1

Agenda

- Today: fibers, systems, networks
- Fiber innovation pathways
- Implications on system and network design

Abstract: We will review drivers behind innovation in long-haul and subsea optical fiber technology and potential paths in which these fibers could evolve. We will also discuss the ecosystem changes required for each future fiber pathway.

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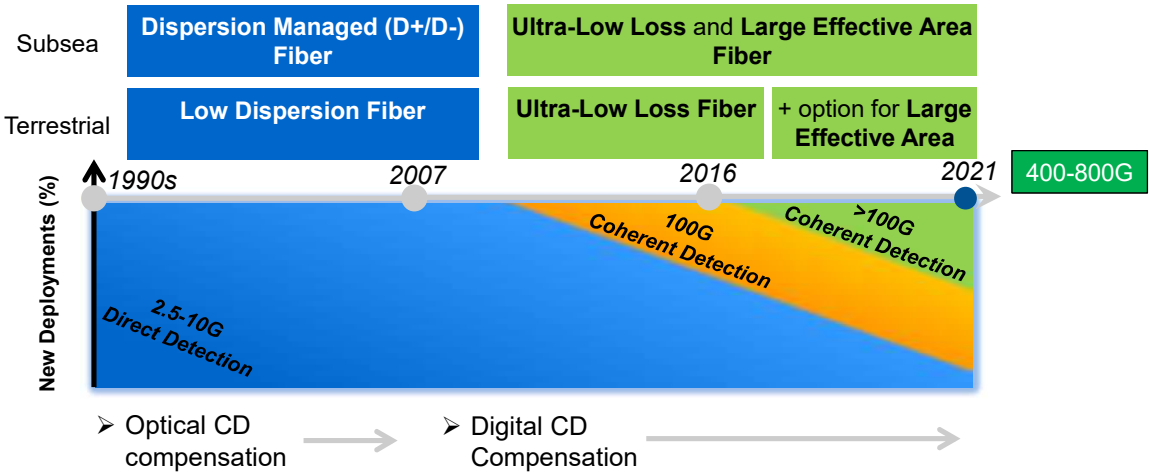
Evolution of long-haul fibers and systems

Today's coherent systems can operate up to 800G/λ (>1T/λ expected soon)



- Optical CD compensation
- Digital CD Compensation

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 3

3

Long-haul fibers today

Fibers from all vendors are designed to be compliant with ITU-T standards

ITU-T Category	Application
G.652.D	Terrestrial
G.655	Terrestrial
G.656	Terrestrial
G.654.B	Subsea
G.654.C	Both
G.654.D	Subsea
G.654.E	Terrestrial

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4

Long-haul fibers today

Fibers from all vendors are designed to be compliant with ITU-T standards

			at 1550 nm		
ITU-T Category	Application	Loss, typ. (dB/km)	A_{eff}, typ. (μm^2)	CD, typ. (ps/nm/km)	Cable cut-off λ, max. (nm)
G.652.D	Terrestrial				
G.655	Terrestrial				
G.656	Terrestrial				
G.654.B	Subsea				
G.654.C	Both				
G.654.D	Subsea				
G.654.E	Terrestrial				

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Long-haul fibers today

Fibers from all vendors are designed to be compliant with ITU-T standards

			at 1550 nm		
ITU-T Category	Application	Loss, typ. (dB/km)	A_{eff}, typ. (μm^2)	CD, typ. (ps/nm/km)	Cable cut-off λ, max. (nm)
G.652.D	Terrestrial	0.18 - 0.20			
G.655	Terrestrial	0.19 - 0.22			
G.656	Terrestrial	0.20 - 0.22			
G.654.B	Subsea	0.15 - 0.17			
G.654.C	Both	0.15 - 0.17			
G.654.D	Subsea	0.15 - 0.17			
G.654.E	Terrestrial	0.16 - 0.18			

Ultra-Low Loss

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Long-haul fibers today

Fibers from all vendors are designed to be compliant with ITU-T standards

			at 1550 nm			
	ITU-T Category	Application	Loss, typ. (dB/km)	A_{eff}, typ. (μm^2)	CD, typ. (ps/nm/km)	Cable cut-off λ, max. (nm)
	G.652.D	Terrestrial	0.18 - 0.20	~80		
	G.655	Terrestrial	0.19 - 0.22	50 - 72		
	G.656	Terrestrial	0.20 - 0.22	50 - 72		
Ultra-Low Loss	G.654.B	Subsea	0.15 - 0.17	110 - 115		
Ultra-Low Loss	G.654.C	Both	0.15 - 0.17	~80		
Ultra-Low Loss	G.654.D	Subsea	0.15 - 0.17	110 - 150		
Ultra-Low Loss	G.654.E	Terrestrial	0.16 - 0.18	110 - 130		

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Long-haul fibers today

Fibers from all vendors are designed to be compliant with ITU-T standards

			at 1550 nm			
	ITU-T Category	Application	Loss, typ. (dB/km)	A_{eff}, typ. (μm^2)	CD, typ. (ps/nm/km)	Cable cut-off λ, max. (nm)
	G.652.D	Terrestrial	0.18 - 0.20	~80	16-18	
	G.655	Terrestrial	0.19 - 0.22	50 - 72	~4	
	G.656	Terrestrial	0.20 - 0.22	50 - 72	~8	
Ultra-Low Loss	G.654.B	Subsea	0.15 - 0.17	110 - 115	20 - 22	
Ultra-Low Loss	G.654.C	Both	0.15 - 0.17	~80	16 - 18	
Ultra-Low Loss	G.654.D	Subsea	0.15 - 0.17	110 - 150	20 - 22	
Ultra-Low Loss	G.654.E	Terrestrial	0.16 - 0.18	110 - 130	20 - 22	

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8

Long-haul fibers today

Fibers from all vendors are designed to be compliant with ITU-T standards

	ITU-T Category	Application	Loss, typ. (dB/km) at 1550 nm	A_{eff}, typ. (μm^2) at 1550 nm	CD, typ. (ps/nm/km) at 1550 nm	Cable cut-off λ, max. (nm)
	G.652.D	Terrestrial	0.18 - 0.20	~80	16-18	1260
	G.655	Terrestrial	0.19 - 0.22	50 - 72	~4	1450
	G.656	Terrestrial	0.20 - 0.22	50 - 72	~8	1450
Ultra-Low Loss	G.654.B	Subsea	0.15 - 0.17	110 - 115	20 - 22	1530
Ultra-Low Loss	G.654.C	Both	0.15 - 0.17	~80	16 - 18	1530
Ultra-Low Loss	G.654.D	Subsea	0.15 - 0.17	110 - 150	20 - 22	1530
Ultra-Low Loss	G.654.E	Terrestrial	0.16 - 0.18	110 - 130	20 - 22	1530

Source: compilation of data from ITU standards and specifications from several fiber vendors

