *J of Lightwave Technol.* 2020 (early access)

Polarisation in Anti-resonant HCFs

PM - PBGF



***Material-free* propagation in ARFs provides…**

- *Pure, interaction-free propagation for long interferometers & resonators*
- *Ultra-low polarization coupling despite minimal birefringence*

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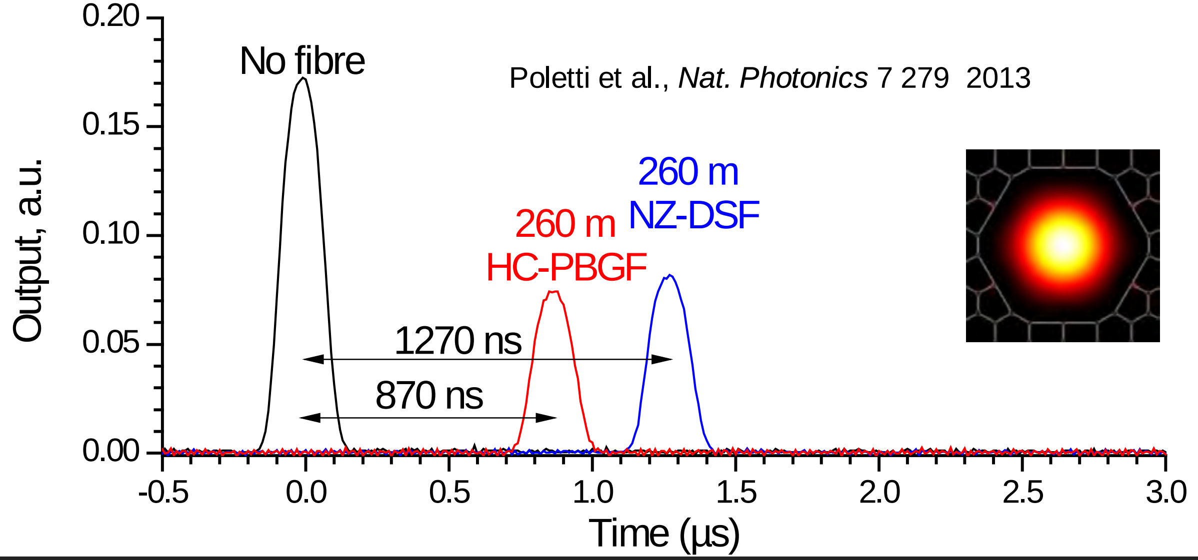
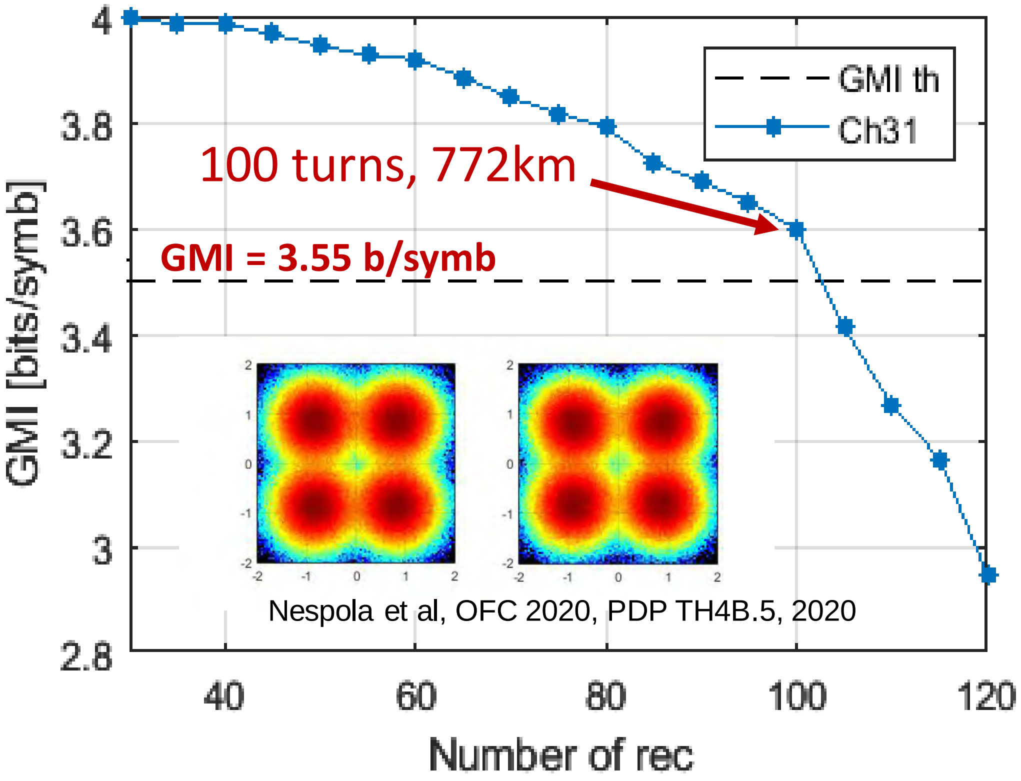
Data transmission in HCF: why?

