Recent Developments in Hollow-Core Optical Fiber

Presented by:

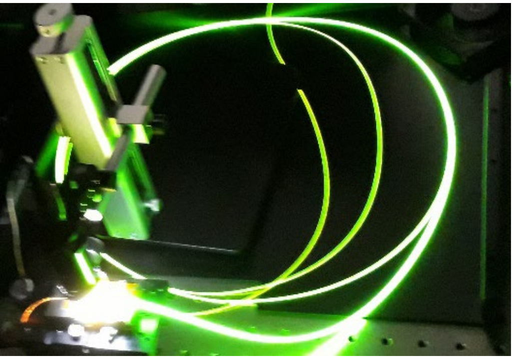
OSA Fiber Modeling and Fabrication Technical Group

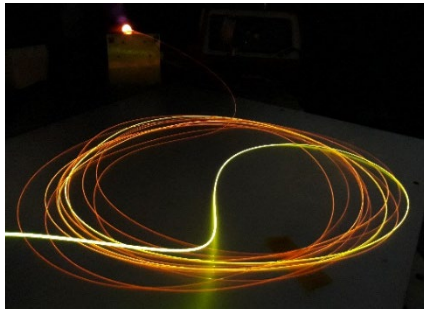
Fiber Modeling
and Fabrication
Technical Group

Fiber Modeling and Fabrication Technical Group

Welcomes You for the webinar on Recent Development in Hollow-Core Optical Fiber

November 14th 2019, 08:00-09:00 (Beijing Time)





Fiber Modeling and Fabrication Technical Group

About us: A unique group of more than 900 researchers from 70+ countries from North America, South America, Europe, Asia, Africa, and Oceania.

Goals:

To benefit **OSA members** having interest in Fiber Design, Modeling, Fabrication, and Applications of fibers.

To Provide a platform to Fiber Community for connecting, Engaging and Exciting with others.

To Organize Webinars, Technical and Networking Events, and Special Journal Issues.

Find us:-

https://www.osa.org/FF

Join Us:

https://www.facebook.com/groups/OSAfibermodelingandfabrication/

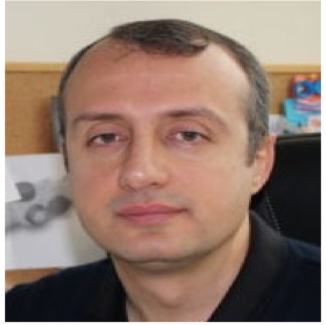
https://www.linkedin.com/groups/8302193/


Deepak Jain, Chair
University of Sydney


Jonathan HU,
Vice-Chair
Baylor University


Bora Ung,
Vice-Chair
ETS, Canada


Rajan Jha,
Vice-Chair
IIT-B, India


Bulend Ortac, Vice-Chair
Bilkent University, Turkey


Xin Jiang,
Vice-Chair
MPL, Germany


Md Selim Habib,
Executive Officer
CREOL, USA


Naresh K Thipparapu,
Executive Officer
ORC, UK


Ivan B. Gonzalo,
Executive Officer
IMDEA, Spain


ThanSingh Saini,
Executive Officer
Toyota Technological,
Japan


Yvonne Q Kang,
Executive officer
Huwaeii, China


Lu Yan, Executive
Officer
Applied Materials,
USA

Find us:-
https://www.osa.org/FF
Join Us:
https://www.facebook.com/groups/OSAfibermodelingandfabrication/
https://www.linkedin.com/groups/8302193/

Manish Sharma,
Executive Officer
ETS, Canada

Tanvi Karpate,
Executive Officer
IEMT, Poland

Fiber Modeling and Fabrication Technical Group

Past/Upcoming Events:

1. Networking Event: Date: Tuesday, 16 Jul 2019 17:00-18:00
Location: Naupaka III, Waikoloa Beach Marriott Resort & Spa, Waikoloa Beach, Hawaii

2. Webinar 1: Everything you always wanted to know about supercontinuum modelling in optical fibers (but were afraid to ask) Date: 26th August 2019, at Swiss time 2pm/ EDT 8am
A/Prof. Alexander Heidt, University of Bern, Switzerland.

3. Webinar 2: The development of thulium and holmium fiber sources
Date: 30th September, 2019 at 1pm (UK time)/ EDT 7am
Dr. Nikita Simakov, DSTO, Australia.

4. Webinar 3: Recent development in hollow-core optical fiber
Date: 14 November, 2019, 8 am Beijing Time
A/Prof. Y Wang, Beijing University of Technology, China.

Many More to come shortly !!!!

How to join this Group:

Fiber Modeling and Fabrication Technical Group

If you are OSA member: Log-in to your OSA Account and chose FF group in Technical Groups Category.

You can join the Facebook Group even if you are not member of OSA:
https://www.facebook.com/groups/OSAfibermodelingandfabrication/

You can contact me if you are interested in giving a Webinar/Talk/Panel Discussion, on **deepakjain9060@gmail.com**

Today's Webinar

Fiber Modeling and Fabrication Technical Group

Recent Development in Hollow-Core Optical Fiber

Dr. Yingying Wang

Beijing University of Technology
Email: wangyingying@bjut.edu.cn

Speaker's Short Bio:

Yingying Wang obtained her Ph.D. degree from University of Bath, UK in 2011. The Department of Physics, University of Bath, awarded the "Albert Freedman Prize" to Wang's Ph.D. thesis. She is currently an associate professor at *Institute of Laser Engineering, Beijing University of Technology*, in which her research interest lies on novel optical fiber design and fabrication. Wang's contributions on hollow-core hypocycloid-core Kagome fiber and hollow-core conjoined-tube negative curvature fiber are well recognized by the microstructured fiber community. She has delivered many post deadline and invited talks in international conferences such as, CLEO, ECOC, Photonics West, CLEO-PR, Advanced Photonics Congress and Workshop on Specialty Optical Fiber. She has authored more than 30 technical papers with >500 total citations.

Recent Developments in Hollow-Core Optical Fiber

Yingying WANG

Email: dearyingyingwang@hotmail.com
Institute of laser engineering, Beijing University of Technology, China
Institute of photonics technology, Jinan University, Guangzhou, China

1

Background

1. *Motivation*
2. *History of HCF development*

2

HCF – understanding, design and fabrication

1. *How we understand*
2. *Broadband HCF*
3. *Ultralow loss HCF*

3

HCF applications

1. *Optical communications*
2. *Ultrafast optics*
3. *Sensing and biophotonics*

4

Conclusion

Fiber optics

Kao, K. C.; Hockham, G. A. (1966). Proc. IEE. ***113*** *(7): 1151–1158.*

Fiber Optics

⇩

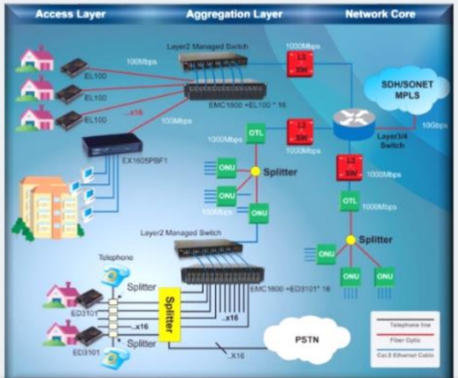
Applications

Optical fiber commnucation

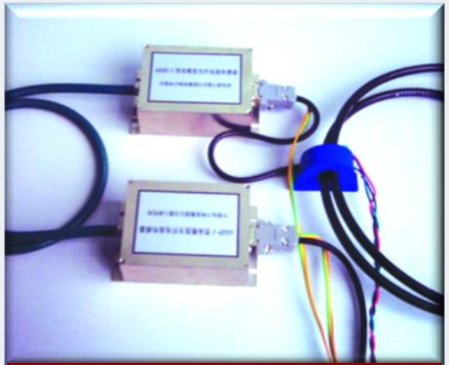
Optical fiber sensing

Fiber laser

Quantum Optics



Capacity crush?



Harsh environment Radiation?

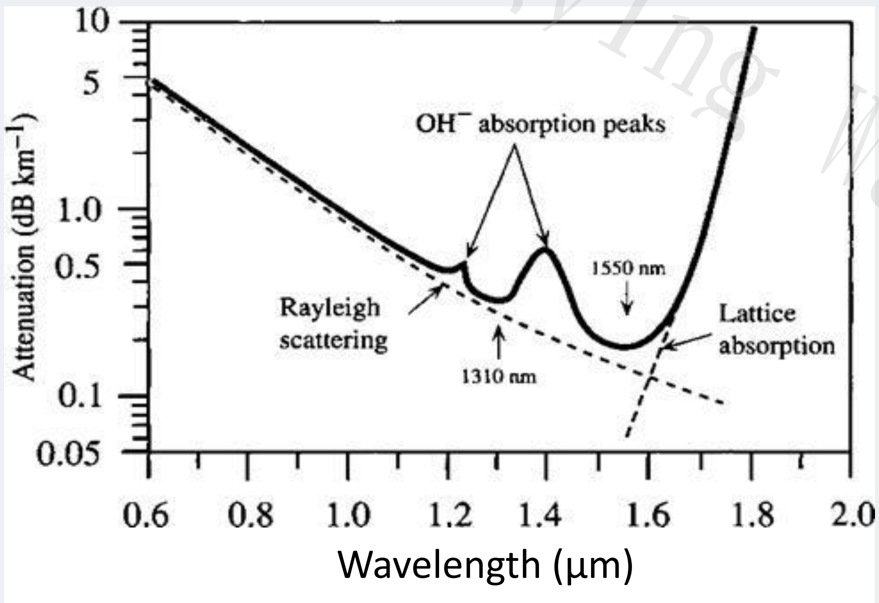
High power, UV, mid-IR?

Biophotonics

。 。 。

Fiber optics

➢ Silica material – intrinsic defect



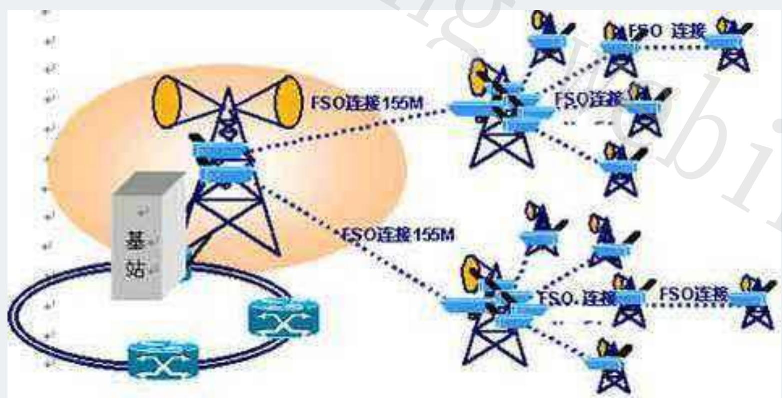
- ➢ **Material loss — Limited transmission window, Rayleigh scattering**
- ➢ **Material dispersion — Pulse broadening, signal delay**
- ➢ **Material nonlinearity—phase distortion**
- ➢ **Material damage — Limited laser power**

G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001.

- **Ideal transmission medium： Air (vacuum)**

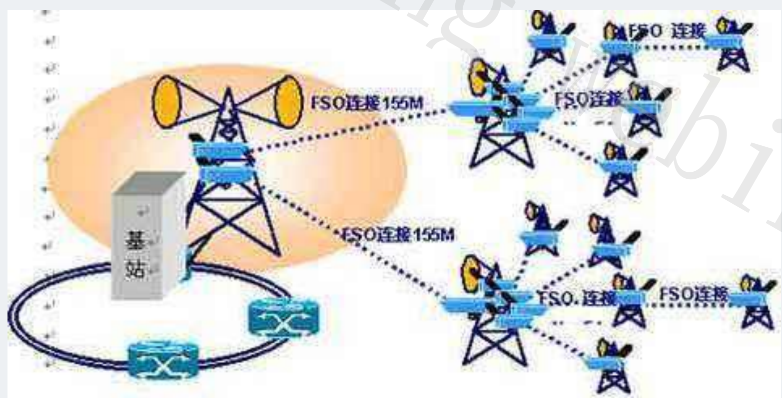
√ No latency √ No dispersion √ No nonlinearity √ No loss

Balefire communication	Free space optical communication	quantum communication



- **Ideal transmission medium： Air (vacuum)**

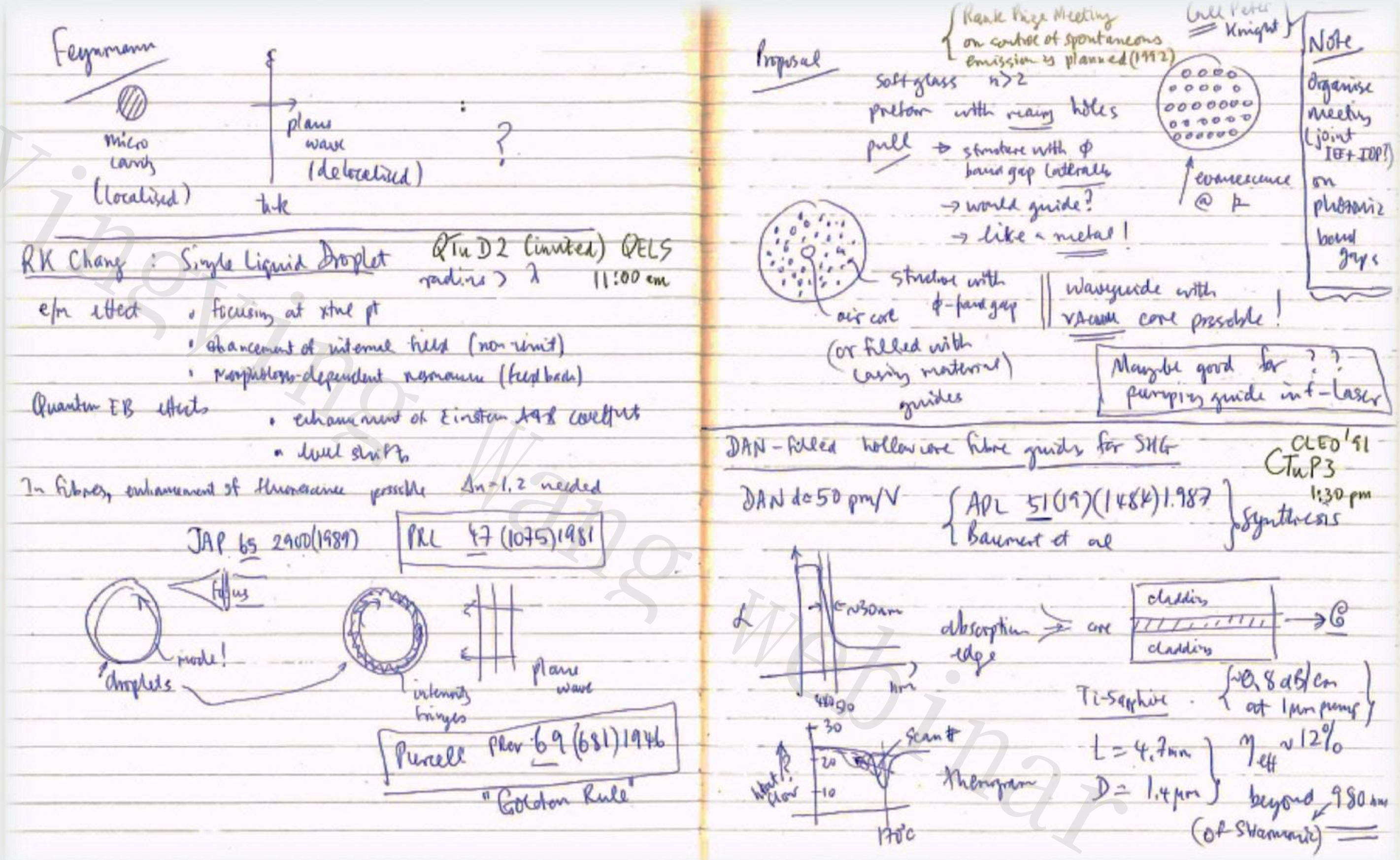
√ No latency √ No dispersion √ No nonlinearity √ No loss

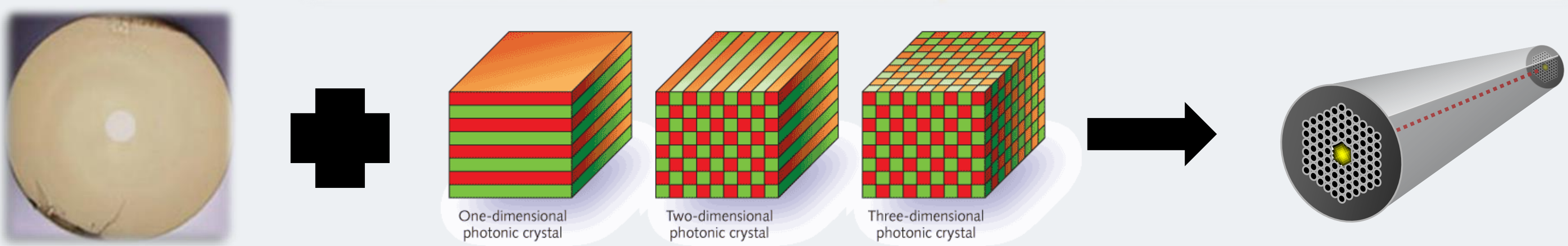
Balefire communication	Free space optical communication	quantum communication
		

fiber+air => ?

28 years ago at CLEO-US (1991)

Philip Russell





1 Background

1. *Motivation*
2. *History of HCF development*

2 HCF – understanding, design and fabrication

1. *How we understand*
2. *Broadband HCF*
3. *Ultralow loss HCF*

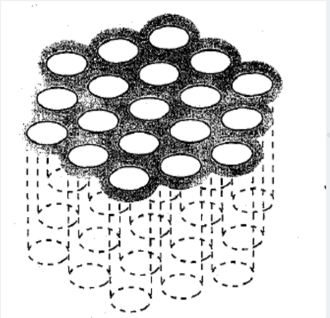
3 HCF applications

1. *Optical communications*
2. *Ultrafast optics: delivery and gas nonlinearity*
3. *Sensing and biophotonics*

4 Conclusion

History of HCF development

1995



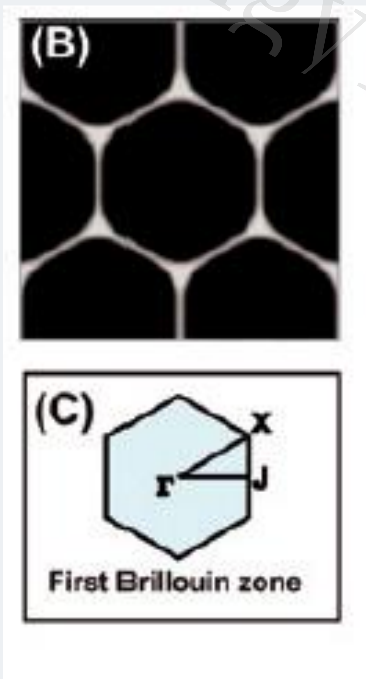
Out-of-plane photonic bandgap guidance prediction

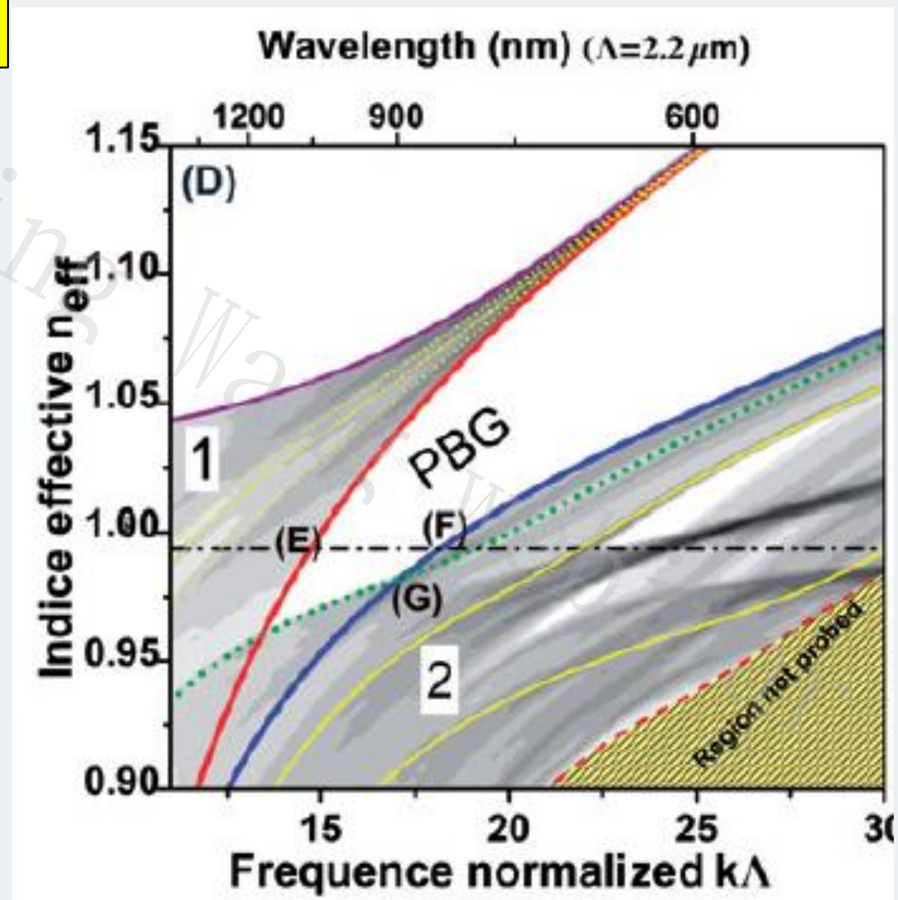
1. T.A.Birks et al, Full 2D photonic bandgaps in silica/air structures, Electron. Letts. 31, 1941, (1995)

History of HCF development

✓ **Zero density of states in photonic bandgap region =>**

unlimited low loss ? ? ?





1. T.A.Birks et al, Full 2D photonic bandgaps in silica/air structures, Electron. Letts. 31, 1941, (1995)
2. F. Benabid et al, Linear and nonlinear optical properties of hollow core photonic crystal fiberJ. Mod. Opt. 58 (2011) 87-124

Solid *VS* Hollow Fiber

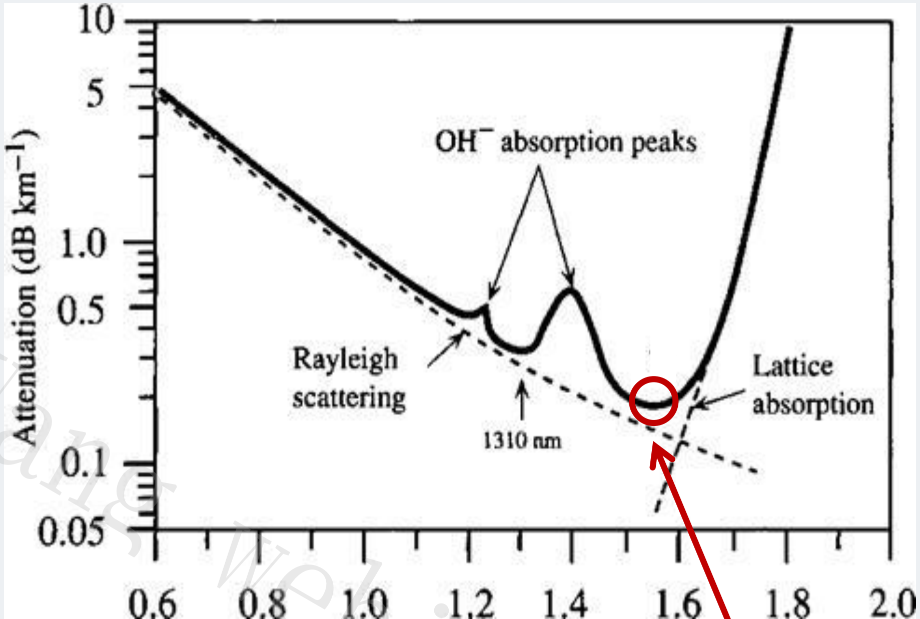
Loss Origin

Ultraviolet absorption

Infrared absorption

Rayleigh Scattering

OH^- absorption



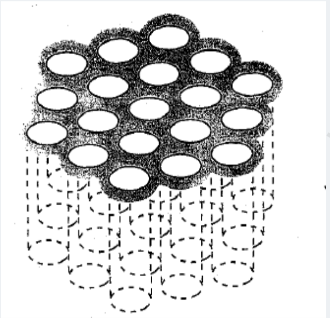
Wavelength (μm)

Dry air: 10^{-3} reduction in RSL limit

Rayleigh scattering limit of fused silica

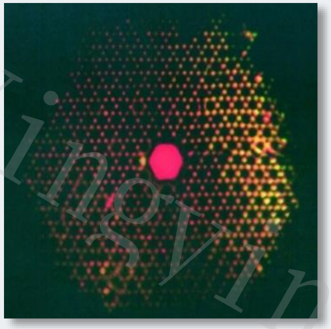
History of HCF development

1995



Out-of-plane photonic bandgap guidance prediction

1999

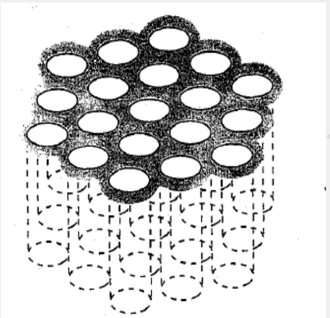


1st HC-PBGF

R. F. Cregan *et al.*, "Single-mode photonic band gap guidance of light in air," *Science*, vol. 285, no. 5433, pp. 1537–1539, Sep. 1999.

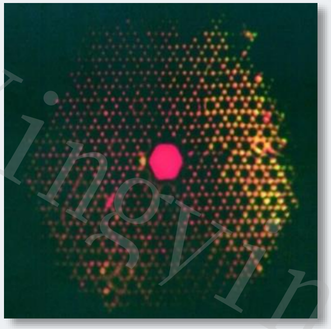
History of HCF development

1995



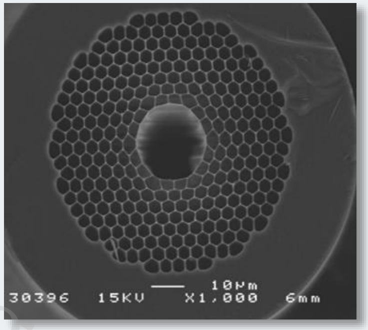
Out-of-plane photonic bandgap guidance prediction

1999



1st HC-PBGF

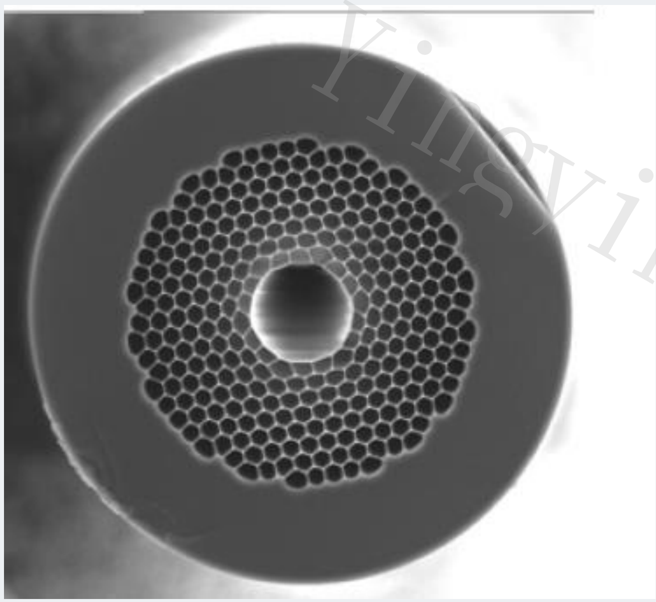
2004

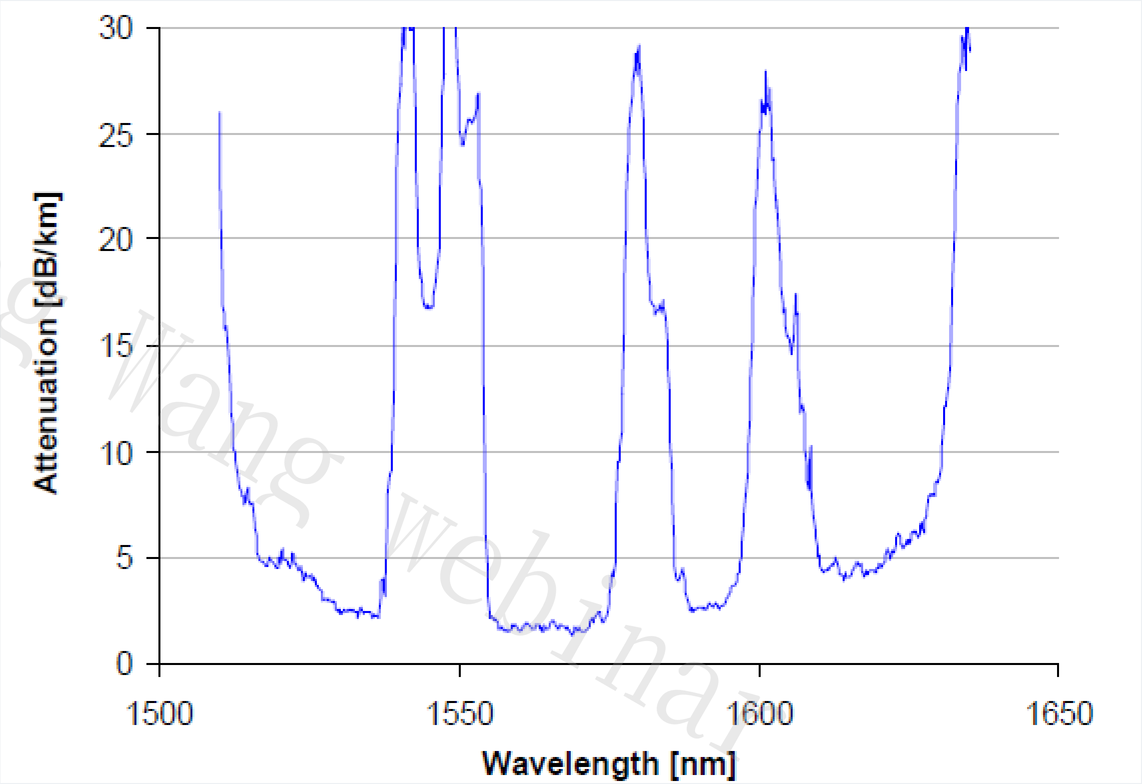


1.7 dB/km,
20 nm bandwidth

Mangan BJ *et al*, Low loss (1.7 dB/km) hollow core photonic bandgap fiber. OFC 2004, PDP 24

History of HCF development

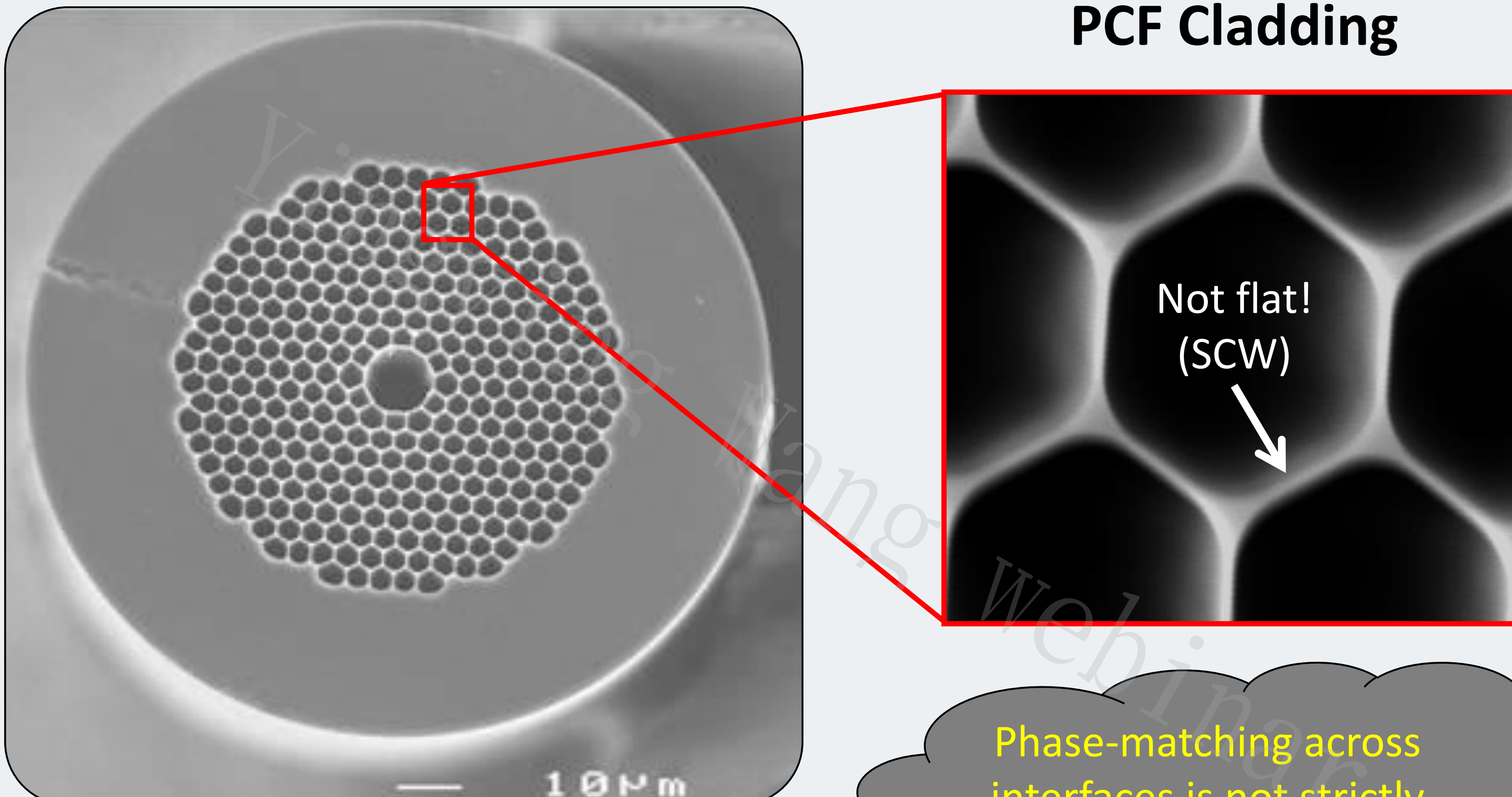




Mangan BJ *et al*, Low loss (1.7 dB/km) hollow core photonic bandgap fiber. OFC 2004, PDP 24

An important finding in 2005: Surface scattering loss (SSL)

PCF Cladding

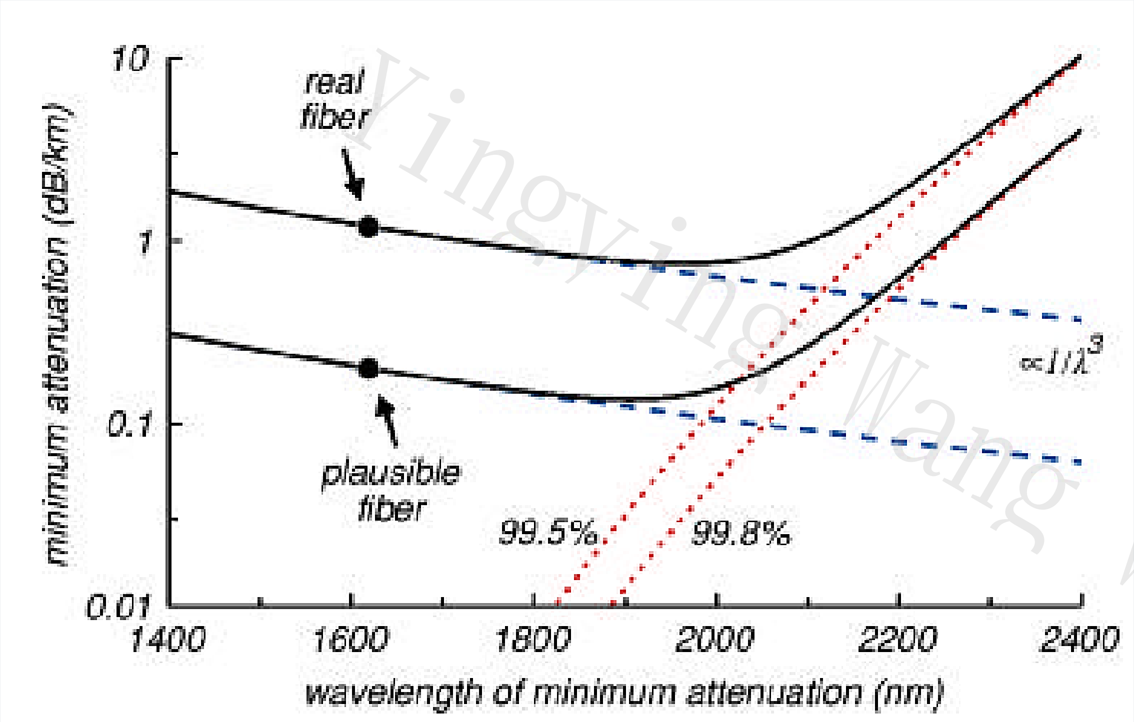


Phase-matching across interfaces is not strictly preserved!

Roberts, P. J., Couny, F., Sabert, H., Mangan, B. J., Williams, D. P., Farr, L., Mason, M. W., Tomlinson, A., Birks, T. A., Knight, J. C. & Russell, P. St. J. Ultimate low loss of hollow-core photonic crystal fibres. Opt. Express 13, 236-244 (2005).

History of HCF development

◆ **Surface Scattering Loss: Fundamental Limit**



Possible Solution?

2 µm wavelength?

37 Cell?

Structure optimization?

Key Issues

Surface Scattering Loss

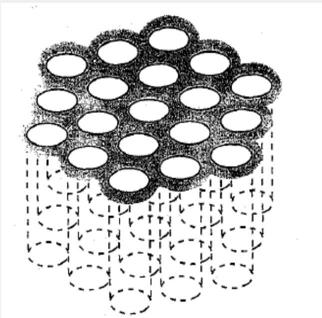
Surface mode

Only 99.8% of light in air

Roberts, P. J., Couny, F., Sabert, H., Mangan, B. J., Williams, D. P., Farr, L., Mason, M. W., Tomlinson, A., Birks, T. A., Knight, J. C. & Russell, P. St. J. Ultimate low loss of hollow-core photonic crystal fibres. Opt. Express 13, 236-244 (2005).

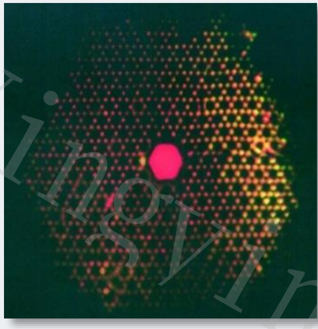
History of HCF development

1995



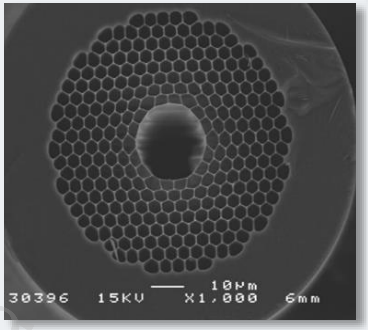
Out-of-plane photonic bandgap guidance prediction

1999



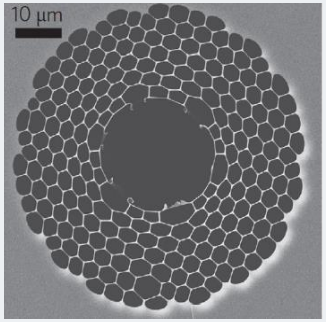
1st HC-PBGF

2004



1.7 dB/km,
20 nm bandwidth

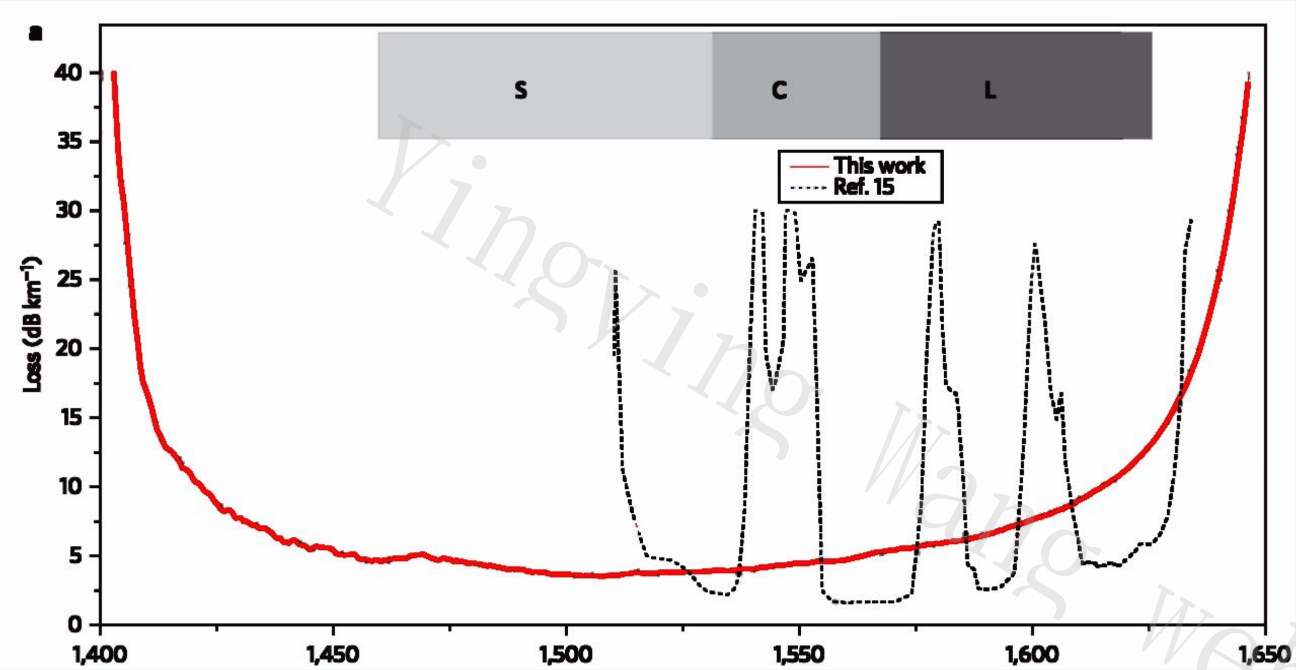
2013

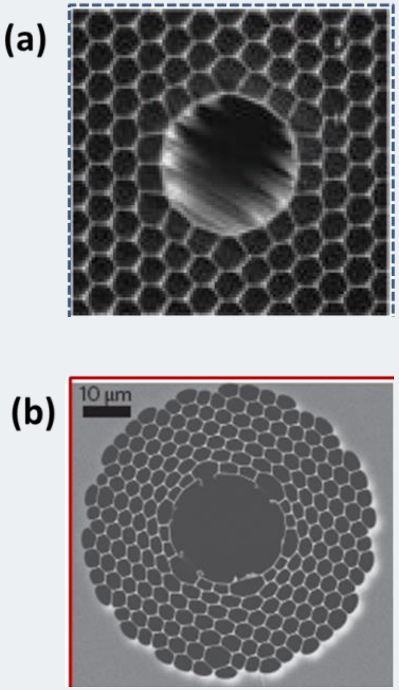


3.5 dB/km,
160 nm bandwidth

Poletti, Towards high-capacity fibre-optic communications at the speed of light in vacuum. Nature Photon. 279–284 (2013).

History of HCF development

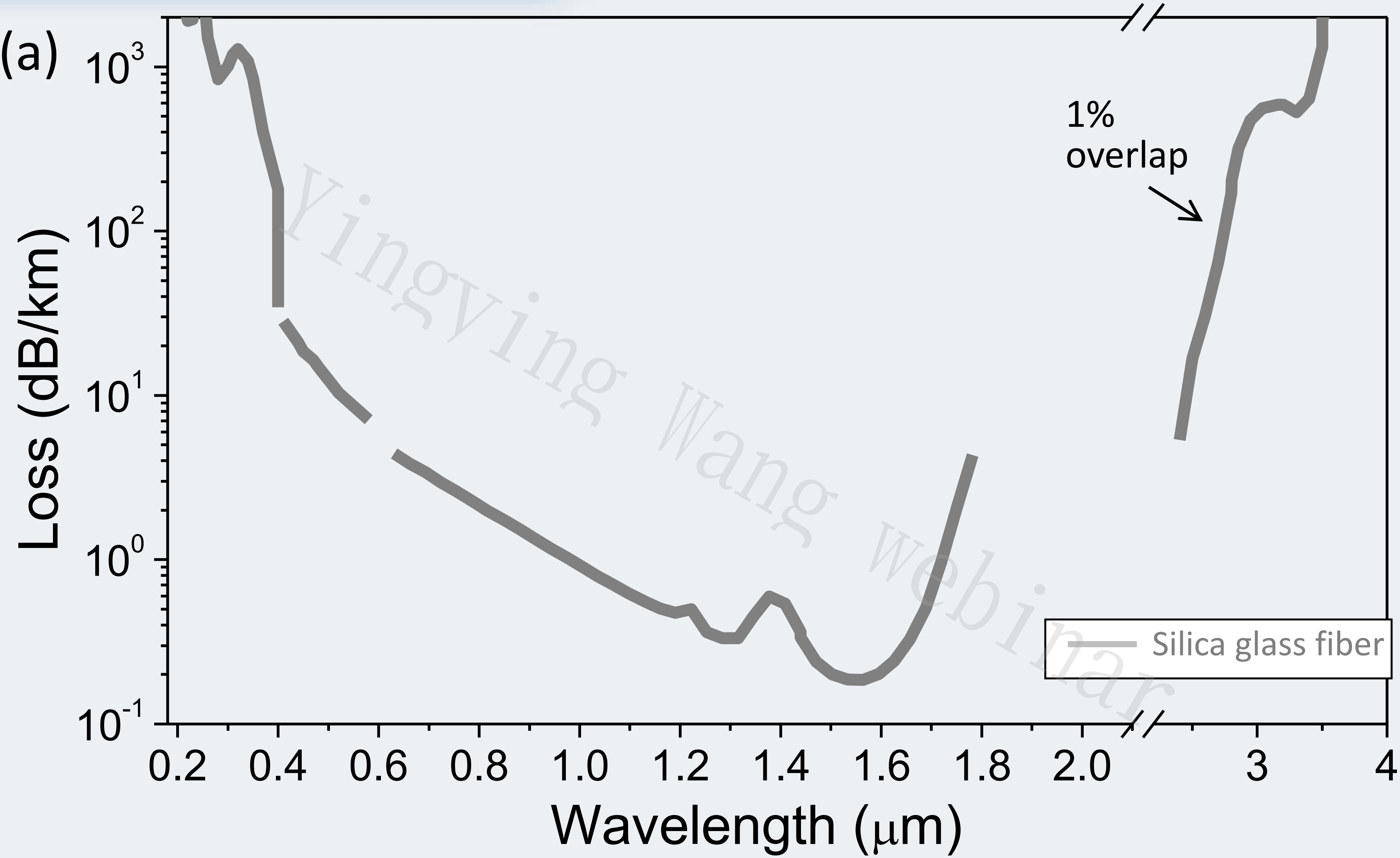




2004	1.7dB/km@1560nm	<20nm (2.5THz)
2013	3.5dB/km@1550nm	160nm (32THz)

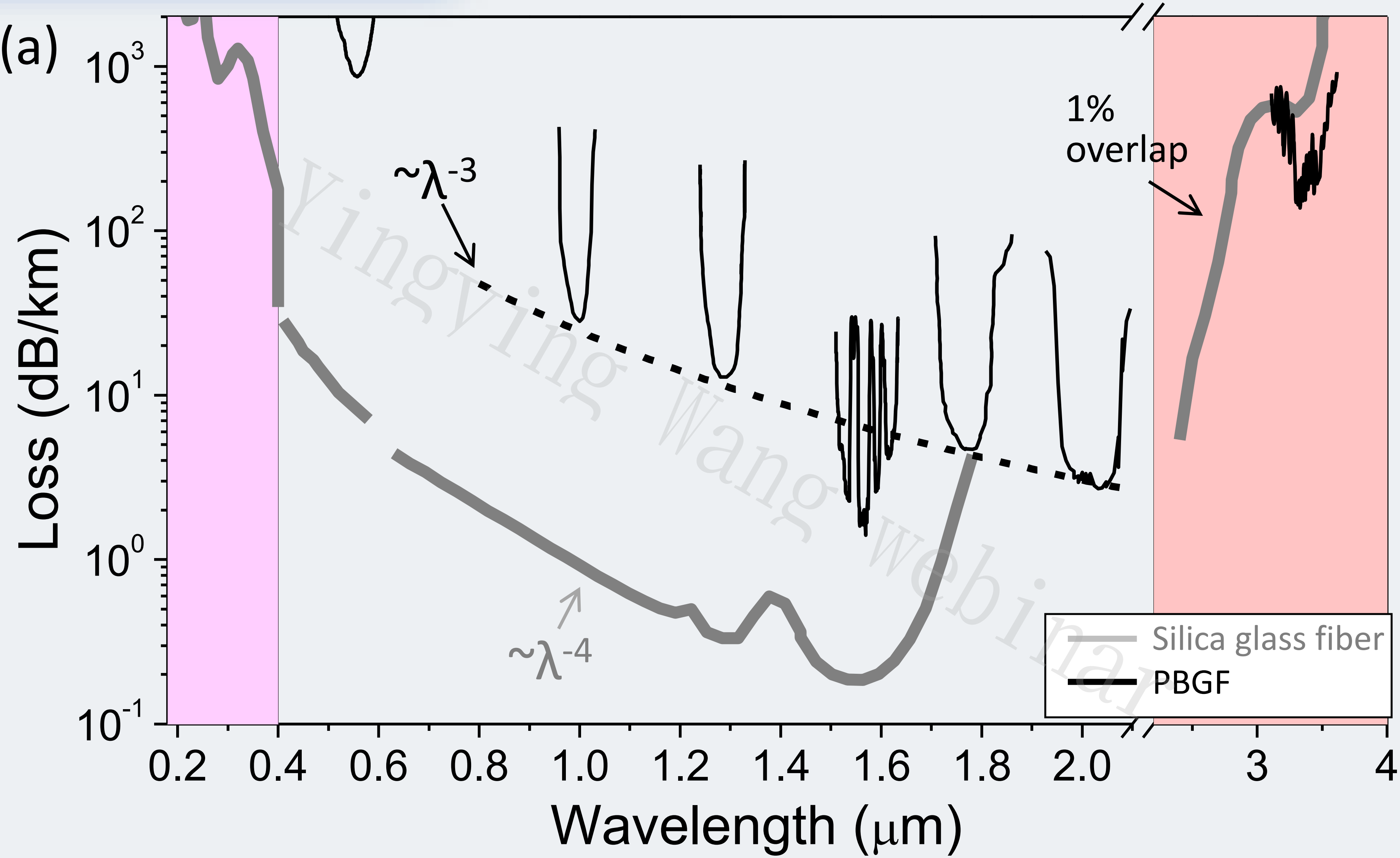
1.Mangan, B., Farr, L., Langford Optical Fiber Communication Conference, PD24 (Los Angeles, CA, USA, 2004).
2.Poletti, Towards high-capacity fibre-optic communications at the speed of light in vacuum. Nature Photon. 279–284 (2013).