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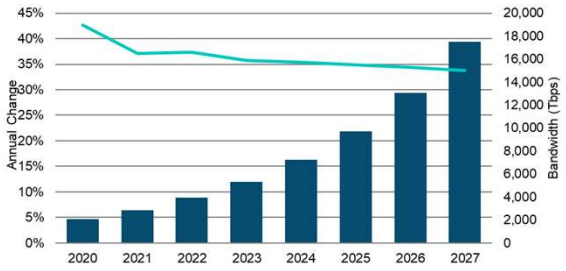
Macroview 1

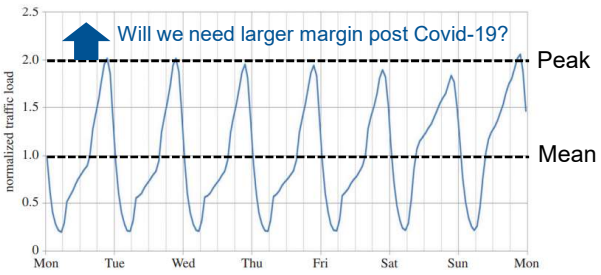
Need for more bandwidth and more bandwidth "buffer"

Total used international bandwidth



Source: TeleGeography, 2021

Peak vs. Mean Traffic



Source: A. Lord, "Impact of capacity growth in national telecommunications network", BT, 2015

Higher bandwidth demand trends: more video-conference (symmetric traffic), more and 4K on-demand video, emerging technologies

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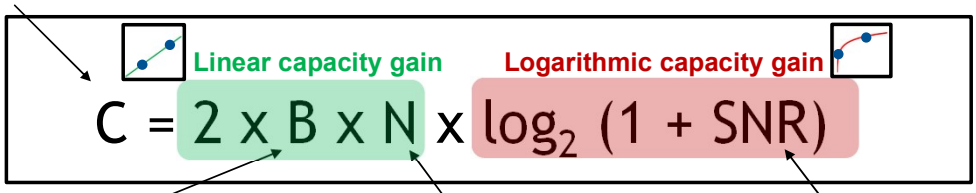
Macroview 2: Shannon limits explains why industry is interested in "N"

Can be via more fibers / high-density cables, or novel fibers

Cable capacity (Shannon formula)



S + C + L
Difficult to scale further

Spatial paths
Scalable, happening today

Increase in capacity via SNR only is getting difficult to achieve

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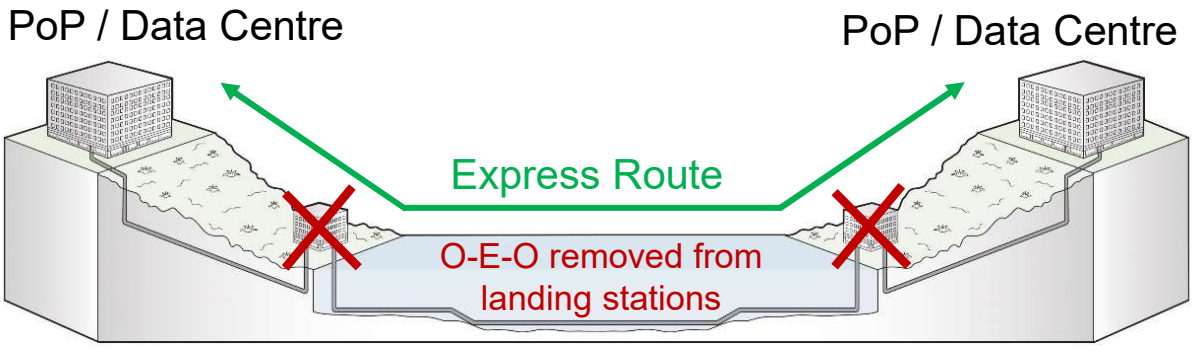
Macroview 3: Networks are becoming more integrated



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Key points thus far…

- Transmission systems have continuously evolved throughout history - fibers adapted and made remarkable progress
- Bandwidth needs to continue to grow but SNR increase alone is no longer sufficient (pivot to a mix of SNR and N, maybe B)
- New architecture trends make networks more inter-dependent (integration of terrestrial with subsea)

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Agenda

- Today: fibers, systems, networks
- Fiber innovation pathways
- Implications on system and network design

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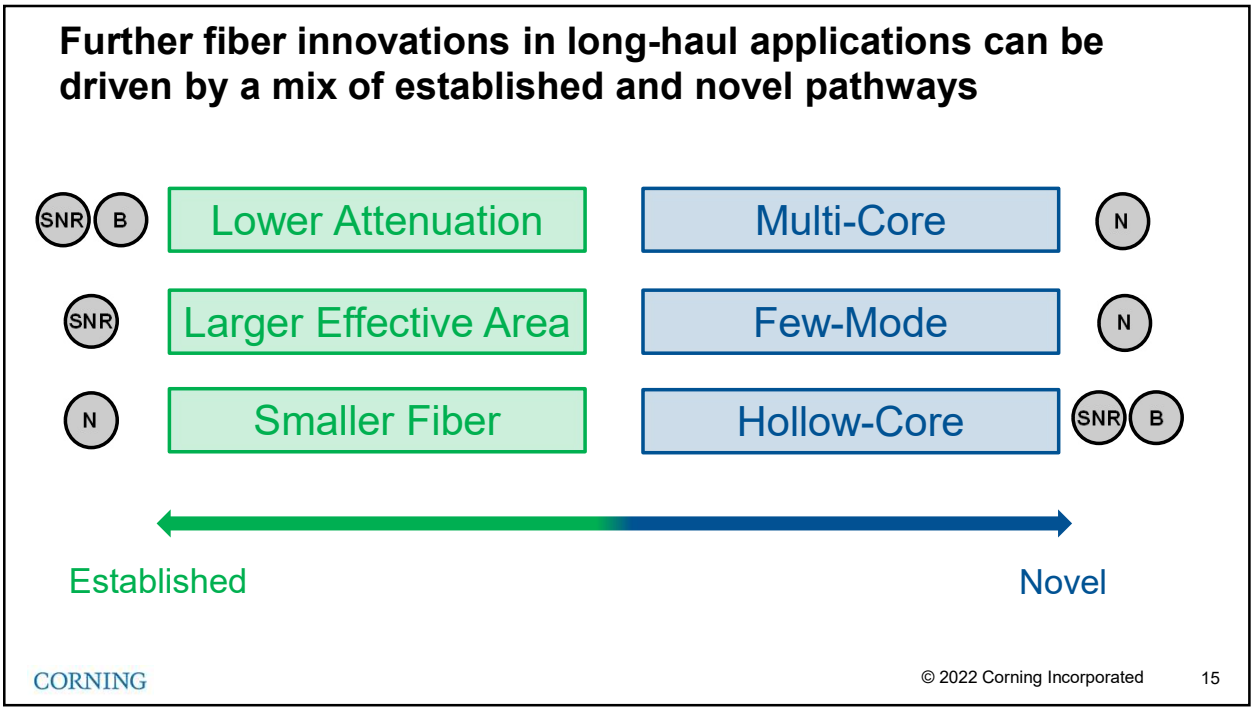