- Ultimate low latency: 1.54 μs/km lower latency than SMF
- Low Nonlinearity: can launch higher signal power
- Wide Bandwidth: more than C band
- Potential for ultra low loss….



Poletti et al., *Nat. Photonics* 7 279 2013

- ***longest transmission in any HCF: 618 km with PM-QPSK***
  - previous record was 341km but only center channel



Nespola et al, OFC 2020, PDP TH4B.5, 2020

Record distance transmission in HCFs

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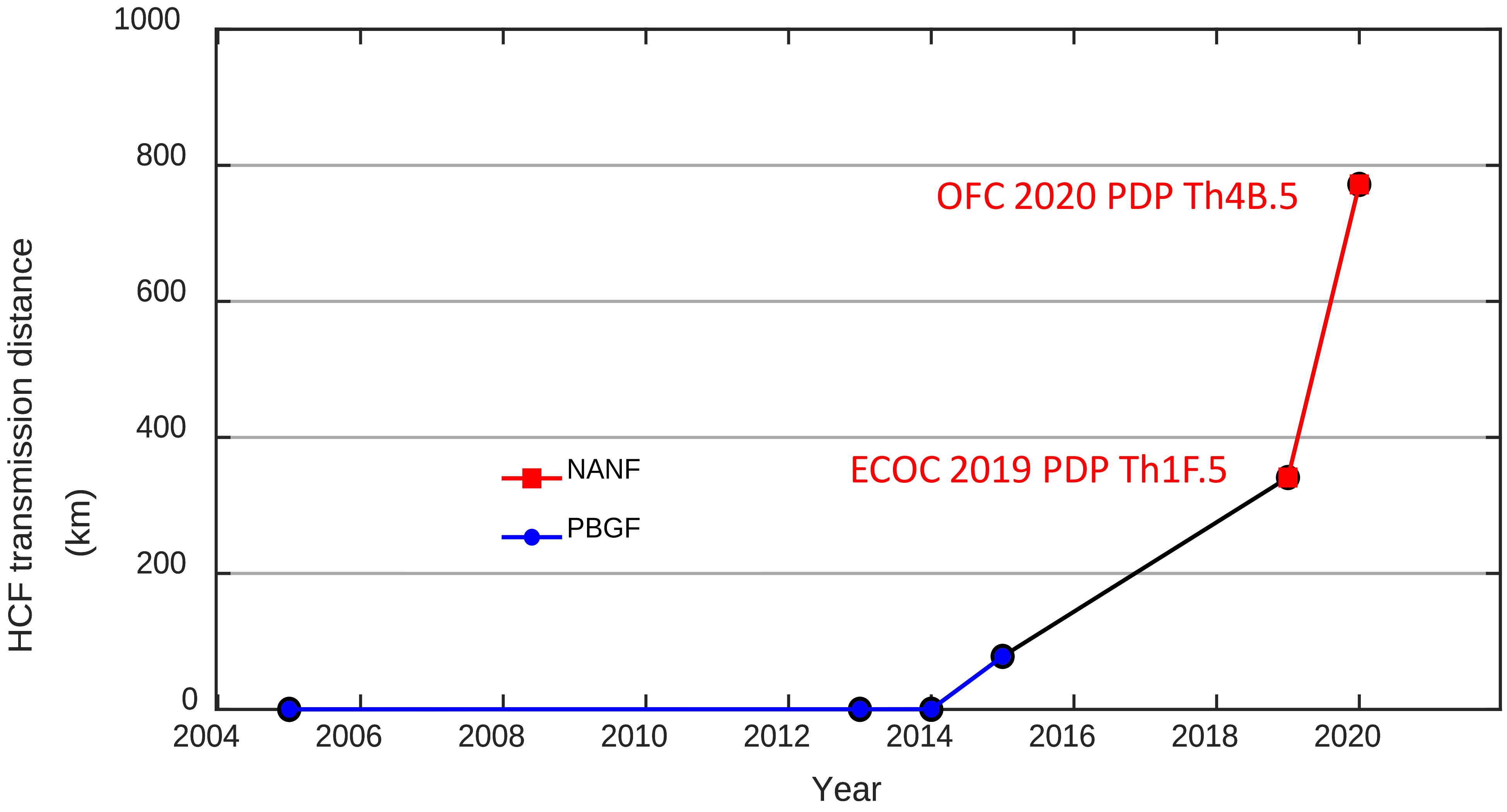