Loss record of silica glass fiber



G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001.
I. A. Bufetov et al, Fibers, 2018, 6, 39;

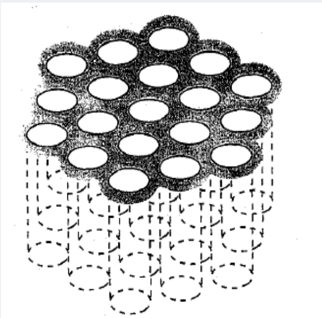
Loss achieved in PBGF



G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al*
OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014;

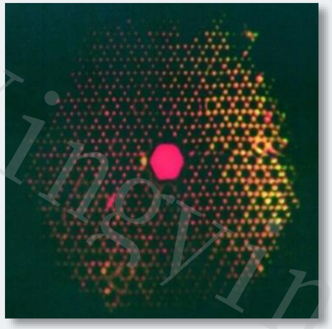
History of HCF development

1995



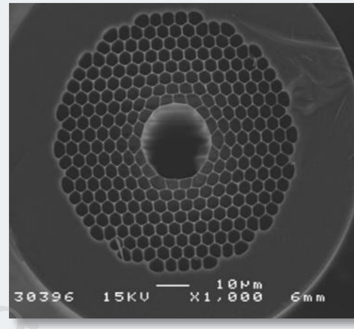
Out-of-plane photonic bandgap guidance prediction

1999



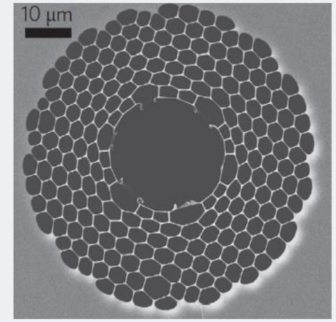
1st HC-PBGF

2004



1.7 dB/km,
20 nm bandwidth

2013



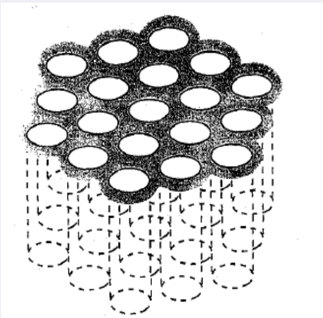
3.5 dB/km,
160 nm bandwidth

Future???

Little space for further optimization

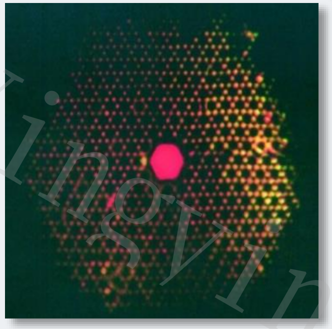
History of HCF development

1995



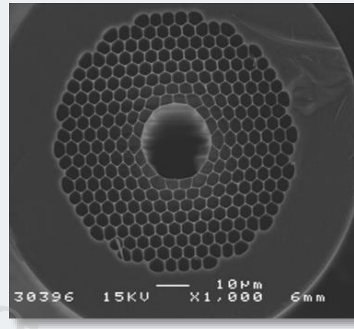
Out-of-plane photonic bandgap guidance prediction

1999



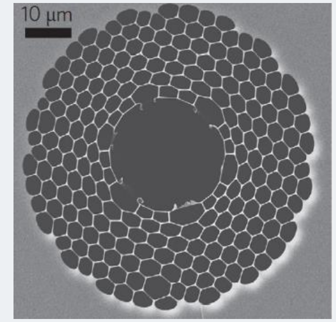
1st HC-PBGF

2004



1.7 dB/km,
20 nm bandwidth

2013

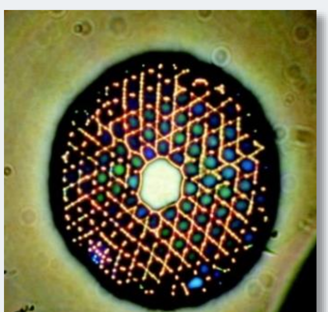


3.5 dB/km,
160 nm bandwidth

Future???

Little space for further optimization

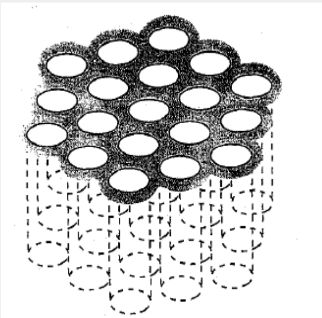
2002



1st Kagome type HCF

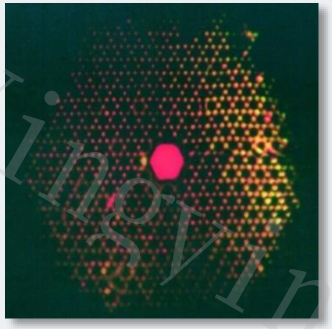
History of HCF development

1995



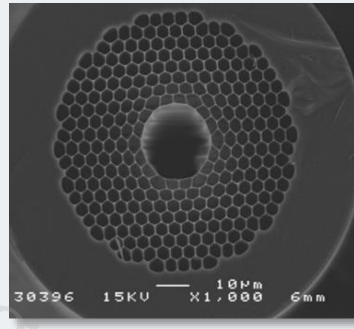
Out-of-plane photonic bandgap guidance prediction

1999



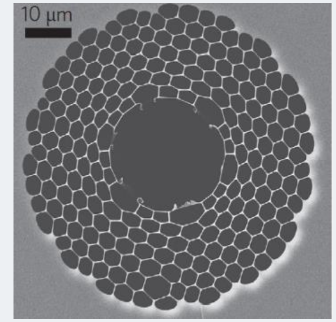
1st HC-PBGF

2004



1.7 dB/km,
20 nm bandwidth

2013

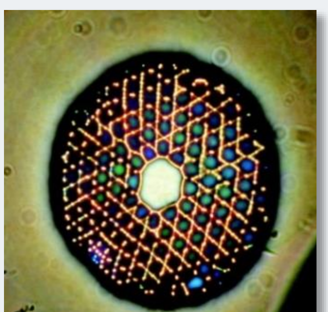


3.5 dB/km,
160 nm bandwidth

Future???

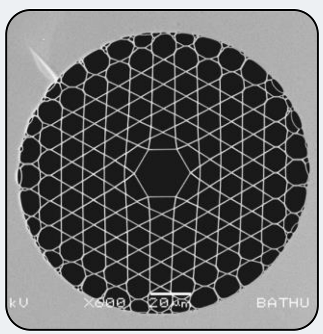
Little space for further optimization

2002



1st Kagome type HCF

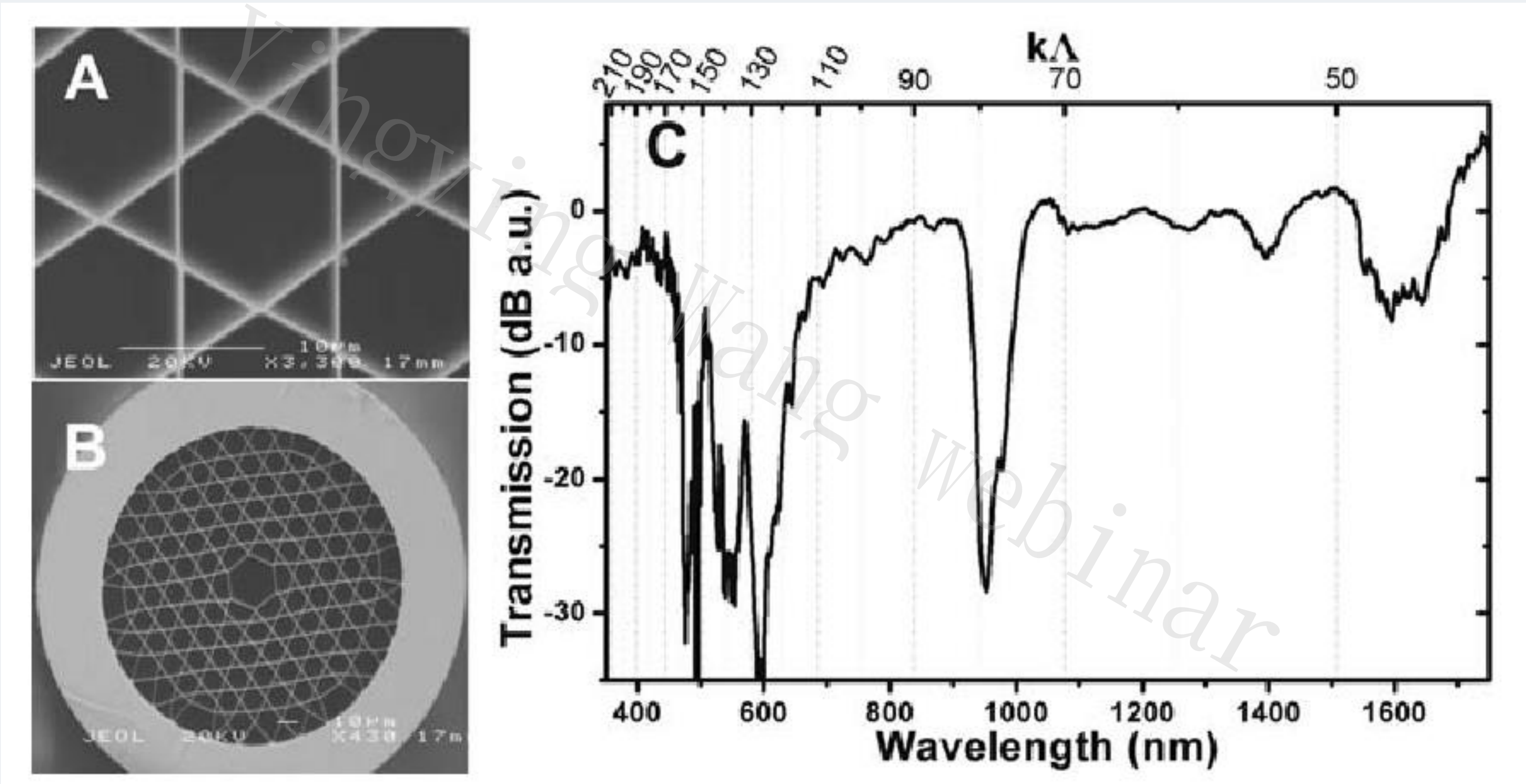
2005



Large pitch Kagome

Kagome HCF in 2005

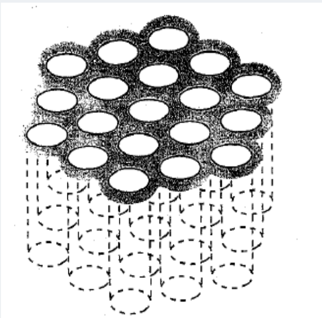
- Broadband guidance
- High loss (~1 dB/m)



F. Couny, *et al.*, *Generation and photonic guidance of multi-octave optical-frequency combs.* Science, 2007. **318**: p. 1118-1121.

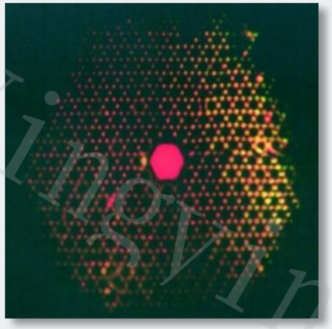
History of HCF development

1995



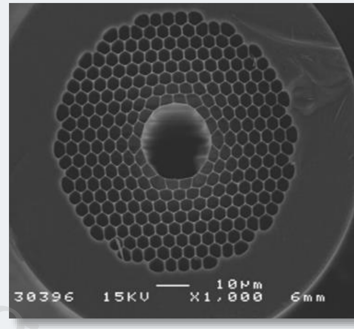
Out-of-plane photonic bandgap guidance prediction

1999



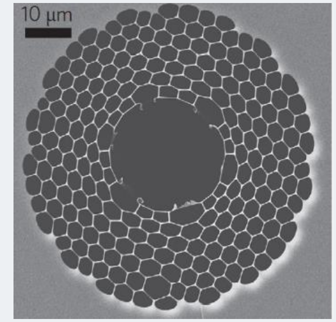
1st HC-PBGF

2004



1.7 dB/km,
20 nm bandwidth

2013

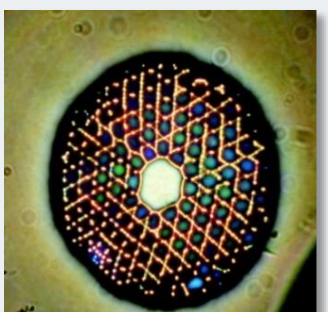


3.5 dB/km,
160 nm bandwidth

Future???

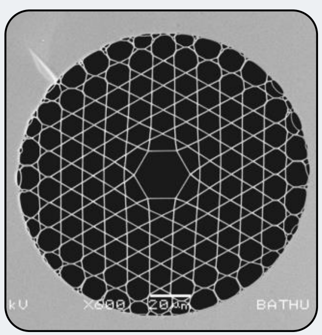
Little space for further optimization

2002



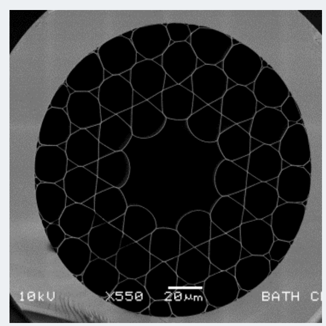
1st Kagome type HC-ARF

2005



Large pitch Kagome

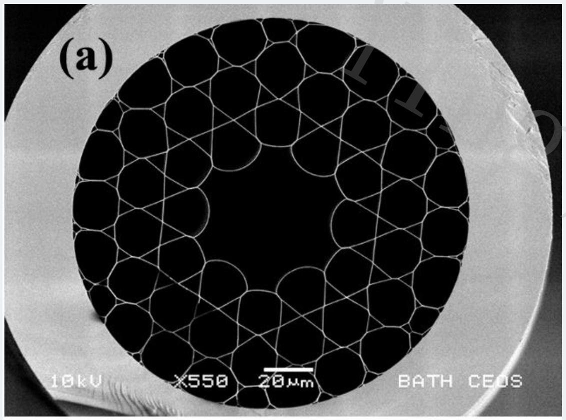
2010

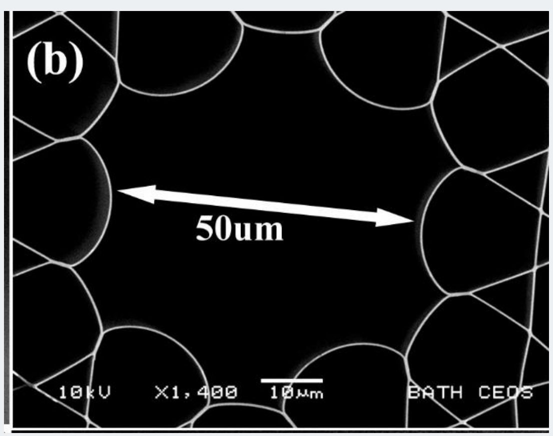


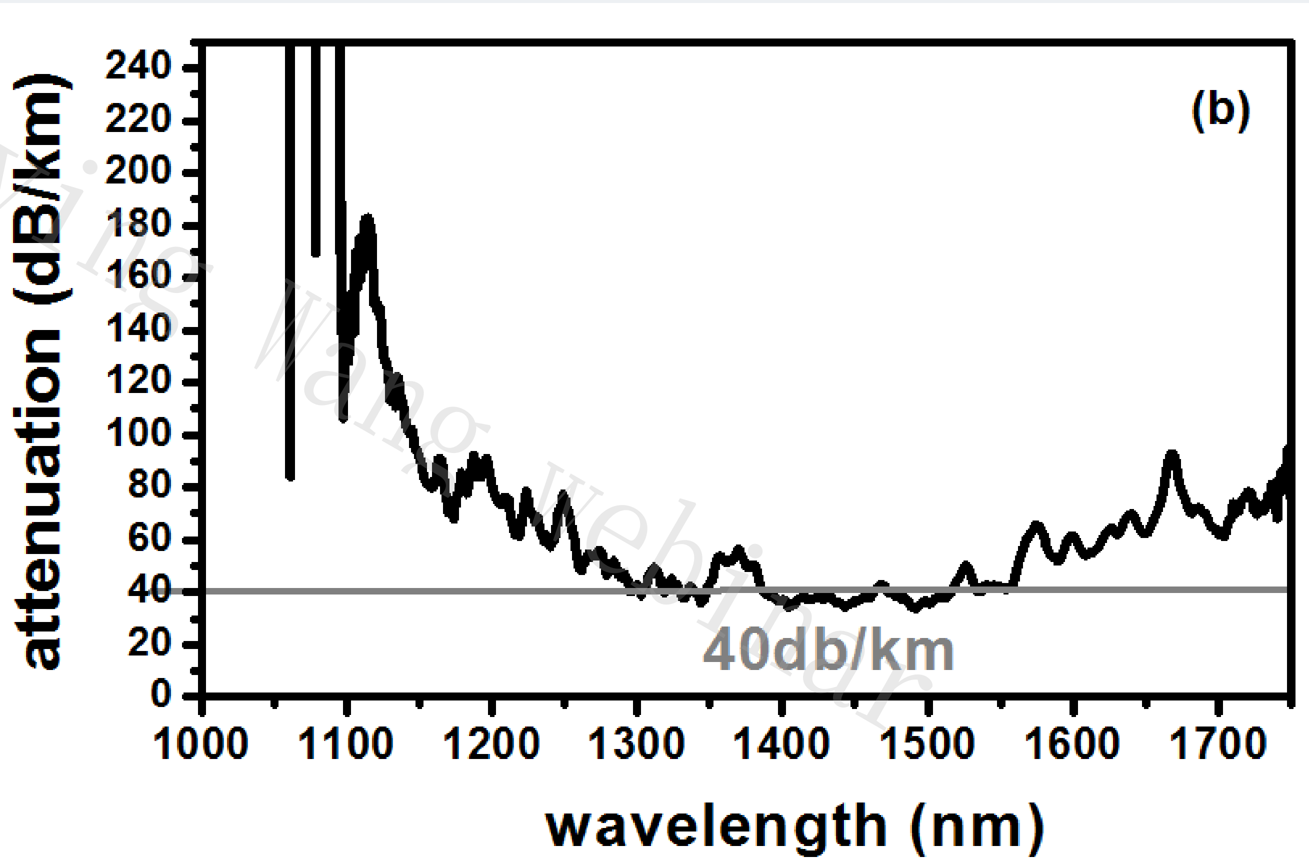
Hypocycloid-Core,
40 dB/km

Hypocycloid core Kagome fiber

- Broadband guidance
- Low loss (~40 dB/km)



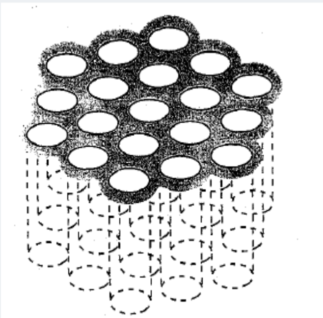




1. Wang, Y. Y et al in Conference on Lasers and Electro-Optics (CLEO, 2010), PDP paper CPDB4.
2. Wang, Y. Y et al . Low loss broadband transmission in hypocycloid-core Kagome hollow-core photonic crystal fiber. *Opt. Lett.* **36,** 669 (2011).
3. Wang Y. Y. et al, Design and fabrication of hollow-core photonic crystal fibers for high-power ultrashort pulse transportation and pulse compression" Opt. Lett. 37 3111-3113 (2012)

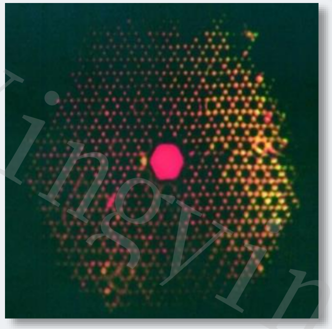
History of HCF development

1995



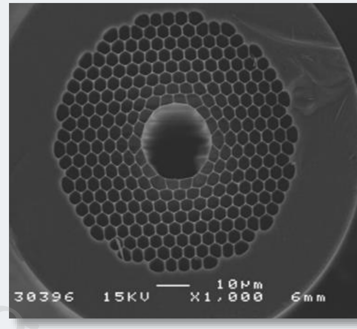
Out-of-plane photonic bandgap guidance prediction

1999



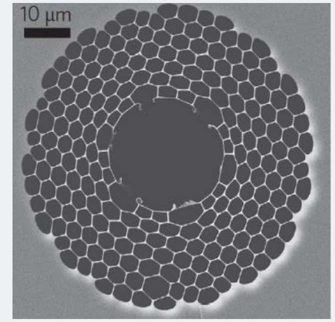
1st HC-PBGF

2004



1.7 dB/km,
20 nm bandwidth

2013

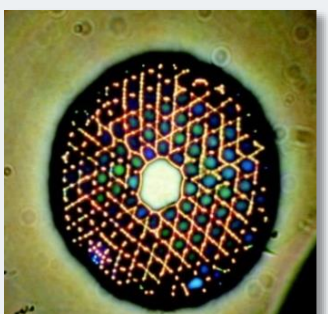


3.5 dB/km,
160 nm bandwidth

Future???

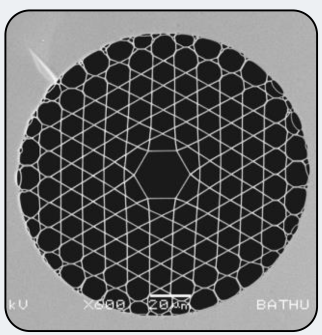
Little space for further optimization

2002



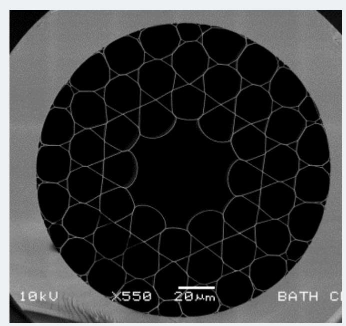
1st Kagome type HC-ARF

2005



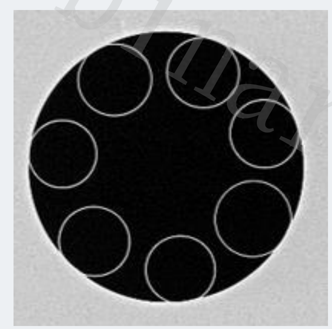
Large pitch Kagome

2010



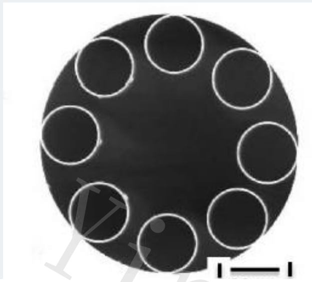
Hypocycloid-Core,
40 dB/km

2016

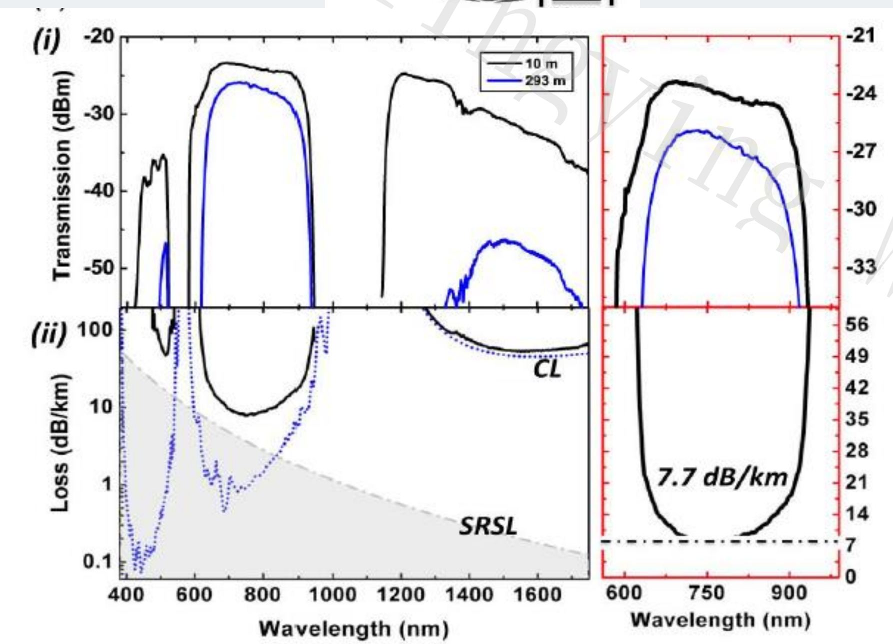


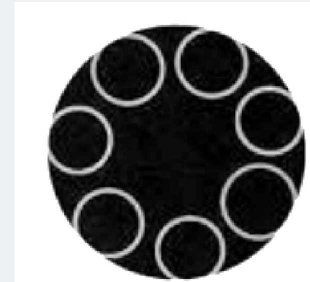
Nodeless single ring
7.7 dB/km

State of the art HC-Negative Curvature Fiber

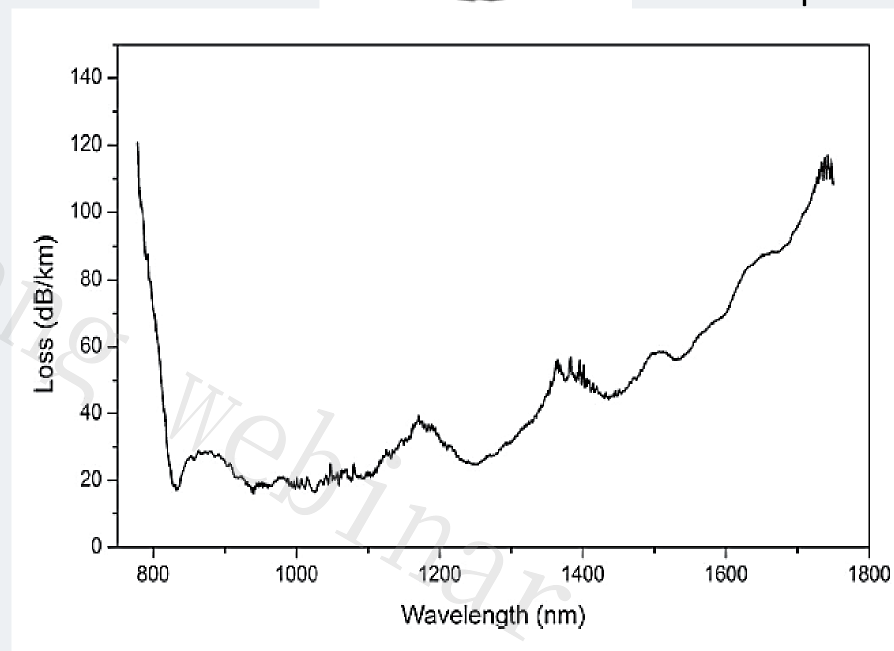


Core 55 µm





Core 38 µm

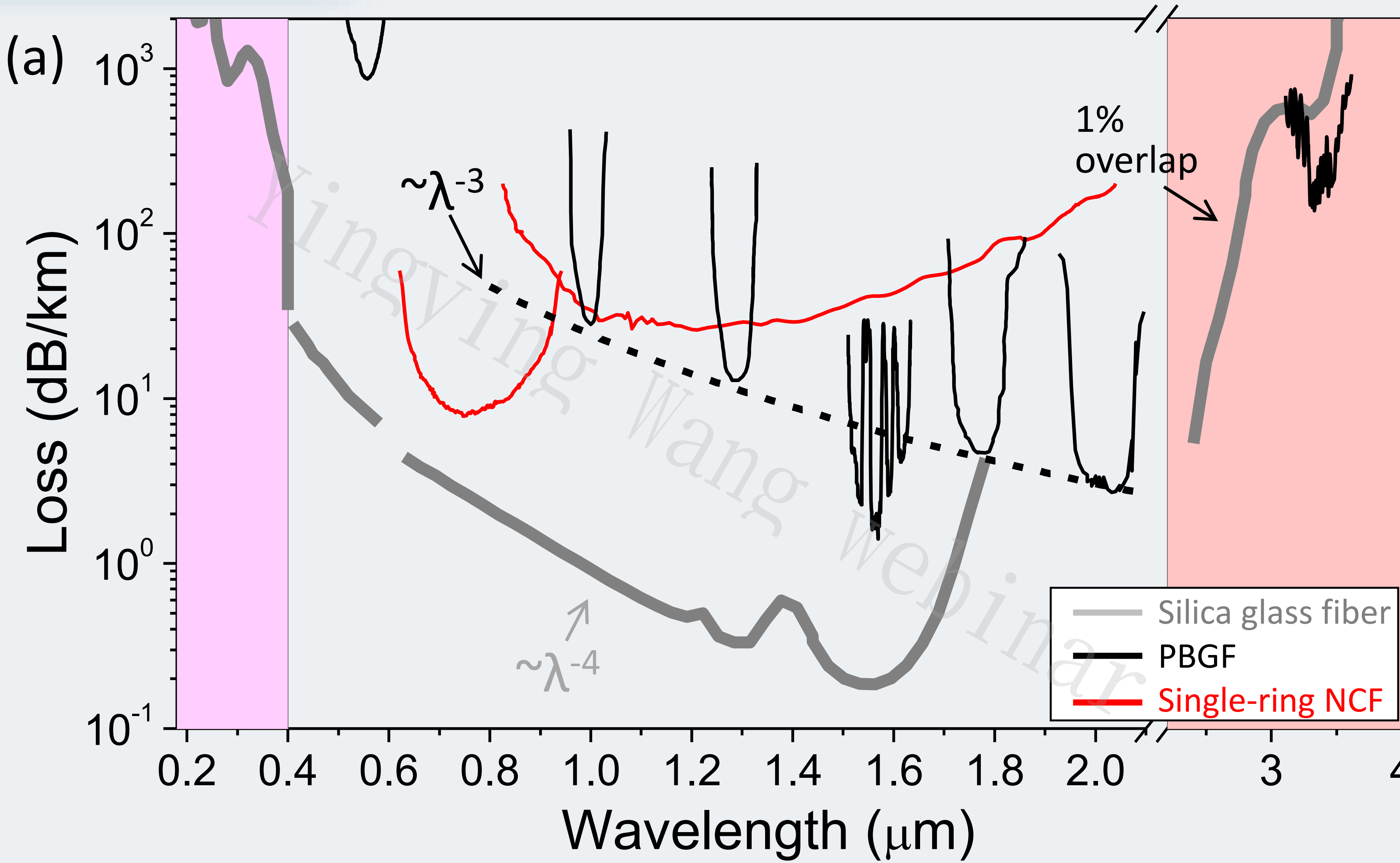


Core size/ wavelength	Transmission loss	Bending loss
55	7.7 dB/km @ 780 nm (r=30 cm)	50 dB/km @ r = 15 cm

Core size/ wavelength	Transmission loss	Bandwidth
38	20 dB/km @ 1 µm	> 1000 nm, < 100 dB/km

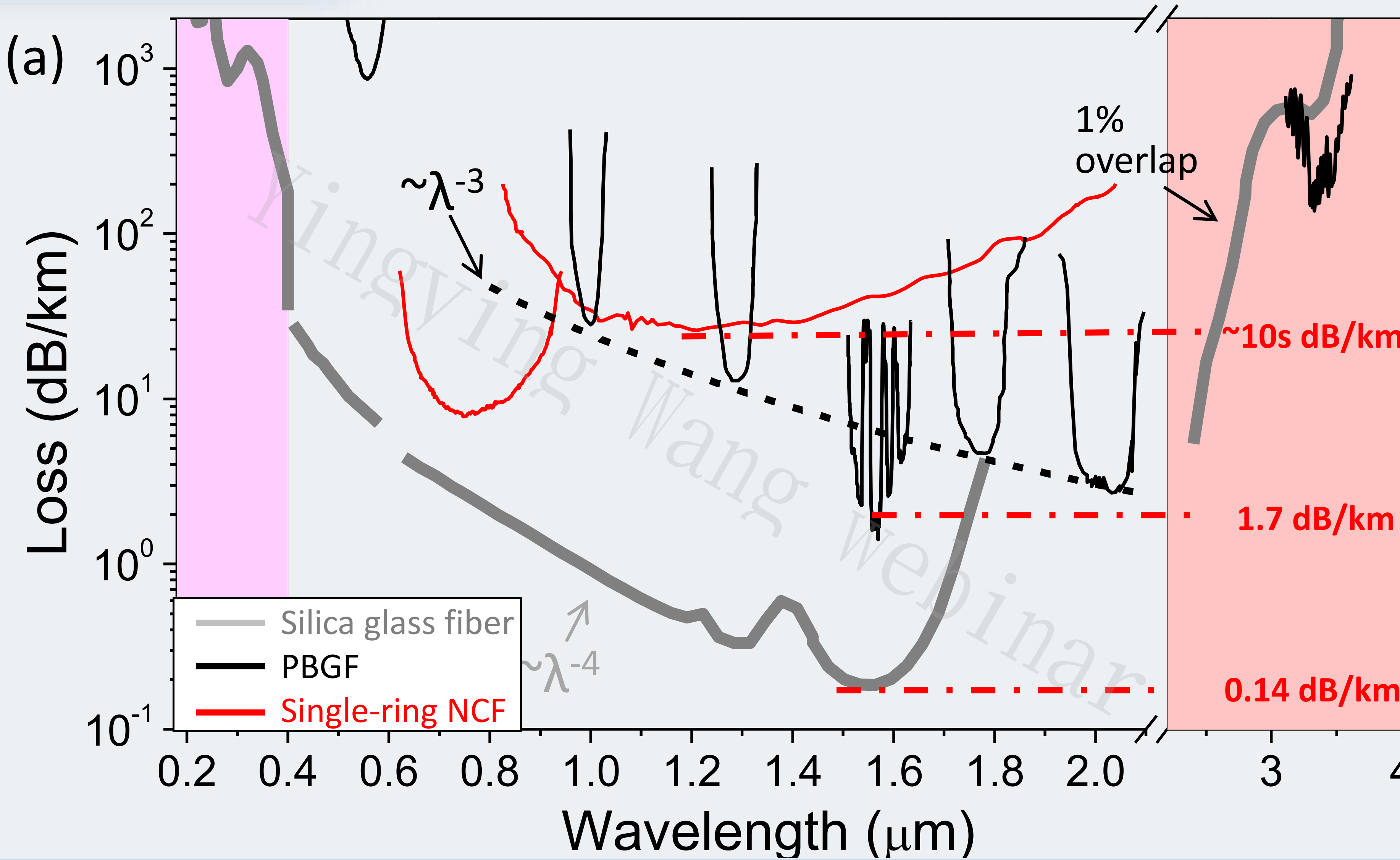
1.Debord, B. Ultralow transmission loss in inhibited-coupling guiding hollow fibers. Optica 4, 209–217 (2017).
2.Hayes, J. R., Antiresonant Hollow Core Fiber With an Octave Spanning Bandwidth for Short Haul Data Communications .JLT 35, 437-442 (2017)

Loss achieved in HC-NCF



G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al* OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017)

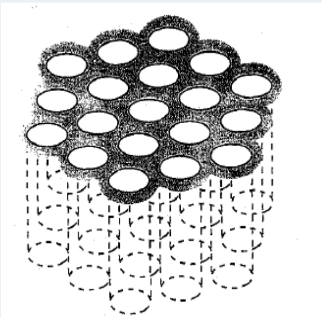
Loss achieved in HC-NCF



G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al* OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017)

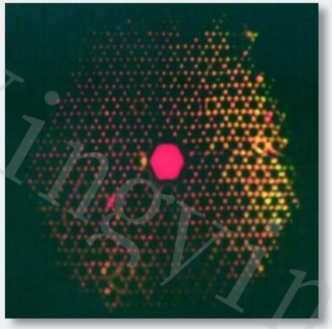
History of HCF development

1995



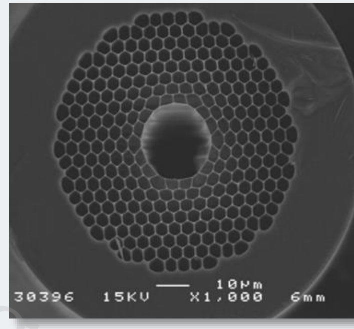
Out-of-plane photonic bandgap guidance prediction

1999



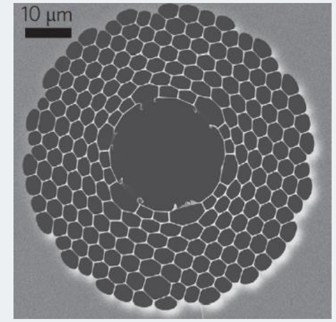
1st HC-PBGF

2004



1.7 dB/km,
20 nm bandwidth

2013

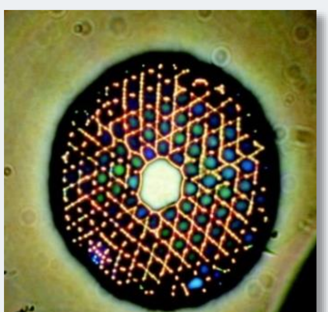


3.5 dB/km,
160 nm bandwidth

Future???

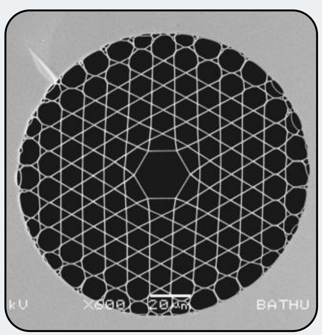
Little space for further optimization

2002



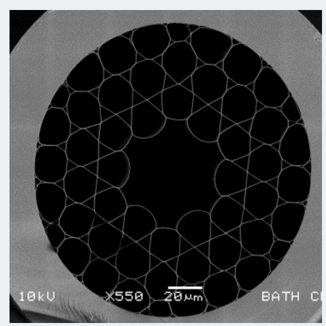
1st Kagome type HC-ARF

2005



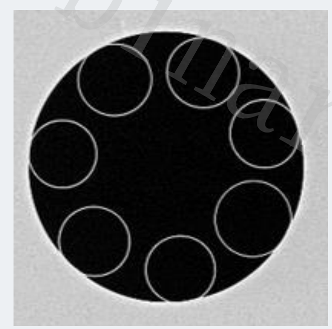
Large pitch Kagome

2010



Hypocycloid-Core, 40 dB/km

2016



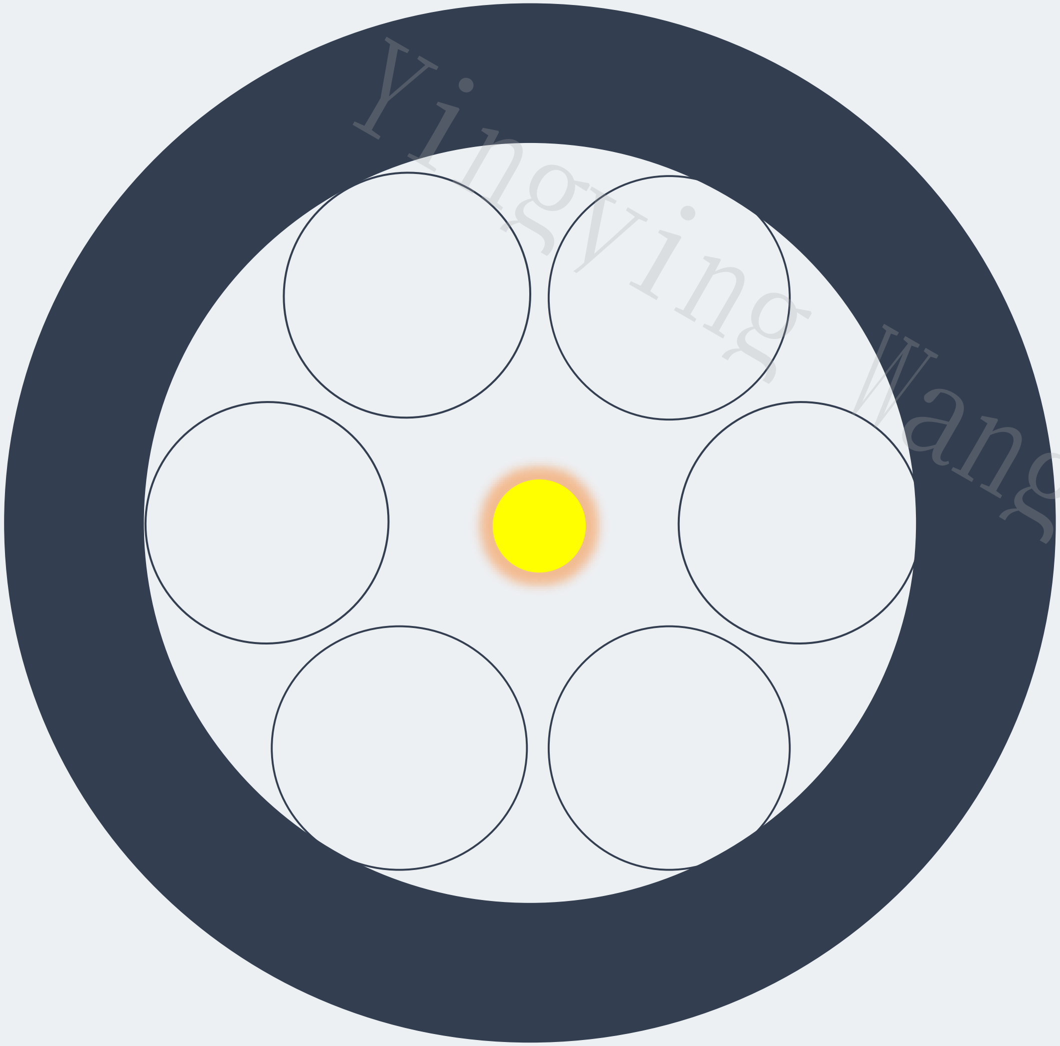
Nodeless single ring
7.7 dB/km

What's next?

1. **Background**
    1. *Motivation*
    2. *History of HCF development*
2. **HCF – understanding, design and fabrication**
    1. *How we understand*
    2. *Broadband HCF*
    3. *Ultralow loss HCF*
3. **HCF applications**
    1. *Optical communications*
    2. *Ultrafast optics: delivery and gas nonlinearity*
    3. *Sensing and biophotonics*
4. **Conclusion**

Intuitive picture of NCF

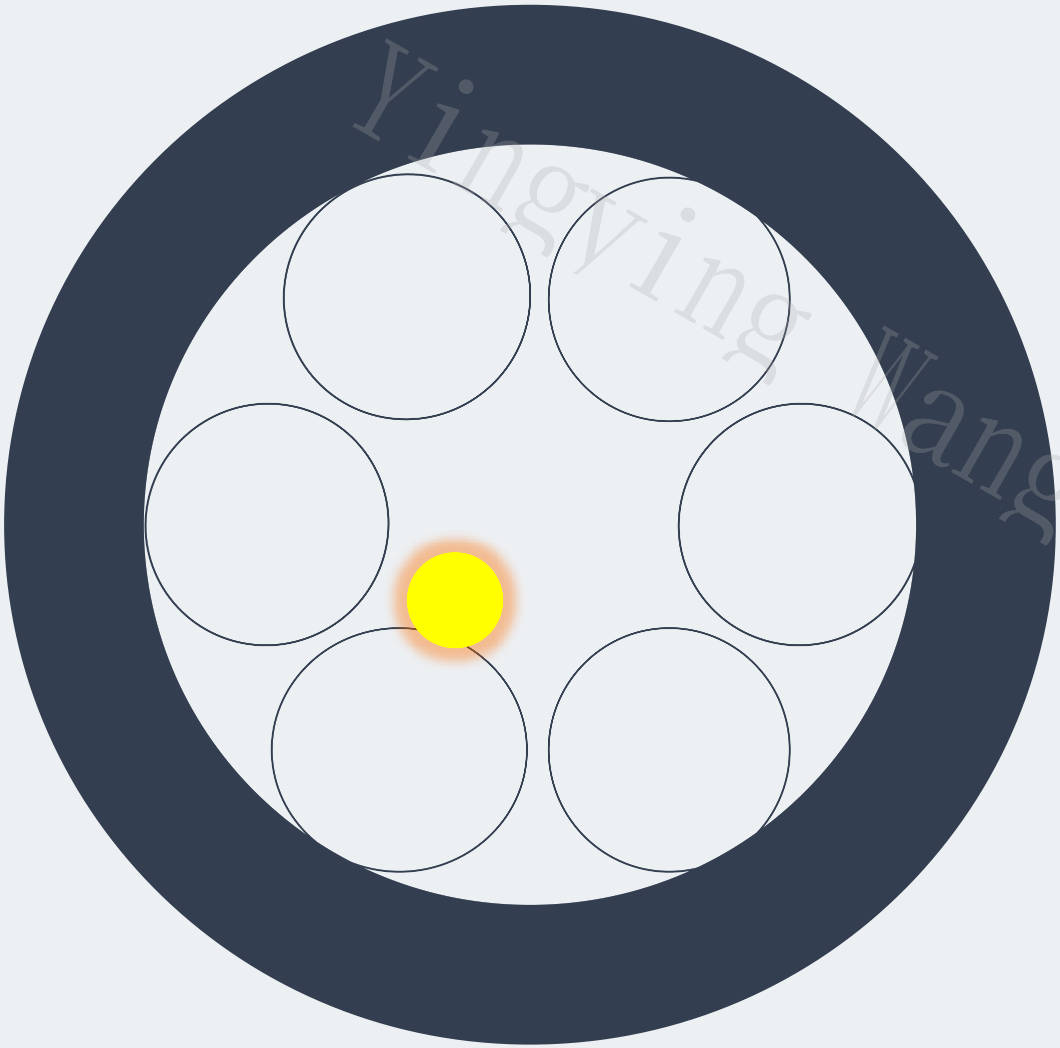
How to quantitatively elucidate light guidance in NCF?



Yingying Wang and Wei Ding, "Confinement loss in hollow-core negative curvature fiber: A multi-layered model," Opt. Express 25, 33122 (2017)

Intuitive picture of NCF

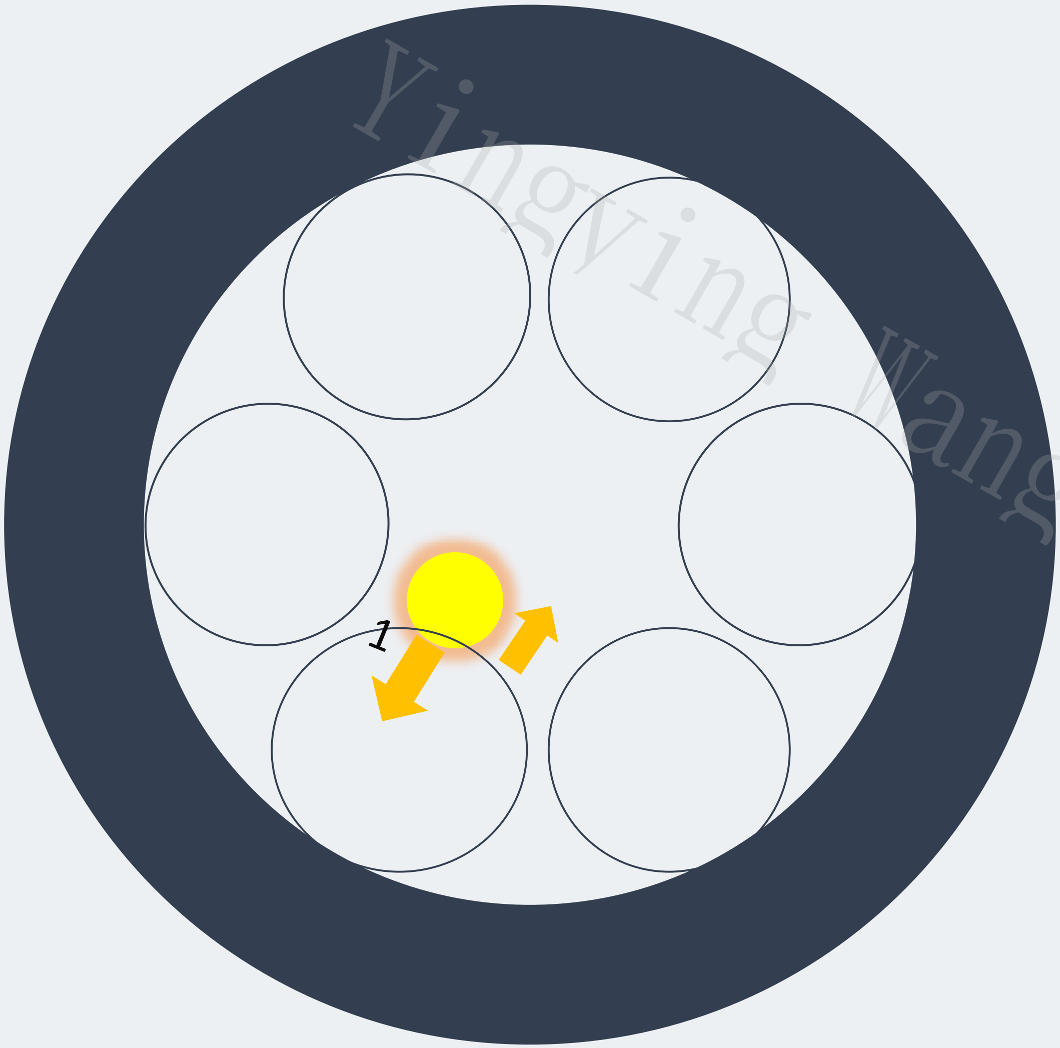
How to quantitatively elucidate light guidance in NCF?