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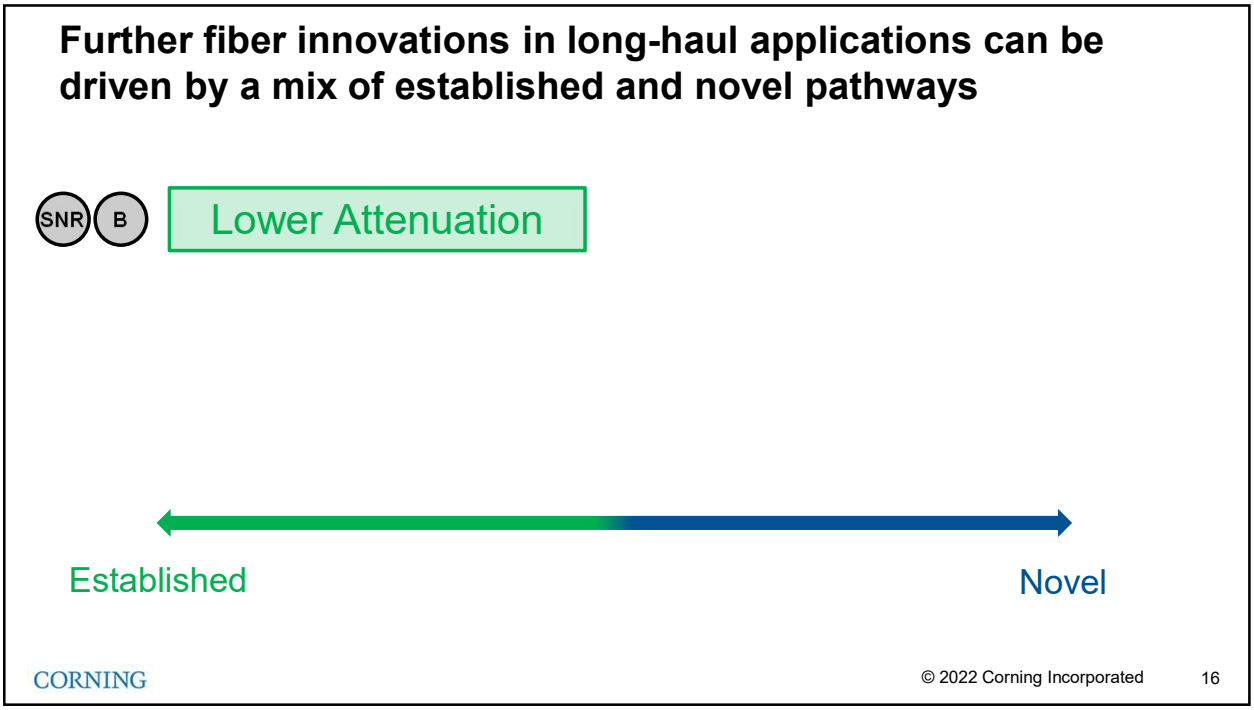

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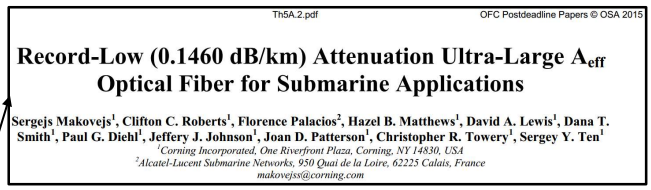
Over the years, the industry made a remarkable progress in attenuation

Record attenuation has now reached 0.1419 dB/km

Year	Record Loss (dB/km)	Record Loss at 1550nm (dB/km)
1970	20	
1973	5	
1976	0.47	
1979	0.20	
1986	0.154	0.154
2002	0.151	0.1521
2002	0.1484	~0.1495
2013	0.1480	0.1490
2015	0.1460	0.1467
2017	0.1419	0.1424


Th5A.2.pdf OFC Postdeadline Papers © OSA 2015

Record-Low (0.1460 dB/km) Attenuation Ultra-Large A_{eff} Optical Fiber for Submarine Applications

Sergejs Makovejs[1], Clifton C. Roberts[1], Florence Palacios[2], Hazel B. Matthews[1], David A. Lewis[1], Dana T. Smith[1], Paul G. Diehl[1], Jeffery J. Johnson[1], Joan D. Patterson[1], Christopher R. Towery[1], Sergey Y. Ten[1]

[1]Corning Incorporated, One Riverfront Plaza, Corning, NY 14830, USA
[2]Alcatel-Lucent Submarine Networks, 950 Quai de la Loire, 62225 Calais, France
makovejss@corning.com


Th5D.1.pdf OFC 2017 © OSA 2017

Lowest-Ever 0.1419-dB/km Loss Optical Fiber

Yoshiaki Tamura, Hirotaka Sakuma, Keisei Morita, Masato Suzuki, Yoshinori Yamamoto, Kensaku Shimada, Yuya Honma, Kazuyuki Sohma, Takashi Fujii and Takemi Hasegawa

Optical Communications Laboratory, Sumitomo Electric Industries, Ltd. 1, Taya-cho, Sakae-ku, Yokohama 2448588 JAPAN
Author e-mail address: tamura-yoshiaki@sei.co.jp

Other sources:

Hirano et al., OFC PDP5A.7, 2013
Nagayama et al., Electronics Letters, Vol. 38, No.20, 2002
Nagayama et al., OFC PDP FA10-1, 2002
Kanamori et al., JLT, Vol. LT-4, No. 8, 1986

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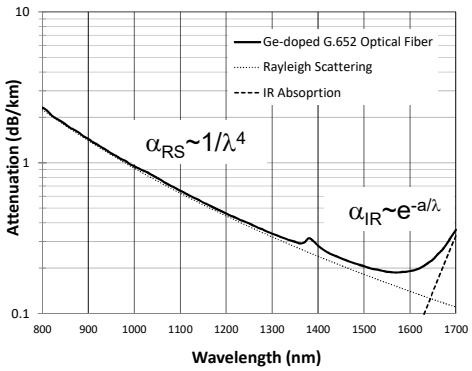
Fiber attenuation is governed by several components

Ge-doped silica optical fiber example

Intrinsic Loss
- Rayleigh scattering (α_{RS})
- IR absorption tail (α_{IR})
- UV absorption tail (electronic) (α_{UV})

Absorption by Impurities
- OH molecular vibration (α_{OH})
- Transition metals(α_{TM})

Waveguide Imperfections
- Non-uniformity at core-clad interface (α_{IM})



$$\alpha = \alpha_{RS} + \alpha_{OTHER} = \alpha_{RS} + (\alpha_{IR} + \alpha_{UV} + \alpha_{TM} + \alpha_{OH} + \alpha_{IM})$$