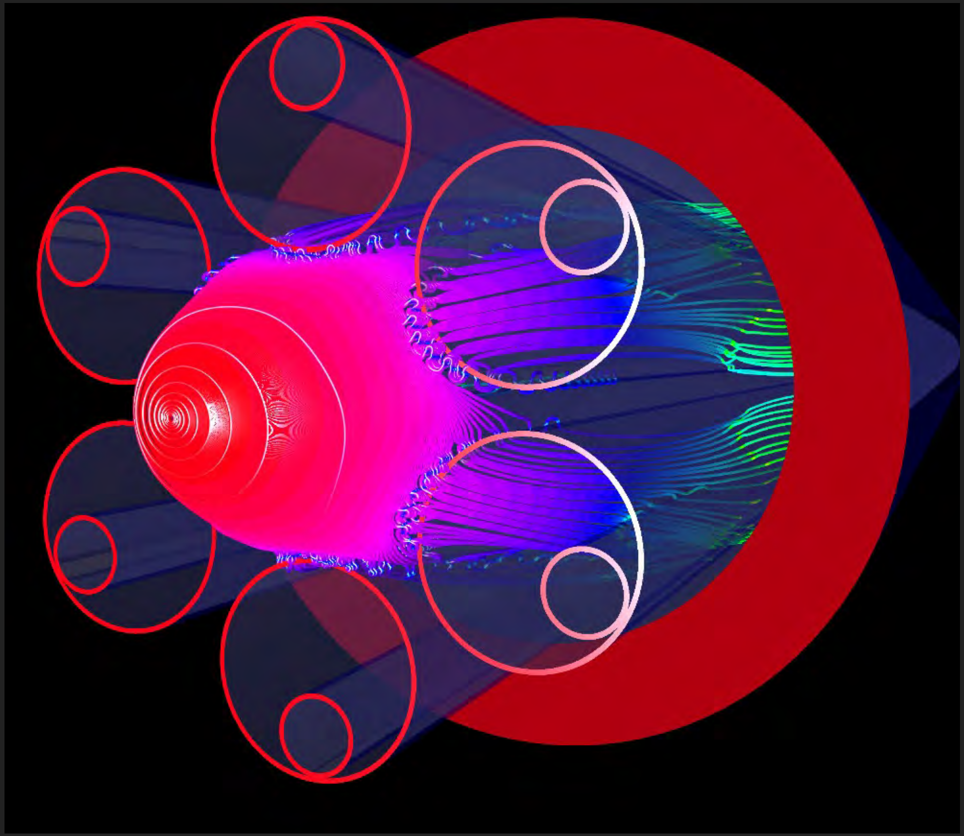


Outlook

- Huge range of exciting applications
  - Nonlinear Optics
  - Telecoms
  - …..
- Splicing/Interconnection
  - Fusion splicing
  - Packaged micro optics
- Rapid development in NANF technology
  - now only 2x higher than pure silica SMF



Further developments are within sight

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Acknowledgements

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The FUTURE PHOTONICS Hub

Advancing the manufacturing of next-generation light technologies