Yingying Wang and Wei Ding, "Confinement loss in hollow-core negative curvature fiber: A multi-layered model," Opt. Express 25, 33122 (2017)

Intuitive picture of NCF

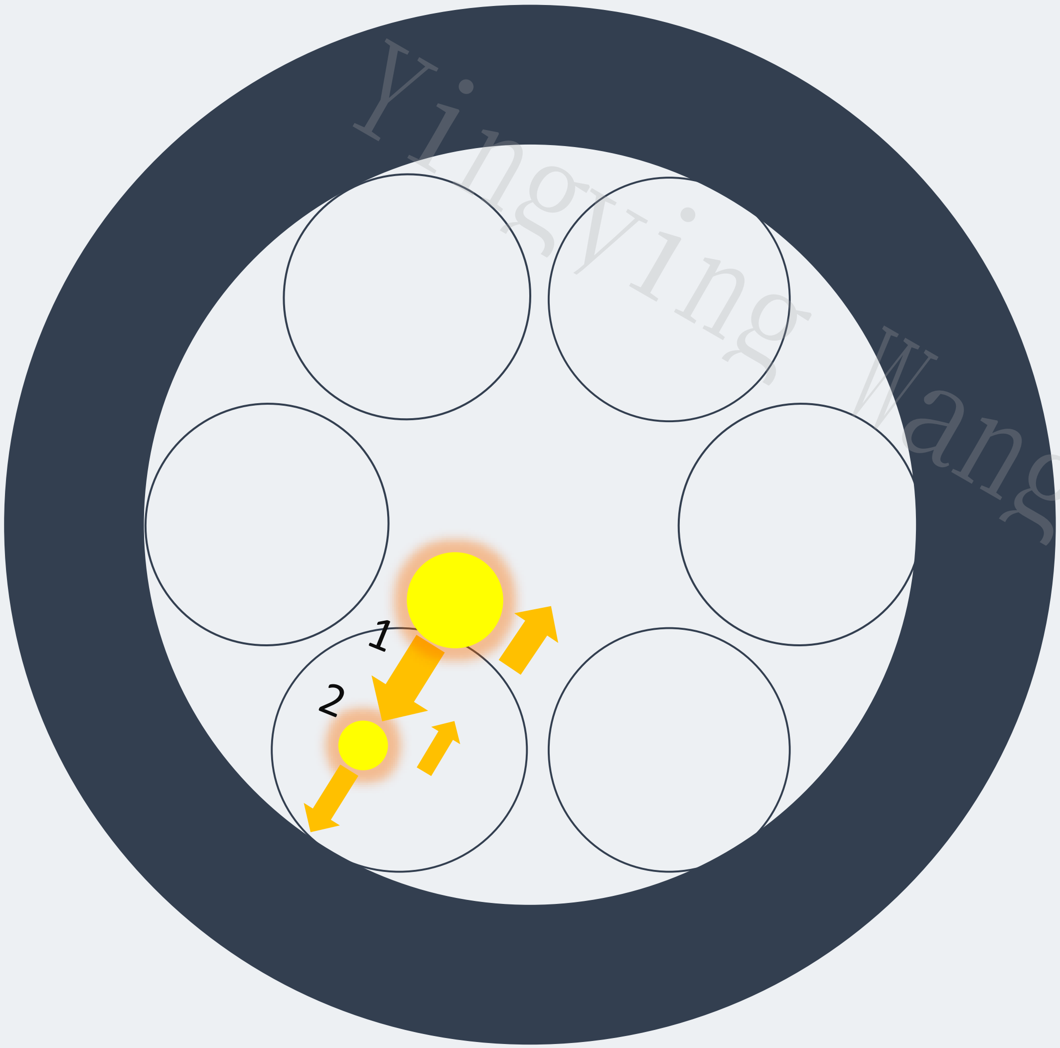
How to quantitatively elucidate light guidance in NCF?



Yingying Wang and Wei Ding, "Confinement loss in hollow-core negative curvature fiber: A multi-layered model," Opt. Express 25, 33122 (2017)

Intuitive picture of NCF

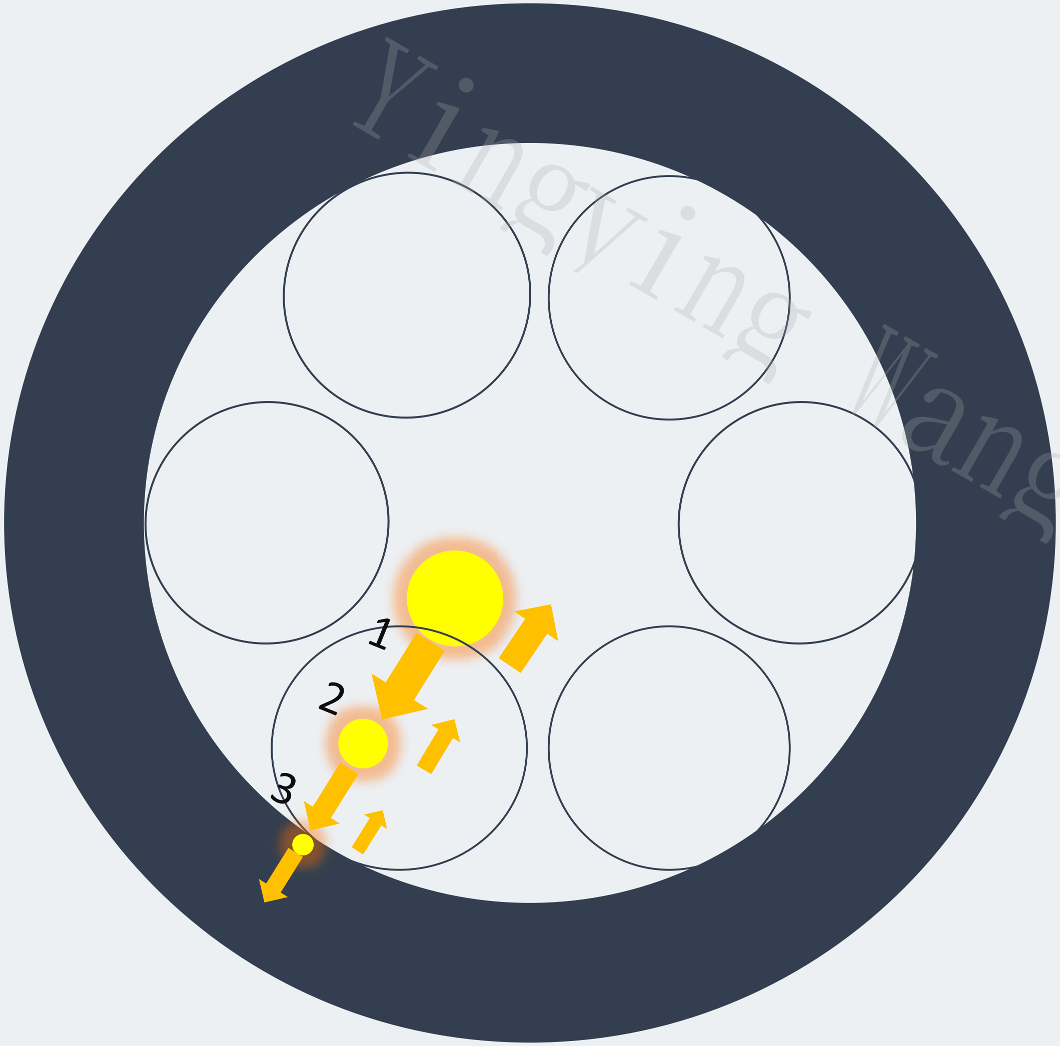
How to quantitatively elucidate light guidance in NCF?



Yingying Wang and Wei Ding, "Confinement loss in hollow-core negative curvature fiber: A multi-layered model," Opt. Express 25, 33122 (2017)

Intuitive picture of NCF

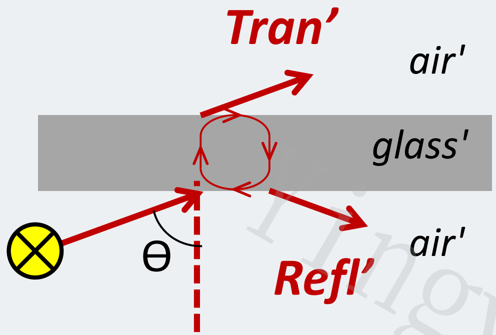
How to quantitatively elucidate light guidance in NCF?



Yingying Wang and Wei Ding, "Confinement loss in hollow-core negative curvature fiber: A multi-layered model," Opt. Express 25, 33122 (2017)

Guidance mechanism

① Near grazing incidence



θ⇑ ➡ *Tran’* ⇓, ⇒0 √

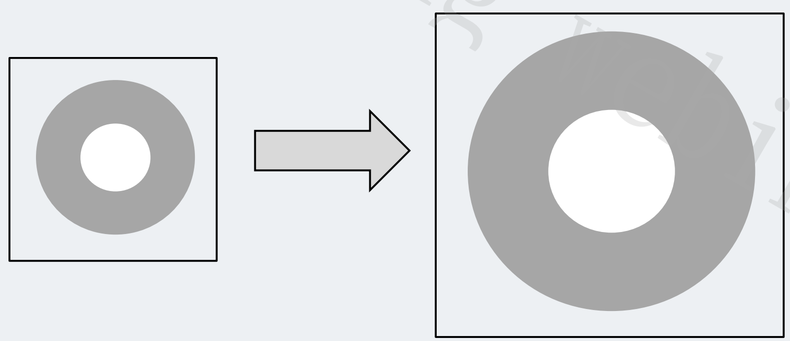
$$Tran' = \frac{(1-r'^2)^2}{(1-r'^2)^2 + 4r'^2 \sin^2(\delta/2)}$$

Grazing incidence

$$r' \to 1$$

Anti-resonance

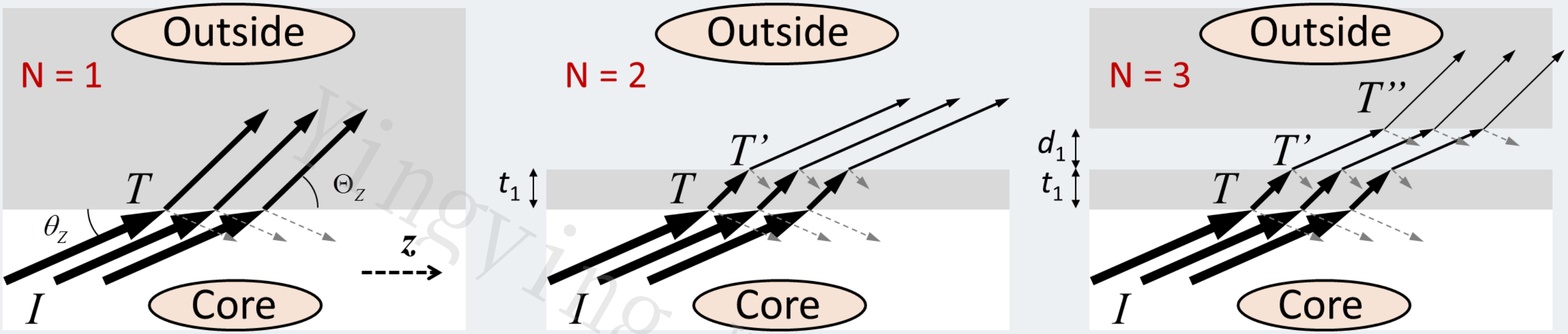
$$Tran' \approx \frac{(1-r'^2)^2}{4 \cdot \sin^2(\delta/2)}$$



Bigger core size => lower confinement loss ☺ => larger bending loss ☹

Yingying Wang and Wei Ding, "Confinement loss in hollow-core negative curvature fiber: A multi-layered model," Opt. Express 25, 33122 (2017)

② Cascaded Fresnel transmissions



$$\overline{T} \approx \frac{I}{2} \cdot \frac{4\sin(\theta_z)}{\sqrt{n^2-1}} \cdot (1+n^2)$$

$$\overline{T'} \approx \frac{I}{2} \cdot \left(\frac{4\sin\theta_z}{\sqrt{n^2-1}}\right)^2 \cdot (1+n^4)$$

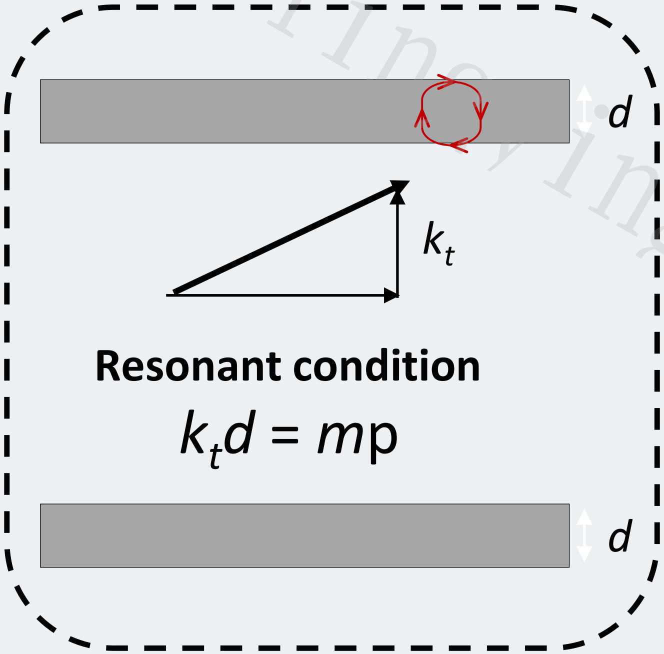
$$\overline{T''} \approx \frac{I}{2} \cdot \left(\frac{4\sin\theta_z}{\sqrt{n^2-1}}\right)^3 \cdot (1+n^6)$$

N⇑ ⇒ *Tran'* ⇓ √

Yingying Wang and Wei Ding, "Confinement loss in hollow-core negative curvature fiber: A multi-layered model," Opt. Express 25, 33122 (2017)

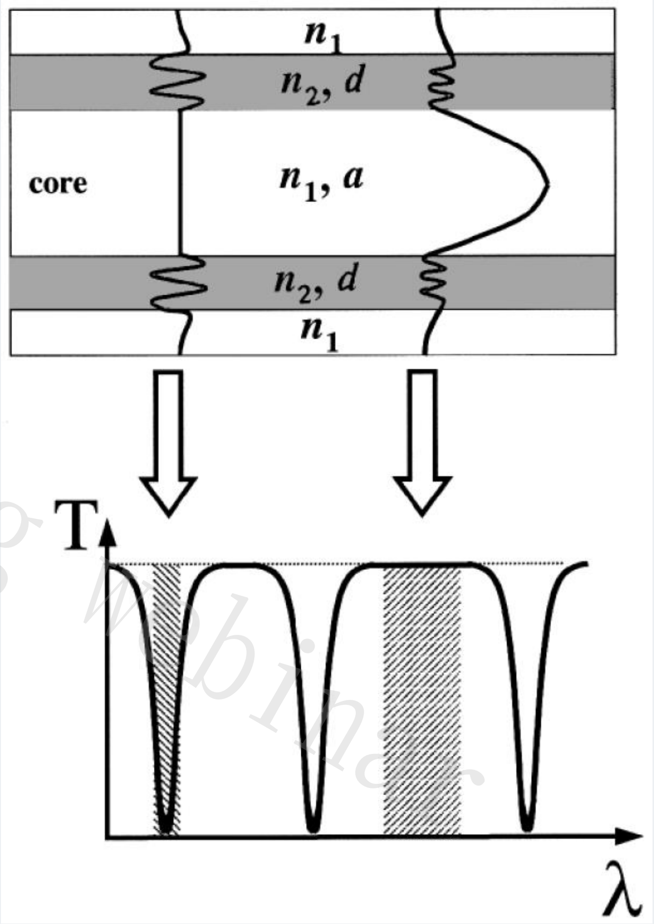
③ Multi-path interference (ARROW)

ARROW model



High-index layer Anti-resonance wavelengths

⇒Maximum transmission of the waveguide



High-index layer resonance wavelength ⇒Minimum transmission of the waveguide

N. M. Litchinitser, et al "Antiresonant reflecting photonic crystal optical waveguides" OL, 27(18),1592 (2002).
J. L Archambault, et al . Loss calculations for antiresonant waveguides. J. Light Technol. 11, 416–423 (1993).

Guidance mechanism

③ Multi-path interference (ARROW)

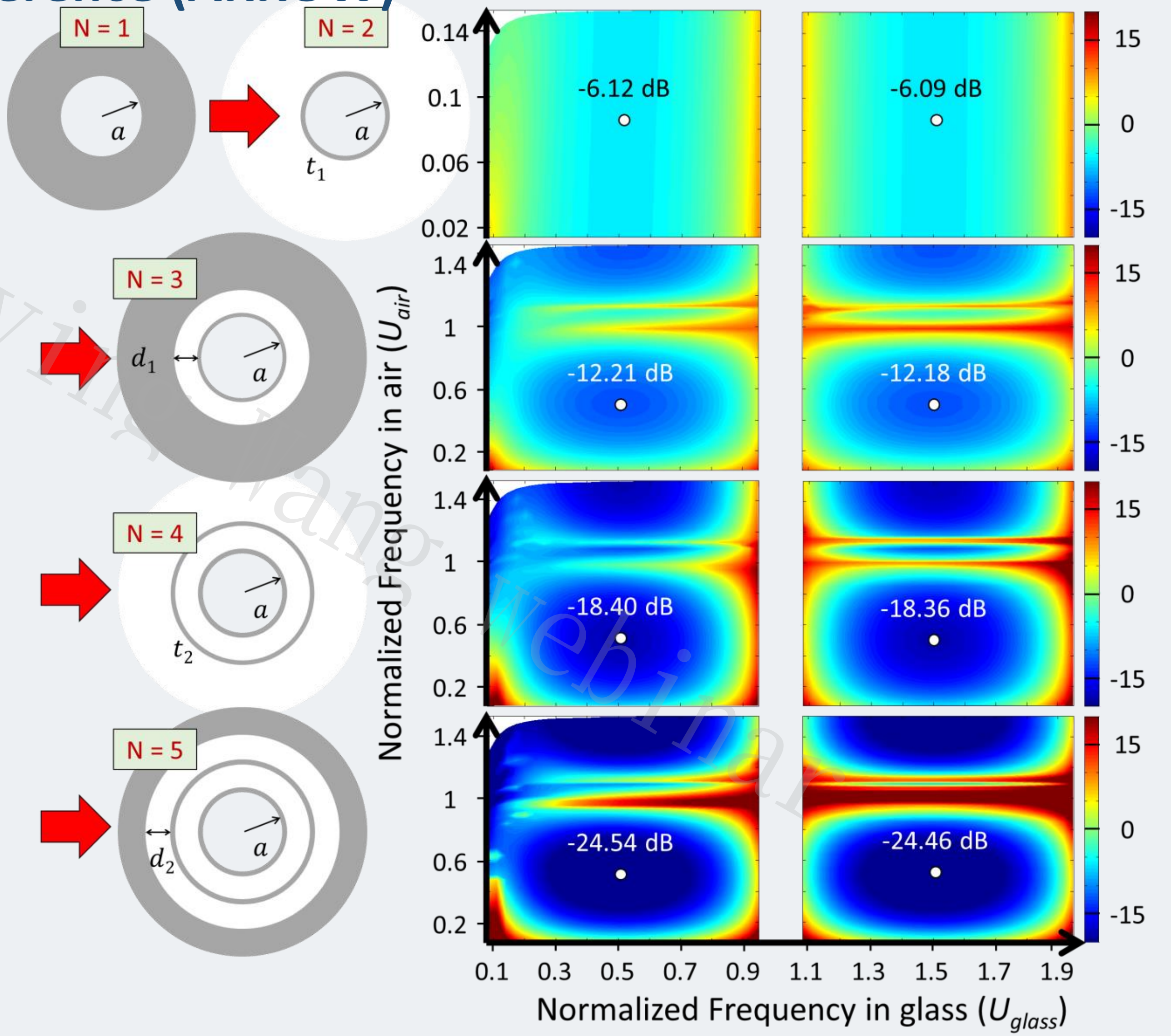
$$F = 2t\sqrt{n^2-1}/\lambda$$

$$U_{glass} = 2t_i\sqrt{n^2-\mathrm{Re}(n_{eff})^2}/\lambda$$

$$U_{air} = 2d_i\sqrt{1-\mathrm{Re}(n_{eff})^2}/\lambda$$

$$FOM\,(dB) = 10\cdot\log_{10}\left\{\frac{\alpha_{fiber}}{\alpha_{capillary}}\cdot\left(\frac{4\sin\theta_z}{\sqrt{n^2-1}}\right)^{-N+1}\cdot\frac{1+n^2}{1+n^{2N}}\right\}$$

$$\alpha_{capillary}[dB/m] = 8.69\left(\frac{u_{01}}{2\pi}\right)^2\frac{\lambda^2}{a^3}\cdot\frac{n^2+1}{2\sqrt{n^2-1}}$$

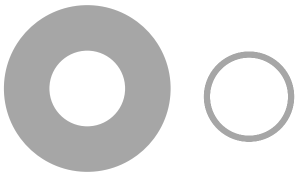


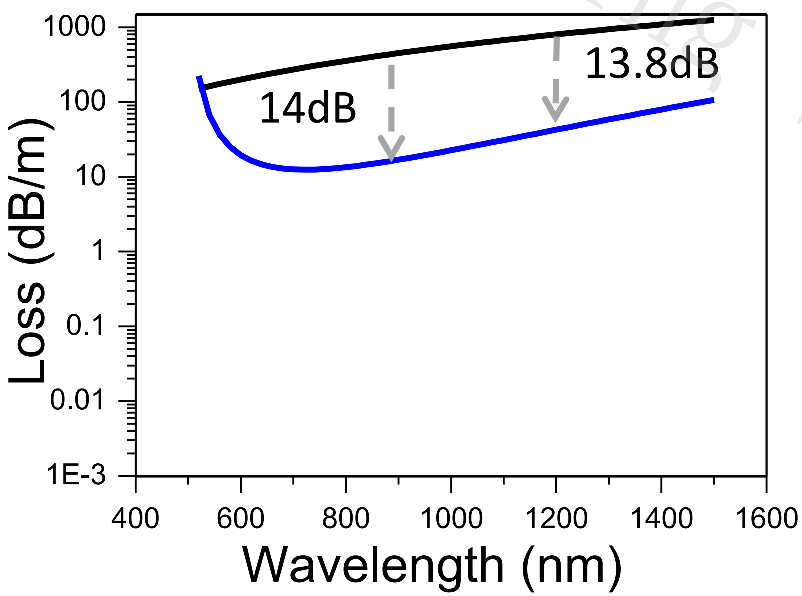
Yingying Wang and Wei Ding, "Confinement loss in hollow-core negative curvature fiber: A multi-layered model," Opt. Express 25, 33122 (2017)

Comparison of annular fiber and NCF

D = 30mm, t = 0.24mm, d = 10mm

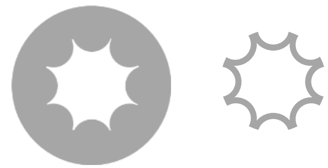
N=1 N=2

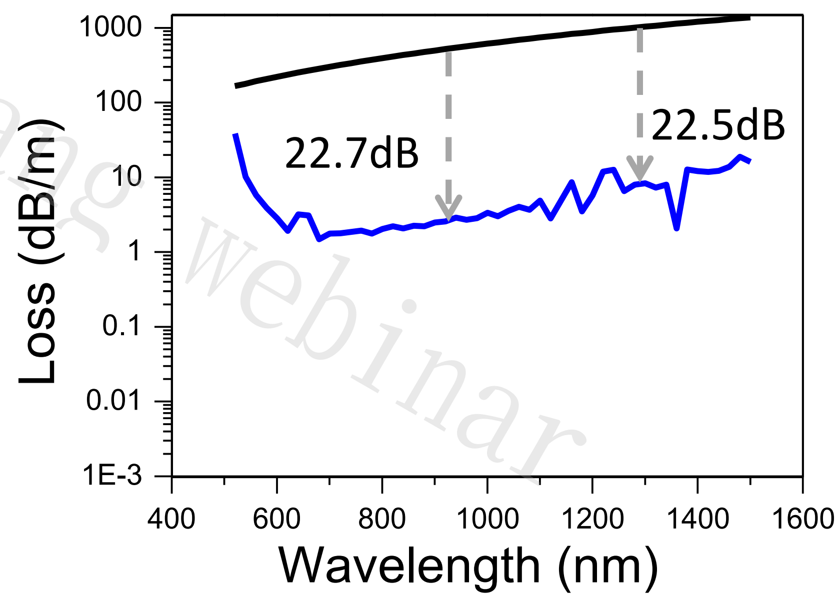




D = 28.66mm, t = 0.24mm, d = 16mm

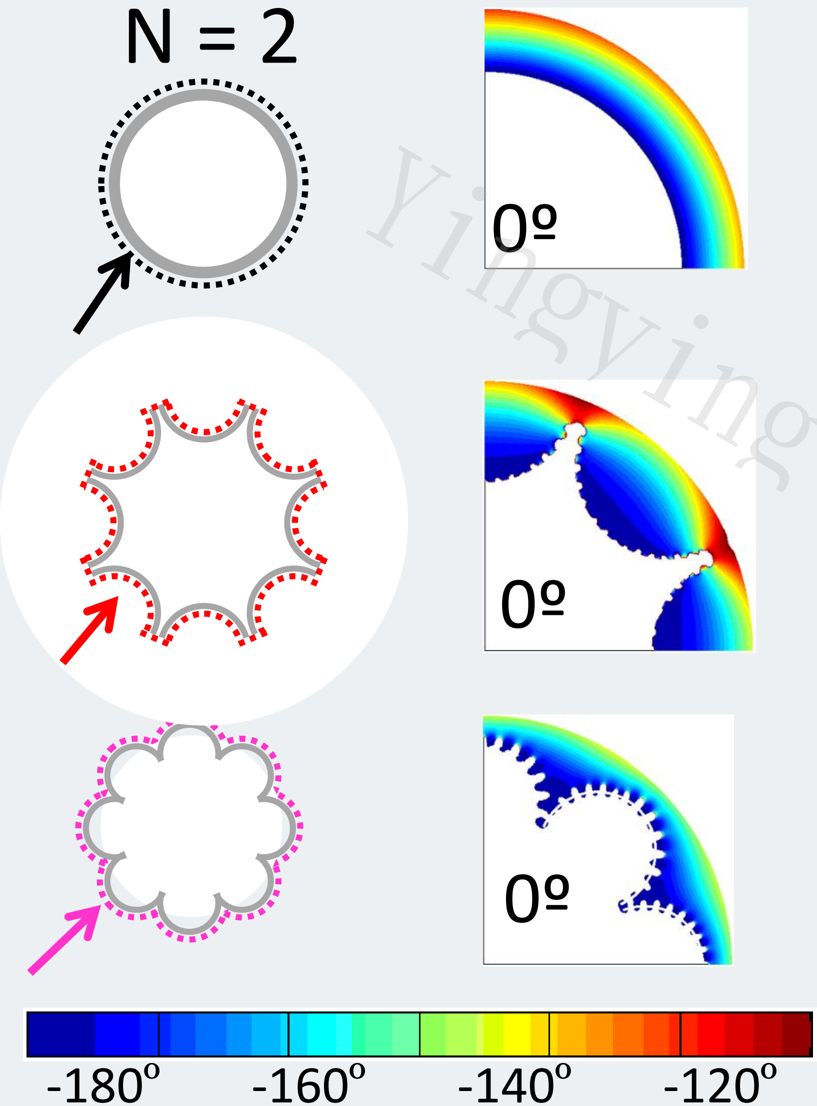
N=1 N=2

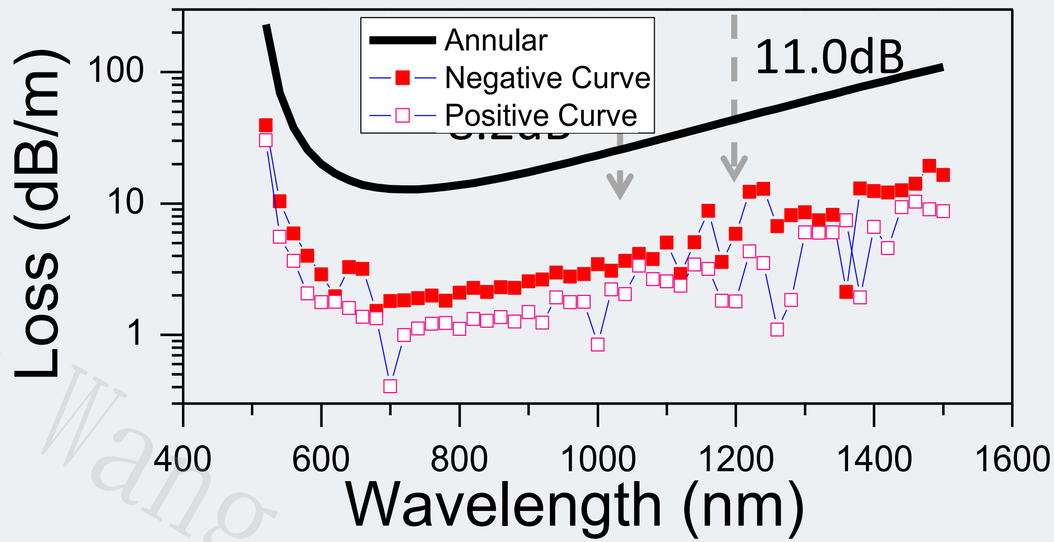




Yingying Wang and Wei Ding, "Confinement loss in hollow-core negative curvature fiber: A multi-layered model," Opt. Express 25, 33122 (2017)

④ Phase-dragging caused by negative curvature

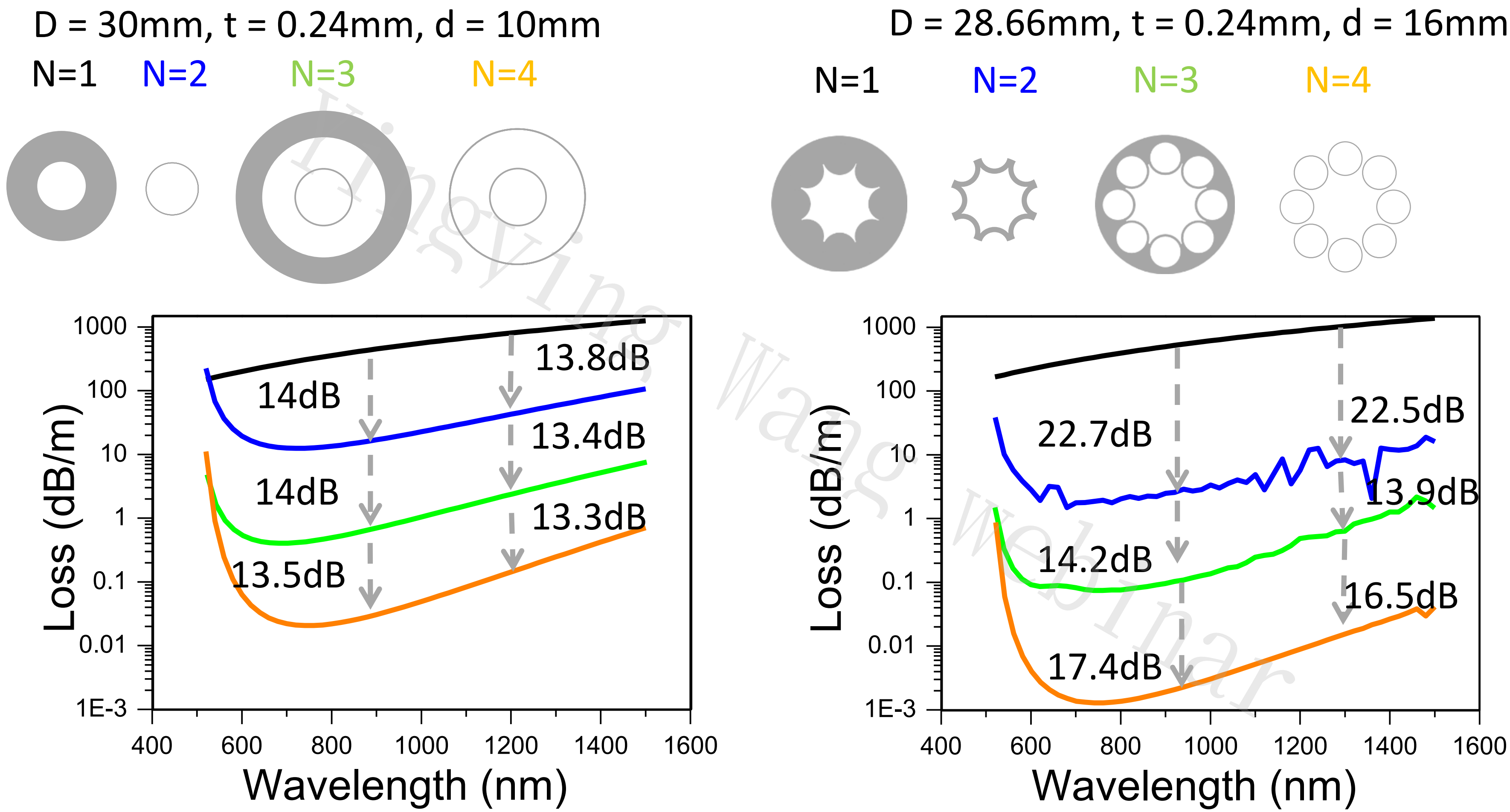




The glass wall drags the phases of the optical rays and suppresses the sequent radiations to the far field by constituting some destructive interference.

W. Ding and Y. Wang, Analytic model for light guidance in single-wall hollow-core anti-resonant fibers, Opt. Express 22(22), 27242–27256 (2014).

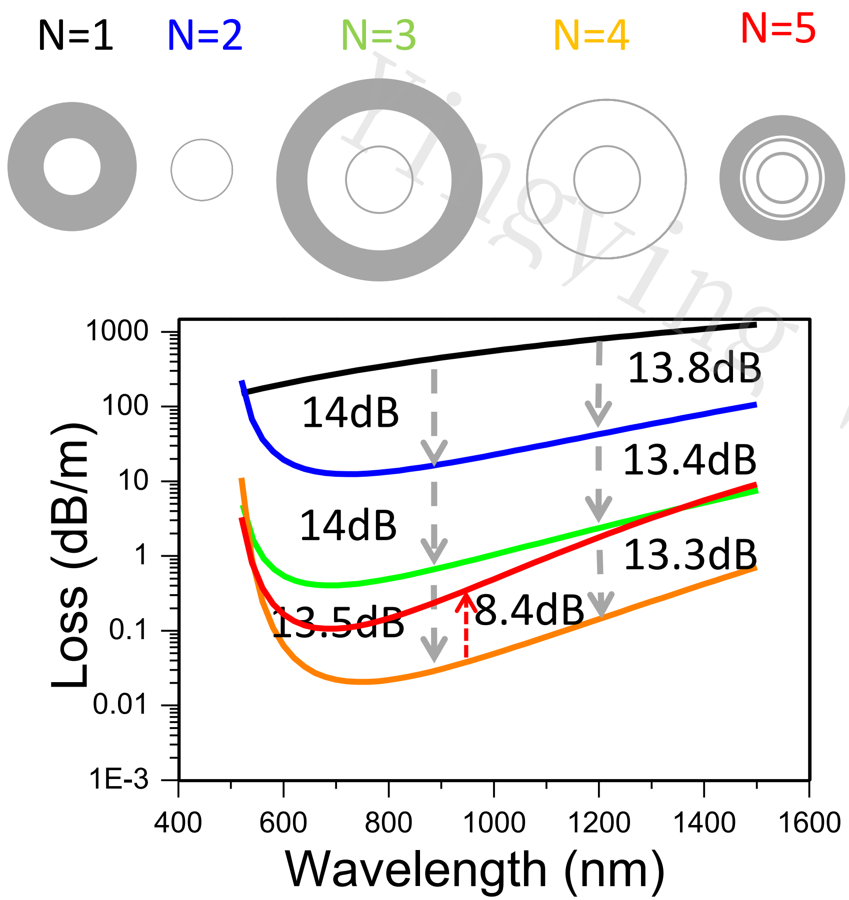
Comparison of annular fiber and NCF



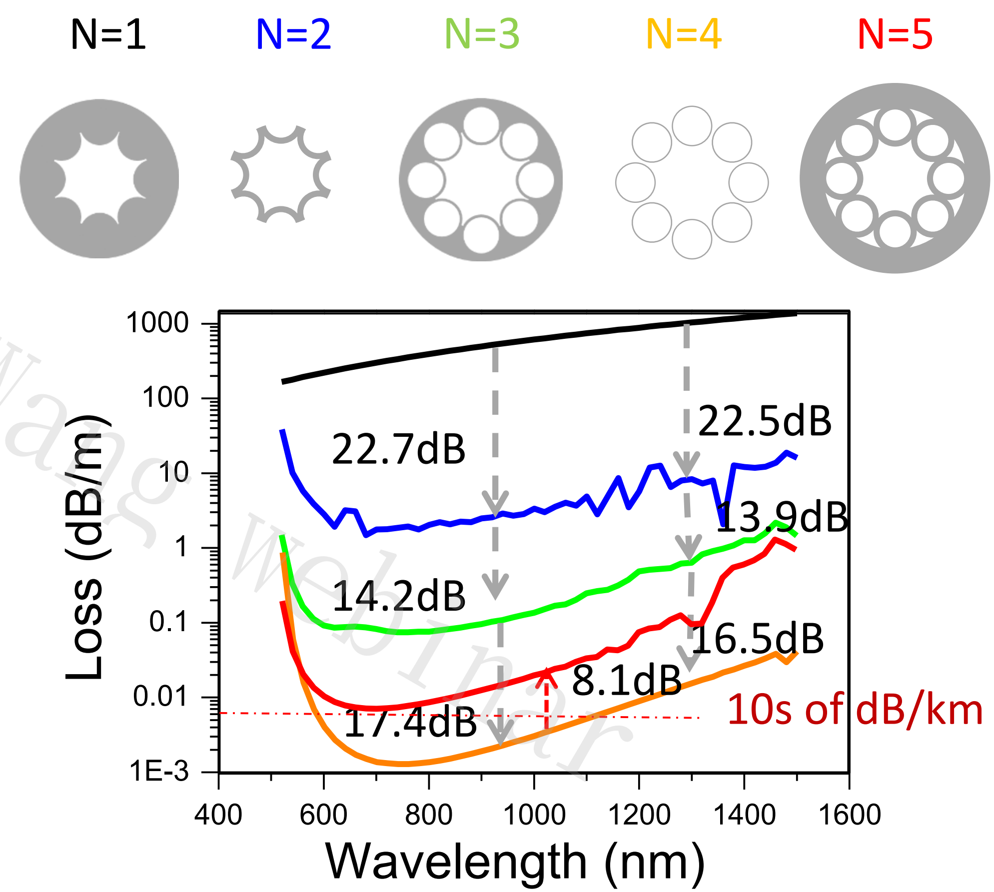
Yingying Wang and Wei Ding, "Confinement loss in hollow-core negative curvature fiber: A multi-layered model," Opt. Express 25, 33122 (2017)

Comparison of annular fiber and NCF

D = 30mm, t = 0.24mm, d = 10mm



D = 28.66mm, t = 0.24mm, d = 16mm

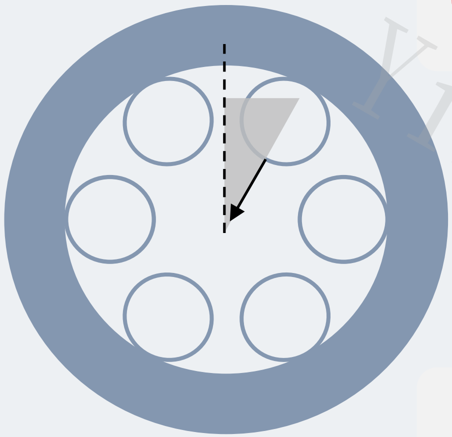


33.6 dB

47dB

Yingying Wang and Wei Ding, "Confinement loss in hollow-core negative curvature fiber: A multi-layered model," Opt. Express 25, 33122 (2017)

Intuitive picture of NCF



Quantitative

&

Intuitive

A Multi-Layered Model :

(OE 25, 33122-33133, 2017)

- Cascaded Fresnel transmissions
- Near-glazing incidence
- Multi-path interference (ARROW)
- Glass-wall shape induced interference

Master Equation

$$\alpha = \alpha_{Capillary} \cdot \left(\frac{4sin\theta_z}{\sqrt{n^2-1}}\right)^{N-1} \cdot \frac{1+n^{2N}}{1+n^2} \cdot FOM(U_{air}, U_{glass}, C)$$

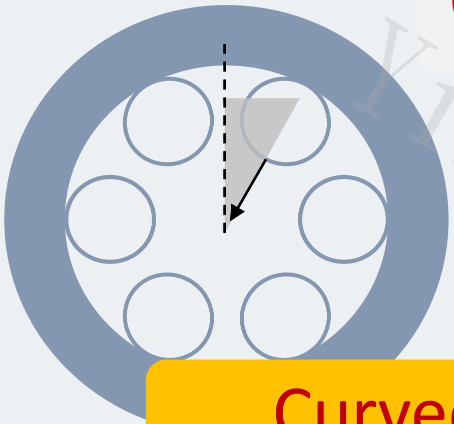
$$FOM(U_{air}, U_{glass}, C) \propto \prod_{i=1}^{N-1} \frac{1}{sin^2(\pi U_i)} \times \prod_{j=2:2:N} \int_0^{2\pi} d\xi \left| \oint_{C_j} (G \cdot \partial_n E_j - E_j \cdot \partial_n G) dl_j \right|^2$$

Wei Ding et al, Ultralow-Loss, Broadband Hollow-Core Anti-Resonant Fiber and its Communication Applications, IEEE Journal of selected topics in quantum electronics, manuscript in revision.

Intuitive picture of NCF

A Multi-Layered Model：

(OE 25, 33122-33133, 2017)



Quantitative

&

- ☐ Cascaded Fresnel transmissions
- ☐ Near-glazing incidence
- ☐ Multi-path interference (ARROW)
- erence

Curved Core Shape + Multi-Layered Cladding

Master Equation

$$\alpha = \alpha_{Capillary} \cdot \left(\frac{4 sin\theta_z}{\sqrt{n^2-1}}\right)^{N-1} \cdot \frac{1+n^{2N}}{1+n^2} \cdot FOM(U_{air}, U_{glass}, C)$$

$$FOM(U_{air}, U_{glass}, C) \propto \prod_{i=1}^{N-1} \frac{1}{sin^2(\pi U_i)} \times \prod_{j=2:2:N} \int_0^{2\pi} d\xi \left| \oint_{C_j} (G \cdot \partial_n E_j - E_j \cdot \partial_n G) dl_j \right|^2$$

Wei Ding et al, Ultralow-Loss, Broadband Hollow-Core Anti-Resonant Fiber and its Communication Applications, IEEE Journal of selected topics in quantum electronics, manuscript in revision.

1 **Background**

1. *Motivation*
2. *History of HCF development*

2 **HCF – understanding, design and fabrication**

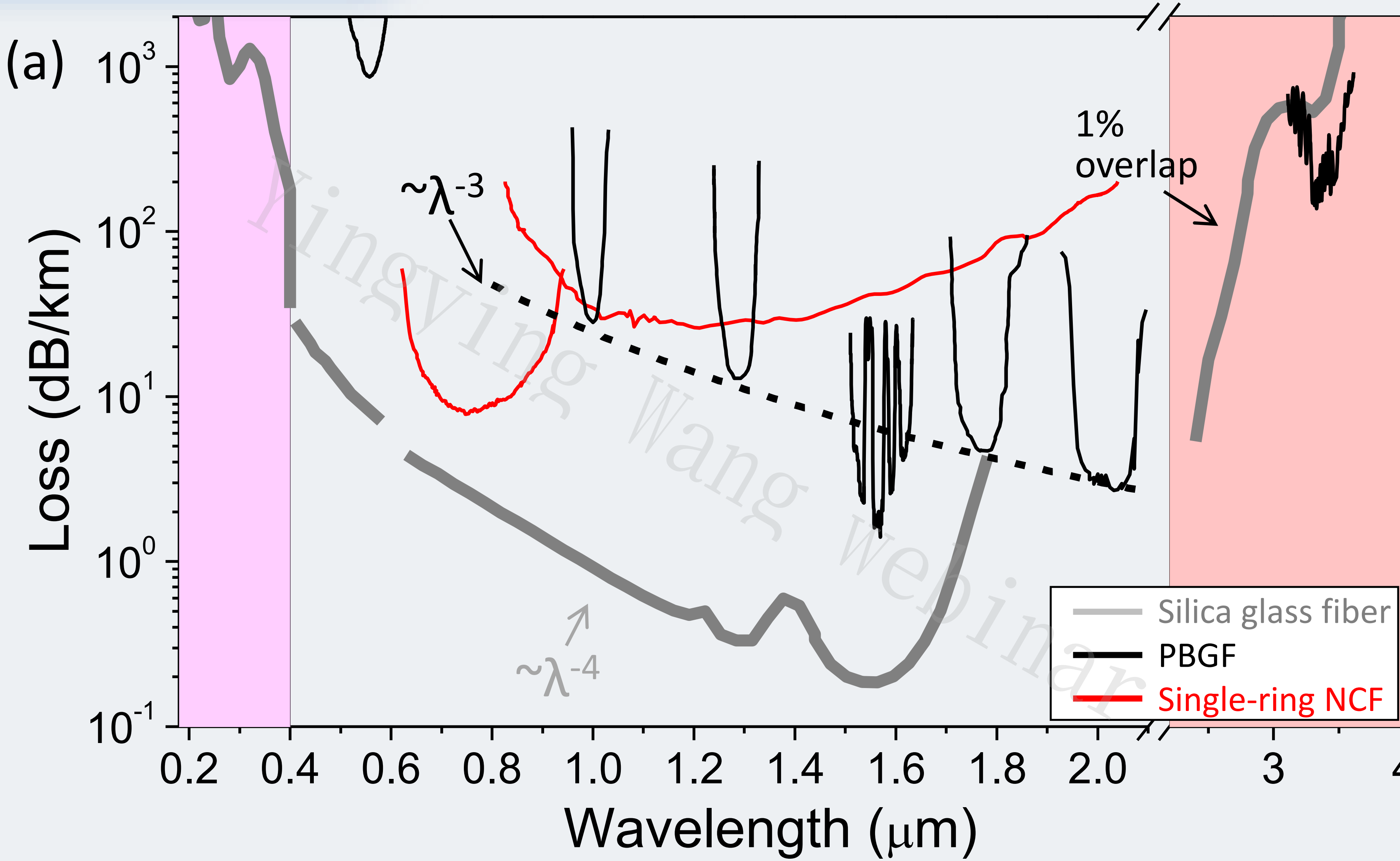
1. *How we understand*
2. *Broadband HCF*
3. *Ultralow loss HCF*

3 **HCF applications**

1. *Optical communications*
2. *Ultrafast optics: delivery and gas nonlinearity*
3. *Sensing and biophotonics*

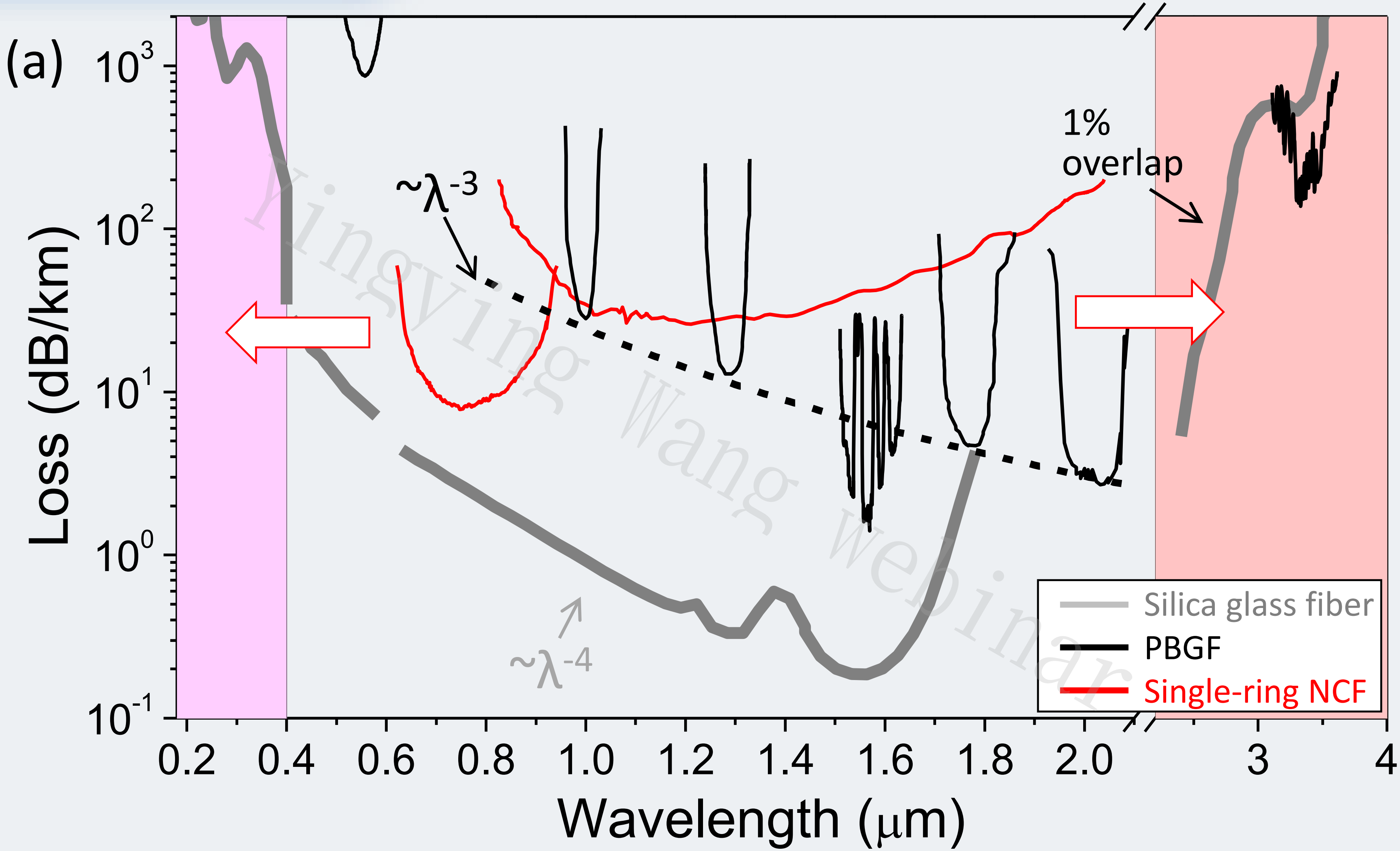
4 **Conclusion**

Loss achieved in HC-NCF



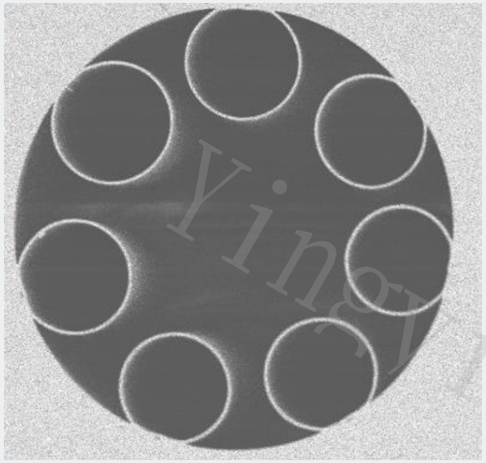
G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al* OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017)