Source: S. Ten, “Ultra-low loss optical fiber technology”, invited talk, OFC 2016

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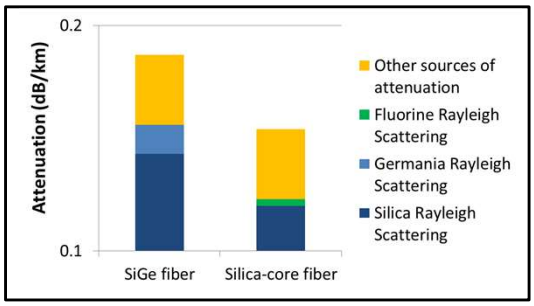
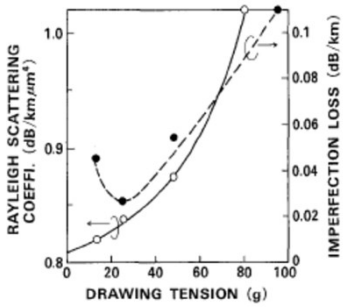
Ultra-low levels of attenuation are enabled using silica-core fibers with matched core-clad viscosity



Source: S. Makovejs, OFC 2015, PDP Th5A.2



*Source: M. Ohashi, JLT **10** (1992), p. 539*

- Silica-core fiber benefits from lower Rayleigh scattering due to no GeO_2, but requires Fluorine to achieve difference in core-clad refractive indices
- Core viscosity needs to be matched to cladding viscosity to reduce residual stress resulting from the manufacturing process (viscosity modification also reduces SiO_2 Rayleigh scattering)
- Other sources of attenuation can be reduced via optimization in fiber draw conditions

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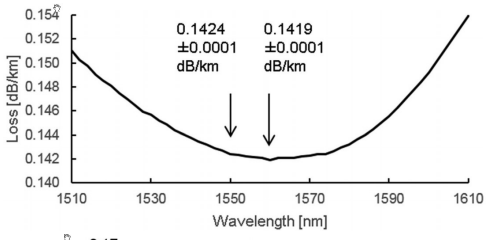
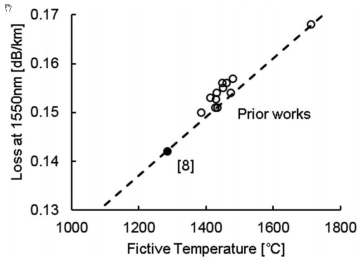
Further discussion on today's record low loss fiber…





Source: Y. Tamura, JLT, Vol. 36, No. 1, 2018

- "…fluorine in the core reduces viscosity and activation energy for relaxation of the microscopic glass network…"
- Fictive T^o is important, "…determined by the relationship between viscosity and T^o and by T^o history of glass relaxation process"
- "…glass composition known to enable promoting reduction in fictive T^o"
- "…reducing the drawing T^o and the drawing speed and passing the annealing furnaces are also effective at reducing fictive T^o..."

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Look into the future

Further reduction in attenuation is difficult, but probably not impossible

- Reduce Rayleigh scattering
- Improve raw material purity
- Reduce stress in fiber
- Introduce new dopants

- Goal:
  - Reduce attenuation for all manufactured fibers
  - Tighter attenuation distribution in production

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Further fiber innovations in long-haul applications can be driven by a mix of established and novel pathways

SNR

Larger Effective Area

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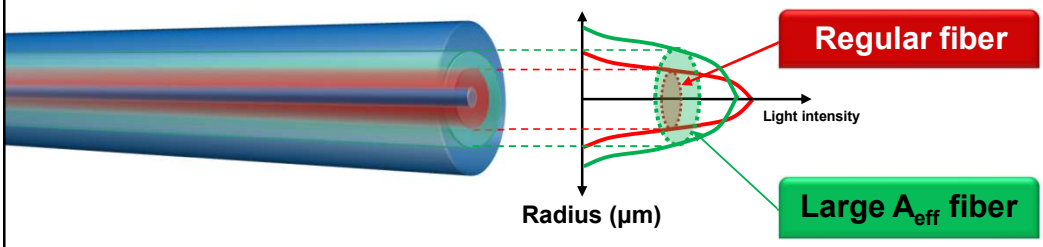
Why Large Effective Area (A_{eff})?

It minimizes non-linear effects, enabling greater power handling

- Effective Area (A_{eff}) represents the cross-sectional area of the light transmitting region of the fiber
- Larger A_{eff} reduces the optical intensity in the core, suppressing non-linear effects
- This allows to transmit higher signal powers without performance degradation



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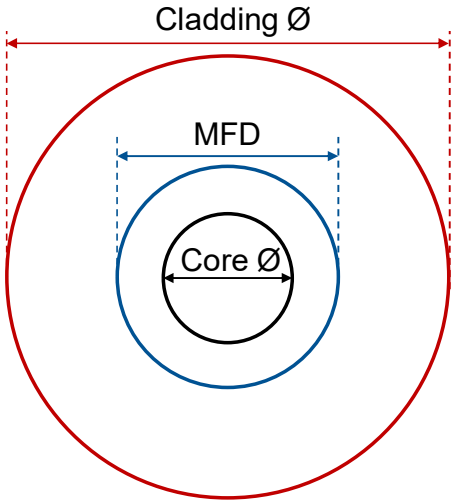
"Fiber" people talk about Mode Field Diameter (MFD), "System" people talk about Effective Area



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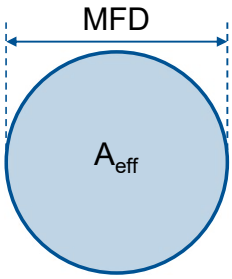
"Fiber" people talk about Mode Field Diameter (MFD), "System" people talk about Effective Area (A_{eff})



$A_{eff} = \pi \times (MFD/2)^2$

Simplistic view, good as crude assessment

$A_{eff} = k(\lambda) \times \pi \times (MFD/2)^2$

$k(\lambda)$ – profile dependant mapping value for more precise MFD to A_{eff} mapping

Further reading:
- TIA/EIA FOTP-191 "Measurement of Mode Field Diameter of Single-Mode Optical Fiber", 1998
- Y. Nakamira, "Relationship between nonlinear effective area and modefield diameter for dispersion shifted fibres", Electronics Letters, 1994
- M. Vastag, "Mode field diameter and effective area", White Paper, 2001

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There is a fine interplay between

Effective area, cut-off wavelength, and bend performance

Effective Area ↑	Nonlinear performance
Cut-off Wavelength ↑	Less wideband transmission
Bend Performance ↓	Could impact cabling and splice joints

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An increase in A_{eff} from 80 to 150 µm² requires to relax requirements on <u>both</u> cut-off wavelength and bend performance