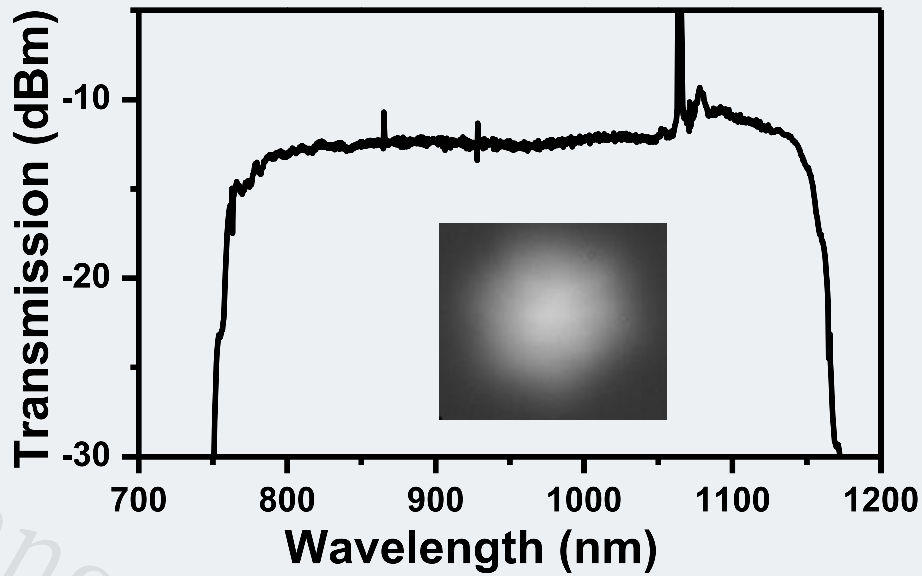
Loss achieved in HC-NCF



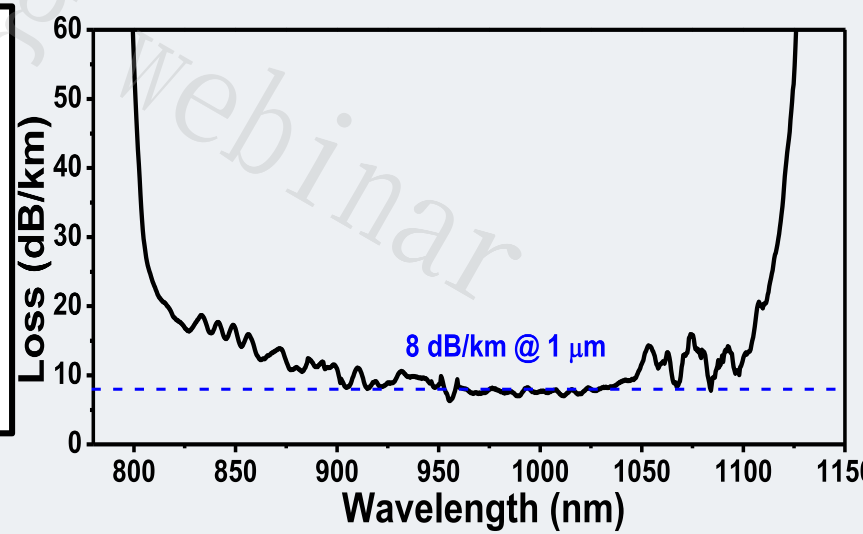
G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al* OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017)

NIR HC-NCF

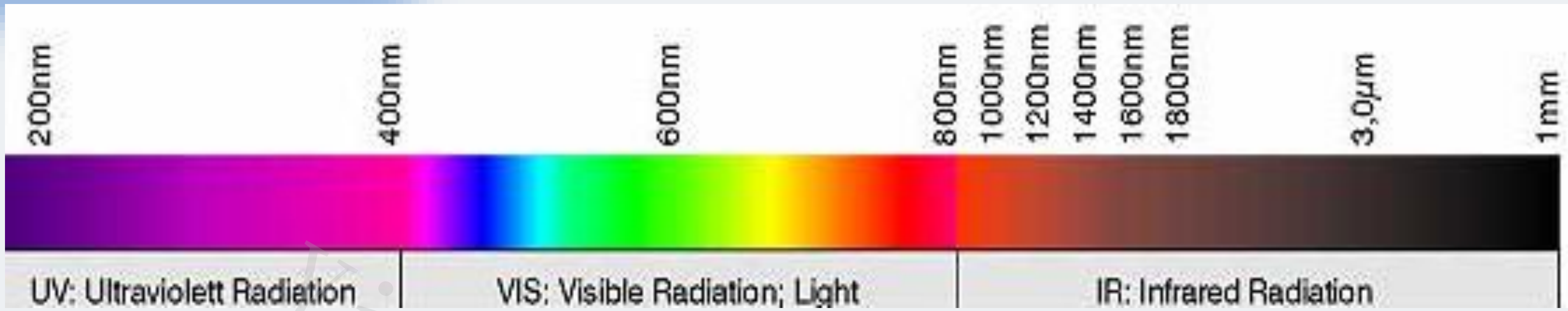




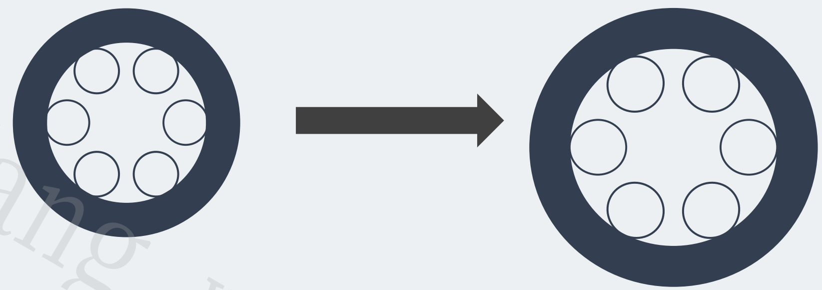
- D = 50 µm, d = 26 µm, t =1 µm
- Measured Transmission loss :
- ~8 dB/km (800 nm -1100 nm)
- Single mode

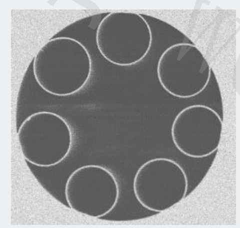


Broadband HC-NCF

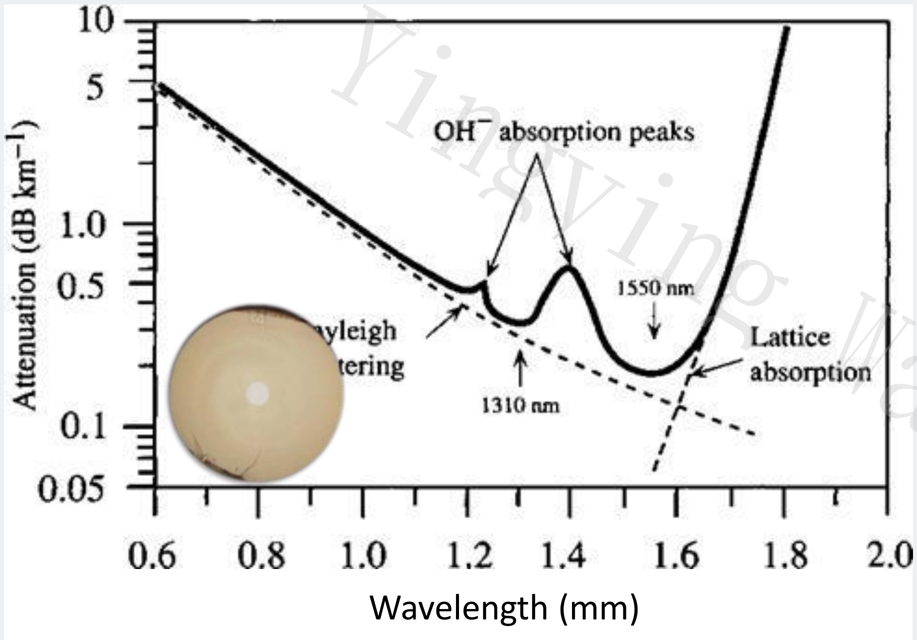


Near IR **Upscale: Mid-Infrared**



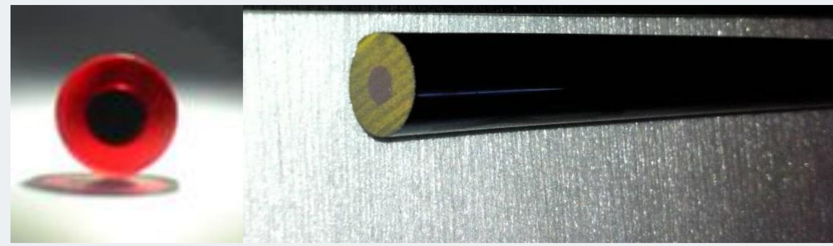


Silica Fiber



High loss above 2.4 mm

Soft glass fiber



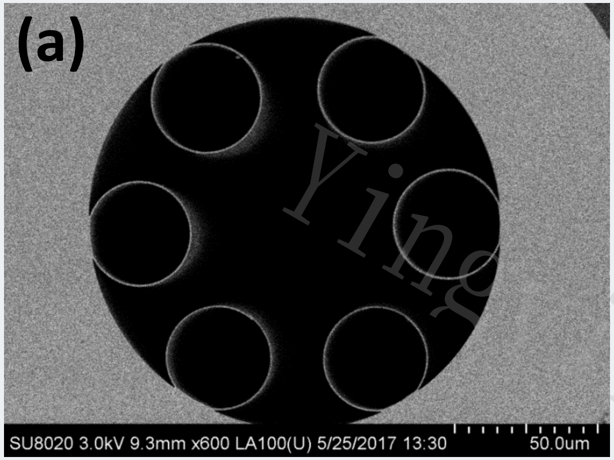
Fabrication and handling difficulties

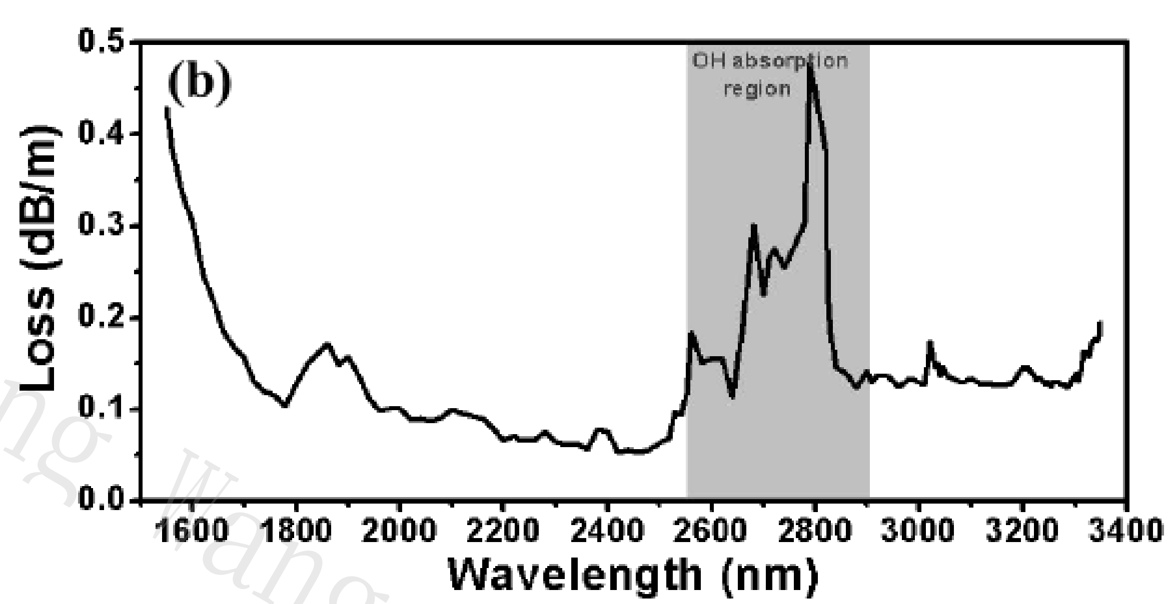
Low Damage Threshold

High nonlinearity

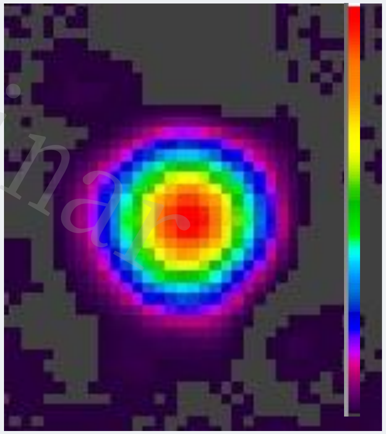
Silica-based hollow core fiber could be an ideal choice for MIR.

MIR HC-NCF





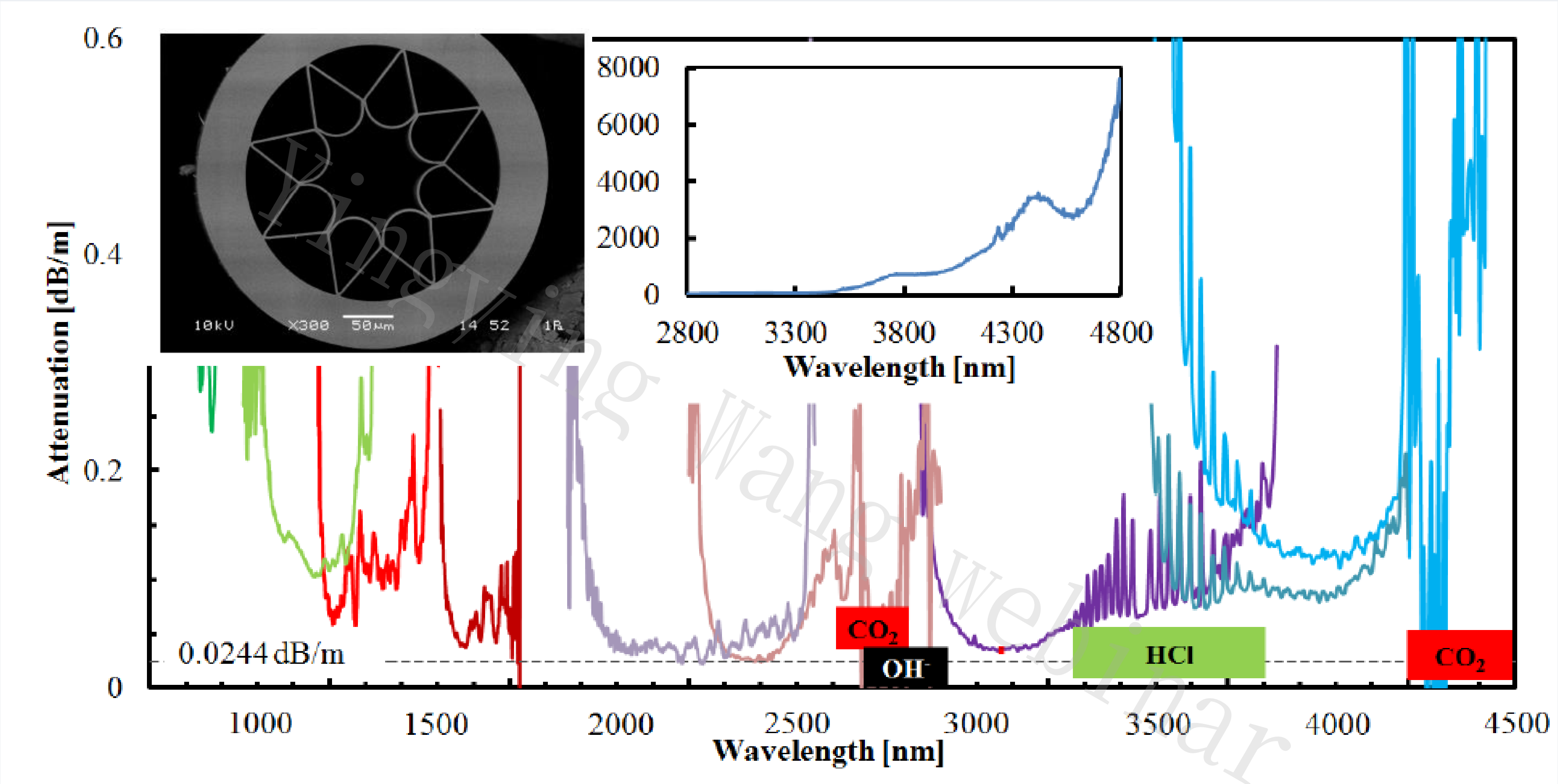
- **D = 70 µm, d = 36 µm, t = 760 nm**
- **Transmission Bandwidth:**
  1600~ > 3400 nm
- **Measured Transmission loss:**
  50 dB/km@ 2.45 µm； 130 dB/km@ 3 µm
- **Single mode**



@ 2.7 µm

Ling Cao, Shou-fei Gao, Zhi-gang Peng, Xiao-cong Wang, Ying-ying Wang, and Pu Wang, "High peak power 2.8 µm Raman laser in a methane-filled negative-curvature fiber," Opt. Express 26, 5609-5615 (2018)

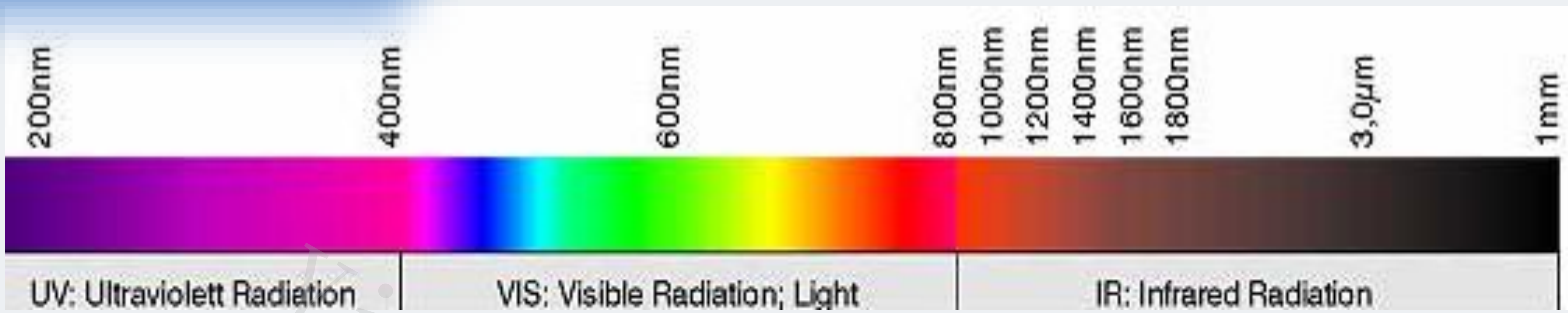
MIR HC-NCF



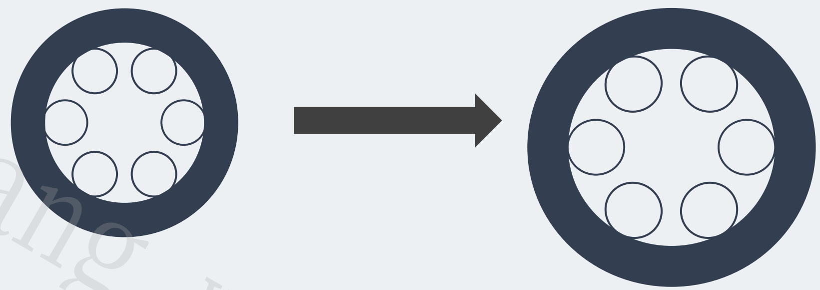
- 24-50 dB/km loss in 2000-4000 nm

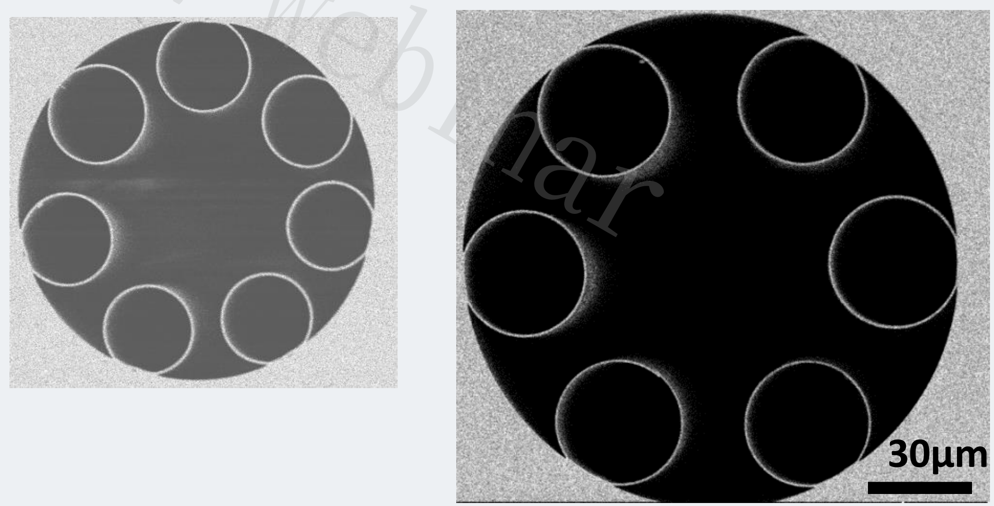
Yu F , Knight J C . Spectral attenuation limits of silica hollow core negative curvature fiber[J]. Optics Express, 2013, 21(18) :21466.

Broadband HC-NCF

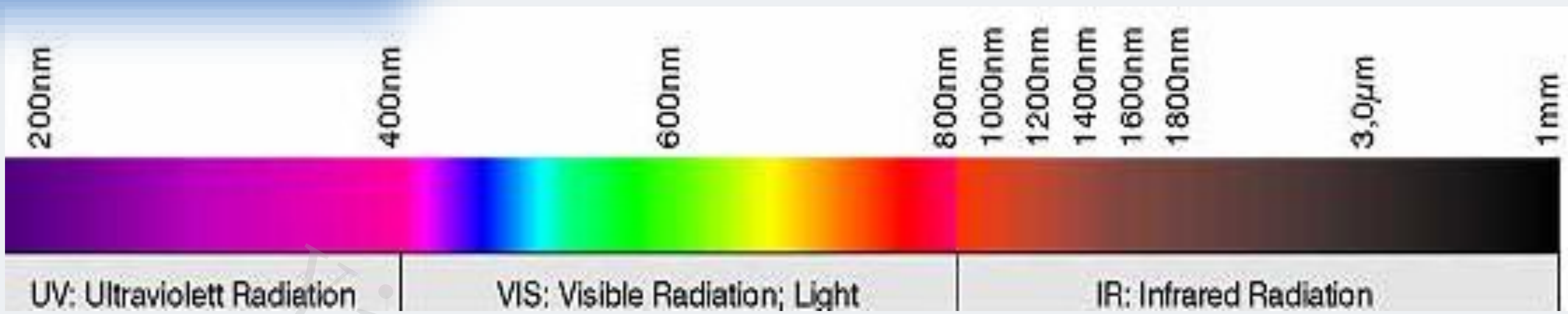


Near IR **Upscale: Mid-Infrared**

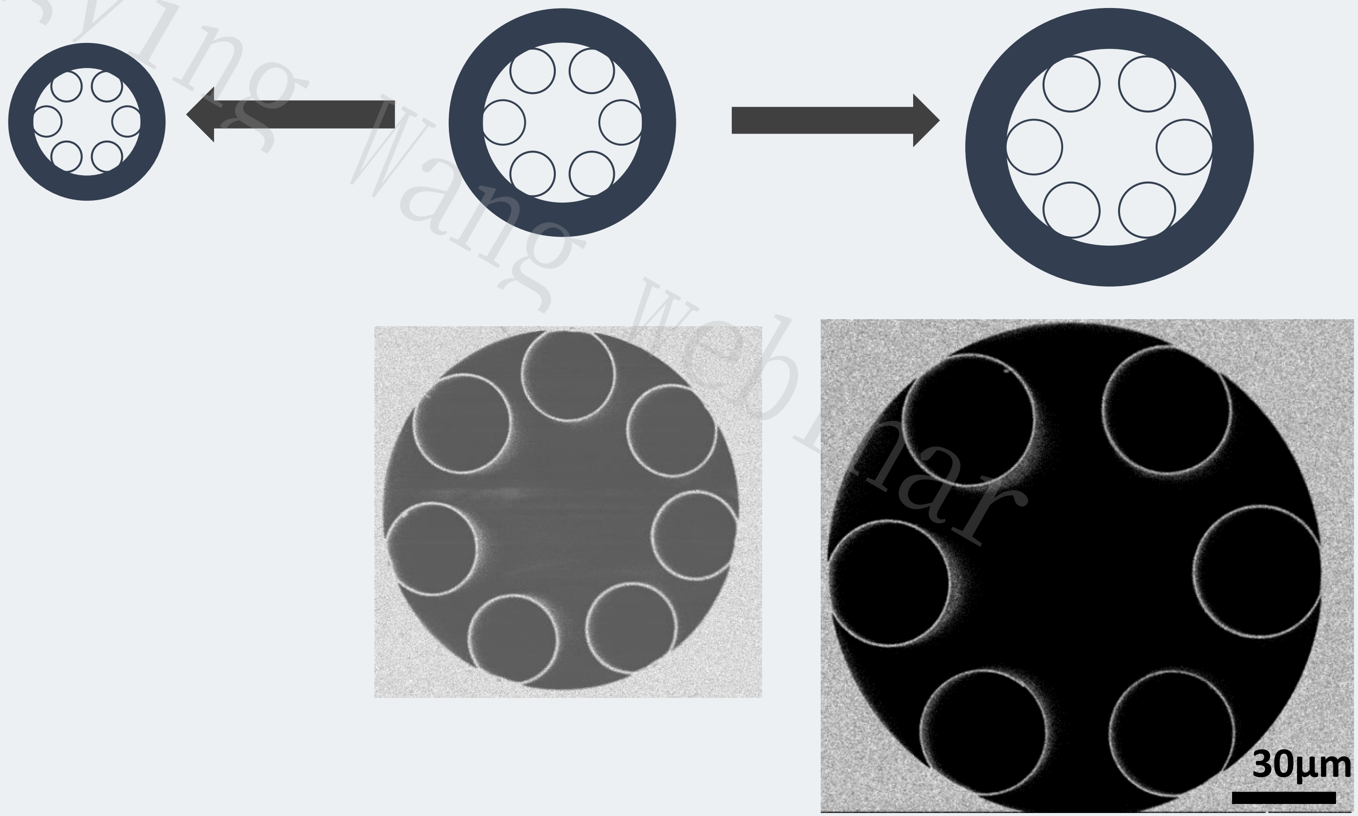




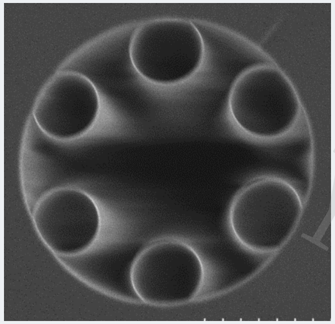
Broadband HC-NCF

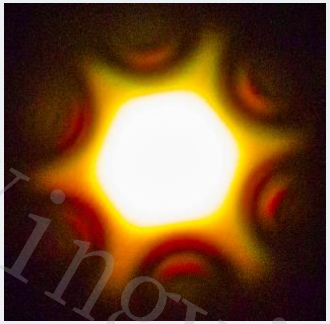


Downscale: Visible | **Near IR** | **Upscale: Mid-Infrared**

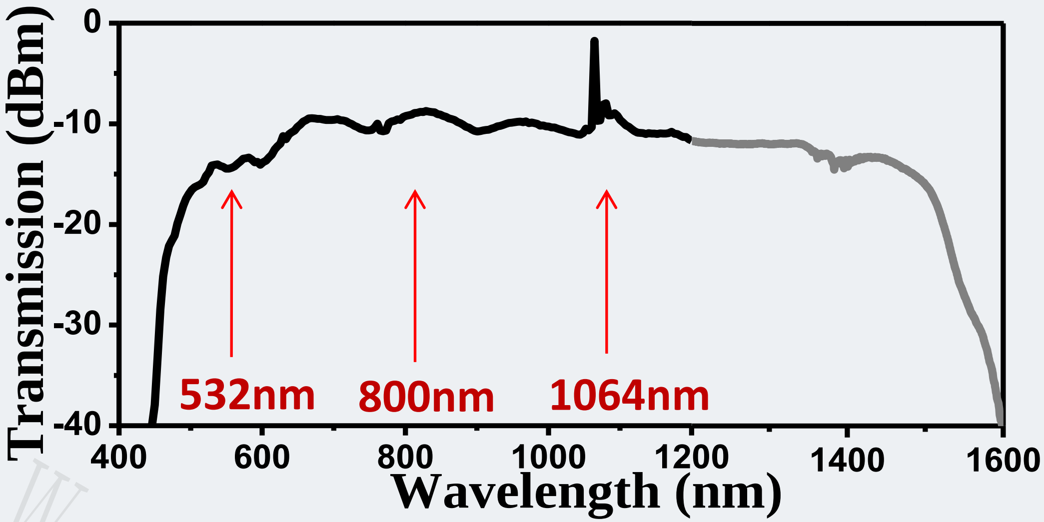


visible HC-NCF

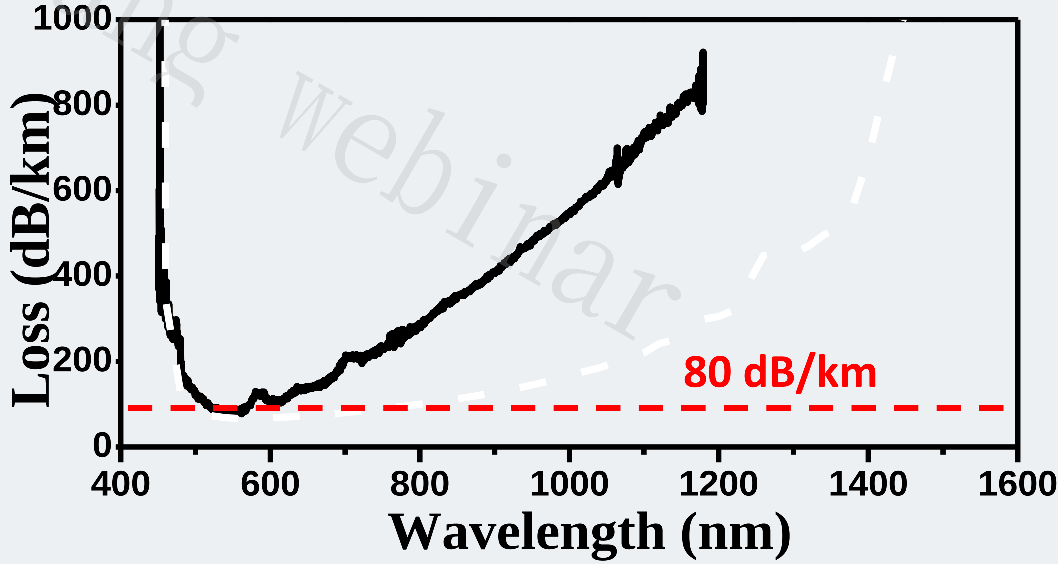




D=26 µm, d=12 µm, t=210 nm

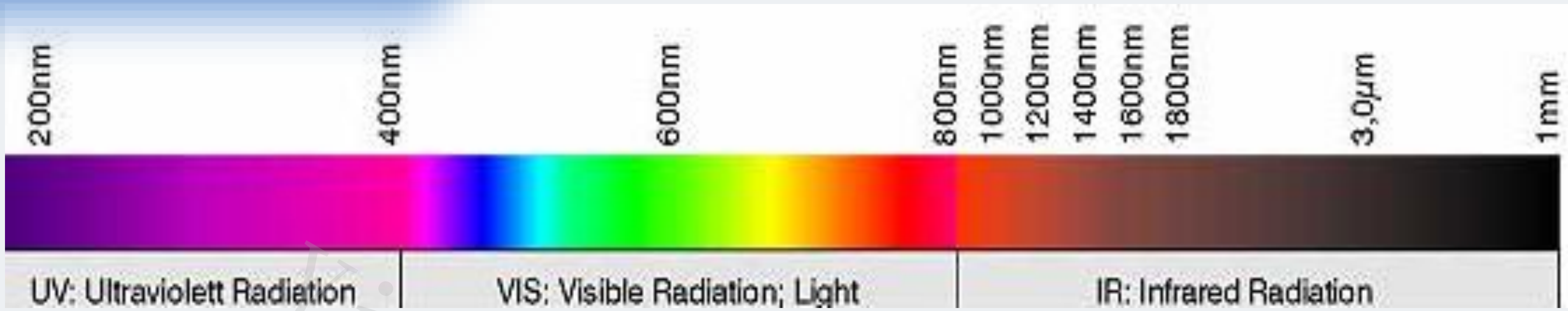


- ***Broaden bandwidth :***
  420 nm –1600 nm (VIS-NIR)
- ***Transmission loss:***
  80 dB/km @ 532 nm
- ***Loss below 300 dB/km:***
  450-850nm (almost entire visible)
- ***Single Mode Guidance***

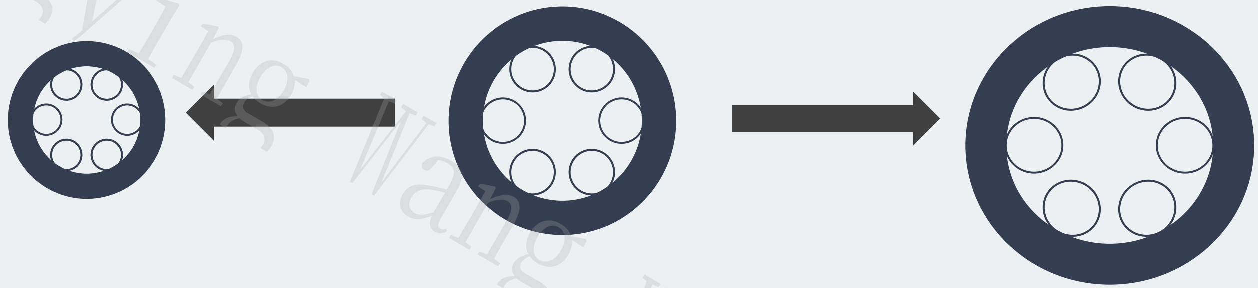


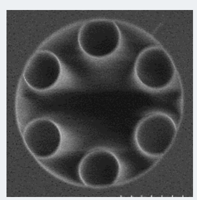
Shou-Fei Gao, Ying-Ying Wang*, Xiao-Lu Liu, Chang Hong, Shuai Gu, Pu Wang*, "Nodeless Hollow-Core Fiber for Visible Spectral Range" Opt. Lett. 42, 61-64 (2017)

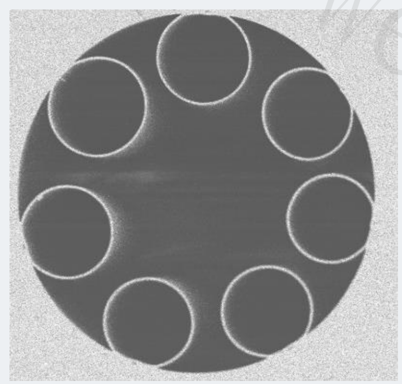
Broadband HC-NCF

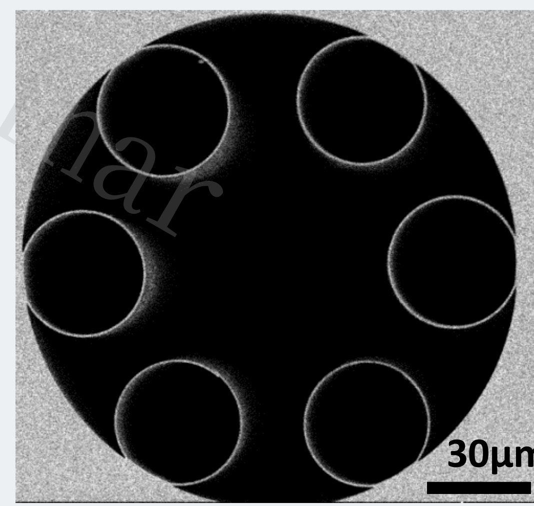


Downscale: Visible | **Near IR** | **Upscale: Mid-Infrared**

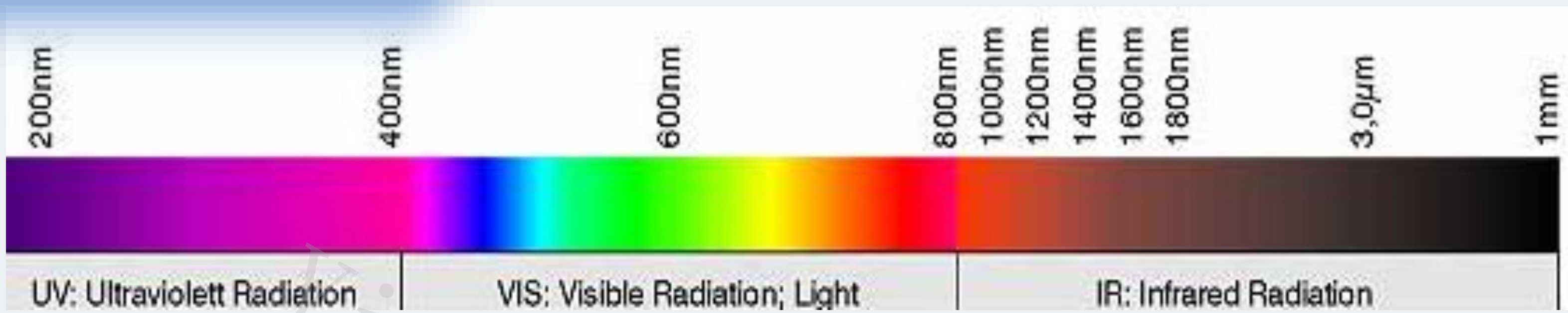




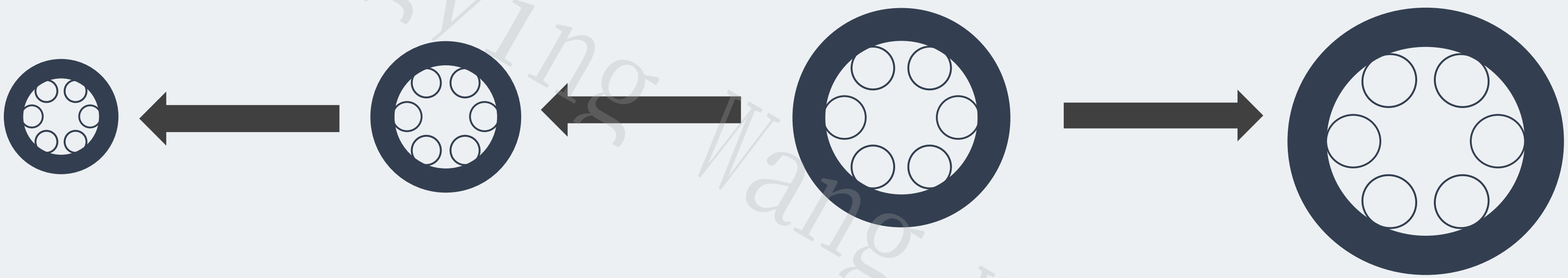


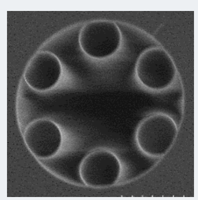


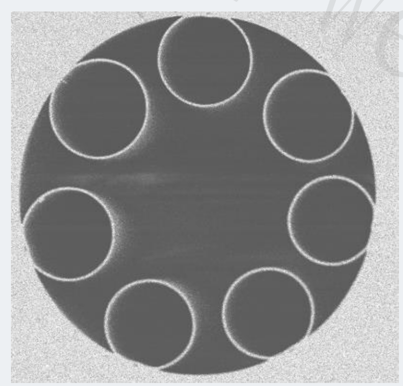
Broadband HC-NCF

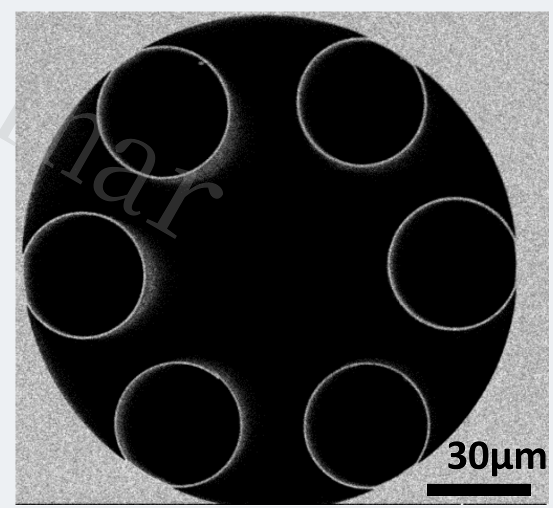


Downscale: UV **Downscale: Visible** **Near IR** **Upscale: Mid-Infrared**

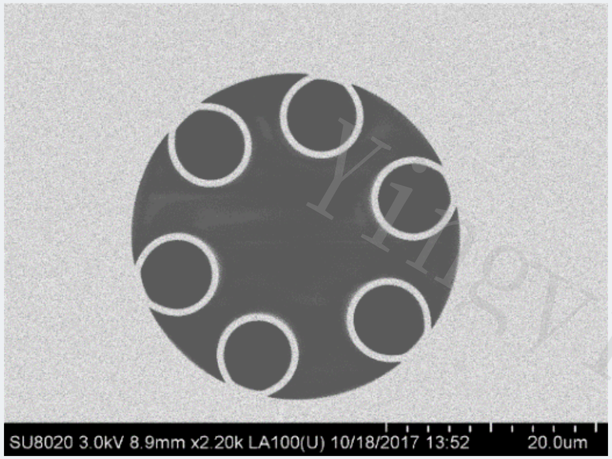


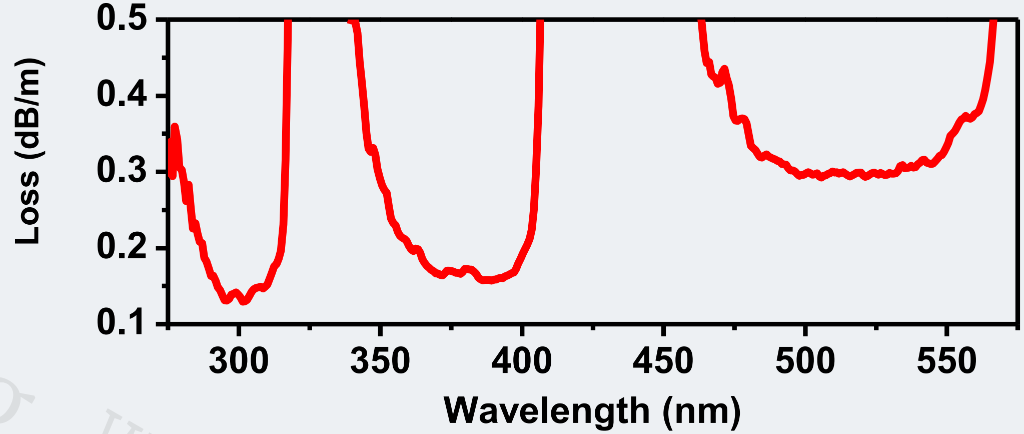






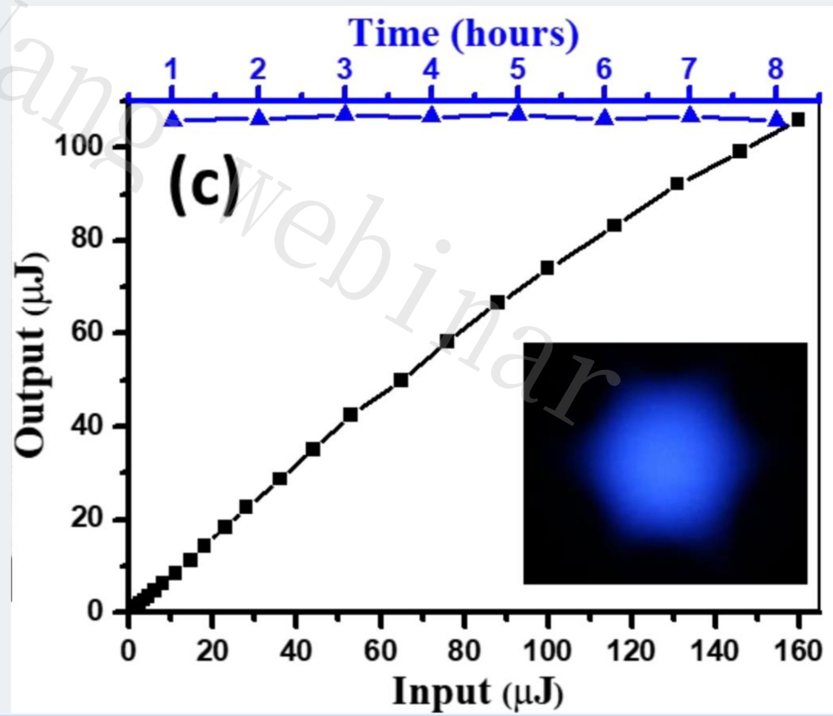
UV guiding HC-NCF





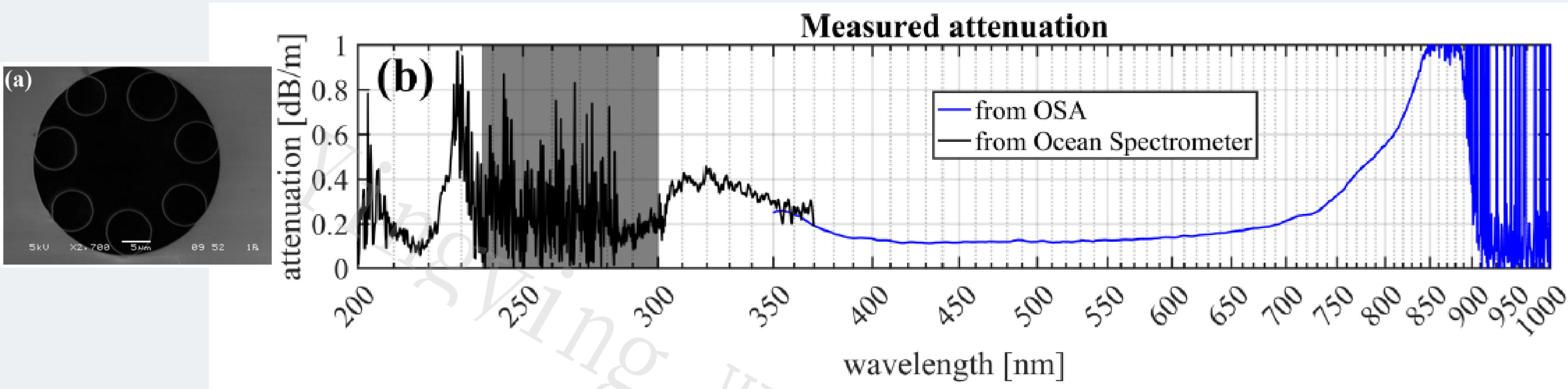
- D=15.4μm, d=7.9μm, t= 615nm, 278nm - 318nm (0.13dB/m) 330nm - 410nm (0.16dB/m)
- Pulse delivery: 355nm, 20ps, 160 μJ, 355nm, 1kHz.

160 uJ input, 100 uJ output.



Shoufei Gao, Yingying Wang, Wei Ding, and Pu Wang, “Hollow-core negative-curvature fiber for UV guidance,” Optics Letters, 43, 1347-1350 (2018).

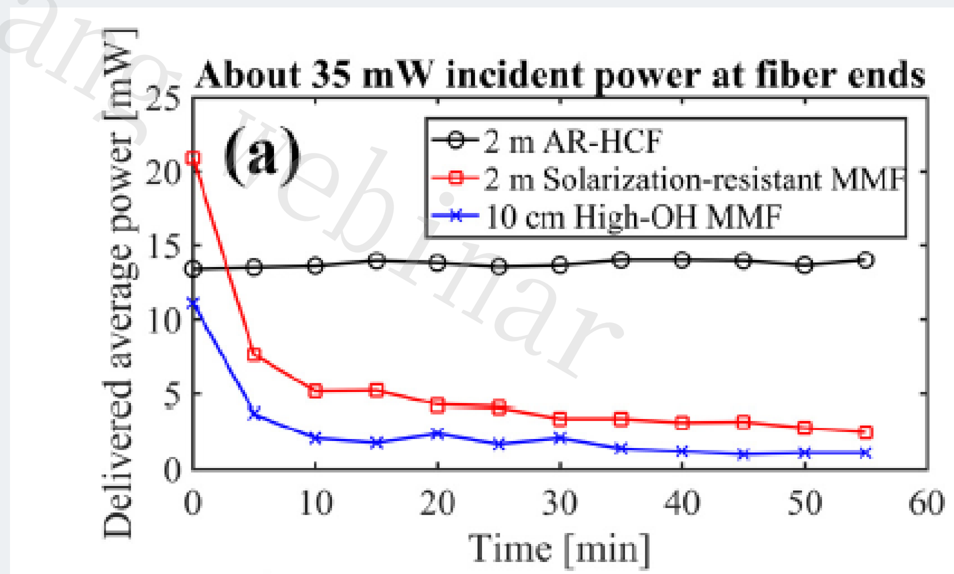
UV guiding HC-NCF



- Below 0.1 dB/m at 218 nm
- 0.26 dB/m at 355 nm
- Pulse delivery:

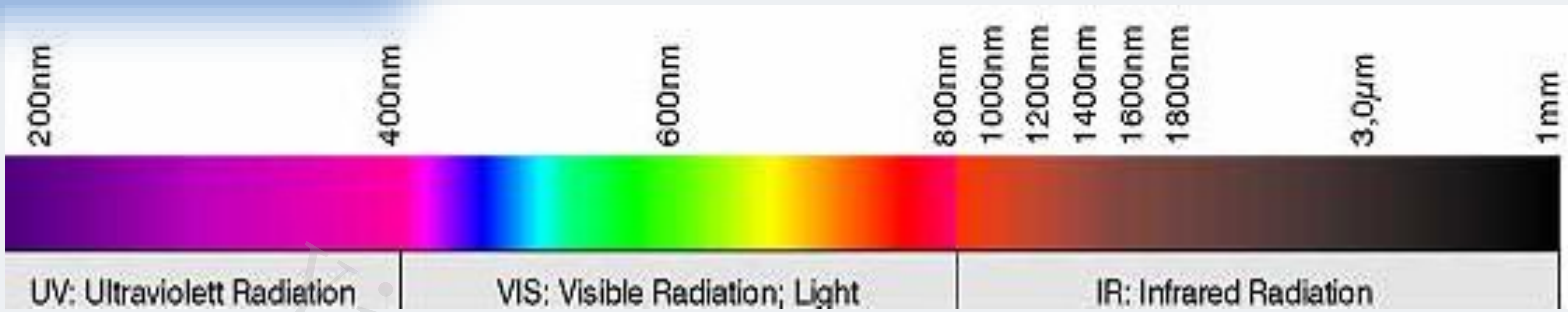
  266nm, 17ns, 30kHz.

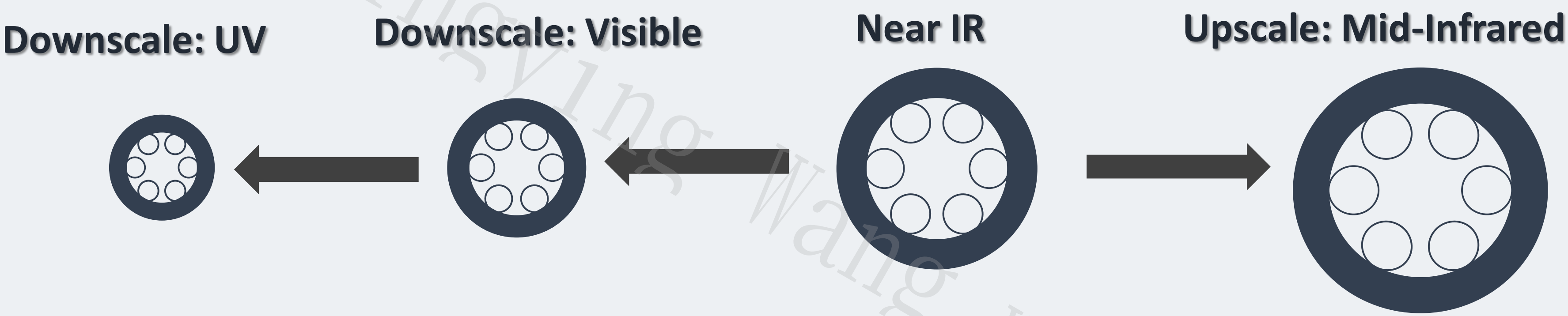
  120 mw input, 10.4 mw output.

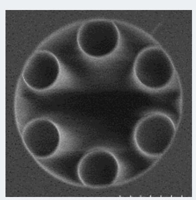


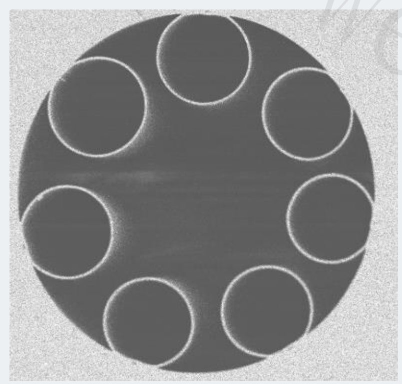
Fei Yu et al, “Single-mode solarization-free hollow-core fiber for ultraviolet pulse delivery”, Optics Express. 26, 10879, 2018

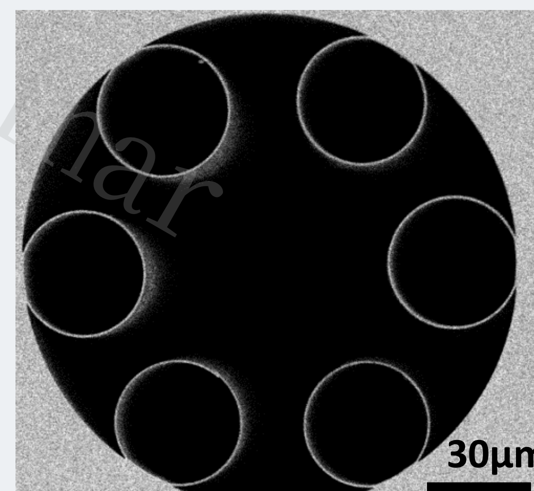
Near IR HC-NCF



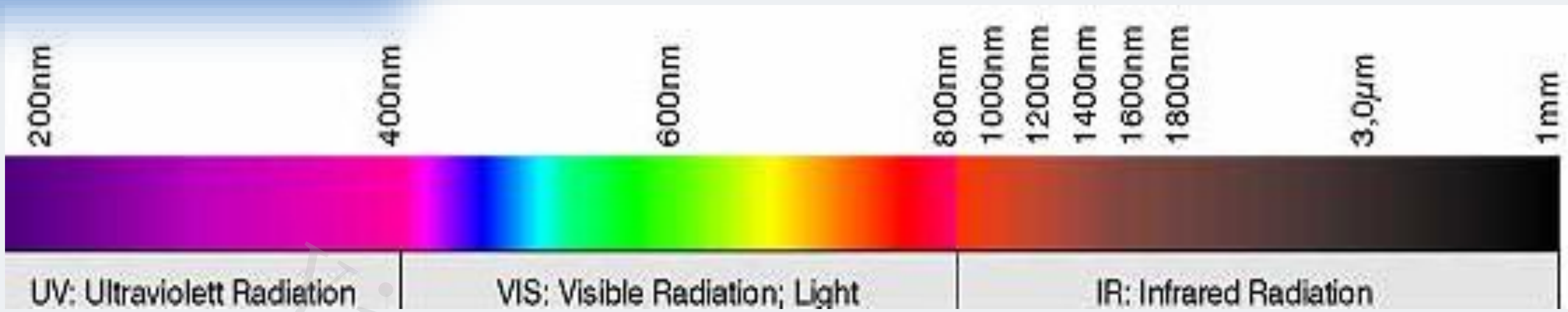


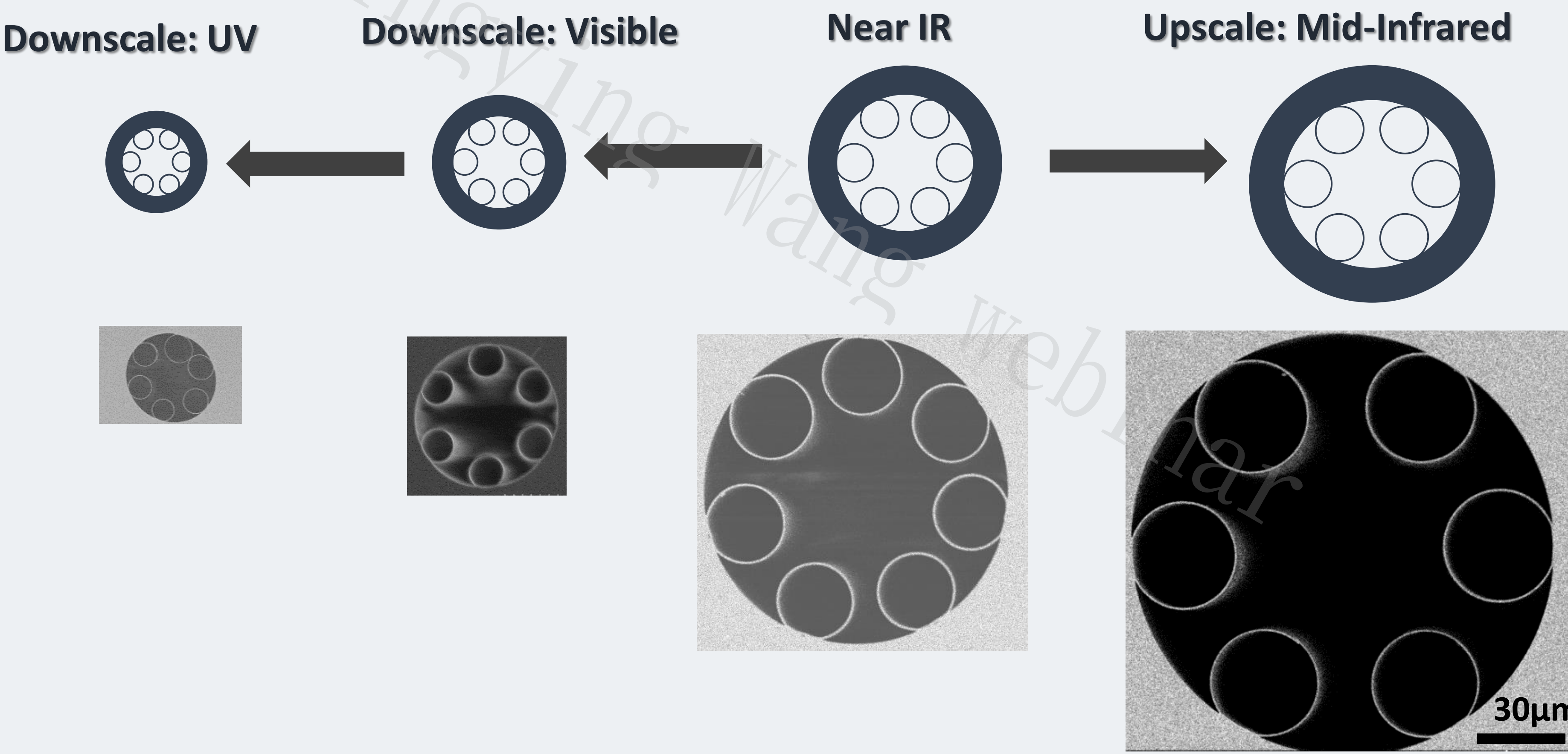




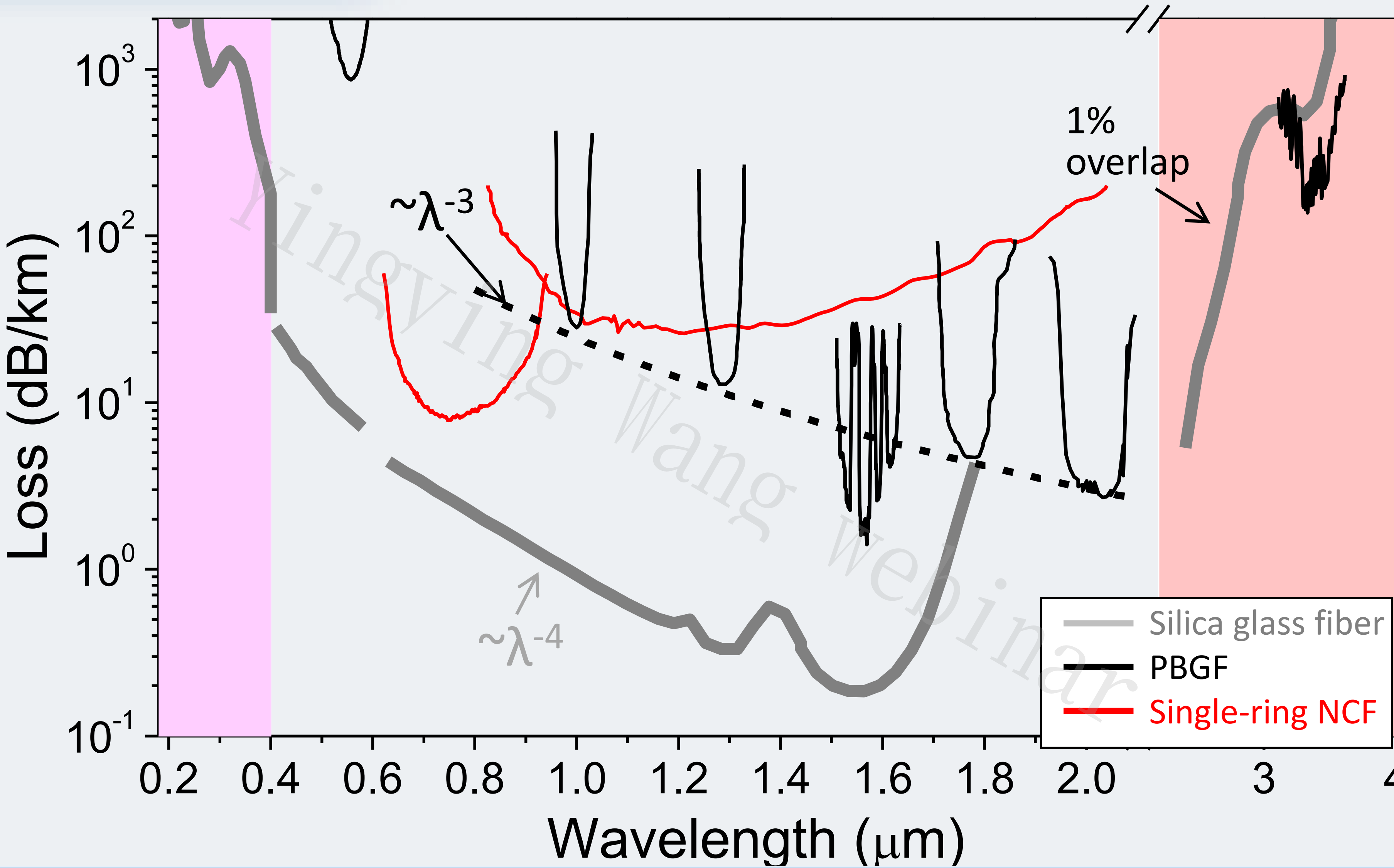


Near IR HC-NCF



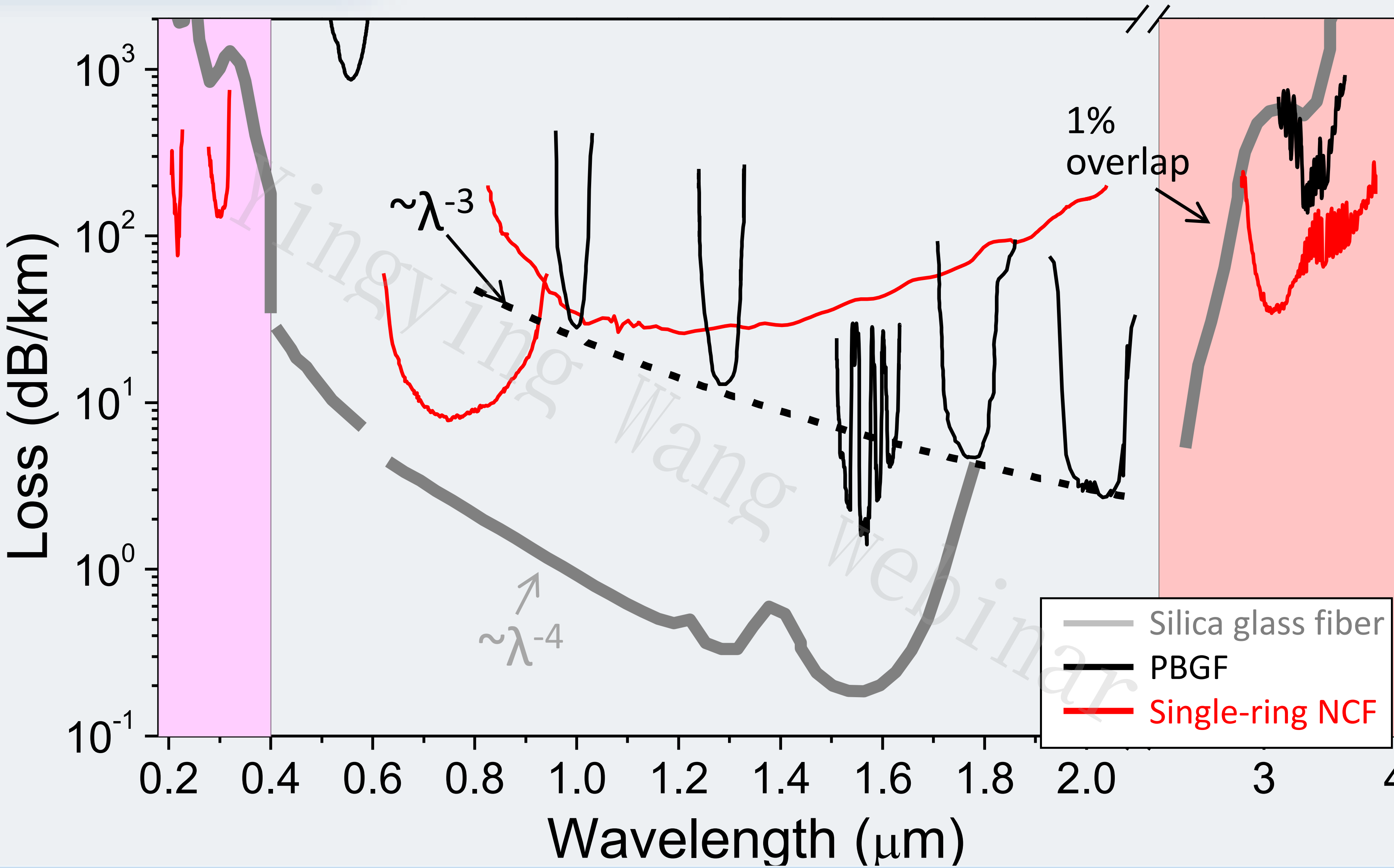


Loss achieved in HC-NCF



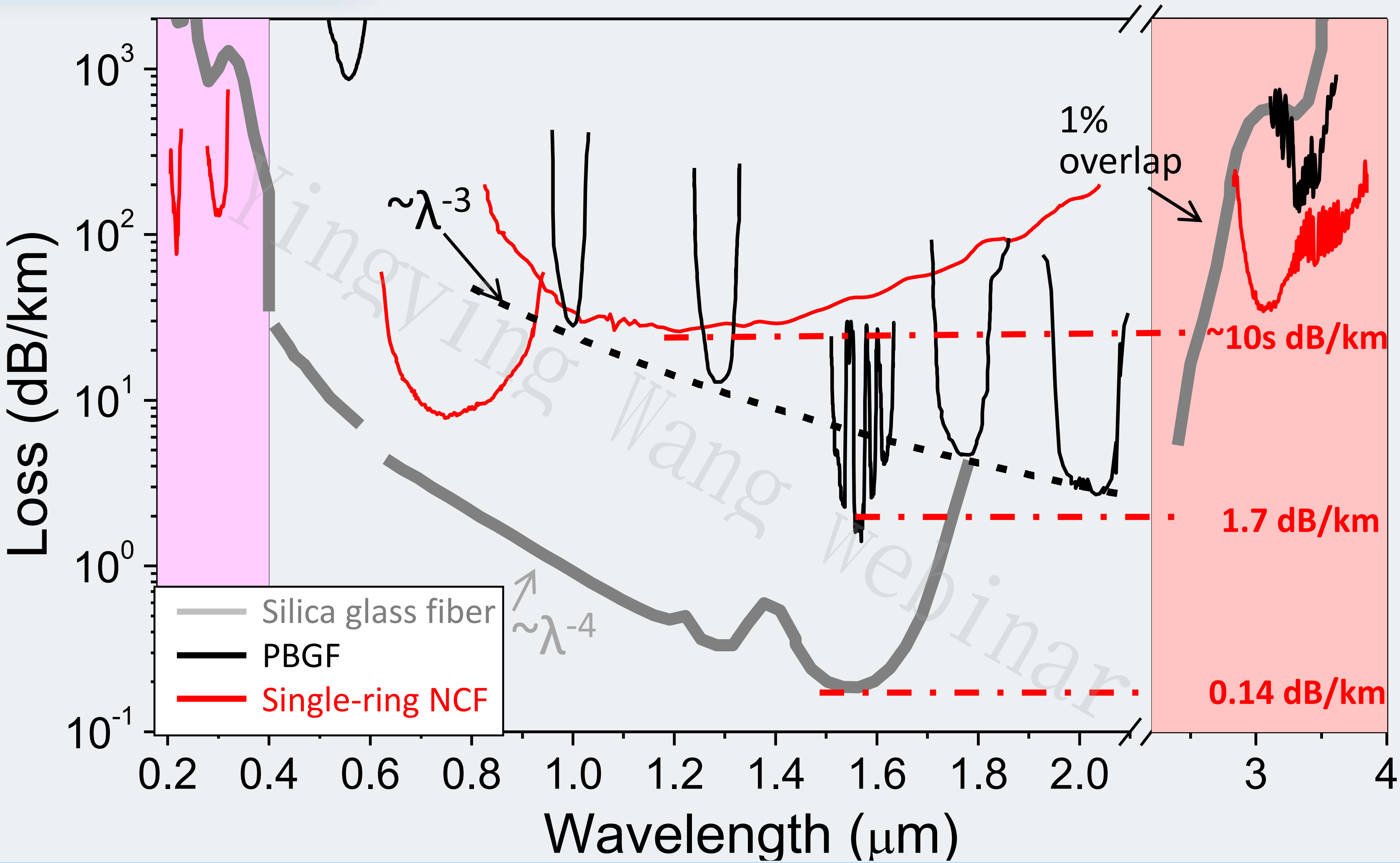
G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al* OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017)

Loss achieved in HC-NCF



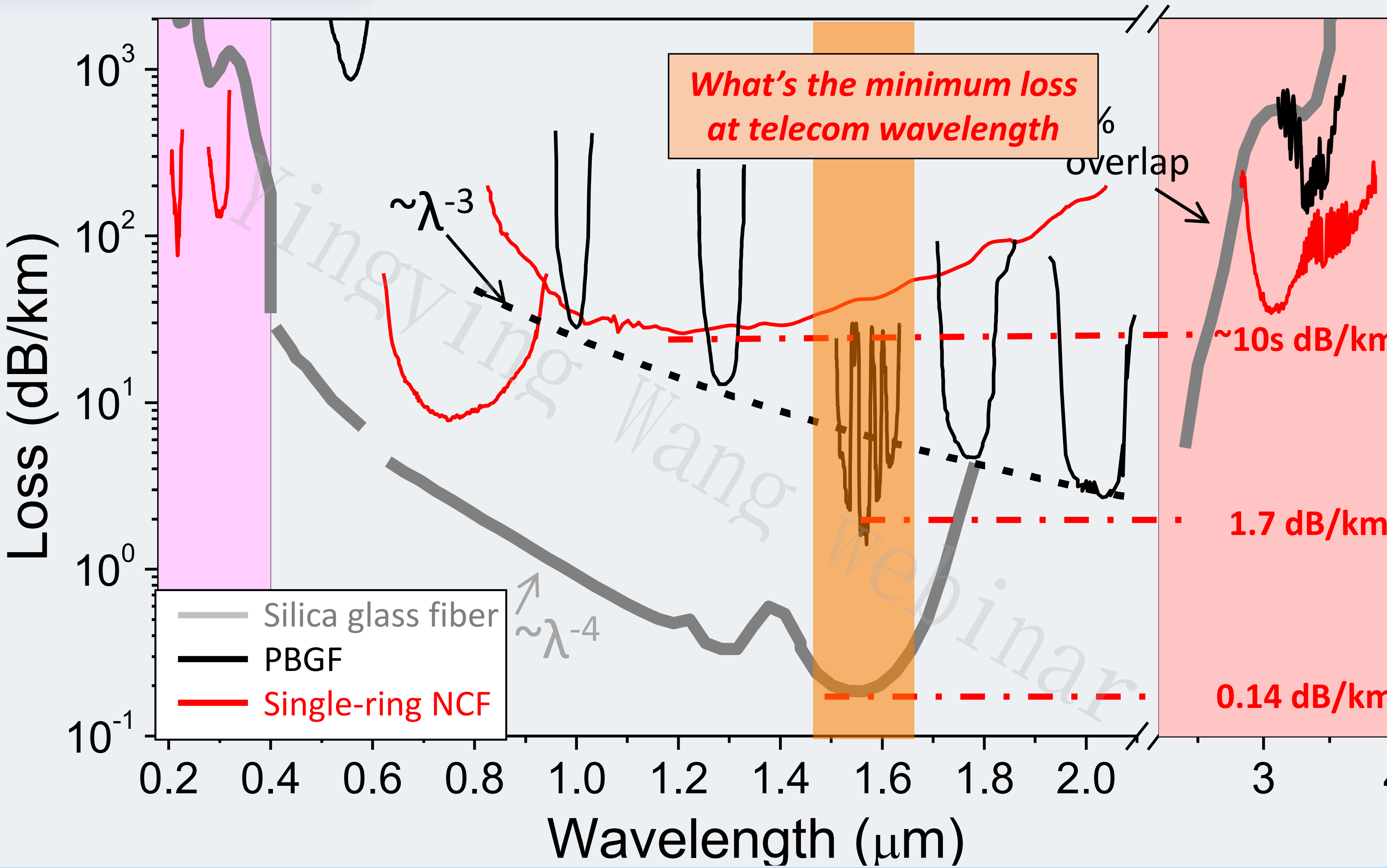
G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al* OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017), S. Gao et al, OL, 43, 1347, 2018. F. Yu et al, OE. 26, 10879, 2018

Loss achieved in HC-NCF



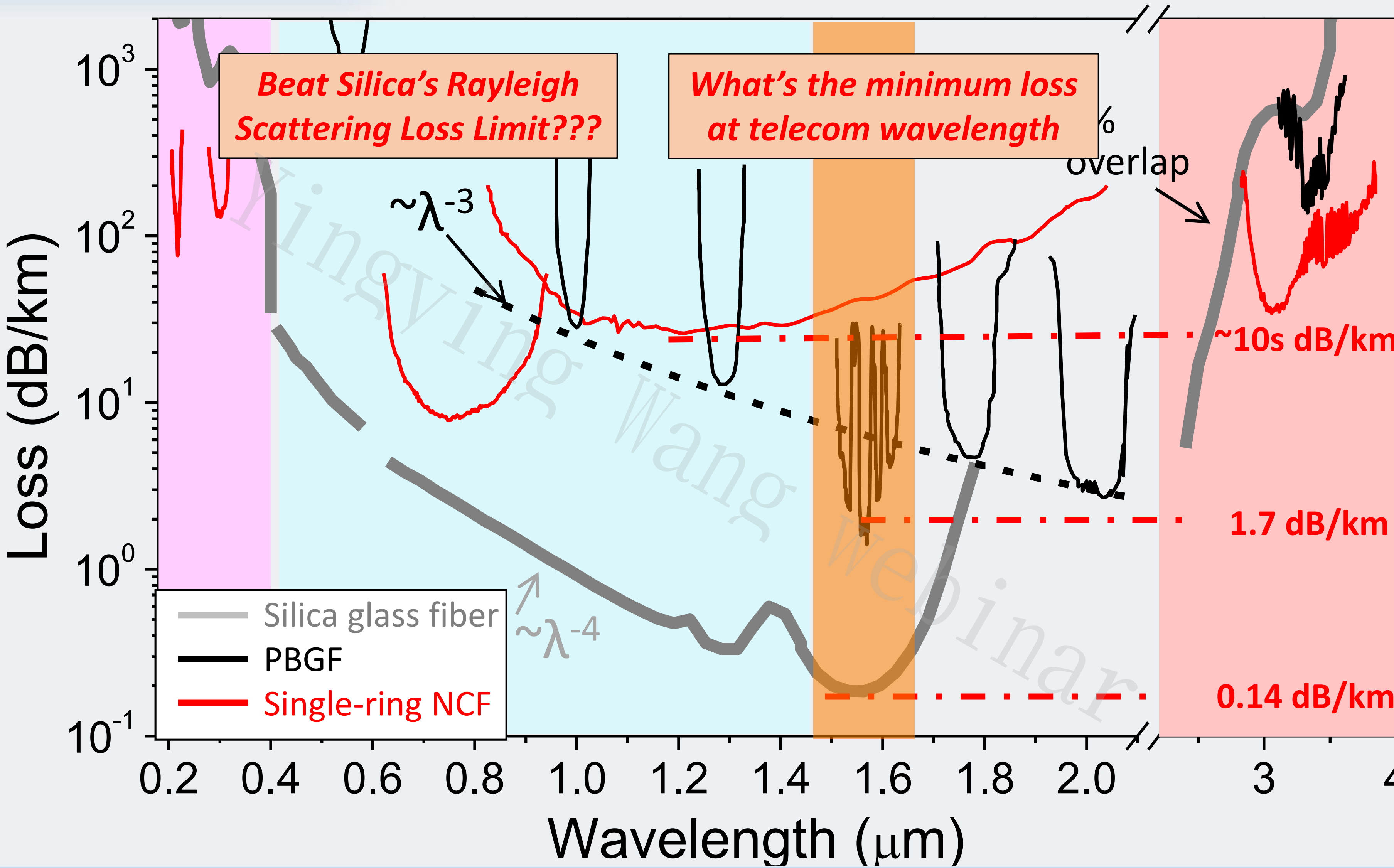
G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al* OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017), S. Gao et al, OL, 43, 1347, 2018. F. Yu et al, OE. 26, 10879, 2018

Loss achieved in HC-NCF



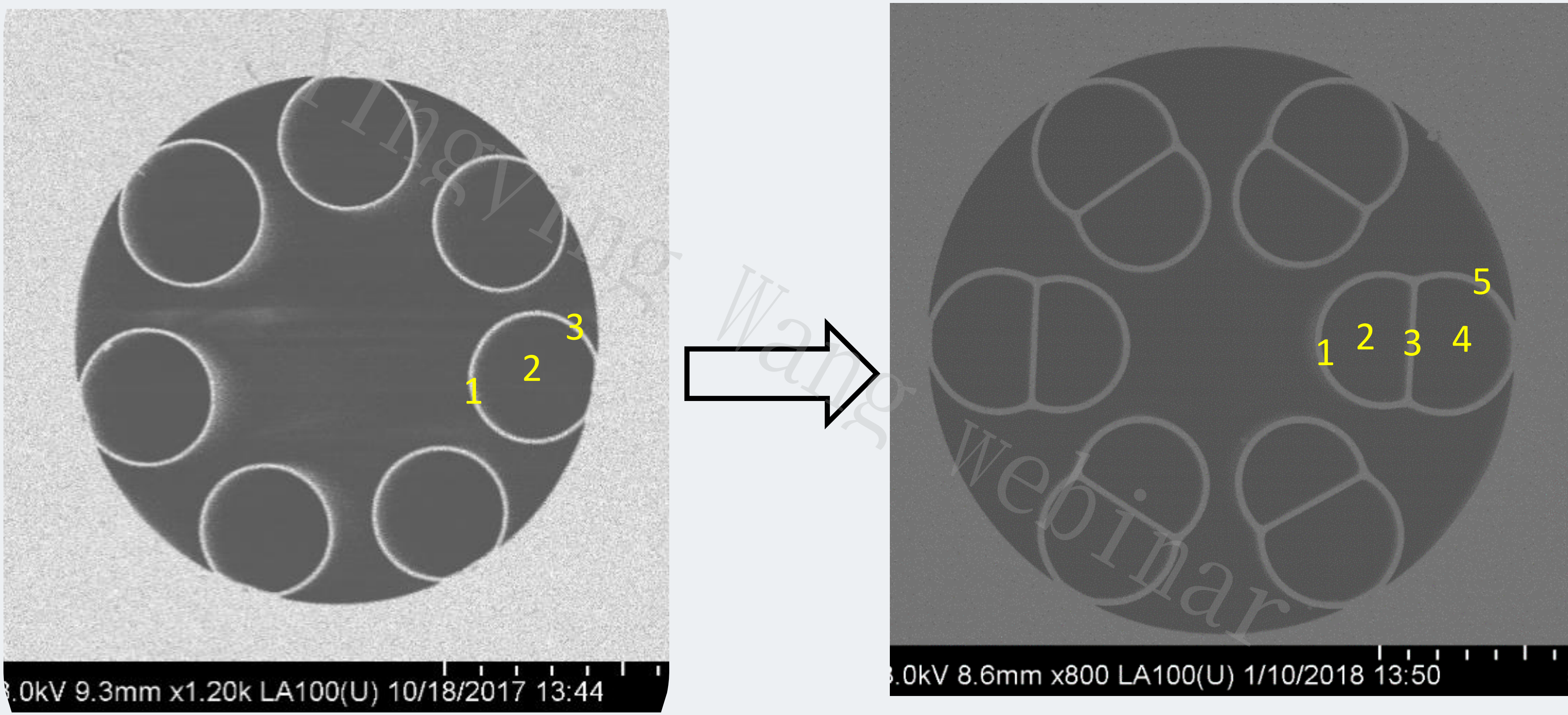
G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al* OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017), S. Gao et al, OL, 43, 1347, 2018. F. Yu et al, OE. 26, 10879, 2018

Loss achieved in HC-NCF



G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al* OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017), S. Gao et al, OL, 43, 1347, 2018. F. Yu et al, OE. 26, 10879, 2018

Adding interface



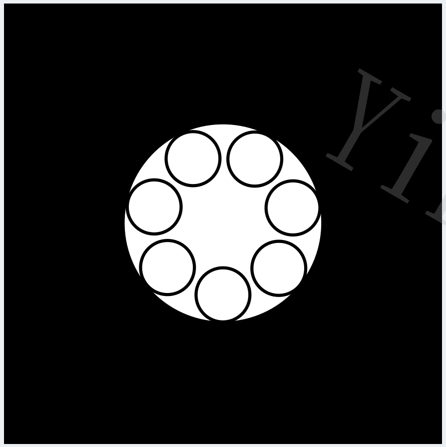
N=3

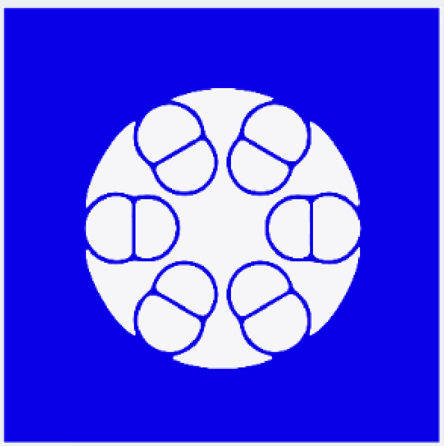
N=5

Shou-fei Gao, Nature Communication, 9, 2828 (2018).

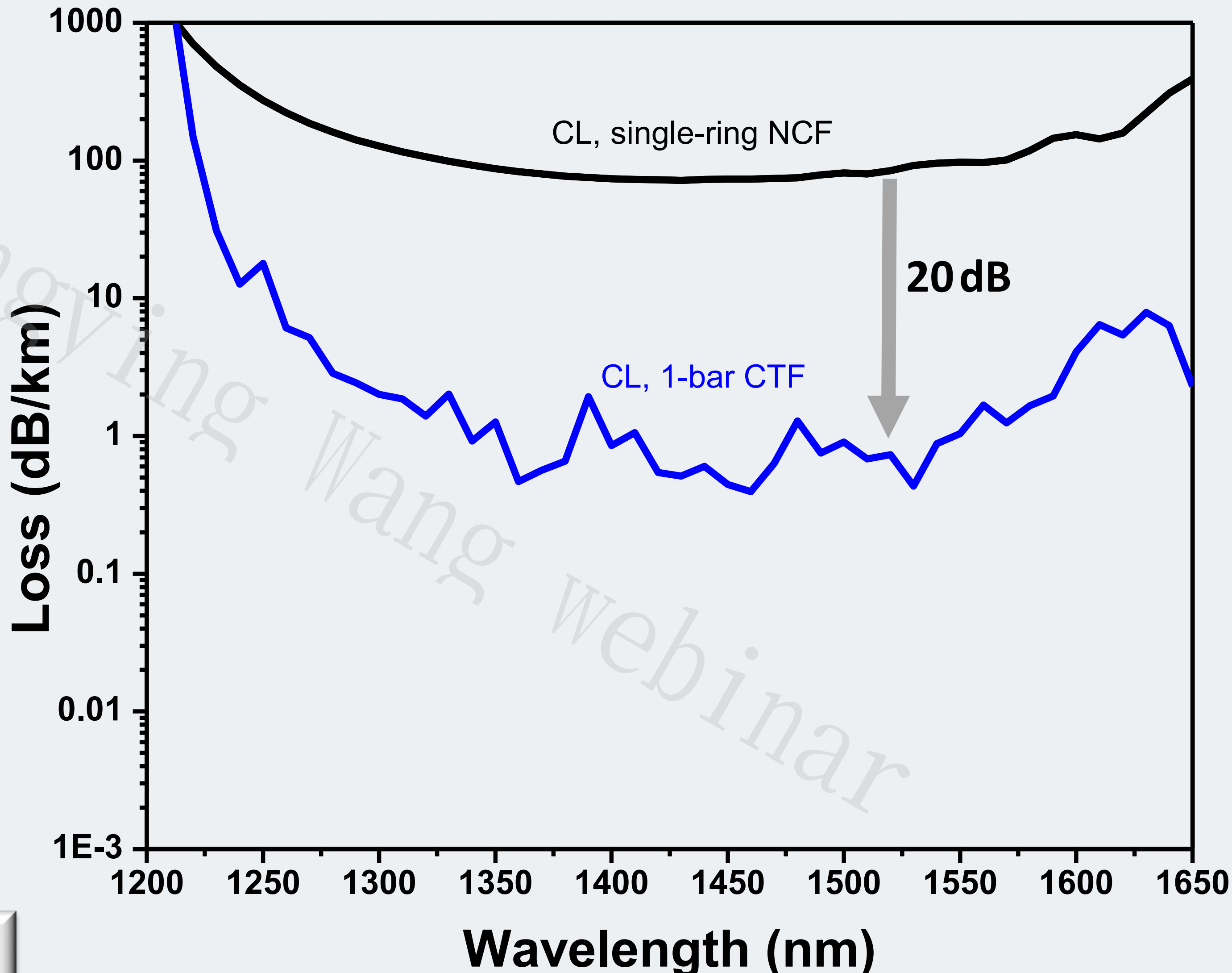
Ultralow loss conjoined-tube NCF

◆ **Simulation results**



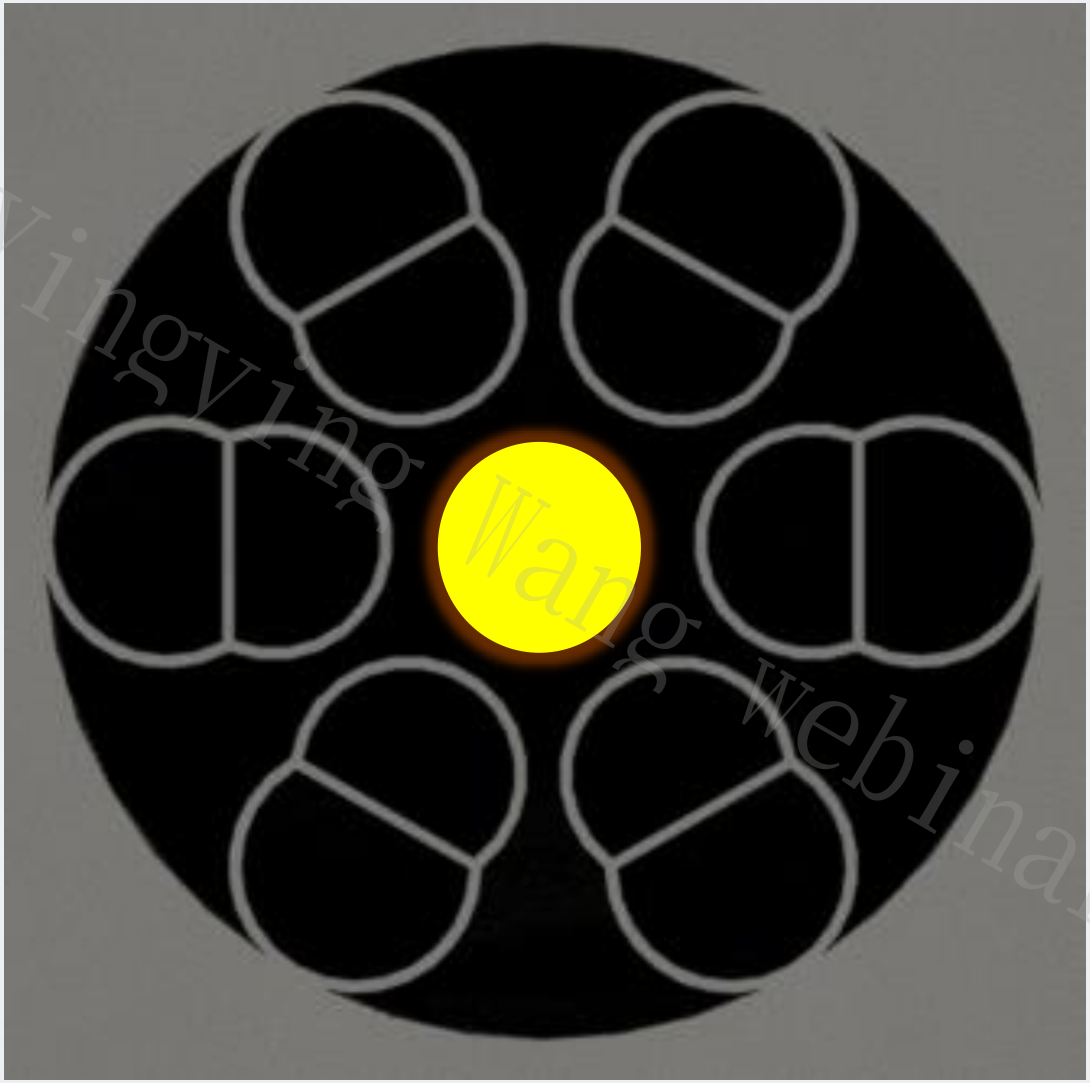


D= 30 µm t=1.12 µm



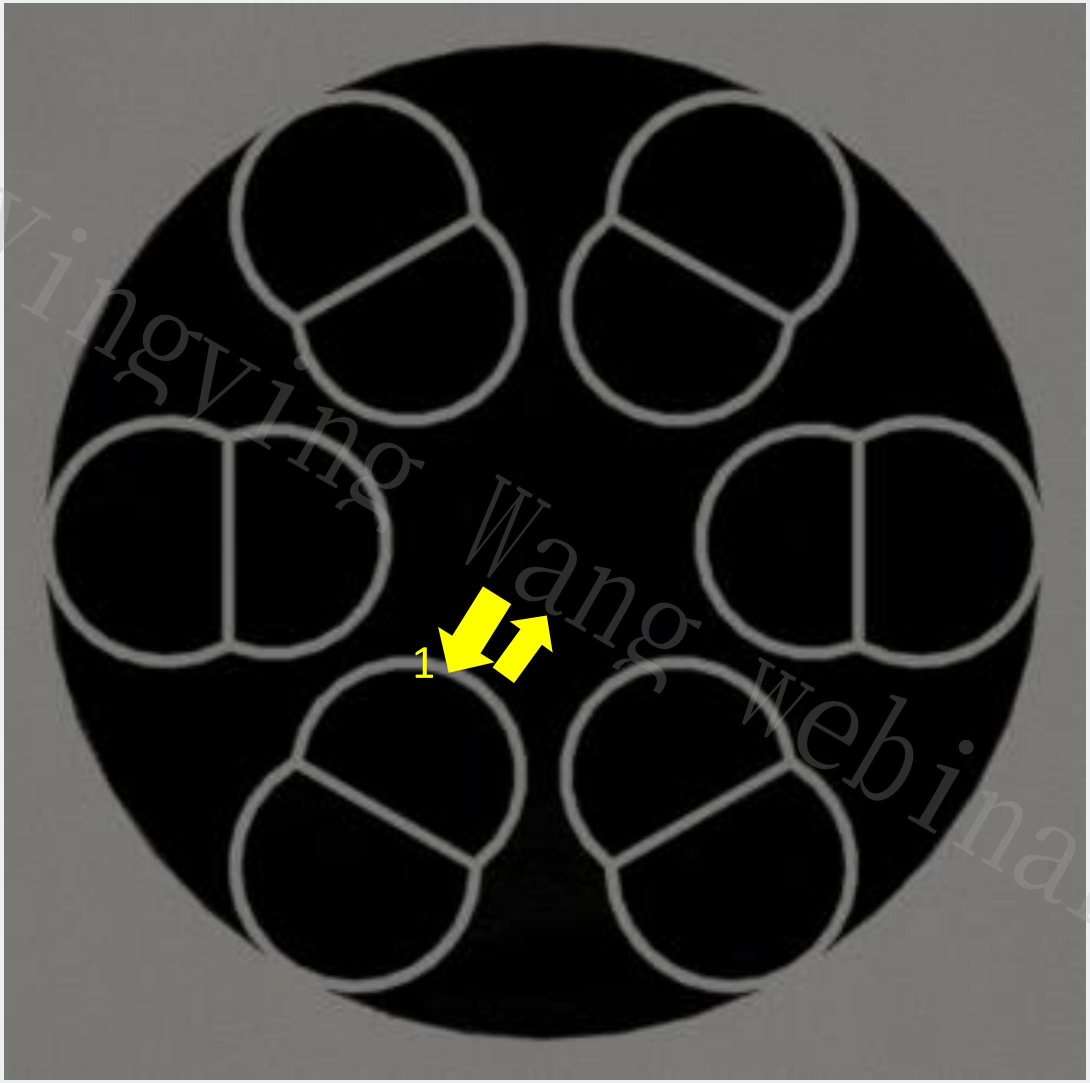
Shou-fei Gao, Nature Communication, 9, 2828 (2018).