Source: ITU-T G.652.D

Attribute	Detail	Value	Unit
Mode field diameter	Wavelength	1310	nm
	Range of nominal values	8.6-9.2	µm
	Tolerance	± 0.4	µm
Cladding diameter	Nominal	125.0	µm
	Tolerance	± 0.7	µm
Core concentricity error	Maximum	0.6	µm
Cladding noncircularity	Maximum	1.0	%
Cable cut-off wavelength	Maximum	1260	nm
Macrobending loss	Radius	30	mm
	Number of turns	100	
	Maximum at 1625 nm	0.1	dB

Source: ITU-T G.654.D

Attribute	Detail	Value	Unit
Mode field diameter	Wavelength	1 550	nm
	Range of nominal values	11.5-15.0	µm
	Tolerance	±0.7	µm
Cladding diameter	Nominal	125	µm
	Tolerance	±1	µm
Core concentricity error	Maximum	0.8	µm
Cladding non-circularity	Maximum	2.0	%
Cable cut-off wavelength	Maximum	1 530	nm
Macrobending loss (Note 4)	Radius	TBD	mm
	Number of turns	TBD	
	Maximum at 1 550 nm	TBD	dB
	Radius	30	mm
	Number of turns	100	
	Maximum at 1 625 nm	2.0	dB

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An increase in A_{eff} beyond today's 150 µm² will require to make further compromises and introduces new challenges

Effective Area	↑↑ Nonlinear performance
Cut-off wavelength	↑↑ Cut-off λ increase to ~2000nm (fiber multimoded in C-band)
Bend Performance	↓ Cabling and splice joints
Mode Coupling & MPI	↑ Excess loss, DSP complexity

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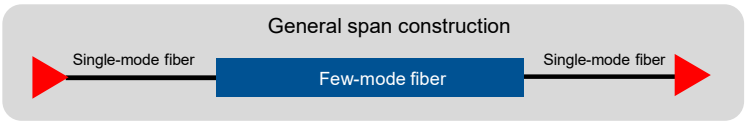
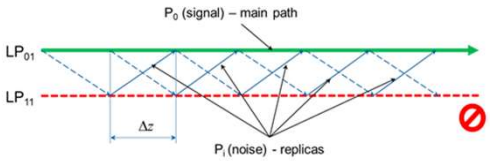
"Quasi" SMF (QSMF) concept

Allow for few mode operation but only launch into the fundamental mode





$$MPI(z) = \frac{\left(P_{01}(z) - P_{signal}(z)\right)}{P_{signal}(z)}$$

Key fiber parameters:

1) Distributed mode coupling coefficient κ (km^{-1})
2) Differential mode attenuation (DMA) $\Delta\alpha$ (km^{-1})

Model Results

$$MPI(z) \cong \frac{\left(\Delta\alpha \cdot z - 1 + e^{-\Delta\alpha \cdot z}\right)}{\Delta\alpha^2}\kappa^2 \quad [1]$$

Excess loss: $EL \equiv P_0(L)/[P_0(0)e^{-\alpha_0 L}] \approx e^{-\kappa}$

Source: M. Mlejnek *et al*, IEEE Photonics J., vol. 7, pp. 1-16 (2015)

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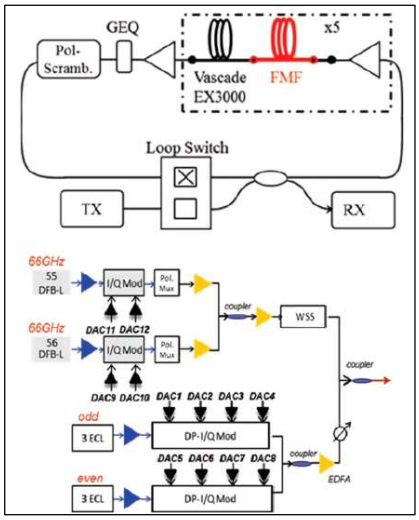
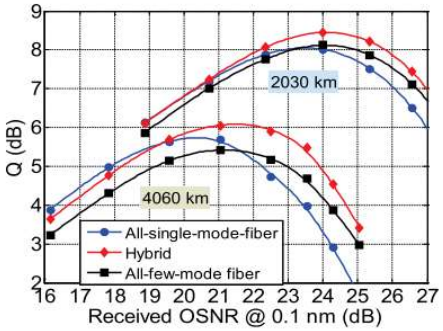
First experimental demonstration of hybrid (QSMF + 150 μm²) fiber transmission over transoceanic distances





Hybrid span: use QSMF for low nonlinearity, and 150 μm² for low loss

Source: F. Yaman, OFC PDP Th5C.7, 2015

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Challenges for QSM fiber and systems

- Essentially trade some nonlinear impairment for new linear impairments
  - Multi-path interference (MPI)
  - Excess loss
- Complexity of DSP for MPI mitigation - can it be practical?
- Can we make A_{eff} large enough to gain significant performance increase vs. 150 μm^2?
- Macrobend and Microbend sensitivity
- Splice loss to standard single-mode fiber
  - "Bridge" fiber; tapered splices ?
- In fact, latest subsea SDM systems are moving towards modest A_{eff}*

* J.-C. Antona, "Evolution of high capacity submarine open cables", S4B.2, ACP 2019

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Further fiber innovations in long-haul applications can be driven by a mix of established and novel pathways

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"Smaller fiber" could represent several different options…

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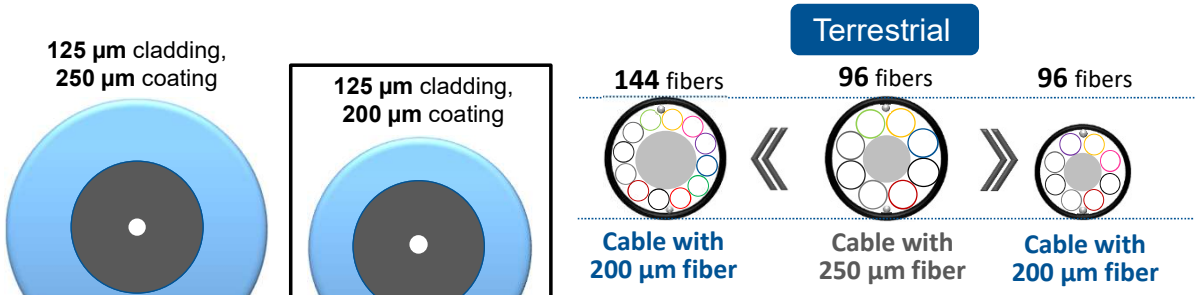
"Smaller fiber" could represent several different options…



Achieved through thinner primary and secondary coating

- 200 → 250 µm: -50% fiber count
- 17mm cable design example*:
  - 200 µm: 48 fiber count

*T. Inoue, "200µm Diameter Fiber for SDM Submarine Networks: Cabling Performance and Record Transmission Result", OFC 2022

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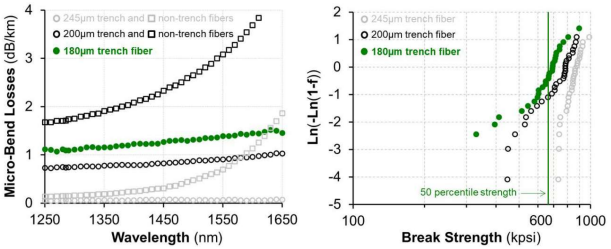
"Smaller fiber" could represent several different options…

125 µm cladding,
250 µm coating

125 µm cladding,
180-190 µm coating

Terrestrial

Additional things to consider for fiber with lower coating diameter



Source: P. Sillard, "180µm-coated bend-insensitive fiber and micro-duct cable", ECOC 2021

Further modifications to glass profile and coating to meet strength and microbend requirements may be needed

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"Smaller fiber" could represent several different options…

125 µm cladding,
250 µm coating

Further reduction in cladding and coating
??

Reduced-cladding fiber

- H. Sato, "160-um coating optical fiber with 80-um cladding for 1,728-fiber cable", IWCS 2021
- S. Bickham, "Reduced cladding diameter fibers for high-density optical interconnects", JLT 2020

Reduced-coating fiber

- W. Niu, "Thin-coated fibers for high-density optical interconnects", M3C.2, OFC 2021

Suitability for long-haul applications is yet to be proven – strength, loss, bend etc.

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Further thoughts…

- First-generation of smaller fibers (200 µm coating) are already being used in long-haul terrestrial networks, and are coming to subsea next
- Further small reductions in size are possible (180-190 µm coating diameter), perhaps only with modest changes to ecosystem
- More significant reduction in size are likely to require some compromises (e.g., splicing, bend, loss, strength, cable design)
  - Currently not clear what the practical limit is on fiber size for long-haul terrestrial and subsea systems
  - Answer may be different for non long-haul applications

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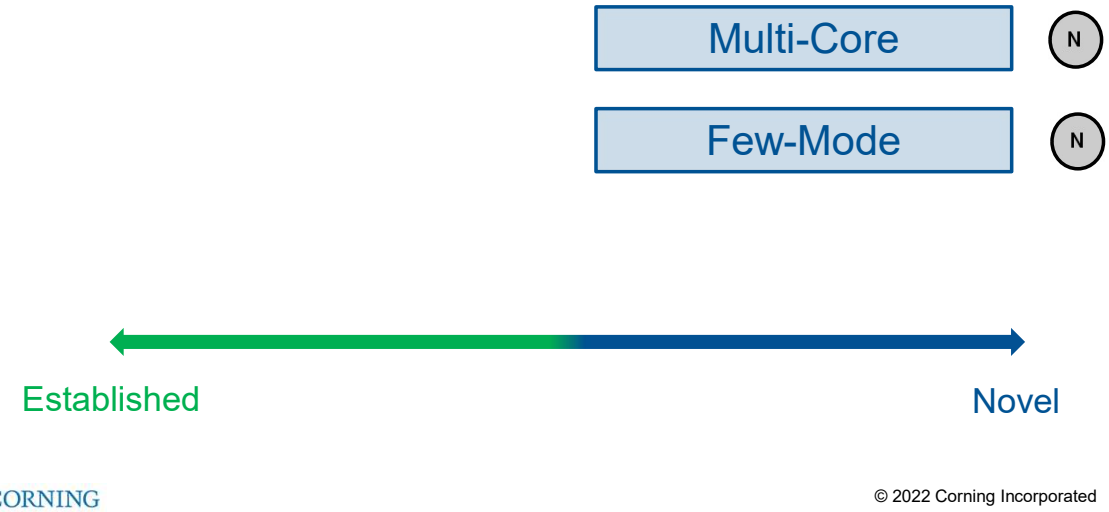
Further fiber innovations in long-haul applications can be driven by a mix of established and novel pathways



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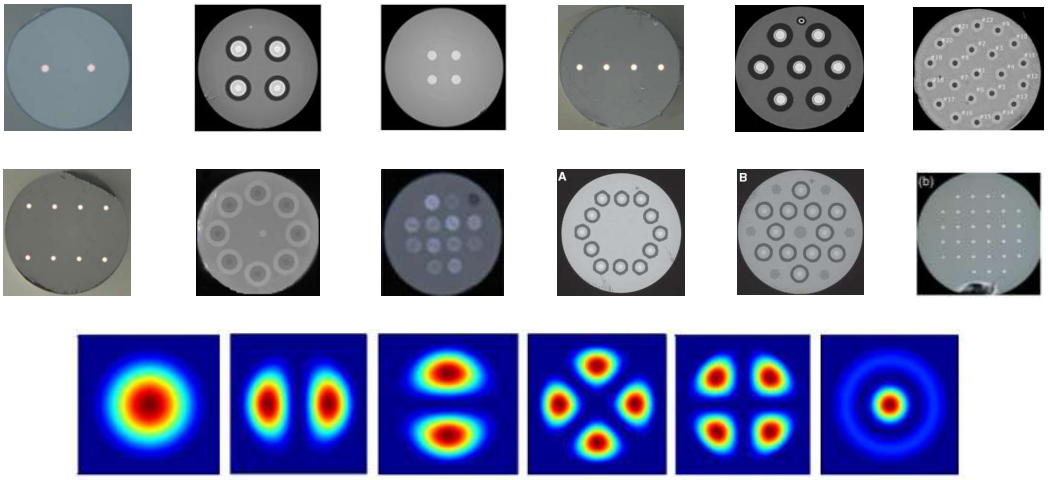
Multiple multi-core and few-mode designs have been reported to date…



Source: compilation of publicly available images (via Google image search)

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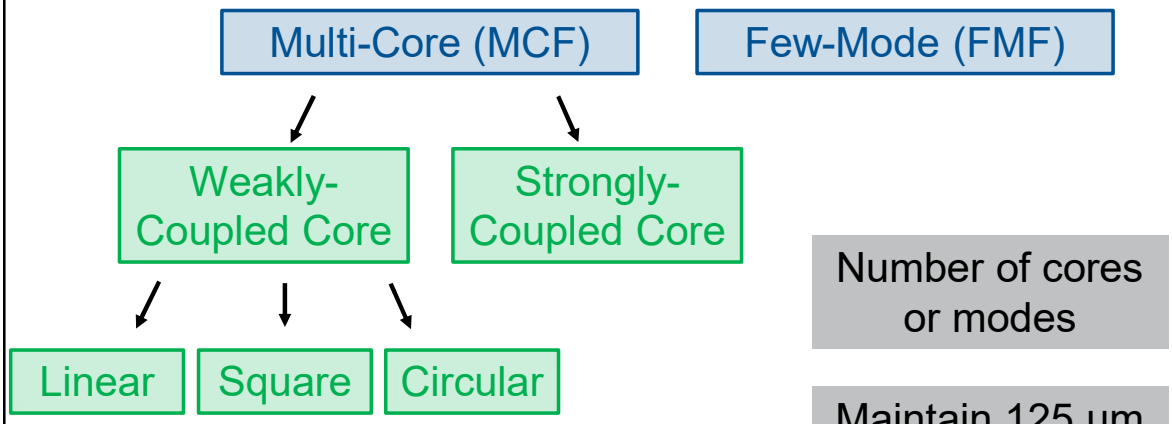
…but they could be split into well-defined categories