Ultralow loss conjoined-tube NCF



Multi-layered model for NCF

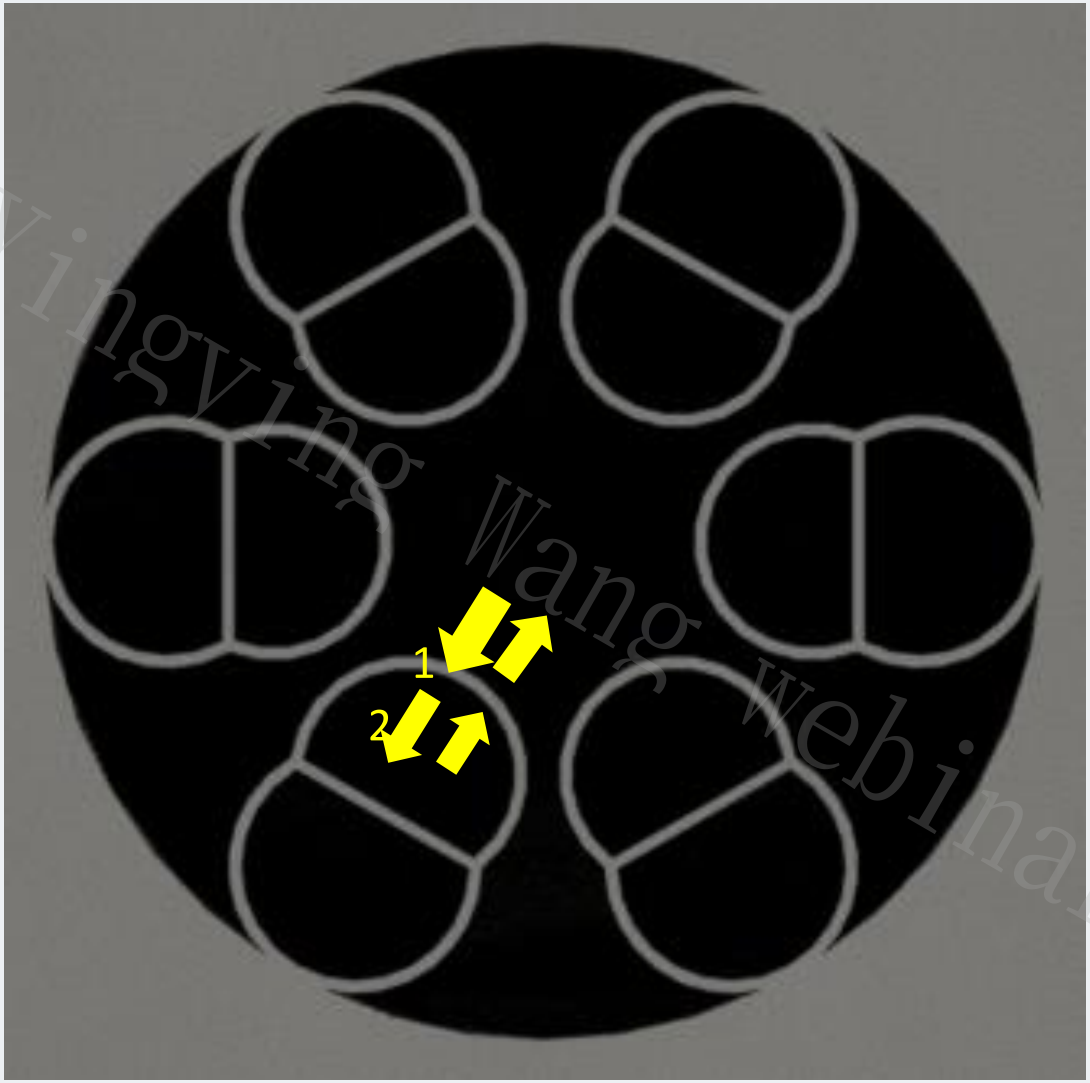
Yingying Wang, *Wei Ding*, Opt. Express 25, 33122 (2017)



Multi-layered model for NCF

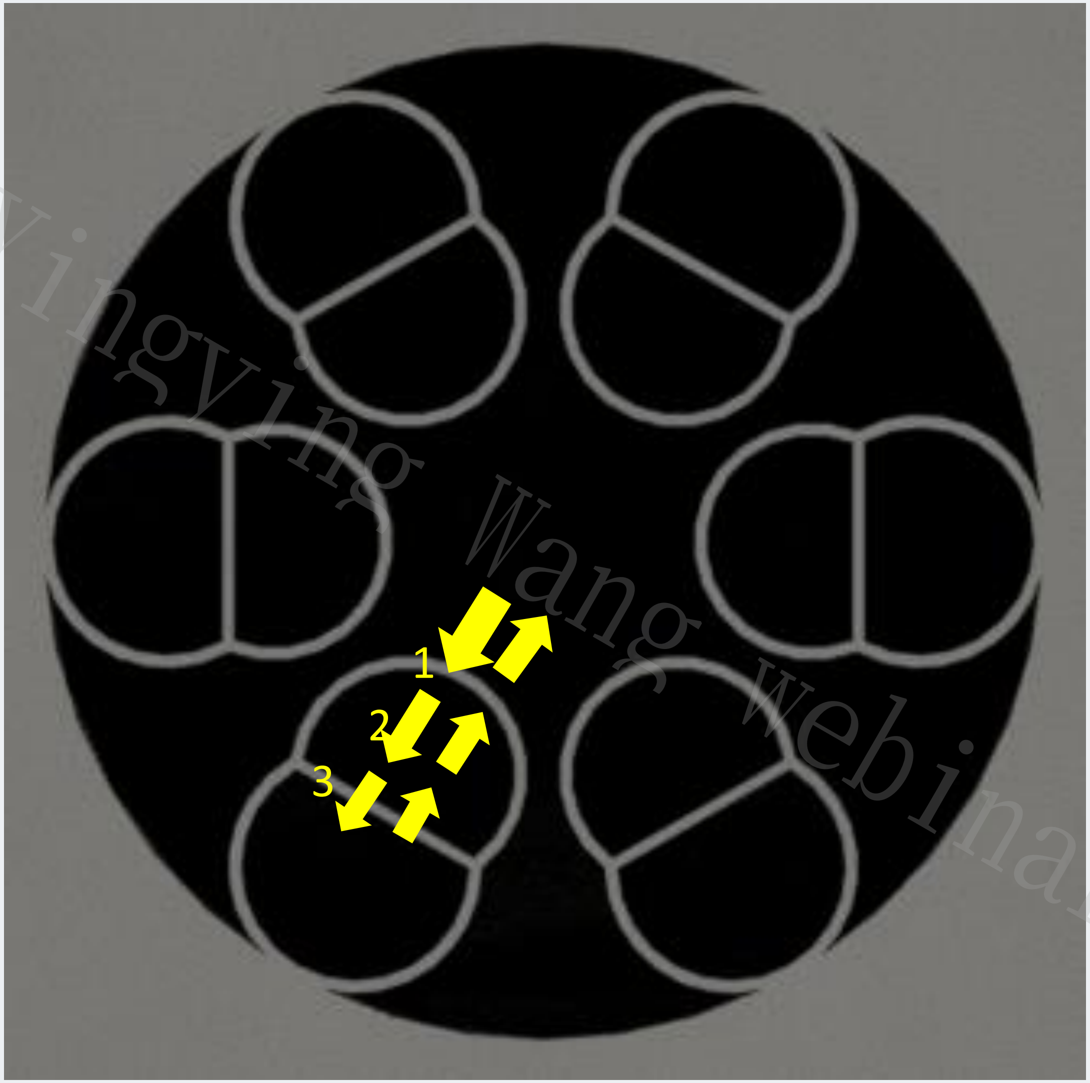
Yingying Wang, *Wei Ding*, Opt. Express 25, 33122 (2017)

Ultralow loss conjoined-tube NCF



Multi-layered model for NCF

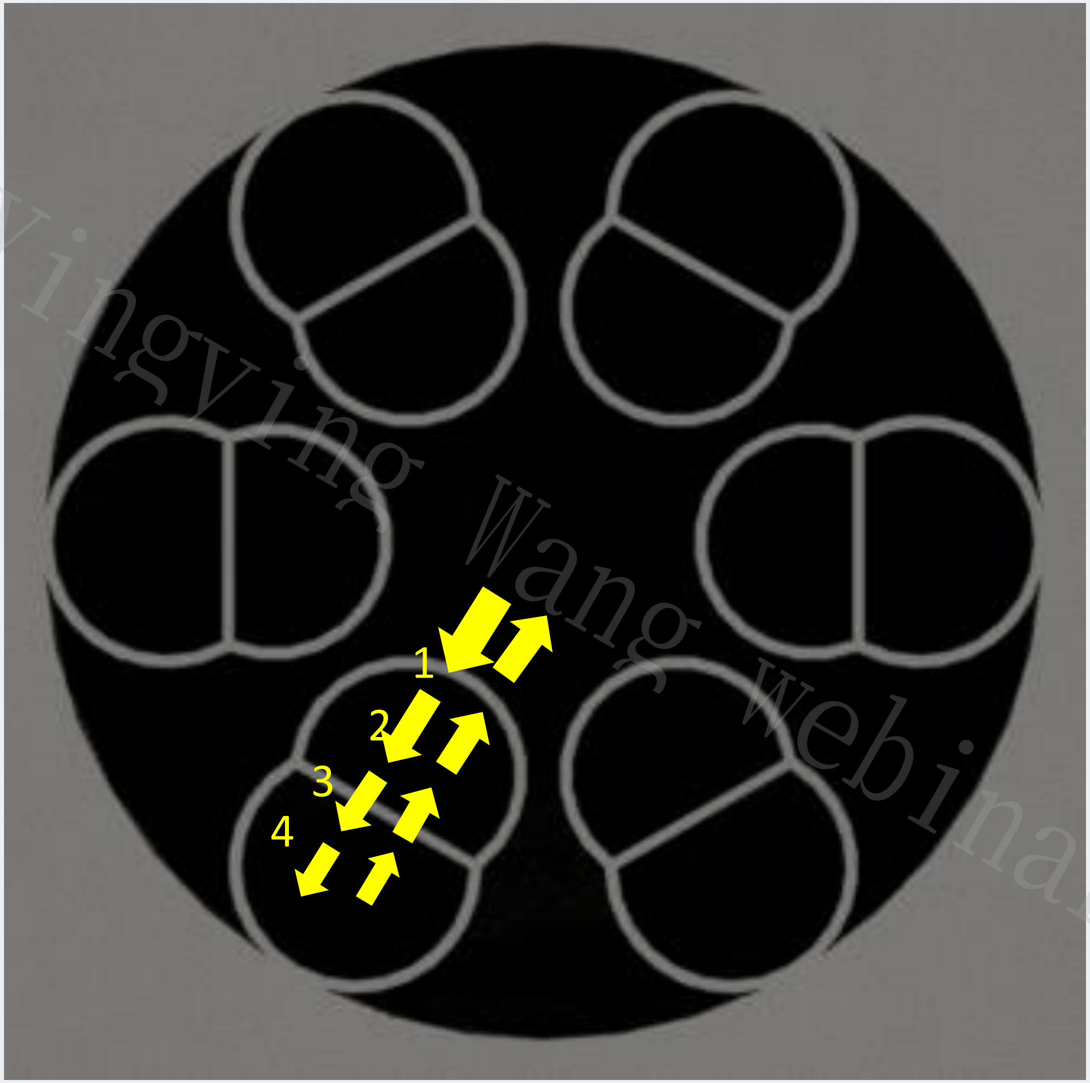
Ultralow loss conjoined-tube NCF



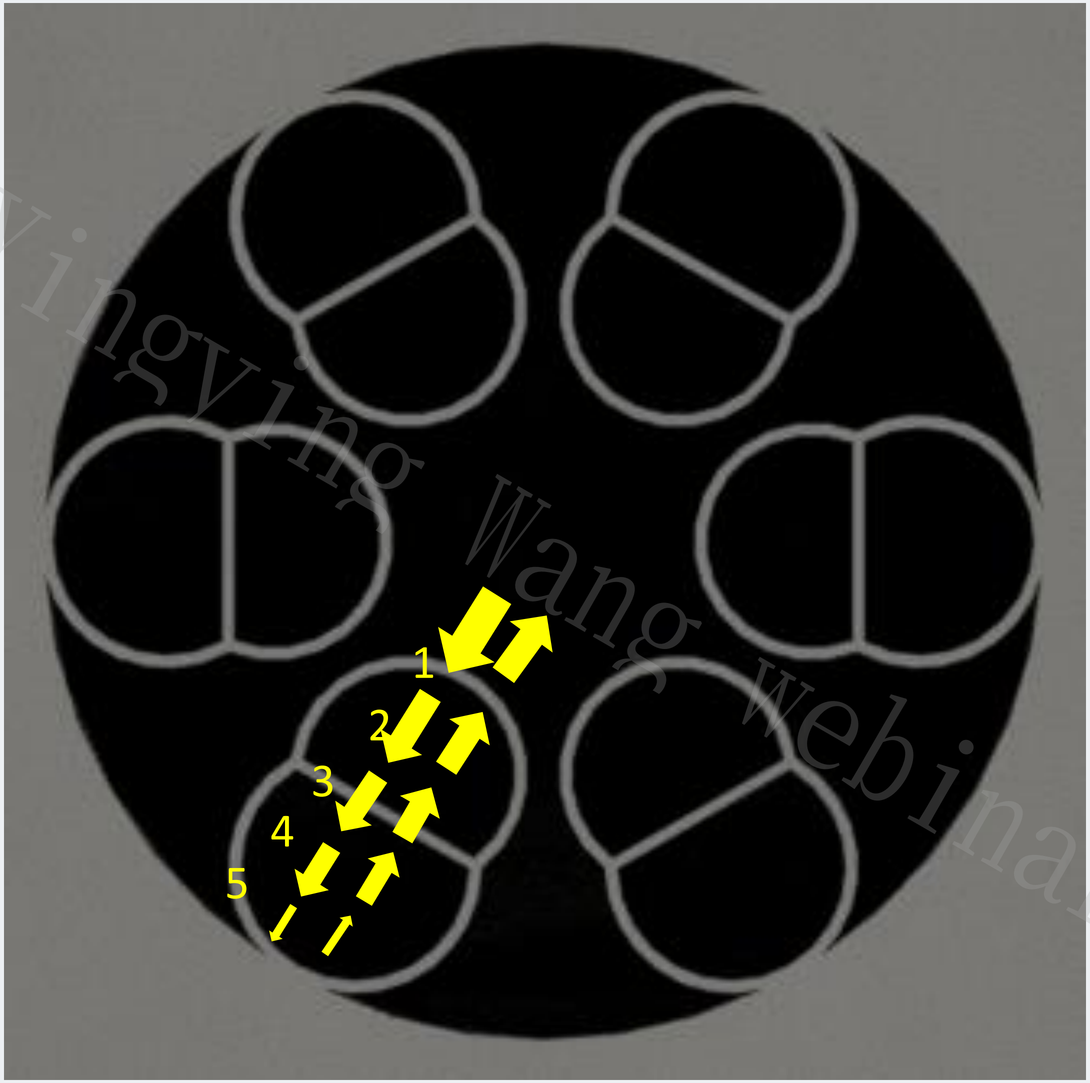
Multi-layered model for NCF

Yingying Wang, *Wei Ding*, Opt. Express 25, 33122 (2017)

Ultralow loss conjoined-tube NCF

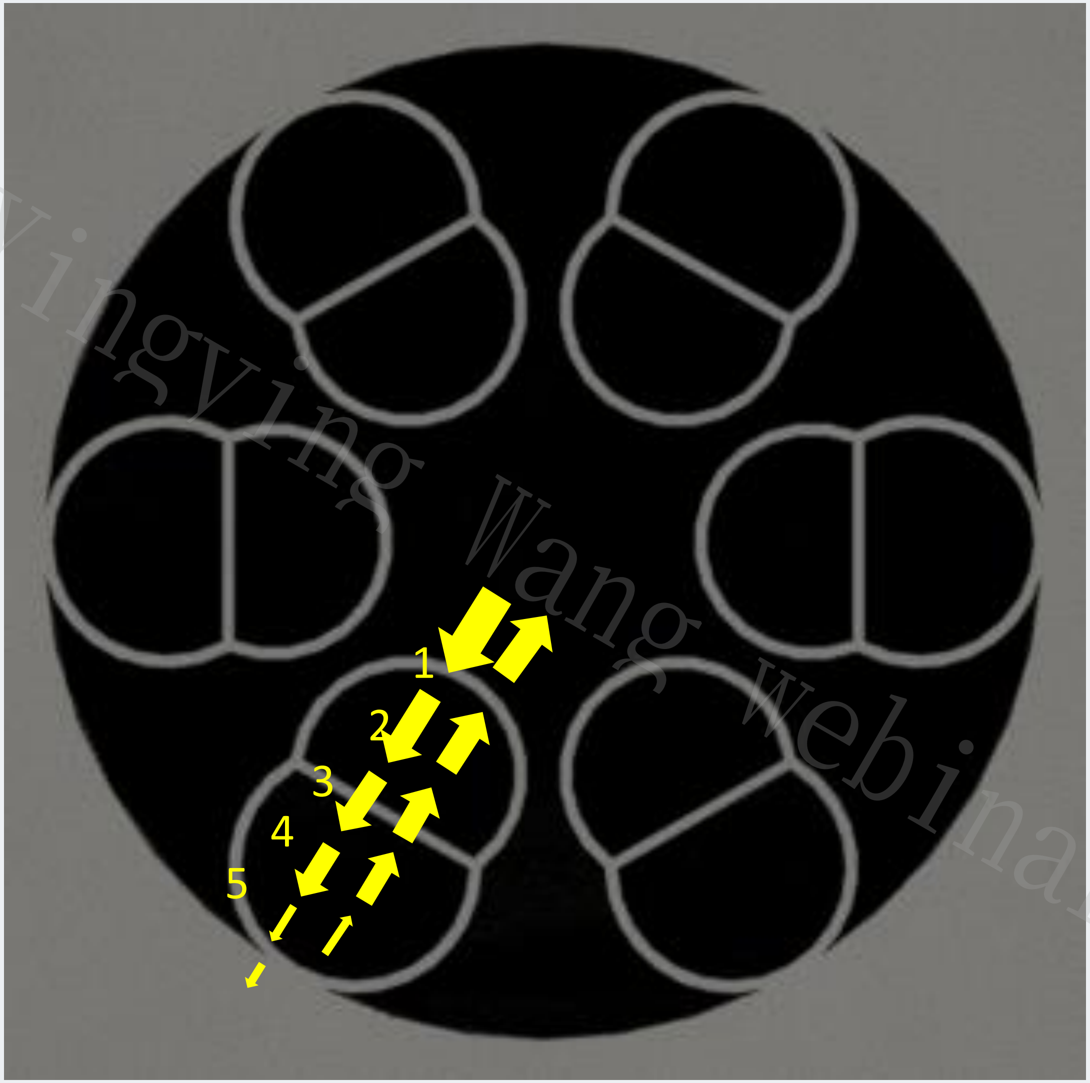


Multi-layered model for NCF



Multi-layered model for NCF

Yingying Wang, *Wei Ding*, Opt. Express 25, 33122 (2017)

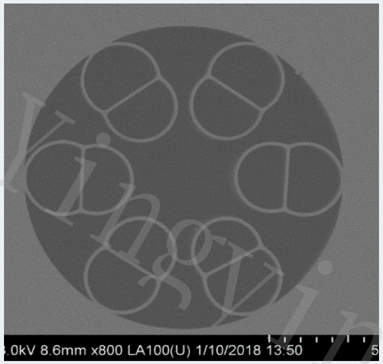


Multi-layered model for NCF

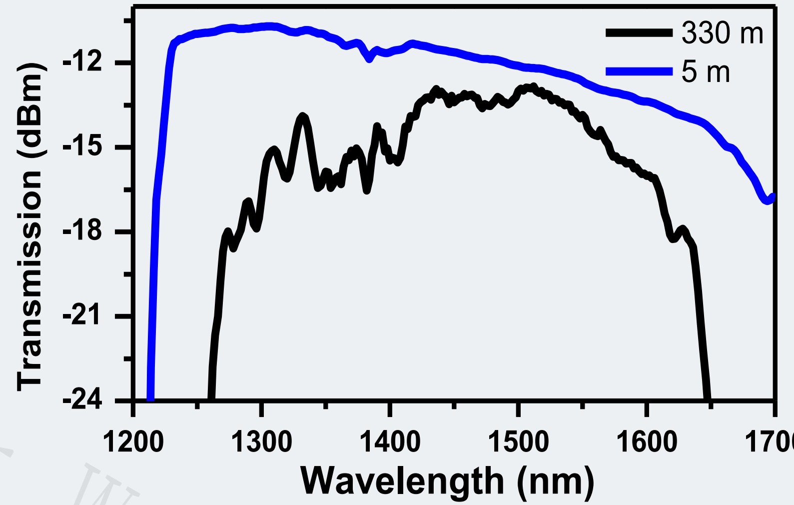
Yingying Wang, *Wei Ding*, Opt. Express 25, 33122 (2017)

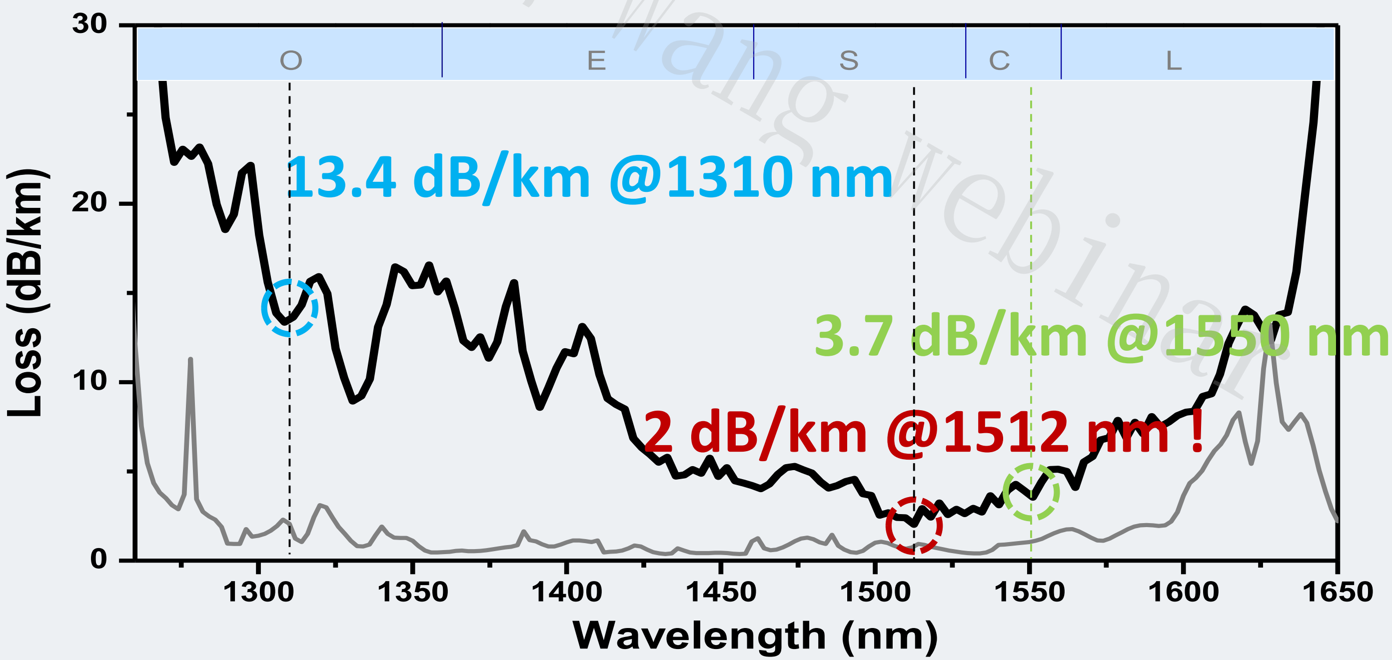
Ultralow loss conjoined-tube NCF

① Measured loss



D= 30 µm, t=1.12 µm

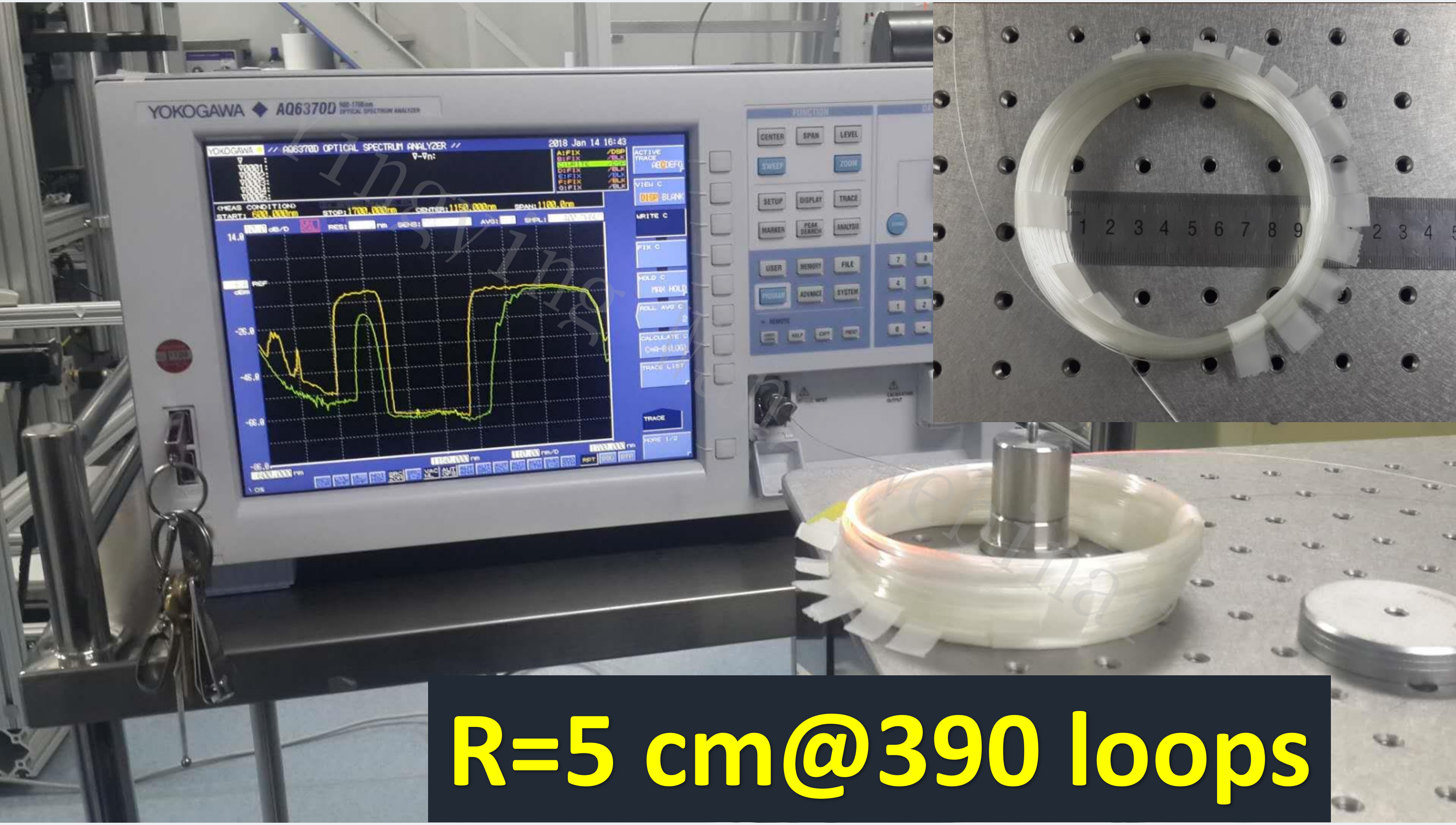




Shou-fei Gao et al, Nature Communication, 9, 2828 (2018).

Ultralow loss conjoined-tube NCF

② Measured bending loss

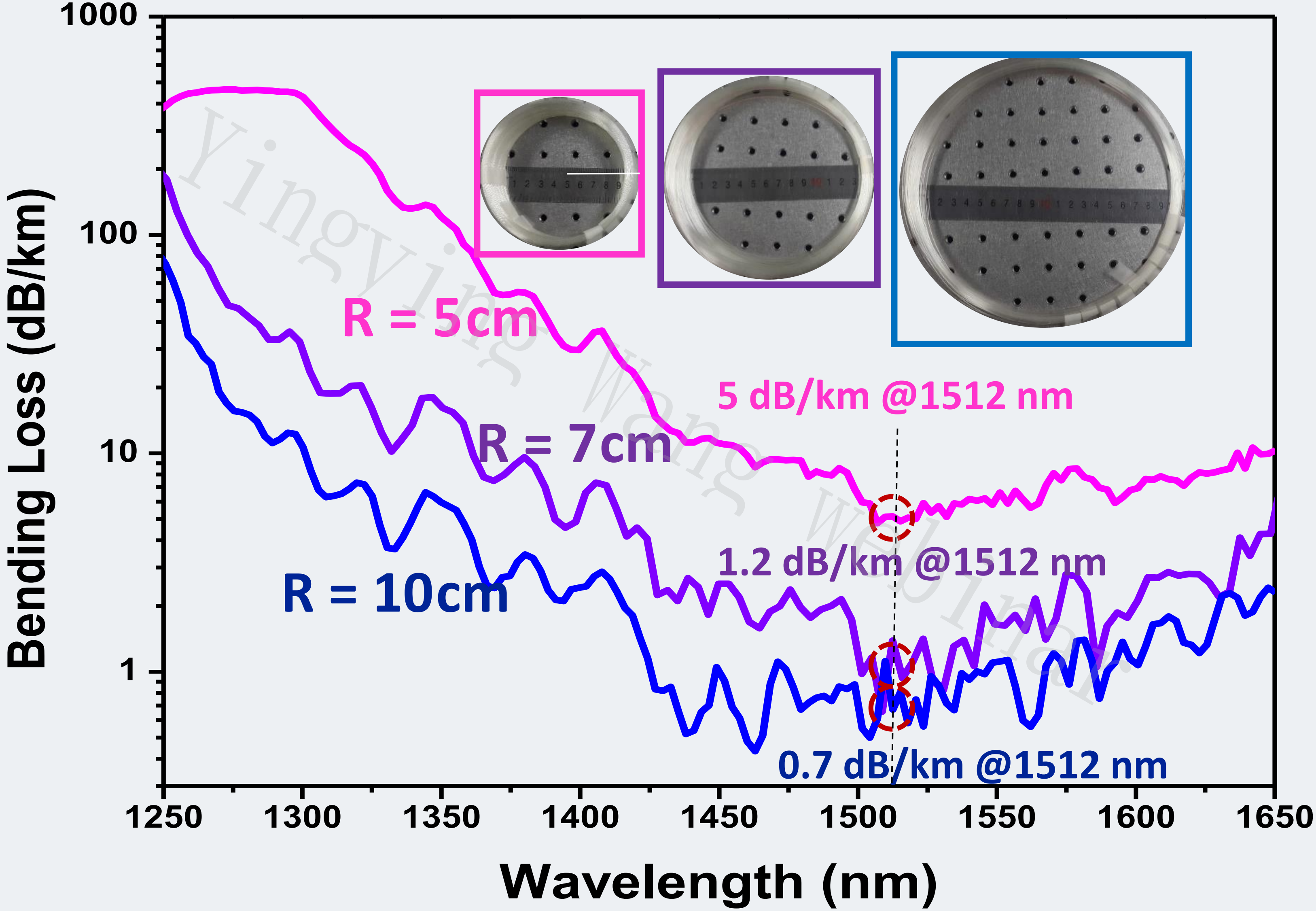


R=5 cm@390 loops

Shou-fei Gao et al, Nature Communication, 9, 2828 (2018).

Ultralow loss conjoined-tube NCF

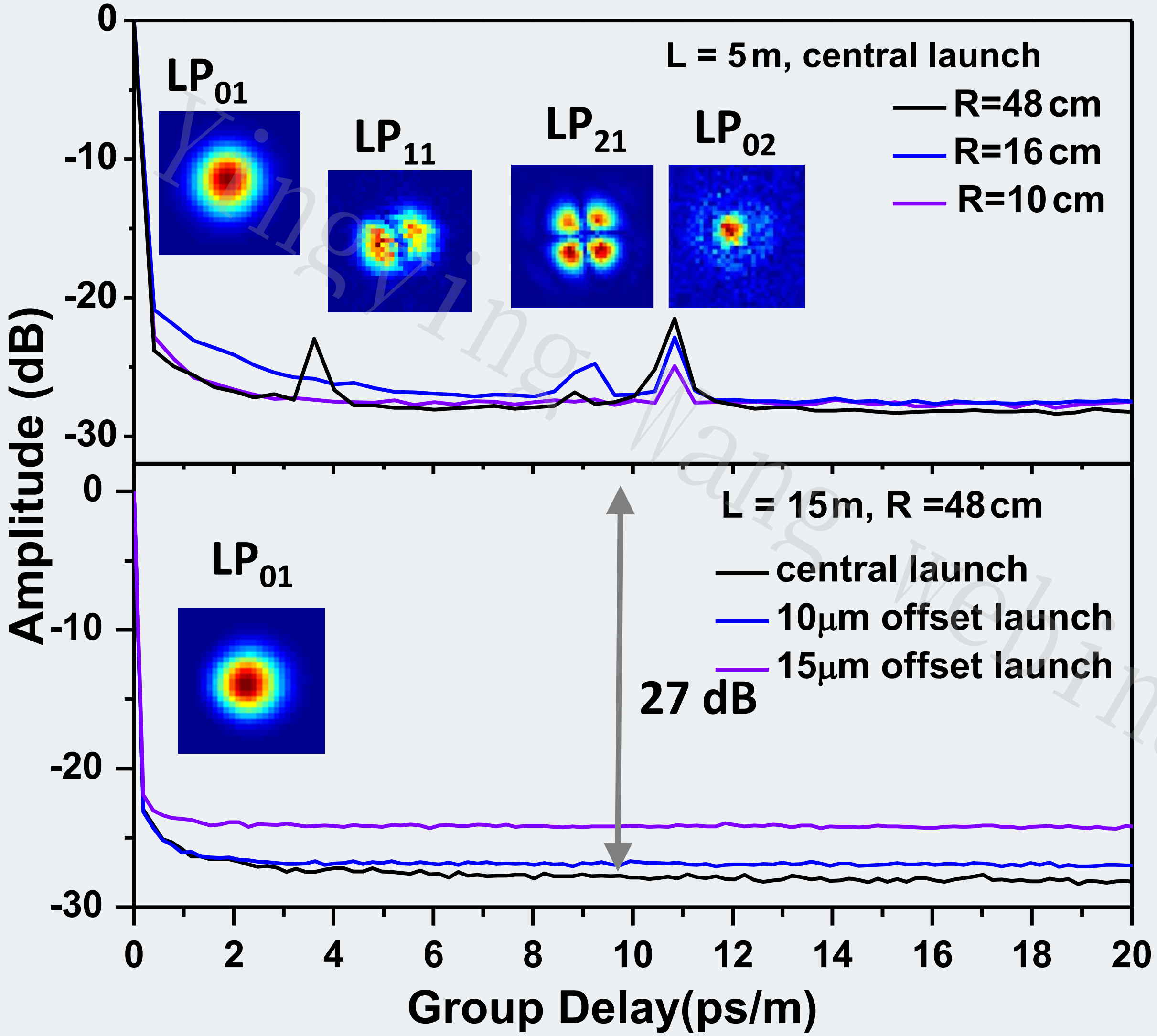
② **Measured bending loss**

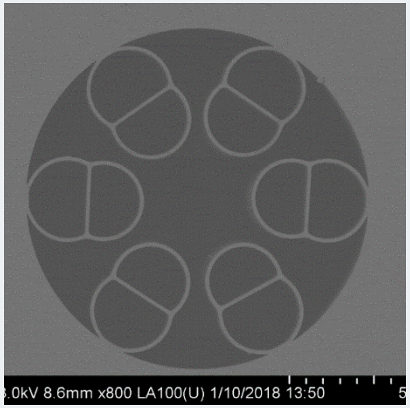


Shou-fei Gao et al, Nature Communication, 9, 2828 (2018).

Ultralow loss conjoined-tube NCF

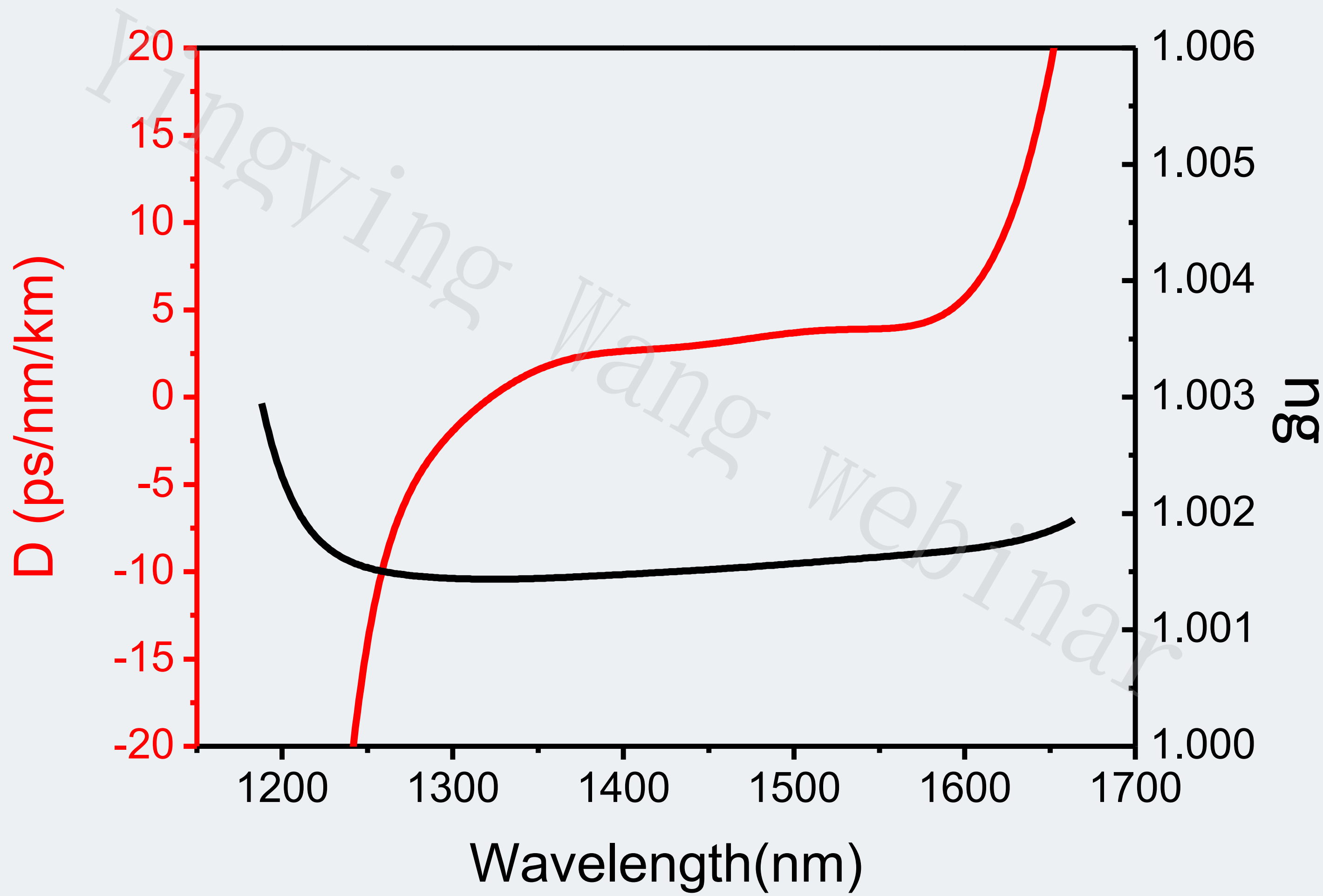
③ **Mode quality (S^2 measurement)**





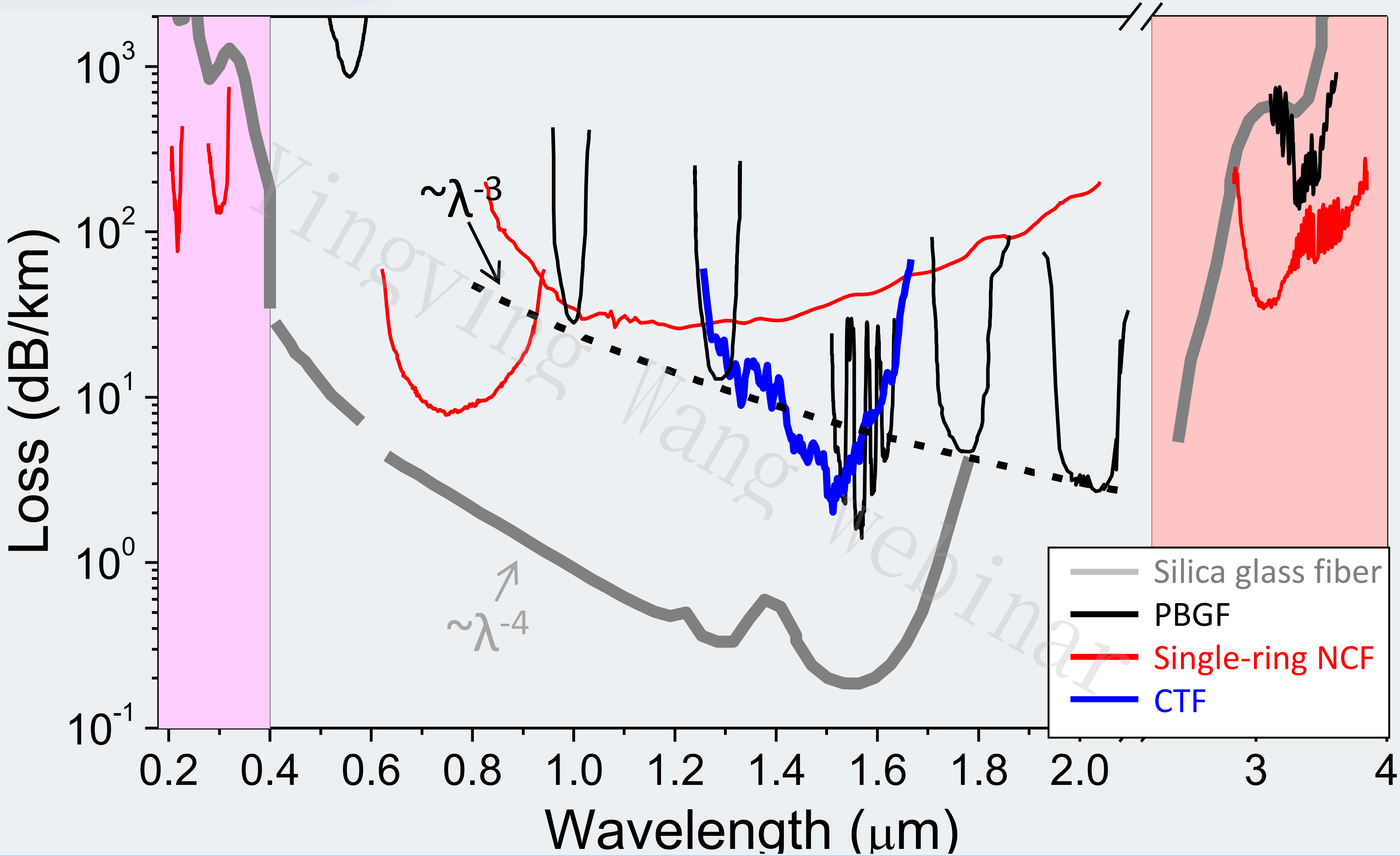
Shou-fei Gao et al, Nature Communication, 9, 2828 (2018).

④ **Dispersion**



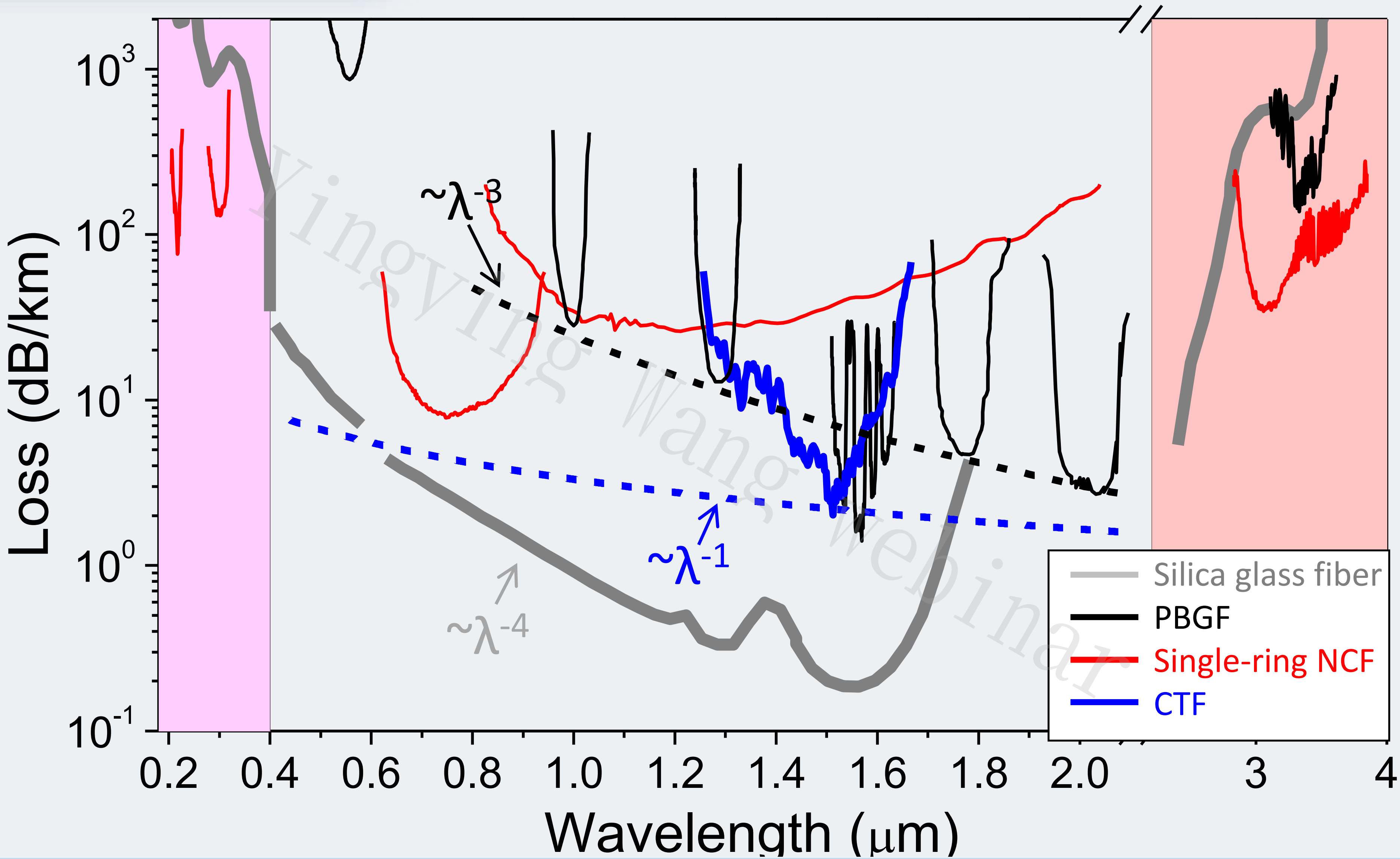
Shou-fei Gao et al, Nature Communication, 9, 2828 (2018).

Loss achieved in HC-NCF



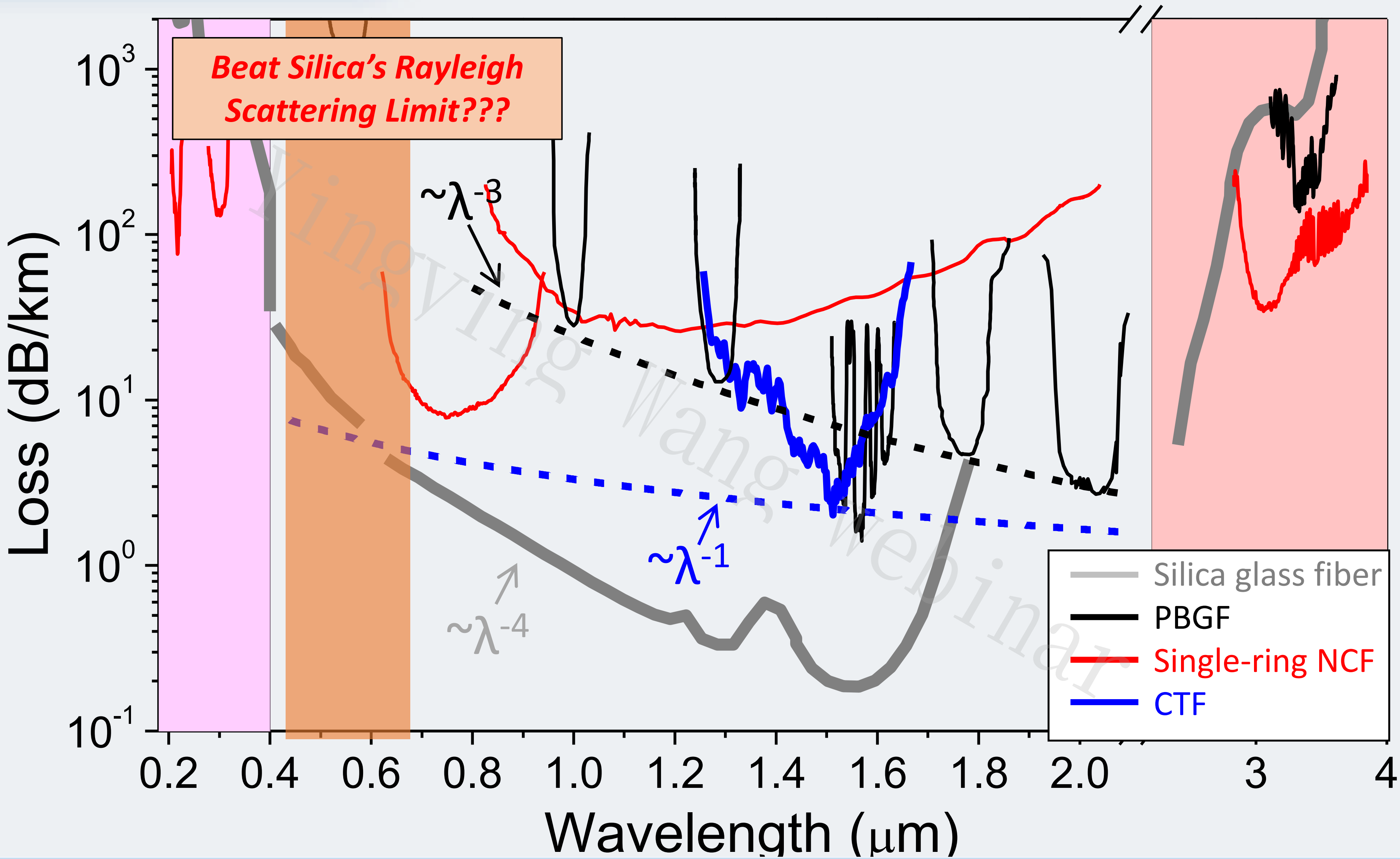
G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al*, OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017), S. Gao et al, OL, 43, 1347, 2018. F. Yu et al, OE. 26, 10879, 2018, S. Gao et al, Nat. Commun, 9, 2828 (2018).

Loss achieved in HC-NCF



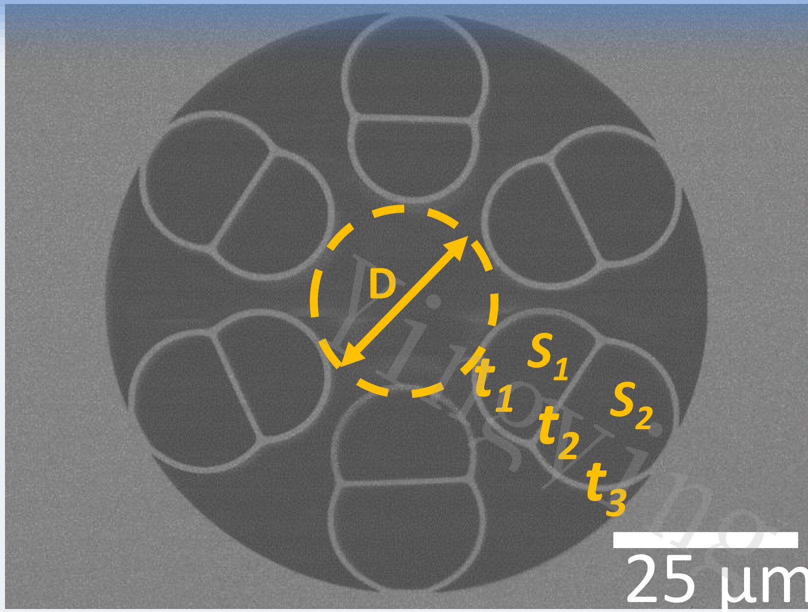
G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al*, OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017), S. Gao et al, OL, 43, 1347, 2018. F. Yu et al, OE. 26, 10879, 2018, S. Gao et al, Nat. Commun, 9, 2828 (2018).

Loss achieved in HC-NCF



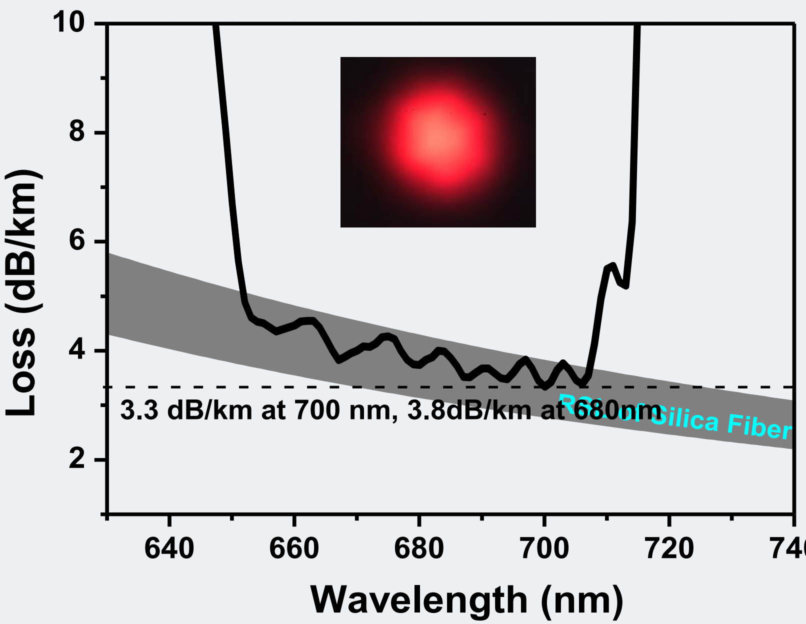
G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al*, OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017), S. Gao et al, OL, 43, 1347, 2018. F. Yu et al, OE. 26, 10879, 2018, S. Gao et al, Nat. Commun, 9, 2828 (2018).