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Strongly-coupled MCF

0.155 dB/km record attenuation at 1550 nm

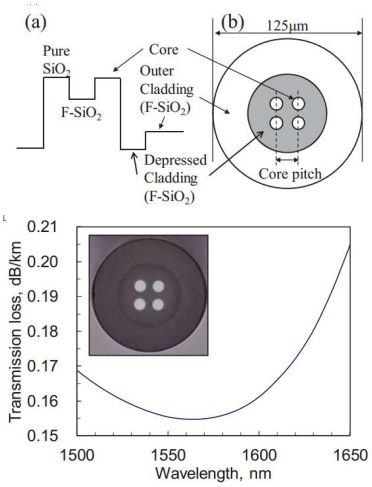

Table 1 Properties of the fabricated C-4CF.

Characteristics	Unit	Value
Fiber length	km	61.0
Core pitch	μm	20.1
Transmission loss*1	dB/km	0.155
Effective area (A_{eff})*1	μm^2	112
Cable cut-off wavelength (λ_{cc})	nm	1480
Chromatic dispersion*1	ps/nm/km	20.4
Dispersion slope	$ps/nm^2/km$	0.06
Bend loss at R=15 mm*1	dB/turn	0.01
Cladding diameter	μm	125
Coating diameter	μm	245

*1: At 1550 nm wavelength

Source: H. Sakuma, "Microbending behavior of randomly-coupled ultra-low-loss multi-core fiber", ECOC 2019

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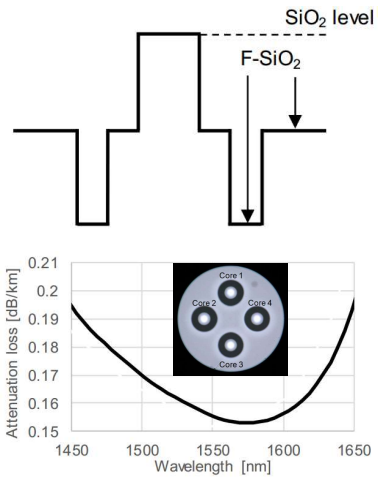
Weakly-coupled MCF

0.155 dB/km record attenuation at 1550 nm



Tab. 1: Characteristics of fabricated MCF at 1550 nm

Characteristics	Unit	Value
Cladding diameter	μm	125
Coating diameter	μm	245
Core pitch	μm	43.0
Effective area	μm^2	87.1
Cut-off wavelength (22m)	nm	1539
Dispersion	ps/nm/km	22.6
Dispersion slope	$ps/nm^2/km$	0.06
Attenuation loss	-	-
Core 1	dB/km	0.155
Core 2	dB/km	0.156
Core 3	dB/km	0.157
Core 4	dB/km	0.155
Inter core crosstalk	-	-
Core 1 – Core 2	dB/100km	-63.8
Core 2 – Core 3	dB/100km	-60.7
Core 3 – Core 4	dB/100km	-62.7
Core 4 – Core 1	dB/100km	-61.8

Source: M.Takahashi, "Uncoupled 4-core fibre with ultra-low loss and low inter core crosstalk", ECOC 2020

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Hero transmission experiments using FMF and MCF

List of some recent examples

- B. Puttnam, “0.715 Pb/s transmission over 2009.6 km in 19-core cladding pumped EDFA amplified MCF link”, OFC 2019
- G. Rademacher, “172 Tb/s C+L band transmission over 2040 km strongly coupled 3-core fiber”, OFC 2020
- G. Rademacher, “10.66 Peta-Bit/s transmission over a 38-core-three-mode fiber”, OFC 2020
- R. Essiambre, “First transmission of a 12D format across three coupled spatial modes of a 3-core coupled core fiber at 4 bits/s/Hz”, OFC 2020
- G. Rademacher, “1.01 Peta-bit/s C+L-band transmission over 15-mode fiber”, ECOC 2020
- B. Puttnam, “319 Tb/s transmission over 3001 km with S, C and L band signals over >120 nm bandwidth in a 125um 4-core fiber”, OFC 2021

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ITU SDM Technical Report brings industry leaders together to determine SDM development roadmap

INTERNATIONAL TELECOMMUNICATION UNION
TELECOMMUNICATION STANDARDIZATION SECTOR
STUDY PERIOD 2017-2020

WD5-2
STUDY GROUP 15
Original: English

Question(s): 5/15 E-Meeting 6-17 December 2021

CONTRIBUTION

Source:	NTT, CLPAJ, KDDI, NEC	
Title:	Proposal for draft TR.sdm	
Purpose:	Proposal	
Contact:	Kazuhide Nakajima NTT Japan	Tel: +81 29 868 6442 Fax: +81 29 868 6440 E-mail: kazuhide.nakajima.gr@hco.ntt.co.jp
Contact:	Yoshinori Yamamoto CLPAJ Japan	Tel: +81 45-853-7267 Fax: +81 45-851-0935 E-mail: yamamoto-yoshinori@sei.co.jp
Contact:	Yuki Niiyama CLPAJ Japan	Tel: +81-80-1000-6144 Fax: +81-3-6281-8639 E-mail: yuki.niiyama@furukawaelectric.com
Contact:	Tsukasa Hosokawa CLPAJ Japan	Tel: +81 43-484-2197 Fax: +81 43-481-1210 E-mail: tsukasa.hosokawa@jp.fujikura.com
Contact:	Yuta Wakayama KDDI Corporation Japan	Tel: +81 70-3508-5774 Fax: E-mail: yu-wakayama@kddi.com
Contact:	Takanori Inoue NEC Japan	Tel: +81-80-8456-5878 E-mail: t-inoue_jm@nec.com
Keywords:	Technical report, space division multiplexing	
Abstract:	This contribution proposes some new contents and modifications to the latest draft TR.sdm.	

- **Purpose:** to establish clear and agreed upon roadmap for SDM optical fiber and cable technologies
  - Incl. test methods, connectivity, maintenance and restoration
- **Scope:**
  - MCF, FMF, and other SDM options
  - Evaluation of geometrical, mechanical and optical properties
  - Examination of application areas

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Source: ITU-T SDM Technical Report, December 2021 draft

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What must happen for multi-core (MCF) and few-mode (FMF) fibers to be successful in long-haul?