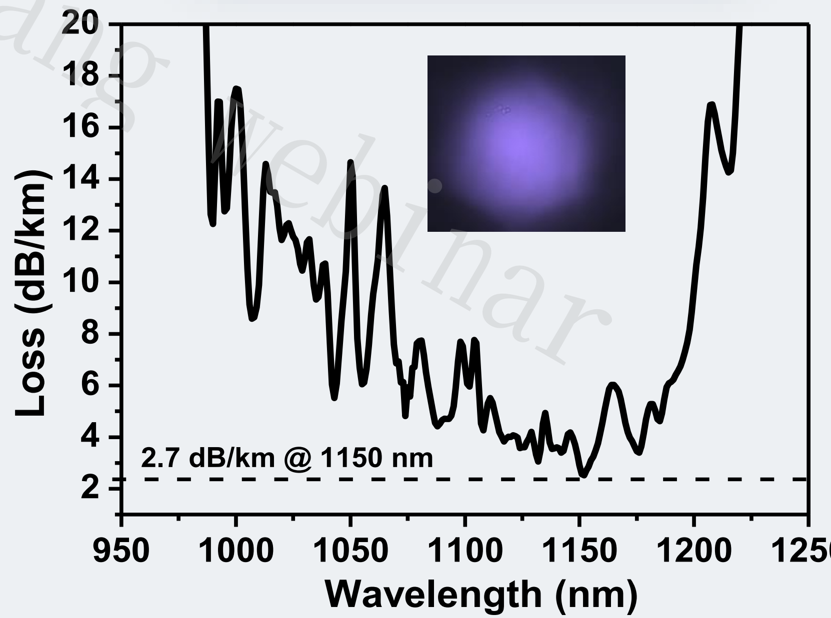
Ultralow loss conjoined-tube NCF



Parameters

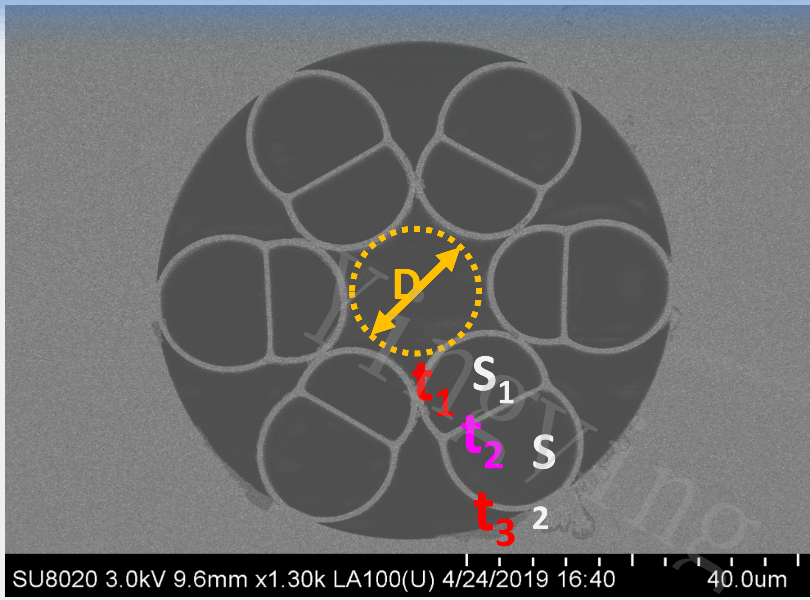
1. D= 25 µm
2. t_1=0.84 µm
3. t_2=0.74 µm
4. t_3=0.83 µm
5. S_1 = 182 µm^2
6. S_2 = 223 µm^2





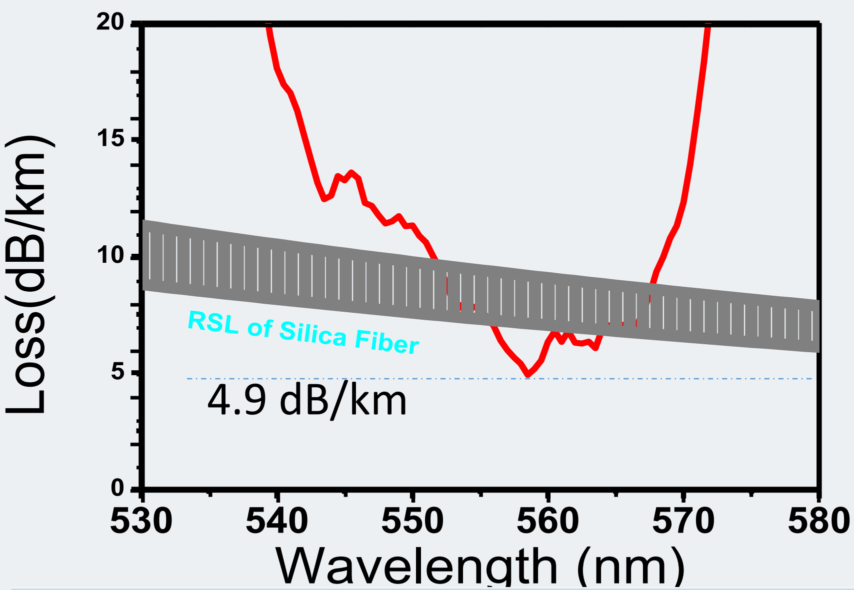
Shoufei Gao, Conquering the Rayleigh scattering limit of silica glass fiber at visible wavelengths with a hollow-core fiber approach, *Laser and photonics review*, in production

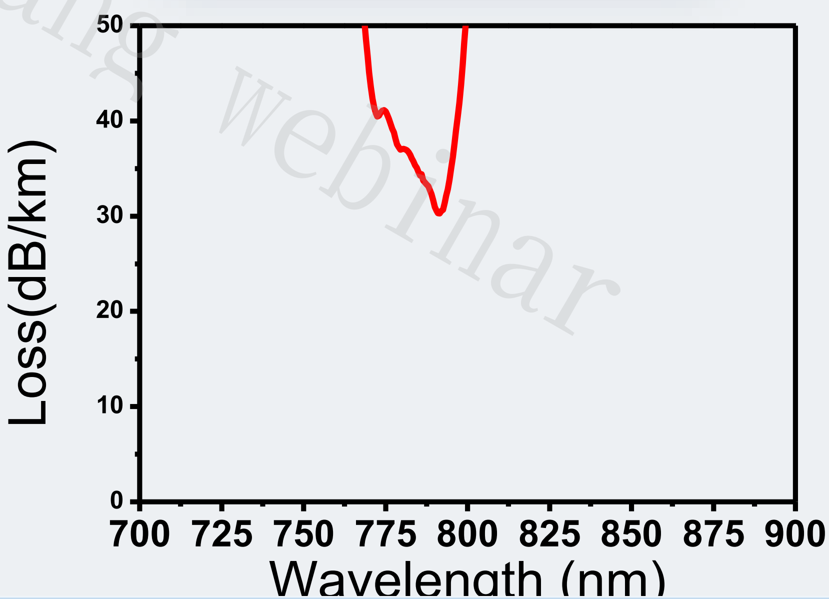
Ultralow loss conjoined-tube NCF



Parameters

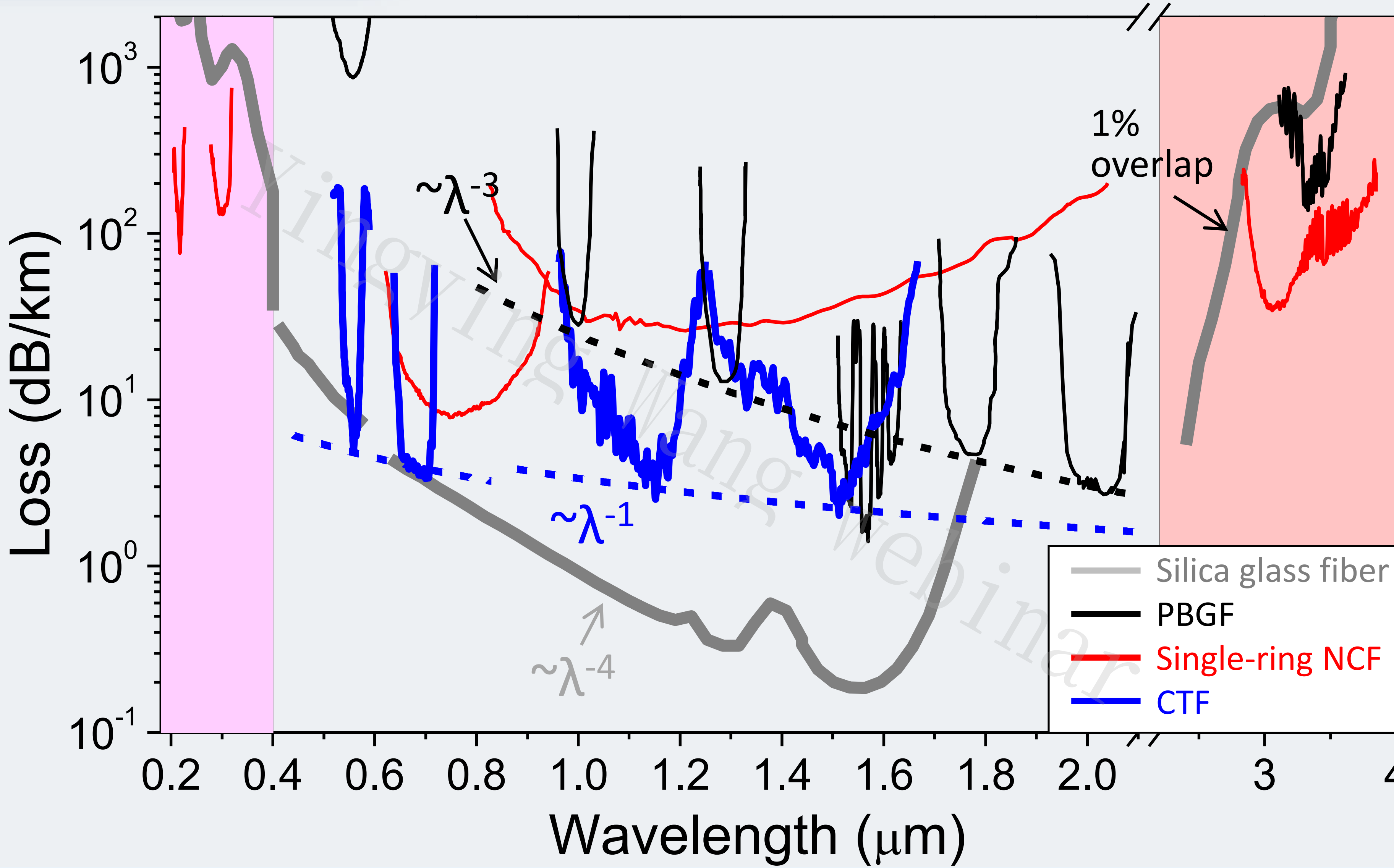
1. D= 20 µm
2. t_1=0.9 µm
3. t_2=0.685 µm
4. t_3=0.833 µm
5. S_1 = 164 μm^2
6. S_2 = 251 μm^2





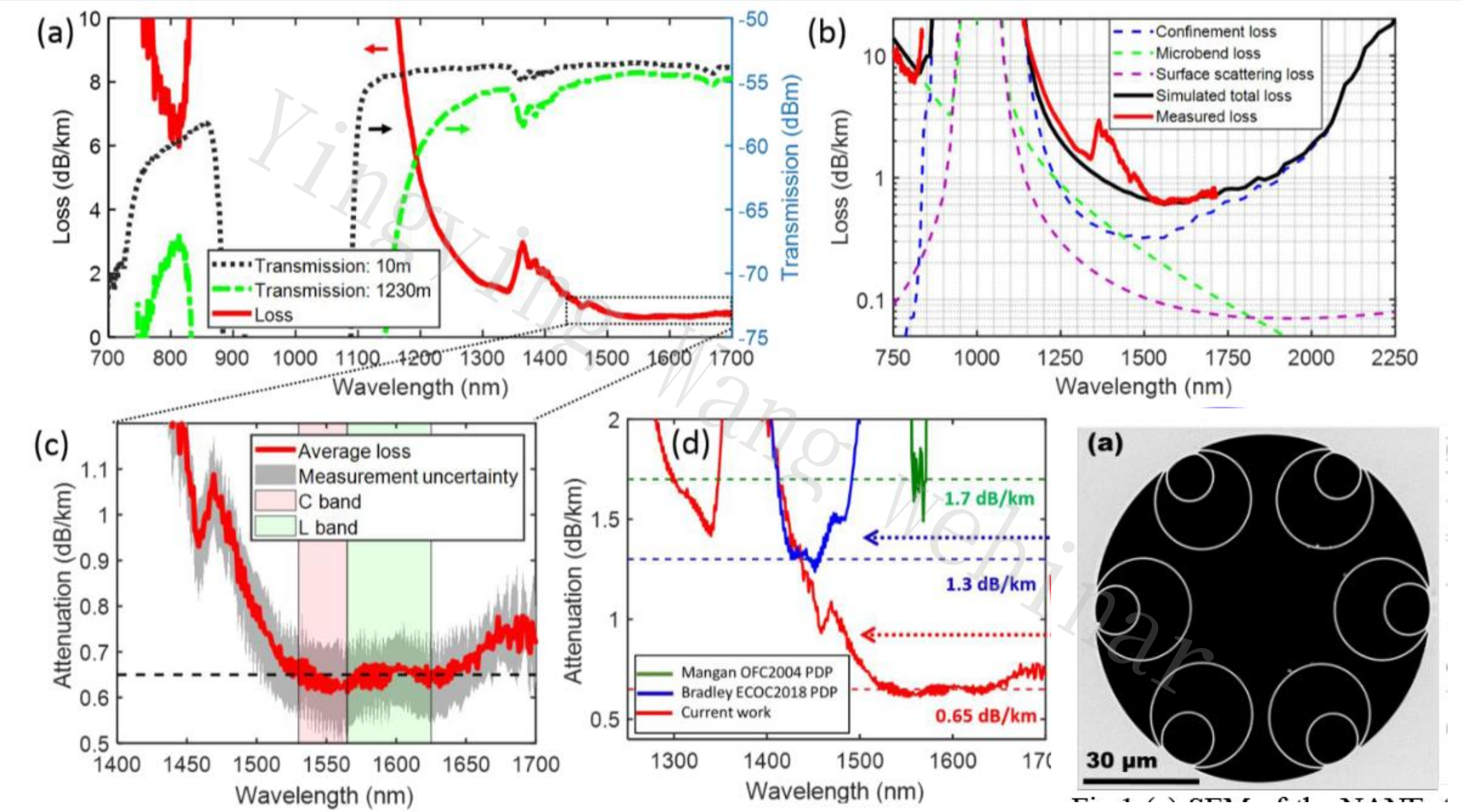
Shoufei Gao, Conquering the Rayleigh scattering limit of silica glass fiber at visible wavelengths with a hollow-core fiber approach, *Laser and photonics review*, in prduction

Loss achieved in HC-NCF



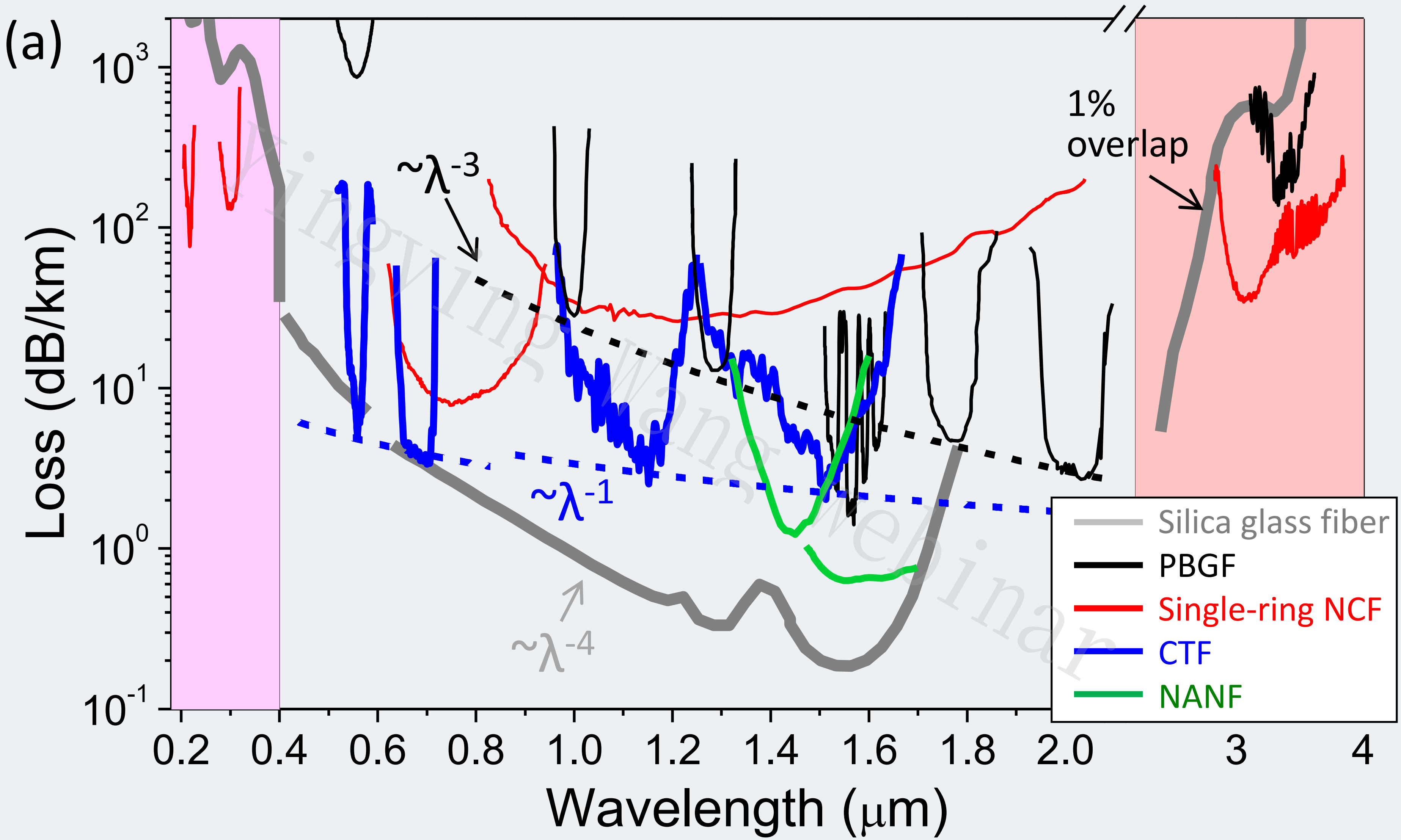
G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al*, OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017), S. Gao et al, OL, 43, 1347, 2018. F. Yu et al, OE. 26, 10879, 2018, S. Gao et al, Nat. Commun, 9, 2828 (2018).

Latest Results: 0.65 dB/km at C and L band



T. D. Bradley, Antiresonant Hollow Core Fibre with 0.65 dBkm Attenuation across the C and L Telecommunication Bands, ECOC PDP 2019

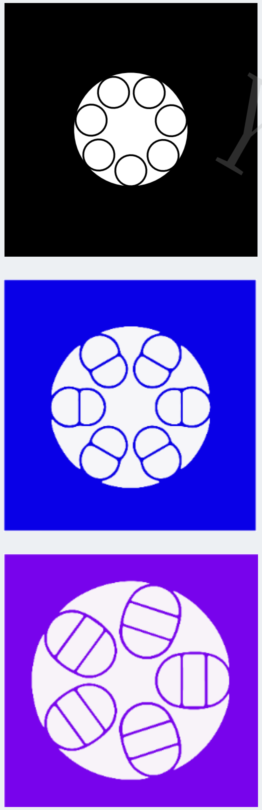
Loss achieved in HC-NCF



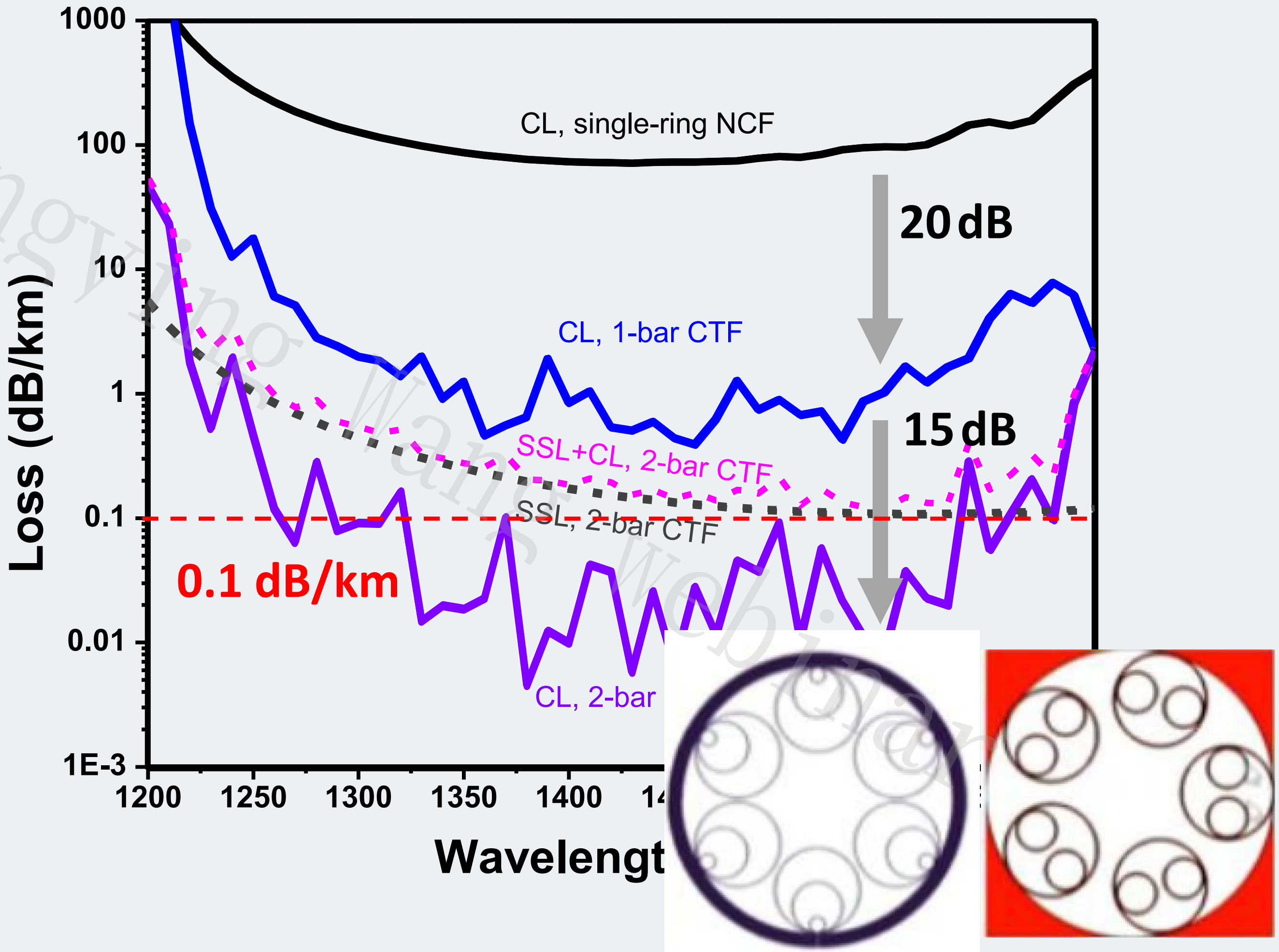
G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al*, OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017), S. Gao et al, OL, 43, 1347, 2018. F. Yu et al, OE. 26, 10879, 2018, S. Gao et al, Nat. Commun, 9, 2828 (2018). T. D. Bradley, ECOC PDP 2018, 2019

Ultralow loss conjoined-tube NCF

◆ ***Further optimization?***

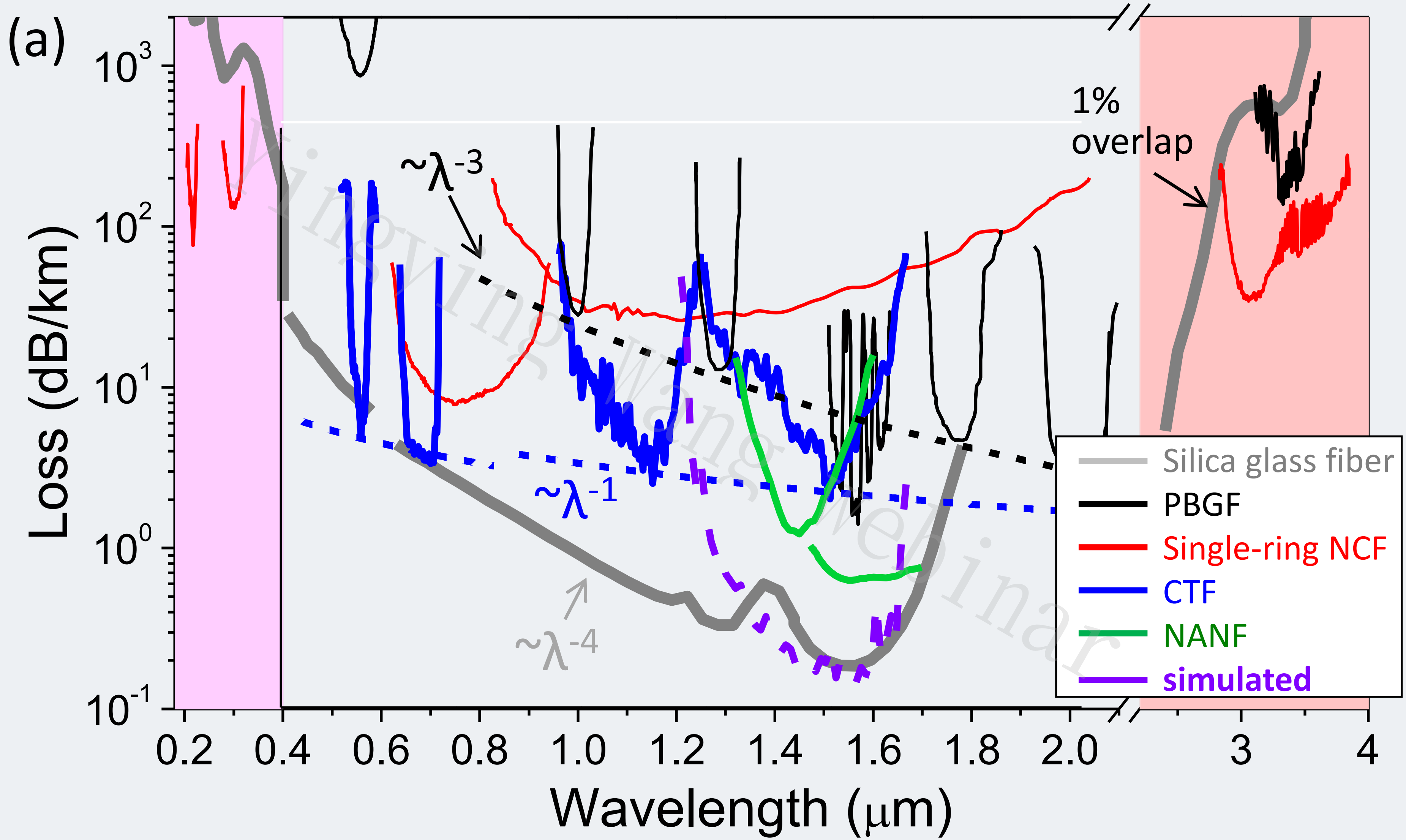


D= 30 µm



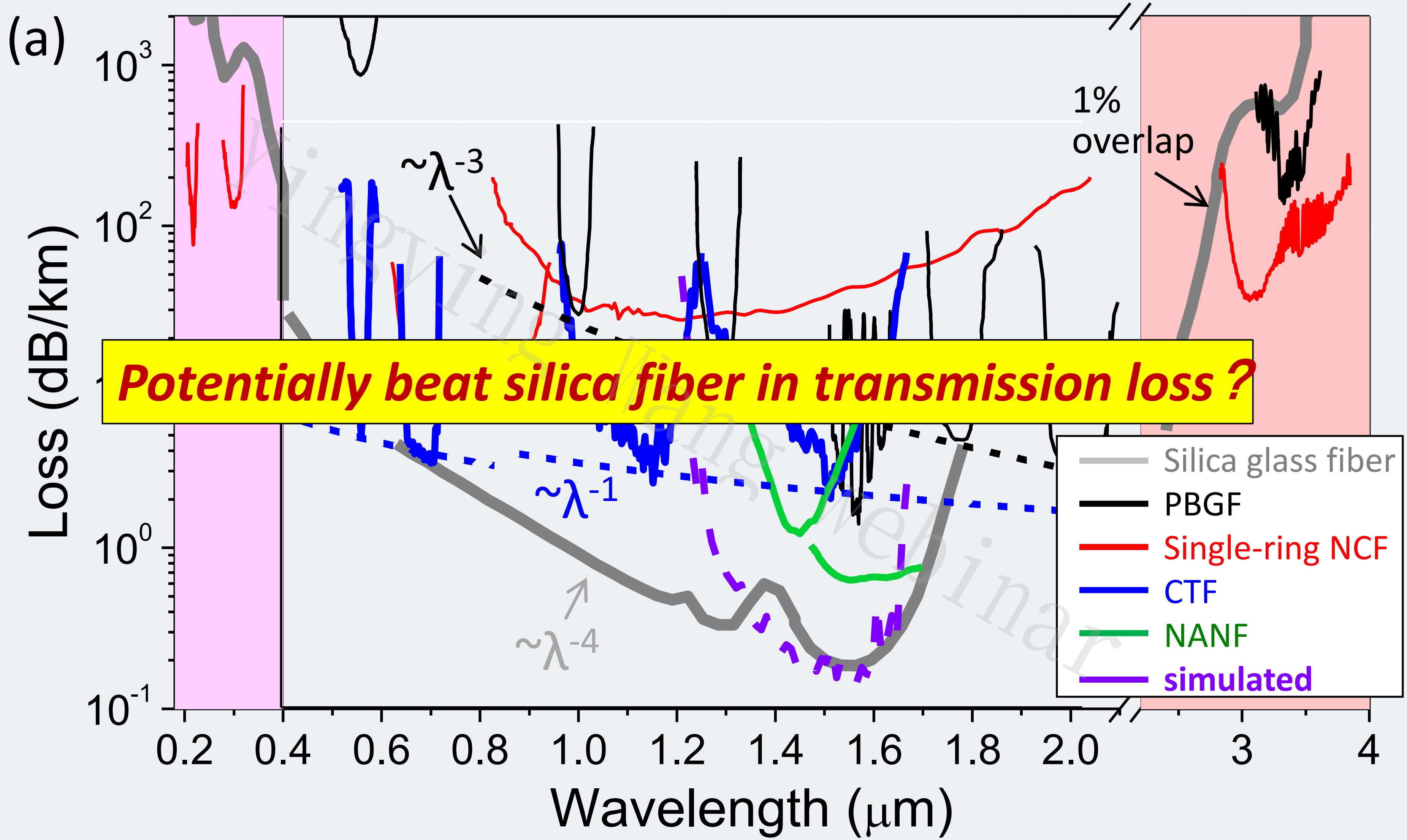
Shou-fei Gao, Ying-ying Wang et al, Nature Communication, 9, 2828 (2018).
F. Poletti, OE, 22, 23807, 2014. Gergory T. Jasion et al, OFC 2019 TH3E.2.

Loss achieved in HC-NCF



G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al*, OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017), S. Gao et al, OL, 43, 1347, 2018. F. Yu et al, OE. 26, 10879, 2018, S. Gao et al, Nat. Commun, 9, 2828 (2018). T. D. Bradley, ECOC PDP 2018, 2019

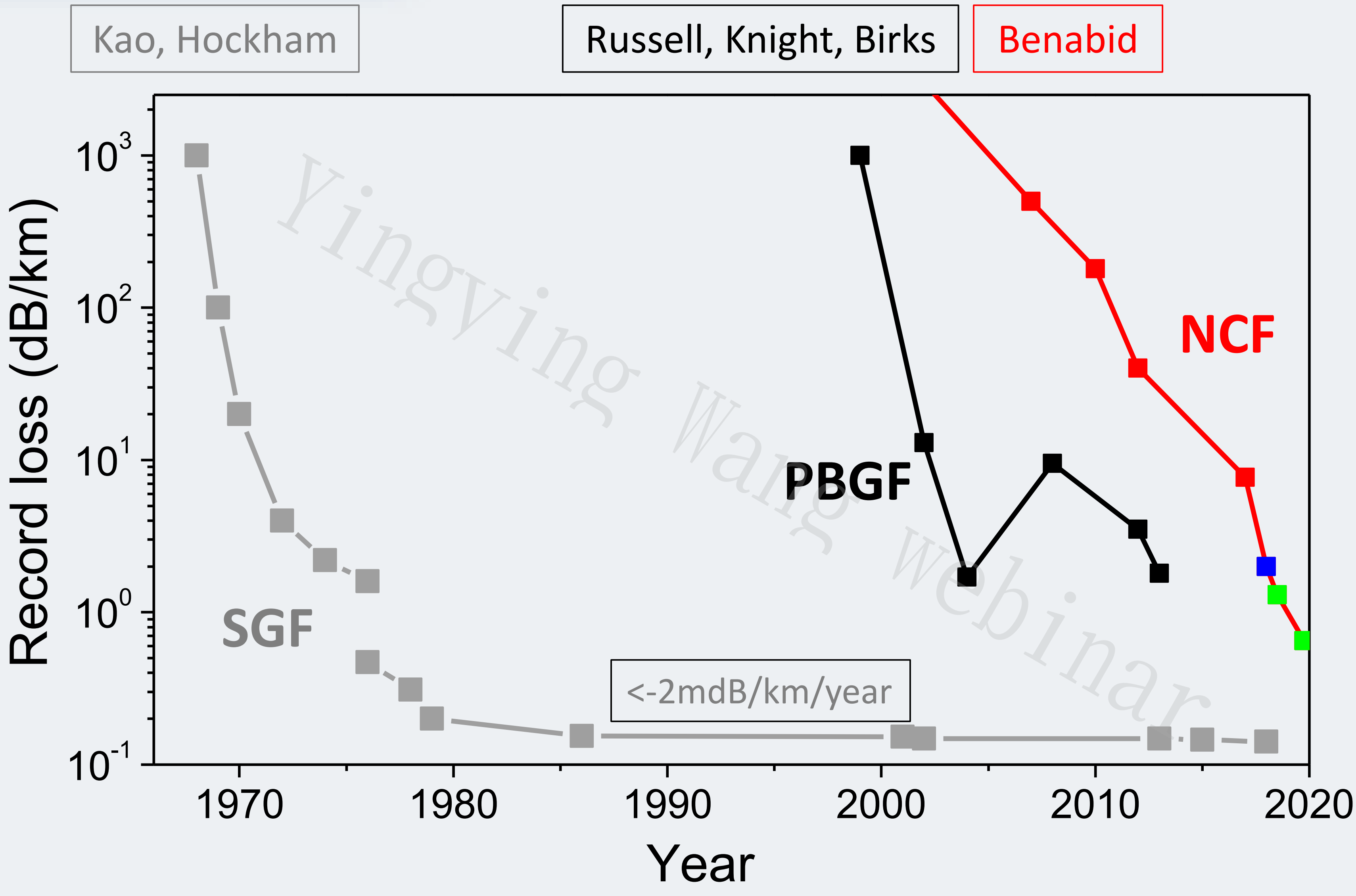
Loss achieved in HC-NCF



Potentially beat silica fiber in transmission loss ?

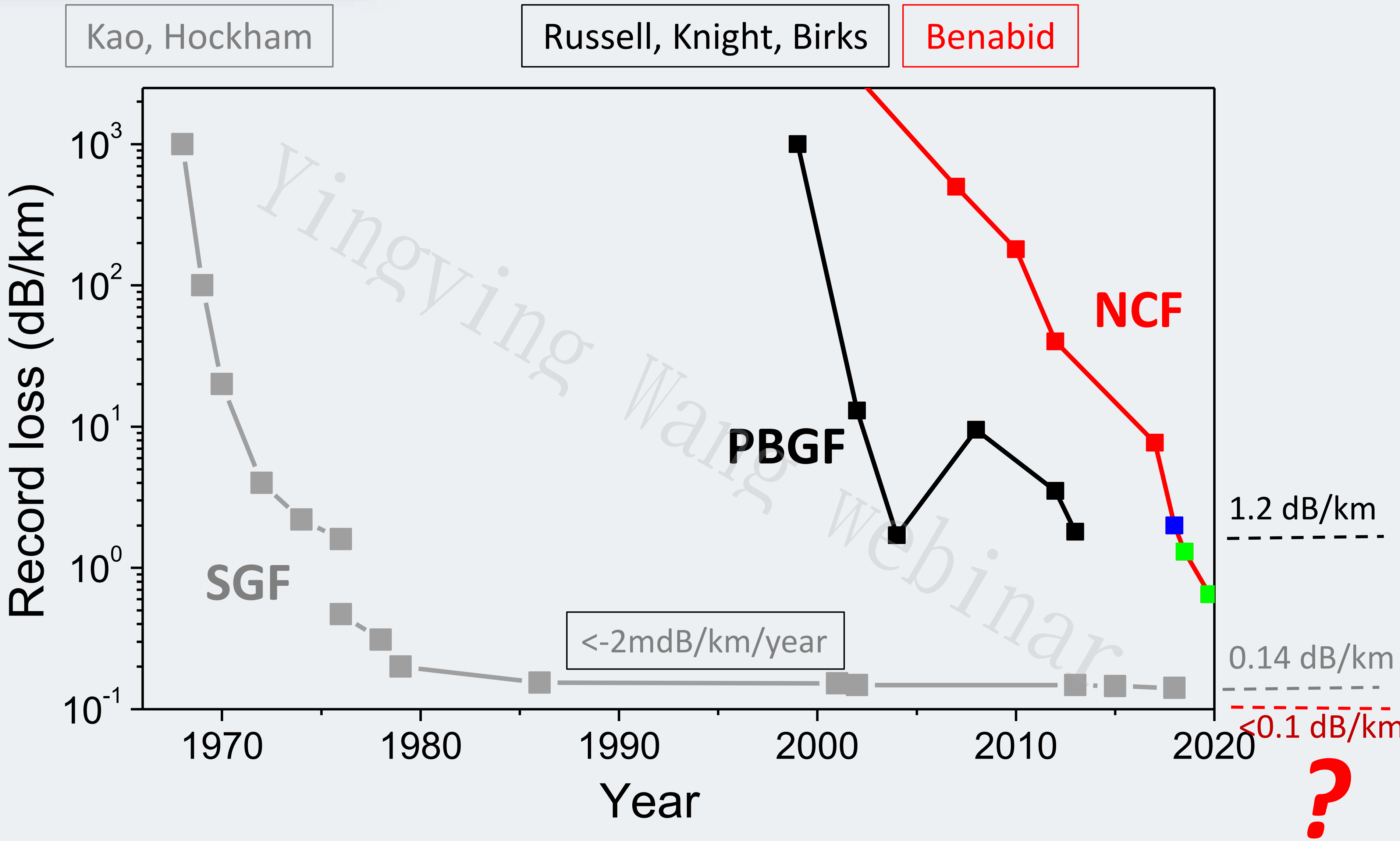
G. P. Agrawal, Nonlinear Fiber Optics. New York: Academic Press, 2001., I. A. Bufetov et al, Fibers, 2018, 6, 39; Mangan BJ *et al*, OFC 2004, PDP 24; Y. Chen et al, OFC 2014, M2F.4; N. V. Wheeler et al, OL, 39, 295, 2014; Debord, B. Optica 4, 209–217 (2017); .Hayes, J. R., JLT 35, 437 (2017), S. Gao et al, OL, 43, 1347, 2018. F. Yu et al, OE. 26, 10879, 2018, S. Gao et al, Nat. Commun, 9, 2828 (2018). T. D. Bradley, ECOC PDP 2018, 2019

Loss Evolution



Wei Ding et al, Ultralow-Loss, Broadband Hollow-Core Anti-Resonant Fiber and its Communication Applications, IEEE Journal of selected topics in quantum electronics, manuscript in revision

Loss Evolution



Wei Ding et al, Ultralow-Loss, Broadband Hollow-Core Anti-Resonant Fiber and its Communication Applications, IEEE Journal of selected topics in quantum electronics, manuscript in revision

1

Background

1. *Motivation*
2. *History of HCF development*

2

HCF – understanding, design and fabrication

1. *How we understand*
2. *Broadband HCF*
3. *Ultralow loss HCF*

3

HCF applications

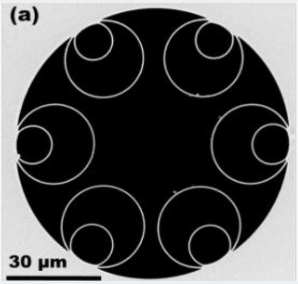
1. *Optical communications*
2. *Ultrafast optics: delivery and gas nonlinearity*
3. *Sensing and biophotonics*

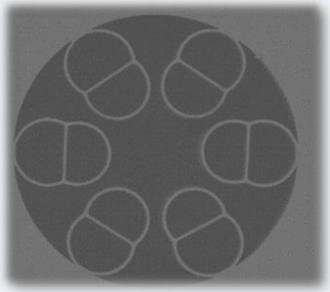
4

Conclusion

Solid *VS* Hollow Fiber

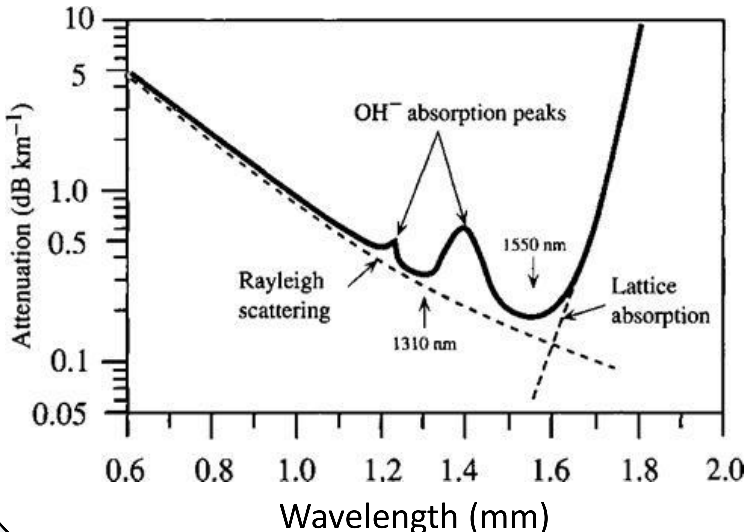
VS





Material limitation

- Absorption
- Dispersion
- Nonlinearity
- Damage threshold

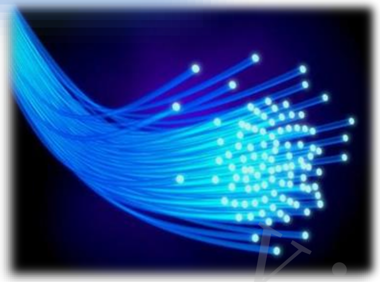


Transmission in air

- Low latency
- Low dispersion
- Low nonlinearity
- High damage threshold
- Arbitrary transmission window

Comparison

Solid core fiber



Loss： 0.14 dB/km √

Length： thousands of kilometers √

Price： <1 $ √

splice： Simple, low loss √

Dispersion： 10s of ps/nm/km ×

Nonlinearity : 2.2~3.4x10^{-20}m^2/*W* ×

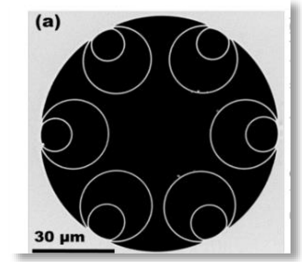
Damage： MW level peak power ×

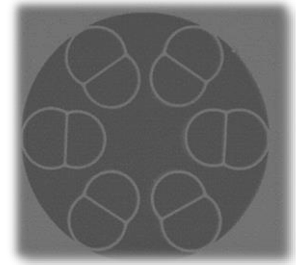
speed： c/1.45 ×

Application： widely used

VS

Hollow core fiber





Loss： 0.65 dB/km ×

Length： kilometers ×

Price： Thousands $ ×

splice： complicated, higher loss ×

Dispersion： A few ps/nm/km √

Nonlinearity： ~10^{-23}m^2/*W* √

Damage： > GW peak power √

speed： ~c √

Application： in its infancy

Hollow core fiber applications

Optical communication

Capacity crush?, Low latency?

- Increase system capacity
- supercomputers, data centers, financial transactions, 5G, time-sensitive applications

Lasers

Higher power, shorter pulse width, More spectral coverage?

- High power ultrafast delivery
- Nonliear optics in gases: Pulse compression, frequency conversion, etc.

Hollow core fiber：

To replace solid fiber in niche applications

Others

Improved efficiency and sensitivity?

- Quantum optics: fill with cold atoms
- Biophotonics: Fill with blood, solvents

Fiber sensing

Harsh environment? Radiation hardness?

- High precision fiber optic gyroscope
- Distributed gas sensing

1 **Background**

1. *Motivation*
2. *History of HCF development*

2 **HCF – understanding, design and fabrication**

1. *How we understand*
2. *Broadband HCF*
3. *Ultralow loss HCF*

3 **HCF applications**

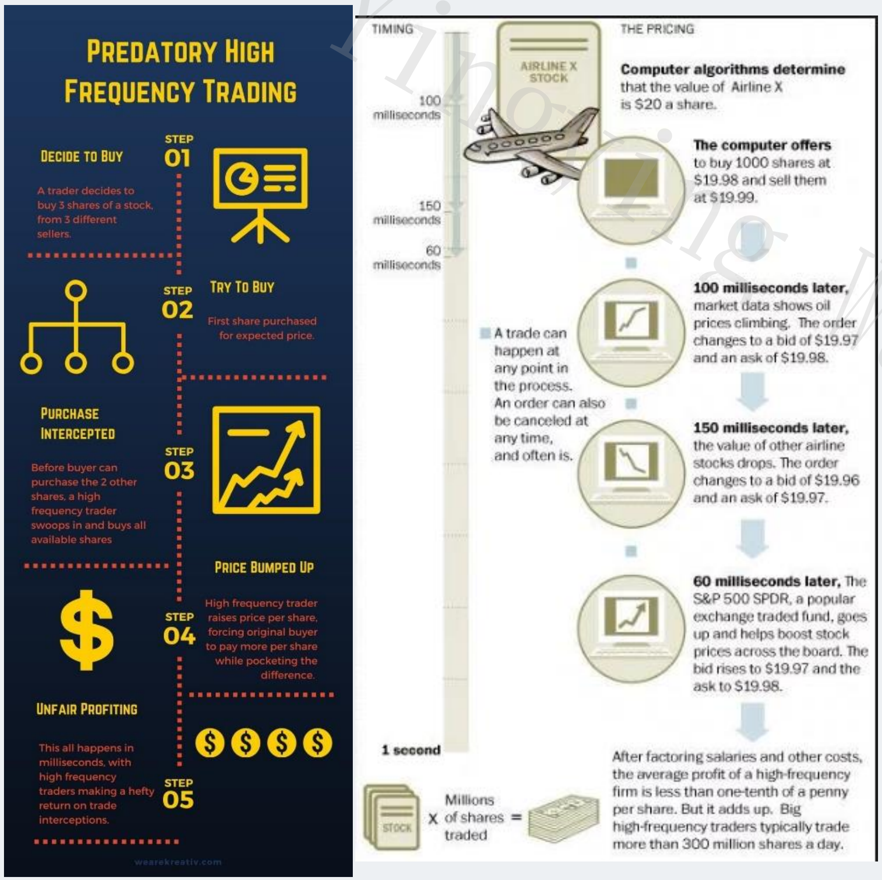
1. *Optical communications*
2. *Ultrafast optics*
3. *Sensing and biophotonics*

4 **Conclusion**

Low Latency, time-sensitive applications

0.75 µs/500 m

5G, High frequency trading, supercomputer, data center



Photos from Google

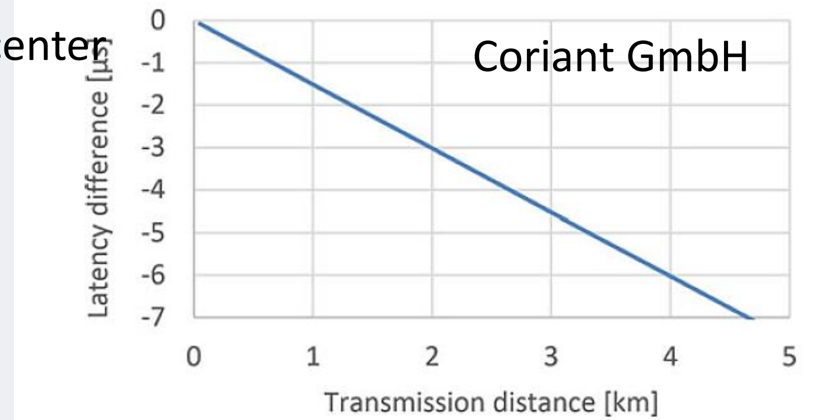
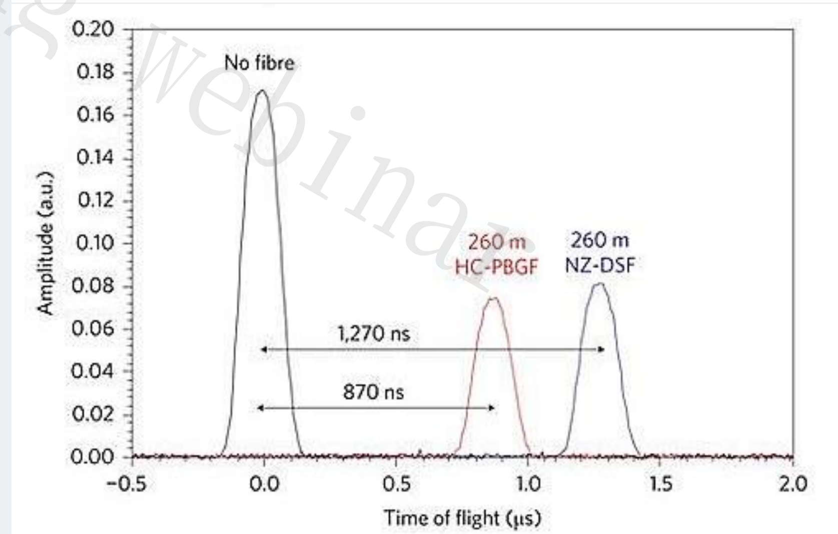


Fig. 2. Latency benefit of hollow-core fiber versus standard single mode fiber.



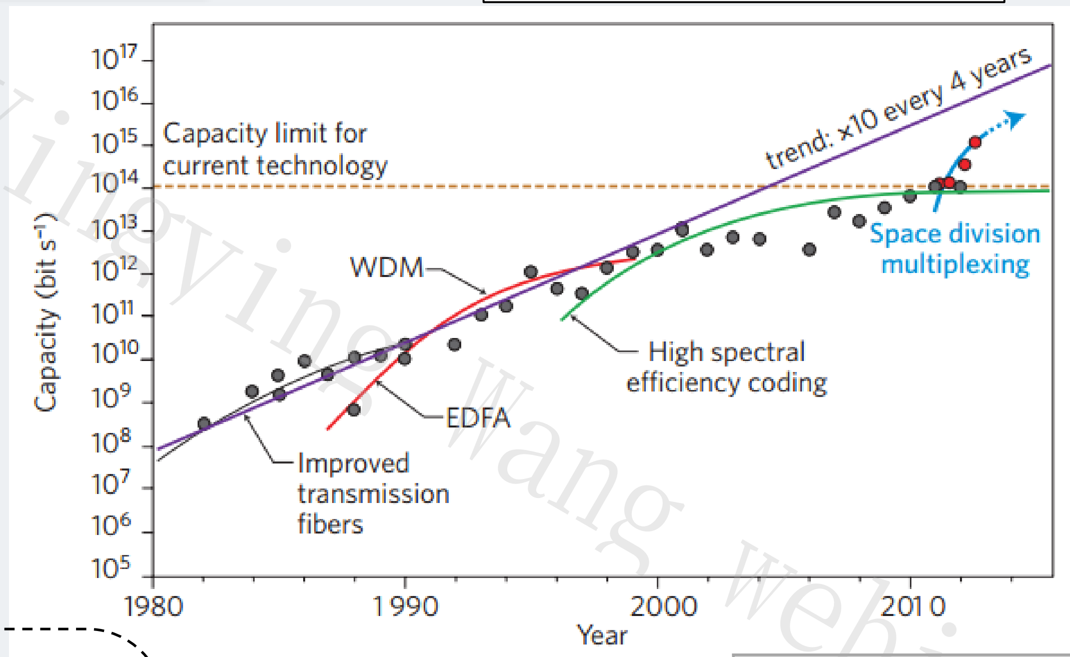
1.F. Poletti et al, Nature Photon., vol. 7, no. 4, pp. 279-284, 2013. 2.M. Kuschnerov, J. Lightwave Technol. 34, 314–320 (2016).

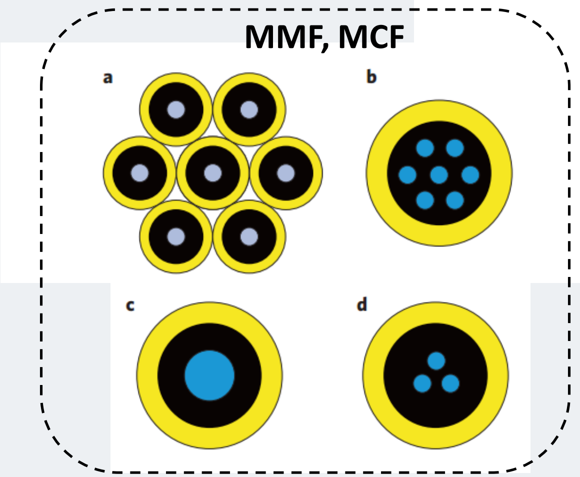
HCF for high capacity

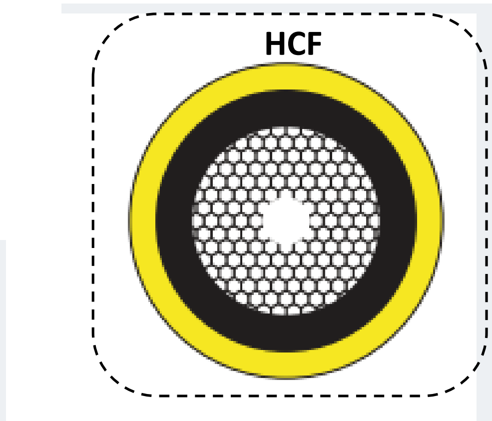
$$C=B\log_2(1+S/N)$$

- *Loss;*
- *Nonlinearity;*
- *Bandwidth;*
- *…*

'capacity crunch'





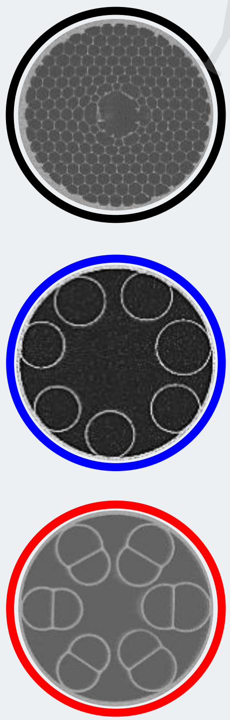


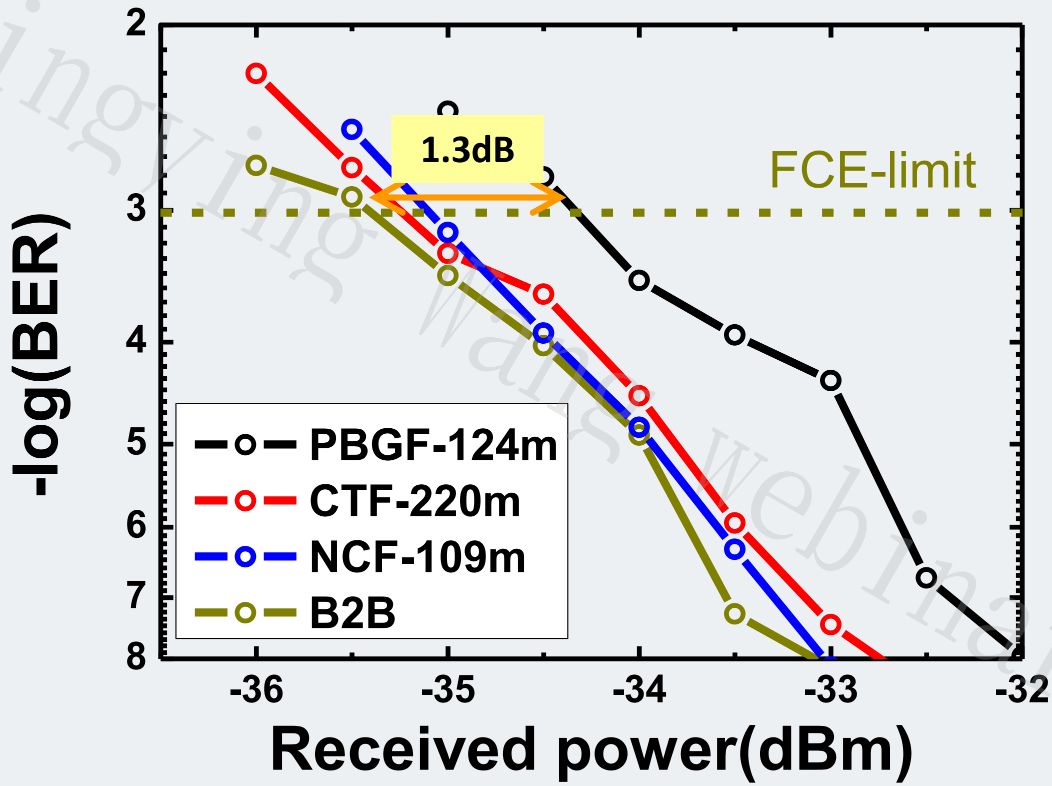
Ultralow nonlinearities ($>10^3$ reduction over SMF)	✓
Low latency (99.7% of *c*)	✓
High damage threshold	✓
Potentially ultralow loss	✓
Broadband width	✓

D. J. Richardson, et al. NP 7, 354 (2013)., M. Kuschnerov, et al. JLT 34, 314 (2016)

Comparison between three fibers for communications

- optimized central launch



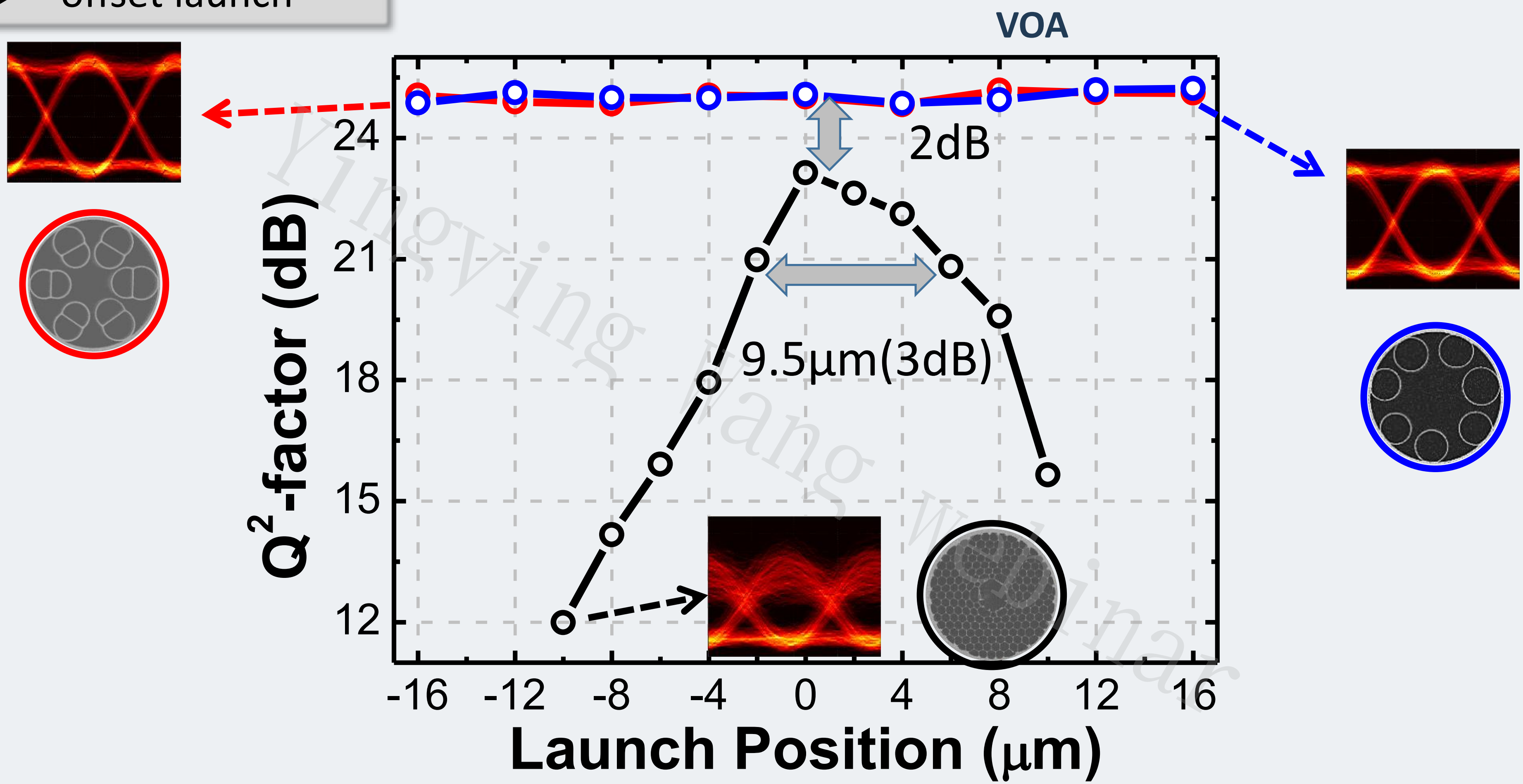


-25dBm

Xiaocong Wang et al,"Hollow-core conjoined-tube negative-curvature fibre for penalty-free data transmission under offset launch conditions", Optics Letters,44,2145(2019)

Comparison between three fibers for communications

- offset launch



CTF shows great resilience to bending and offset launch compared to the other two hollow-core fibers, enabling penalty-free data transmission in realistic environments.

Xiaocong Wang et al,"Hollow-core conjoined-tube negative-curvature fibre for penalty-free data transmission under offset launch conditions", Optics Letters,44,2145(2019)

1 Background

1. *Motivation*
2. *History of HCF development*

2 HCF – understanding, design and fabrication

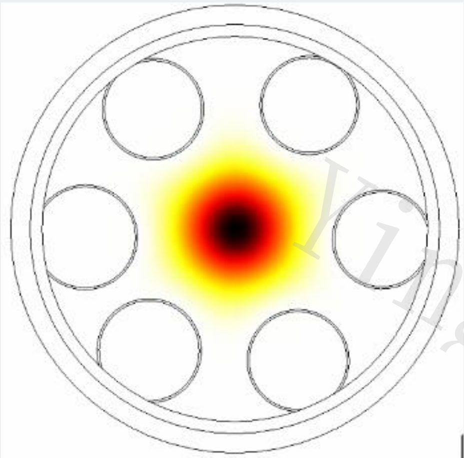
1. *How we understand*
2. *Broadband HCF*
3. *Ultralow loss HCF*

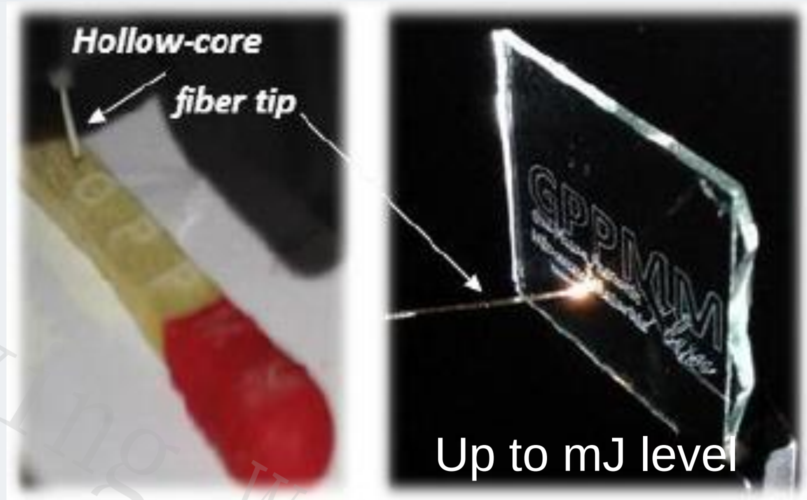
3 HCF applications

1. *Optical communications*
2. *Ultrafast optics: delivery and gas nonlinearity*
3. *Sensing and biophotonics*

4 Conclusion

Flexible delivery of ultrashort pulses





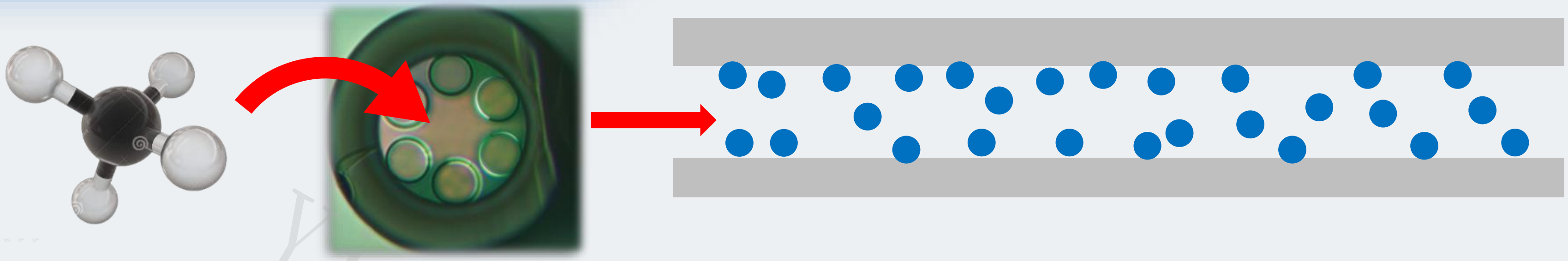
GLO photonics (France)

Photonic Tools (Germany)

Trumpf

B.Debord et al, Opt.Express. 22.10735, 2014, B. Beaudou et al, Opt . Letts. 37, 1430, 2012

Nonlinear optics in gases



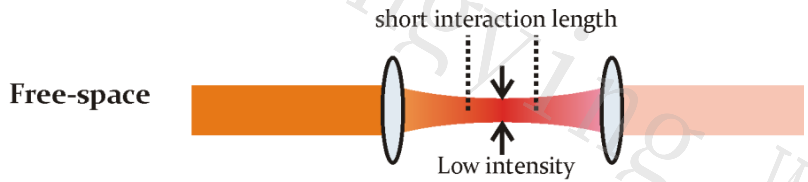


Figure of Merit ~ 2

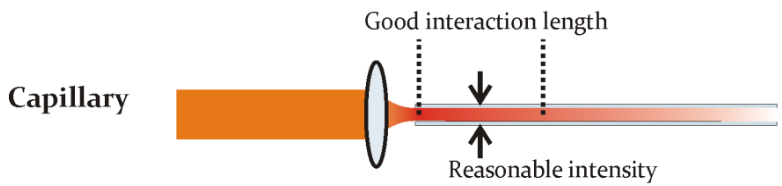


Figure of Merit ~ 20

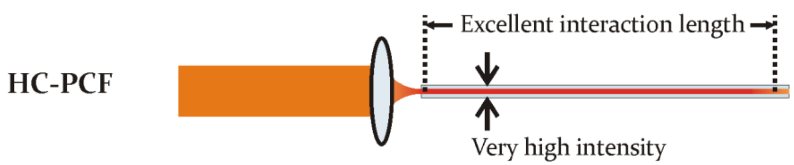


Figure of Merit >2000

$$FOM = L_{int}\,\lambda\,/A_{eff}$$

- ✓ low nonlinear threshold
- ✓ Compact, all fiber structure
- ✓ Wavelength extension
- ✓ high damage threshold

F. Benabid et al, Linear and nonlinear optical properties of hollow core photonic crystal fiberJ. Mod. Opt. 58 (2011) 87-124

Nonlinear optics in gases

Laser
1. τ: CW, ns, ps, fs
2. High power, low power
3. λ: NIR、 MIR、 VIS, UV

\+

Gas
1. Noble gas: Ar, Ne, Xe
2. Raman active gas: H_2 , CH_4, N_2
3. Gas Laser N_2,C_2H_2

\+

Hollow-core Fiber
1. transmission window
2. Adjustable dispersion
3. Loss level
4. mode quality
5. damage threshold

\+

mechanism
1. Population inversion
2. Self phase modulation
3. Raman scattering
4. Dispersion wave
5. Raman soliton
6. High harmonic generation

various combination

=

1. Ultrafast optics: pulse compression to few cycle
2. MIR emission : self-frequency shift, Raman scattering, gas laser
3. NIR, visible light emission: discrete spectral line, supercontinuum
4. UV, DUV emission: dispersive waves, high harmonic generation

Application
- Scientific research
- Military
- Material science
- Fundamental physics

Nonlinear optics in gases

Laser

1064 nm, 12 ps, 1mJ, 1kHz

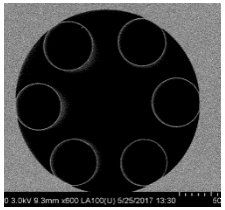
+

Gas

CH_4

+

HCF



Core 70 µm, Window: 900-1300 nm, 1600-3500nm

+

mechanism

Raman scattering

combine

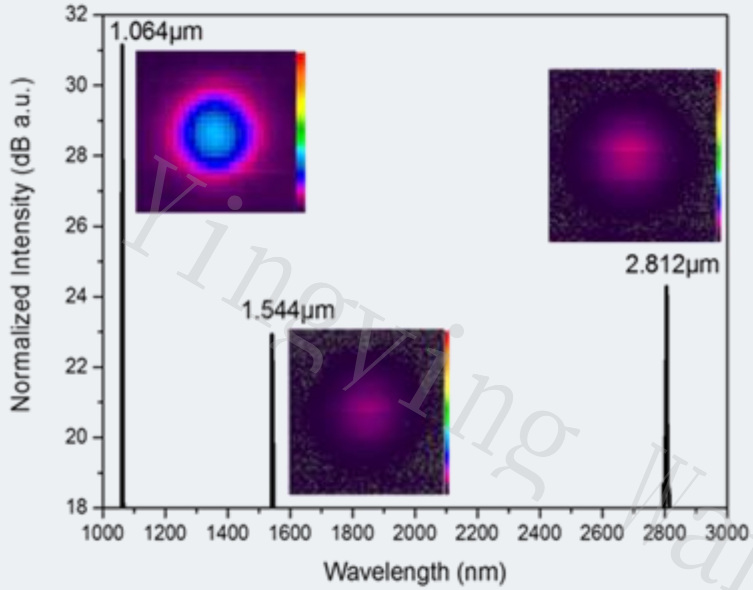
=

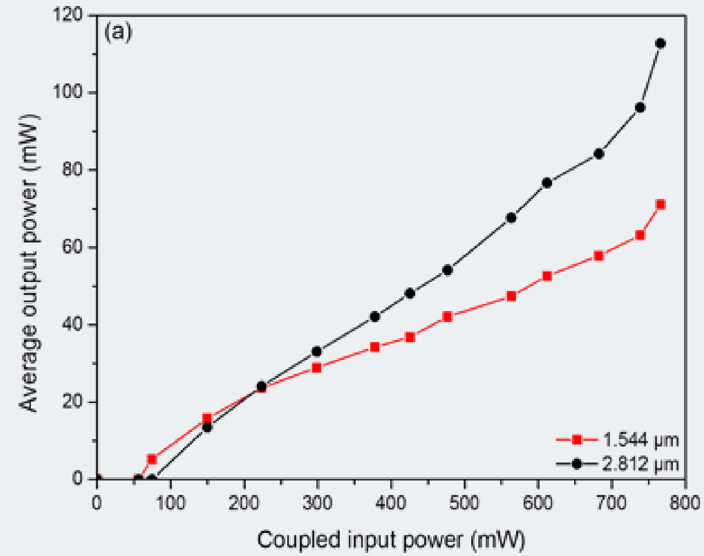
High peak power 2.8 µm Raman laser

Application

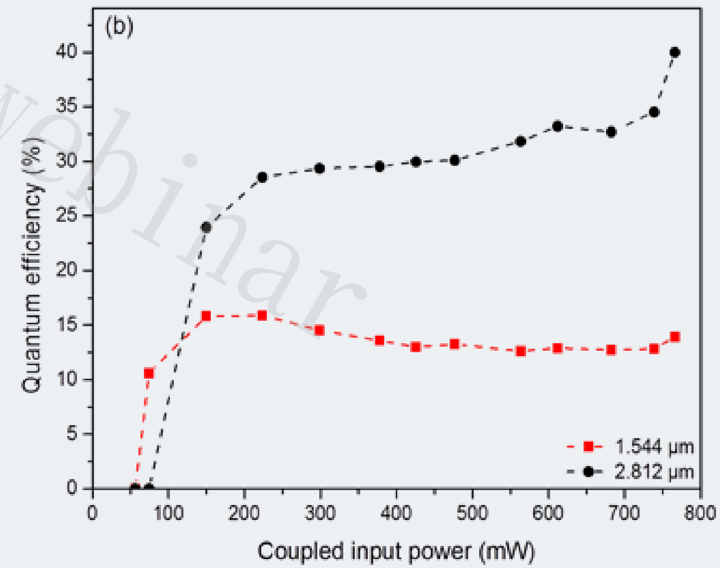
- Environmental Monitoring
- Medicinal science
- Military

Nonlinear optics in gases





	1.544 μm	2.812 μm
Average power	71 mW	113 mW
Peak power	5.9 MW	9.5 MW
Quantum efficiency	14%	40%



High peak power infrared laser source !

Ling Cao et al, "High peak power 2.8 μm Raman laser in a methane-filled negative-curvature fiber," Opt. Express 26, 5609-5615 (2018)

Nonlinear optics in gases

Laser

532 nm, 20 ps,
150 μJ, 1kHz

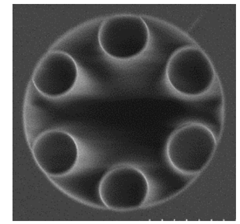
+

Gas

N_2

+

HCF



Core 26 μm,
Window: 270-360 nm,
420-1200nm,

+

mechanism

Raman scattering

combine

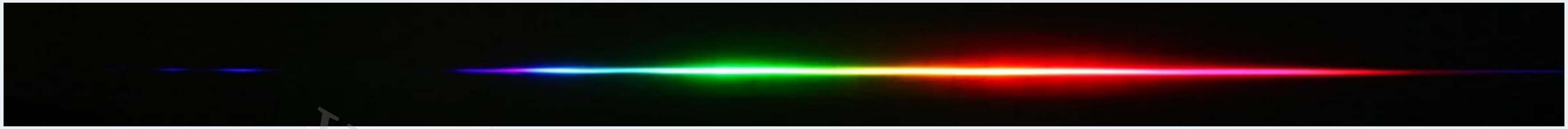
=

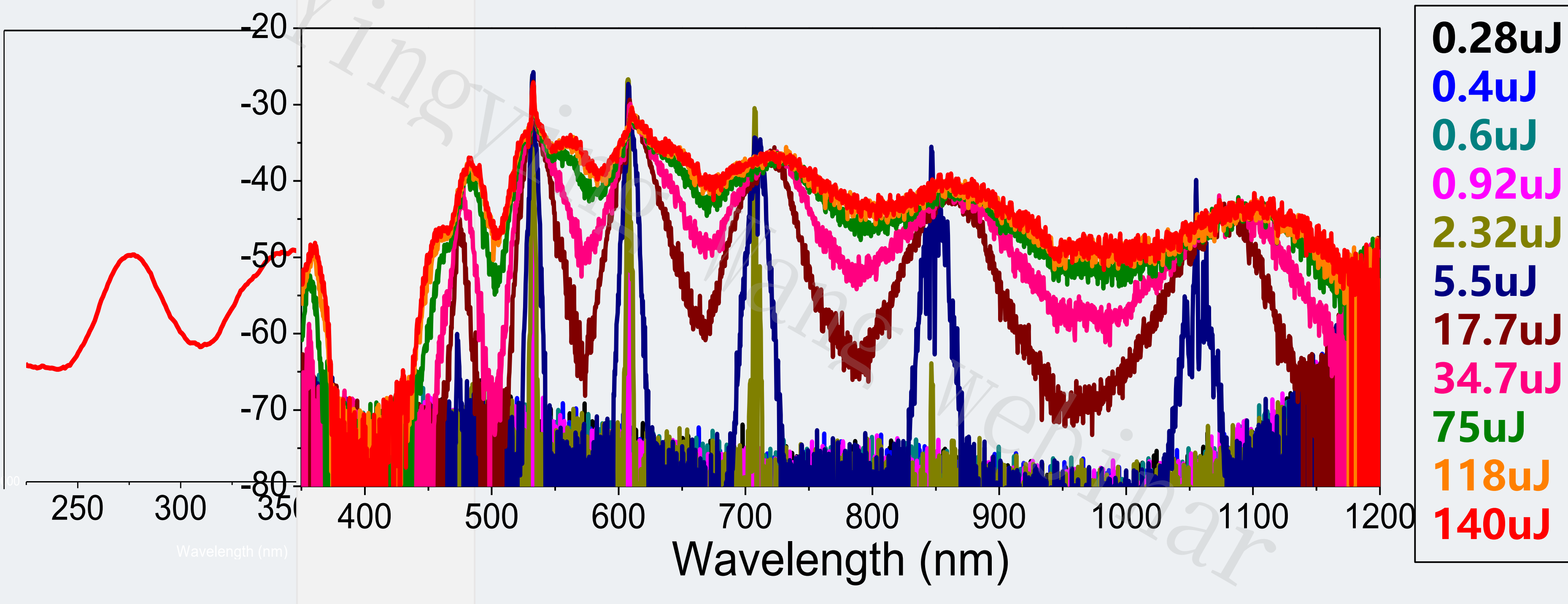
Raman-dominate Supercontinuum source

Application

- Hyperspectral lidar
- UV spectroscopy

Nonlinear optics in gases





Dominated by stimulated Raman scattering,, assisted by Kerr effect

Shoufei Gao et al, manuscript in preparation

1 **Background**

1. *Motivation*
2. *History of HCF development*

2 **HCF – understanding, design and fabrication**

1. *How we understand*
2. *Broadband HCF*
3. *Ultralow loss HCF*

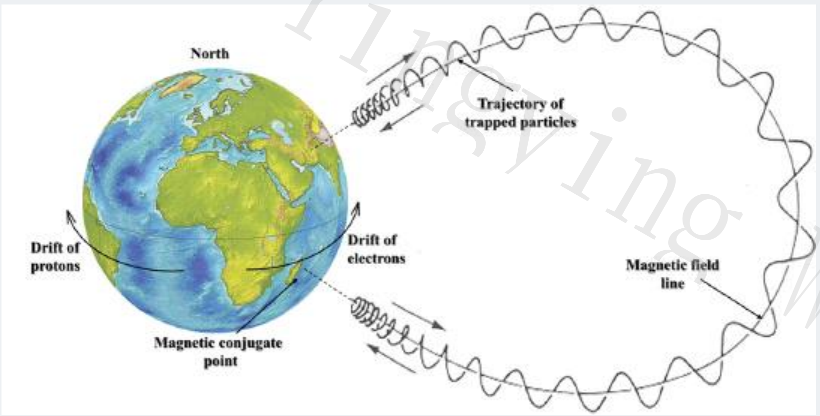
3 **HCF applications**

1. *Optical communications*
2. *Ultrafast optics: delivery and gas nonlinearity*
3. *Sensing and biophotonics*

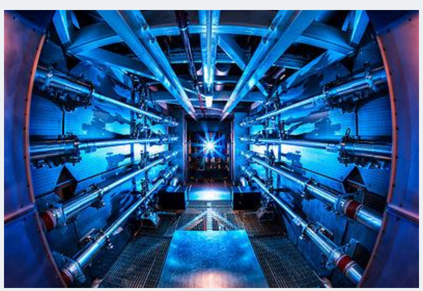
4 **Conclusion**

High Radiation Hardness

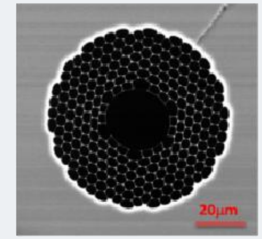
Space, nuclear power station, nuclear fusion

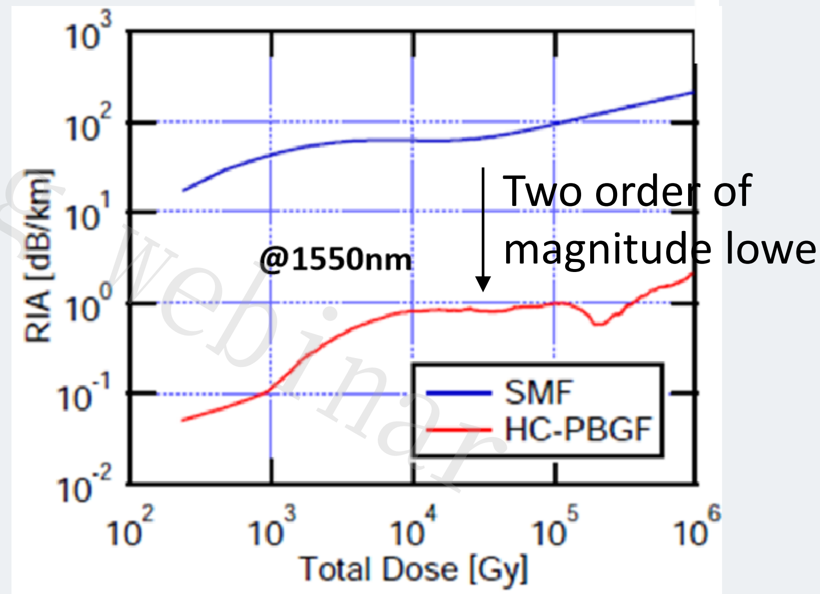


NIF



LHC



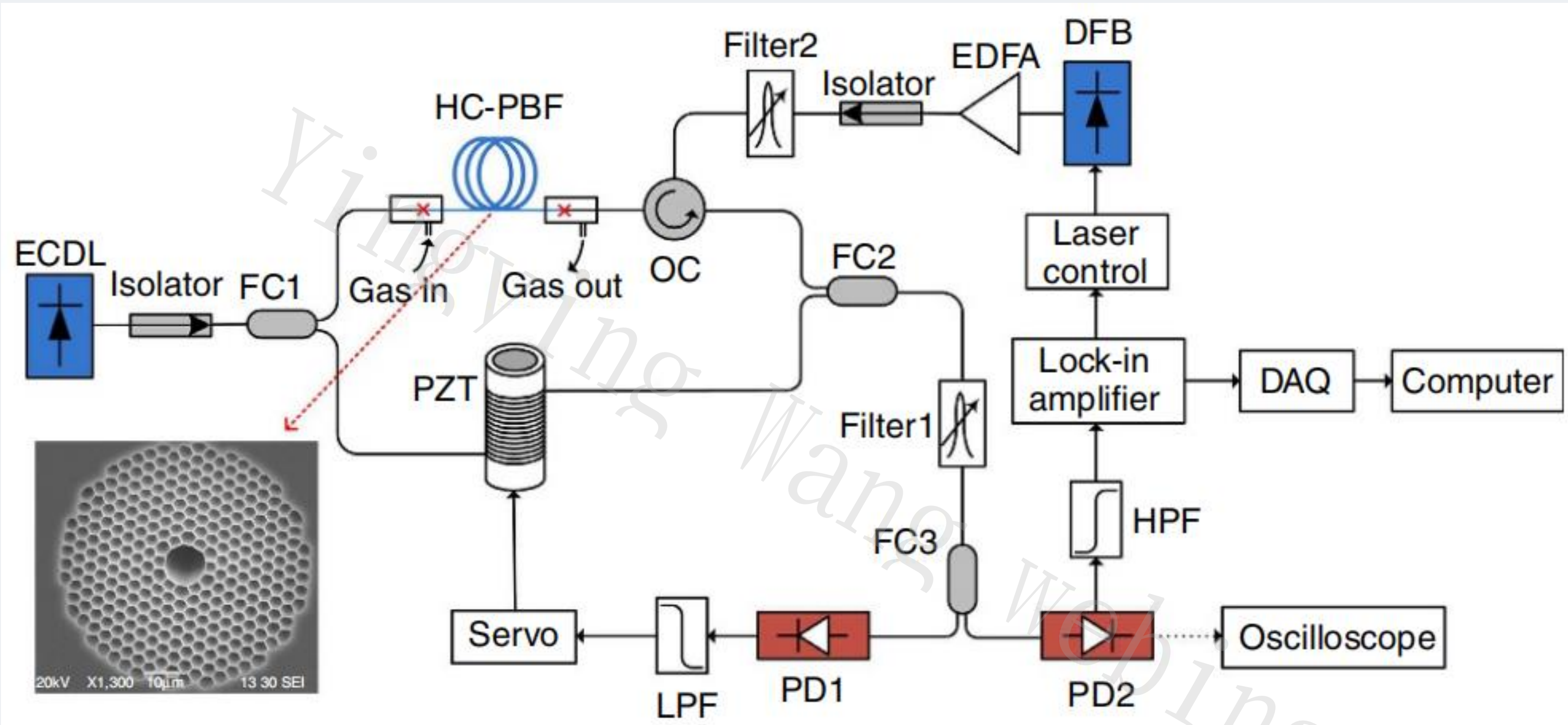


Photos from Google

L. Olanterä et al, "Gamma irradiation of minimal latency hollow-core photonic bandgap fibres," J. Instrum. 8, C12010 (2013).

Distributed gas sensing

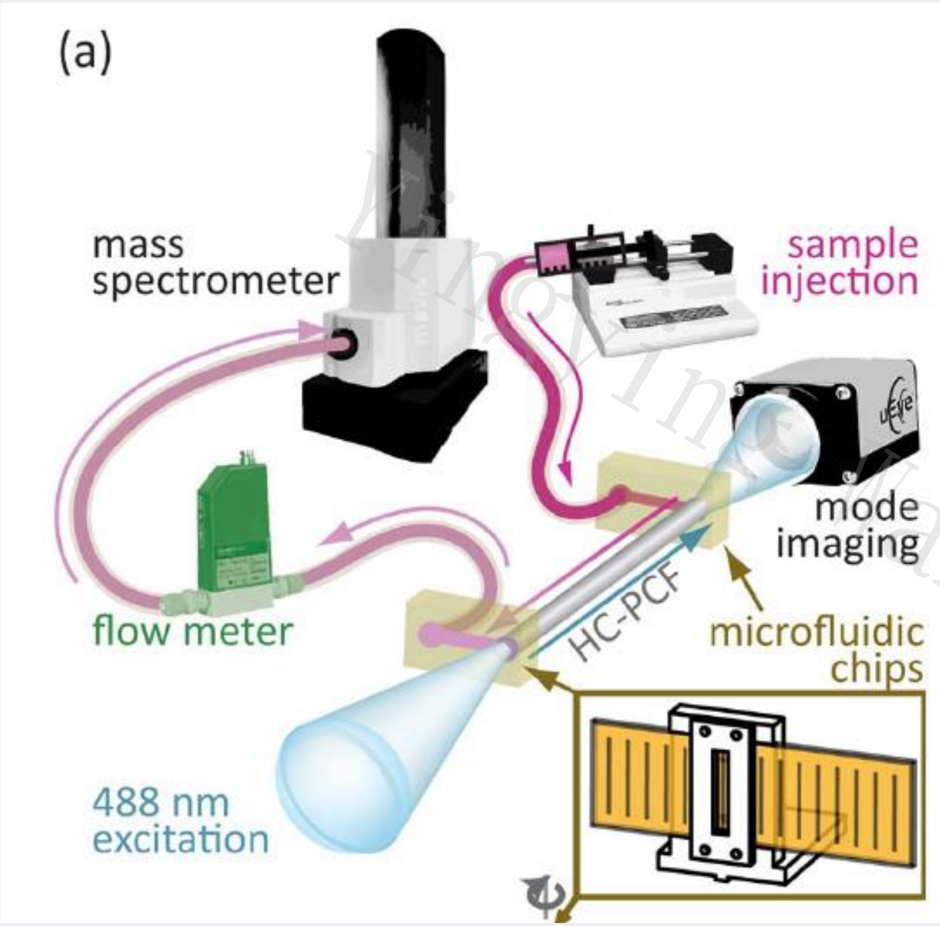
C_2H_2、CH_4、NH_3、C_2H_4、H_2S、CO、CO2、C2H6、H_2、N_2…

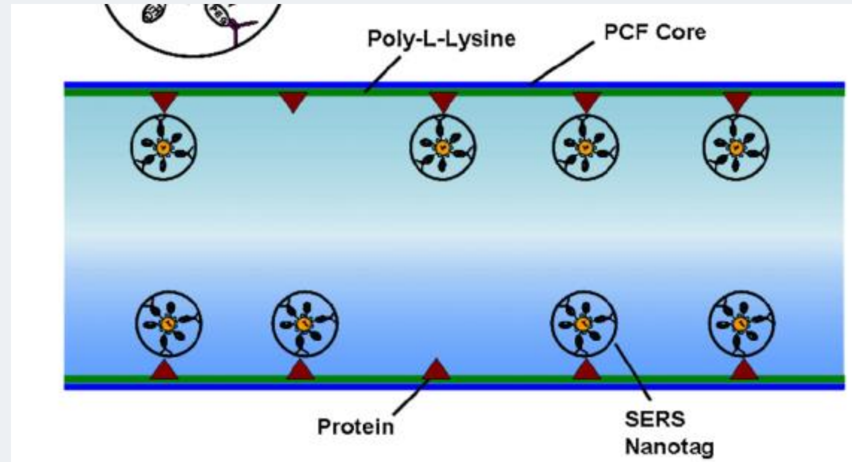


photothermal-induced phase change in a CH_4-filled HCF

- a noise equivalent concentration of 2 p.p.b. (2.3 x10^{-9}cm-^{1} in absorption coefficient)
- High dynamic range of nearly six orders of magnitude.

Wei Jin, Yingchun Cao,Fan Yang& Hoi Lut Ho，“Ultra-sensitive all-fibre photothermal spectroscopy with large dynamic range”Nature Communication,7767,（2015）



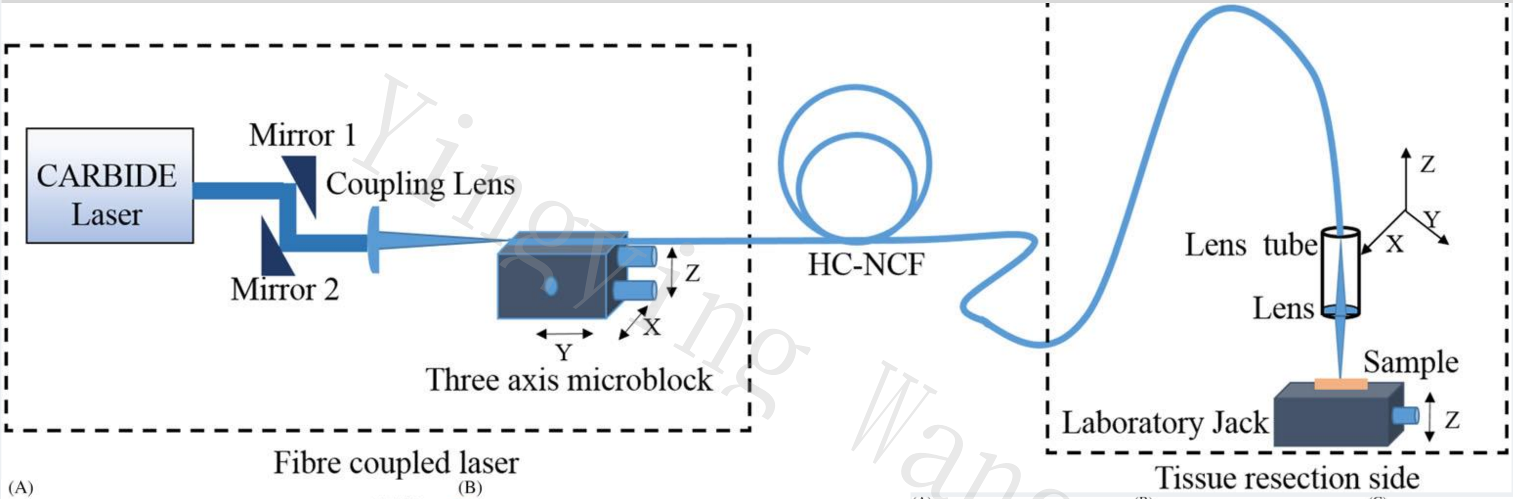


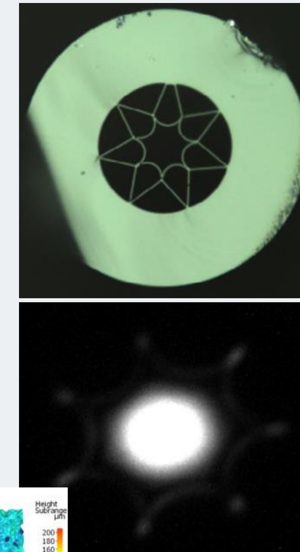
- HCF based surface enhanced Raman scattering (SERS) sensing platform for the ultrasensitive detection of cancer proteins in an extremely low sample volume.
- It has highly sensitive protein sensing for early detection of diseases

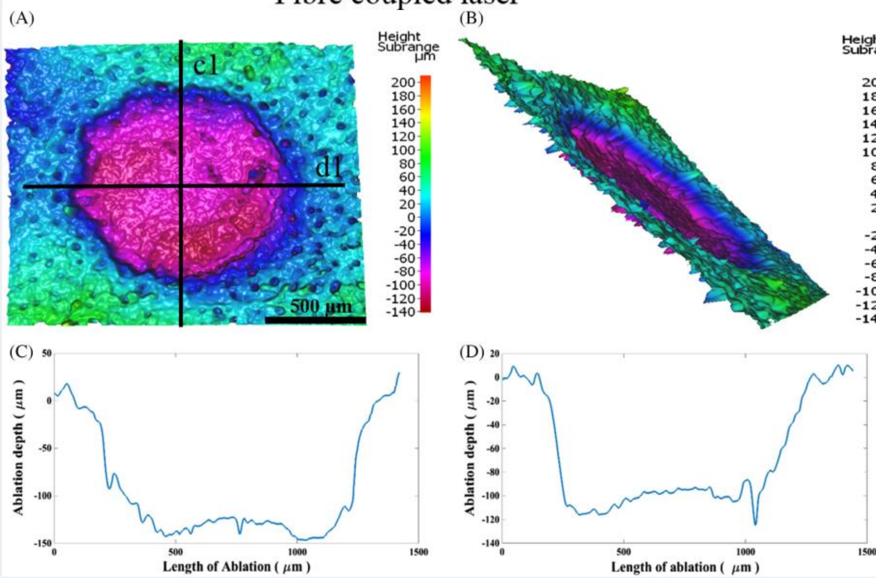
U. S. Dinish, et al, Biosensors and Bioelectronics 33,293, 2012

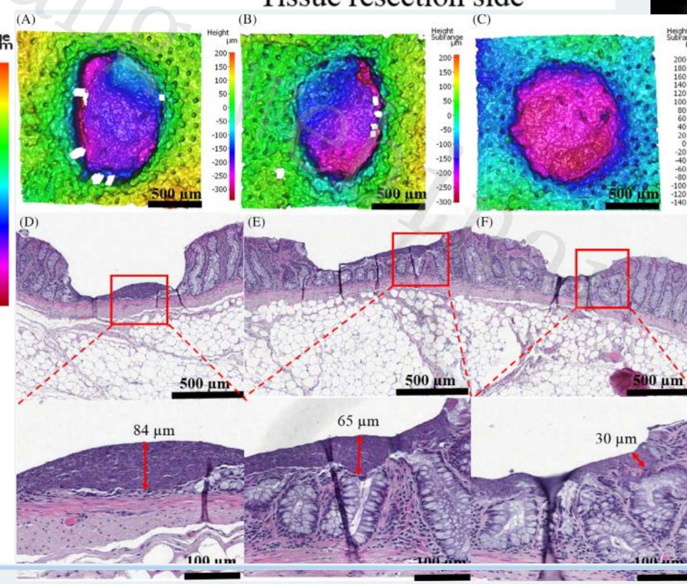
Ultrafast laser scalpel

- ➢ the combination of ultrashort pulses and flexible fibre delivery via HC-NCF present a viable route to new minimally invasive surgical procedures.









Syam M. P. C. Mohanan, et al, Preclinical evaluation of porcine colon resection using hollow core negative curvature fibre delivered ultrafast laser pulses, *Journal of Biophotonics*, 2019;e201900055.

1 **Background**

1. *Motivation*
2. *History of HCF development*

2 **HCF – understanding, design and fabrication**

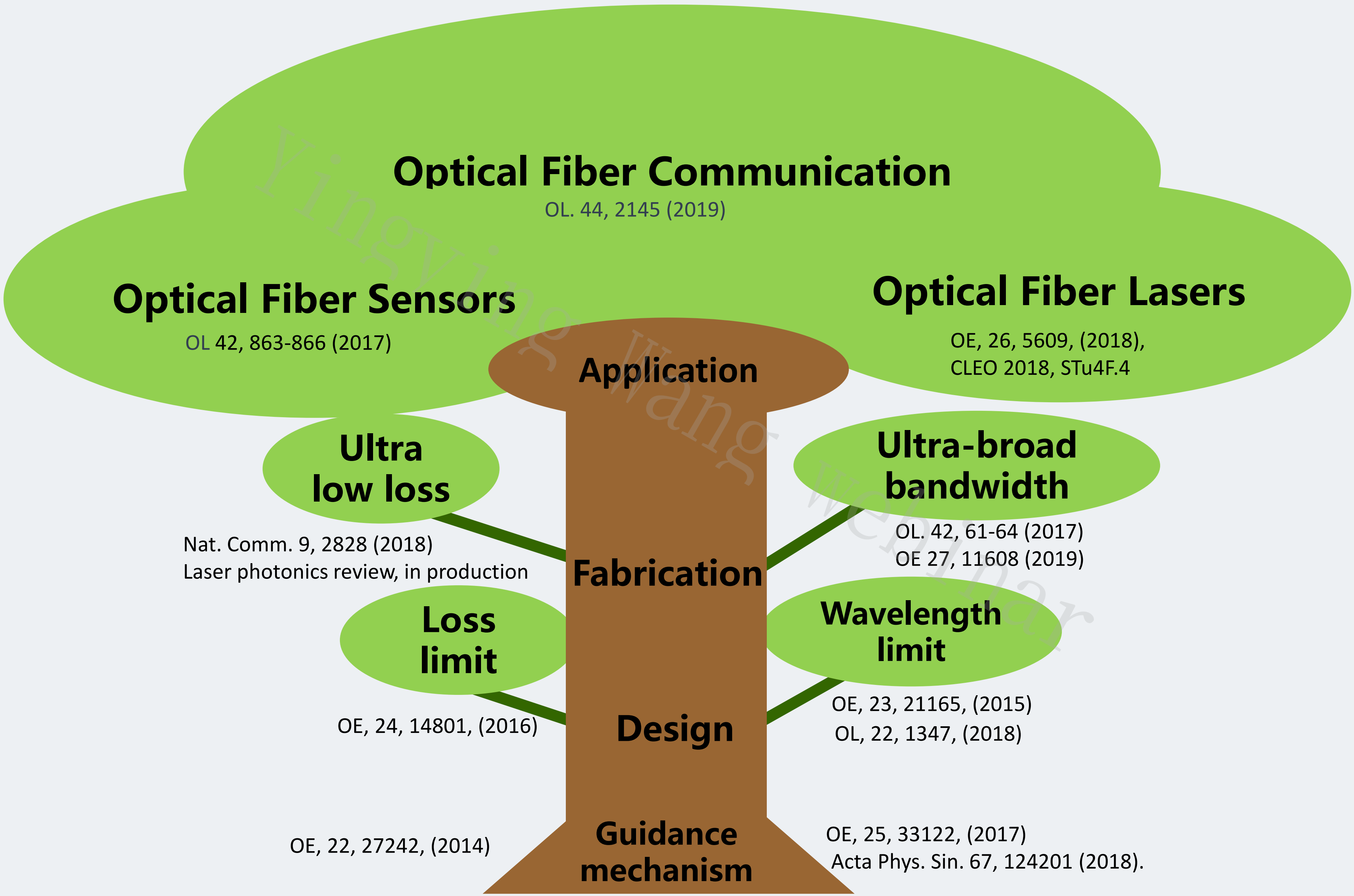
1. *How we understand*
2. *Broadband HCF*
3. *Ultralow loss HCF*

3 **HCF applications**

1. *Optical communications*
2. *Ultrafast optics: delivery and gas nonlinearity*
3. *Sensing and biophotonics*

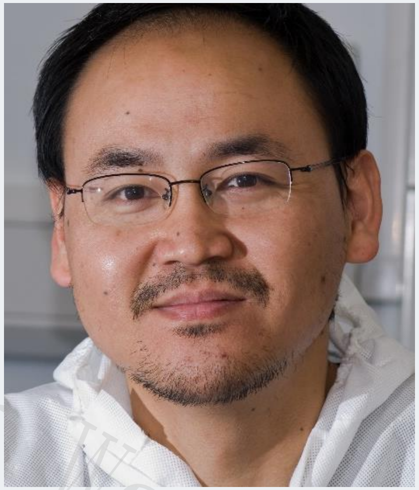
4 **Conclusion**

Towards a Perfect Hollow-Core Fiber



People and Contributions






....

Prof. Pu Wang
wangpuemail@bjut.edu.cn

Prof. Yingying Wang
dearyingyingwang@hotmail.com

Prof. Wei Ding
wding@iphy.ac.cn

Dr. Shoufei Gao
jngaofei@gmail.com

BEIJING UNIVERSITY OF TECHNOLOGY 北京工業大學 1960

暨南大學 JINAN UNIVERSITY 1906

国家自然科学基金委员会 National Natural Science Foundation of China

北京市教育委员会 Beijing Municipal Education Commission

Vacancies

- Postdoc vacancies:

Contact: dearyingyingwang@Hotmail.com

- Joint postdoc from John Travers' groups in Heriot-watt Uni. and Yingying Wang's group in Jinan Uni. on "nonlinear optics in hollow-core fiber".
- Postdoc on "hollow core fiber design and fabrication" in Jinan Uni., Guangzhou, China
- Postdoc on "hollow core fiber for optical communications" in Jinan Uni., Guangzhou, China
- Postdoc on "hollow core fiber for quantum information applications" in Jinan Uni., Guangzhou China

- Others:

- Technical staff, research staff, master and Ph.D students

Thank you for your attention!