- Terrestrial: do we *really* have a transmission capacity bottleneck?
  - 50 Tb/s C+L fiber capacity x # fibers (192-864fc): up to 21.6 Eb/s route capacity (compare with traffic matrix roadmap)
  - Subsea is different: # fibers is much smaller
- Large-scale manufacturability with consistent quality must be proven
- Cost per bit on par or better than single-core fiber
  - Low end-to-end loss (fiber attenuation, fanouts, mode MUX/DEMUX)
  - Low manufacturing cost
- Developed measurement techniques and seamless splicing, MCF or FMF-EDFA a strong bonus
- Redeveloped DSP for strongly-coupled MCF (challenging) or FMF

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Further fiber innovations in long-haul applications can be driven by a mix of established and novel pathways

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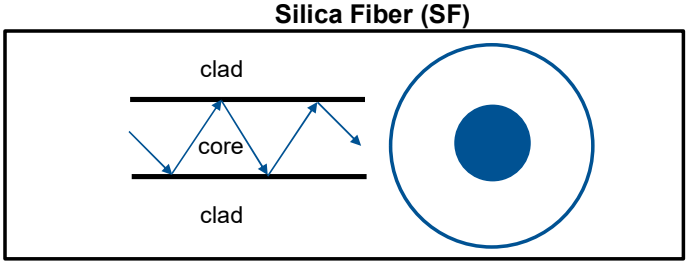
What is hollow-core fiber?

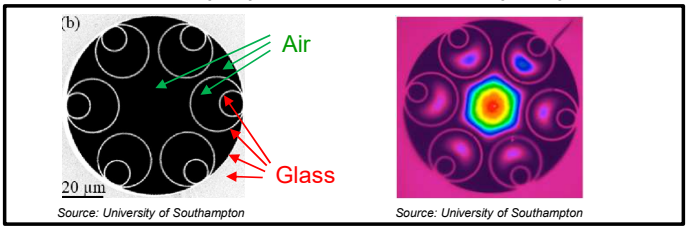
Light is guided in air and confined within the core using engineered microstructures

Silica Fiber (SF)



- **Core:** Silica doped with Germania
- **Cladding:** Silica and sometimes with a fluorine doped trench (ring of lower refractive index)

Anti-resonant (AR) Hollow-Core Fiber (HCF)



- **Core:** hollow (air) core surrounded by a set of glass capillaries that create light confinement
- **Cladding:** formed by limited reflecting interfaces

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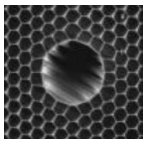
Hollow Core Fiber Types

NANF provides significant attenuation reduction compared to PBGF

Photonic Bandgap Fiber

Record Attenuation
1.2dB/km @ 1620nm



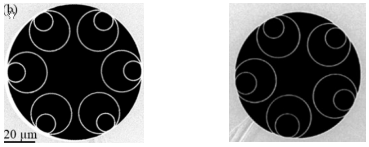
Attenuation levels too high for practical application as data transmission fiber

Source: P. Roberts, "Ultimate low loss of hollow-core photonic crystal fibres", Optics Express, 2004

Nested Anti-Resonant Nodeless Fiber

Record Attenuation
0.28dB/km @ 1550nm*

Record Attenuation
0.22dB/km @ 1625nm**



In latest design, fiber attenuation levels approaching level of standard silica fibers

Sources:
**G. Jasion, "Hollow-core NANF with 0.28 dB/km attenuation in the C and L bands", OFC 2020*
***H. Sakr, "Hollow-core NANFs with five nested tubes and record low loss at 850, 1060, 1300 and 1625nm, OFC 2021*

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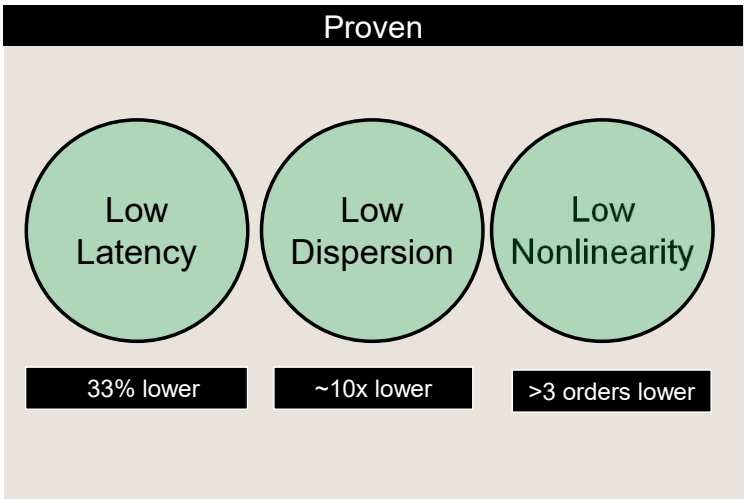
Proven benefits of hollow-core fibers

Low latency, nonlinearity and dispersion



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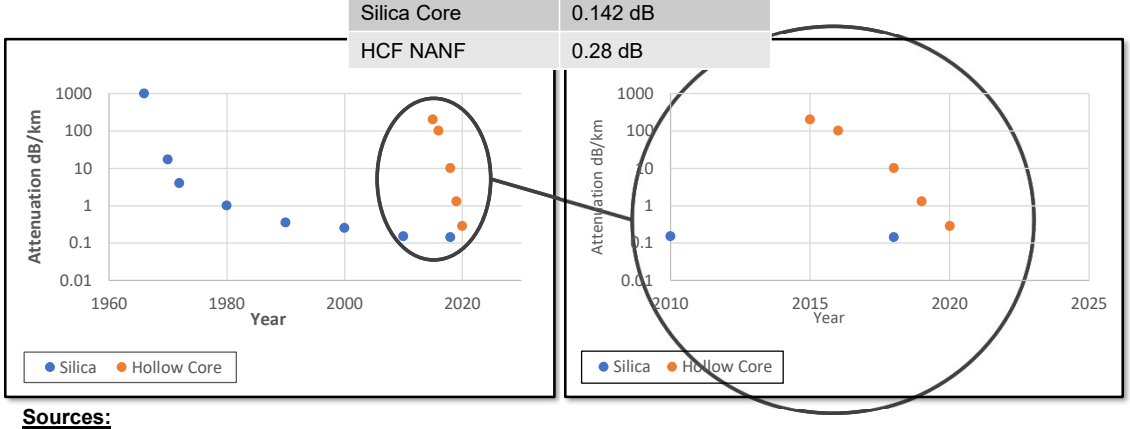
The Attenuation Challenge

HCF attenuation: remains to be seen what further reductions are achievable

Current Record Attenuation @1550nm	
Silica Core	0.142 dB
HCF NANF	0.28 dB



Sources:

Jasion et al., OFC 2020; Bradley et al., ECOC 2018; Belardi, JLT 2015; Kosolapov et al., Quantum Electronics 2016; Tamura et al., OFC 2017; Makovejs et al., OFC 2015; Hirano et al., OFC 2013; Nagayama et al., Electronics Letters 2002; Nagayama et al., OFC 2002; Kanamori et al., 1986

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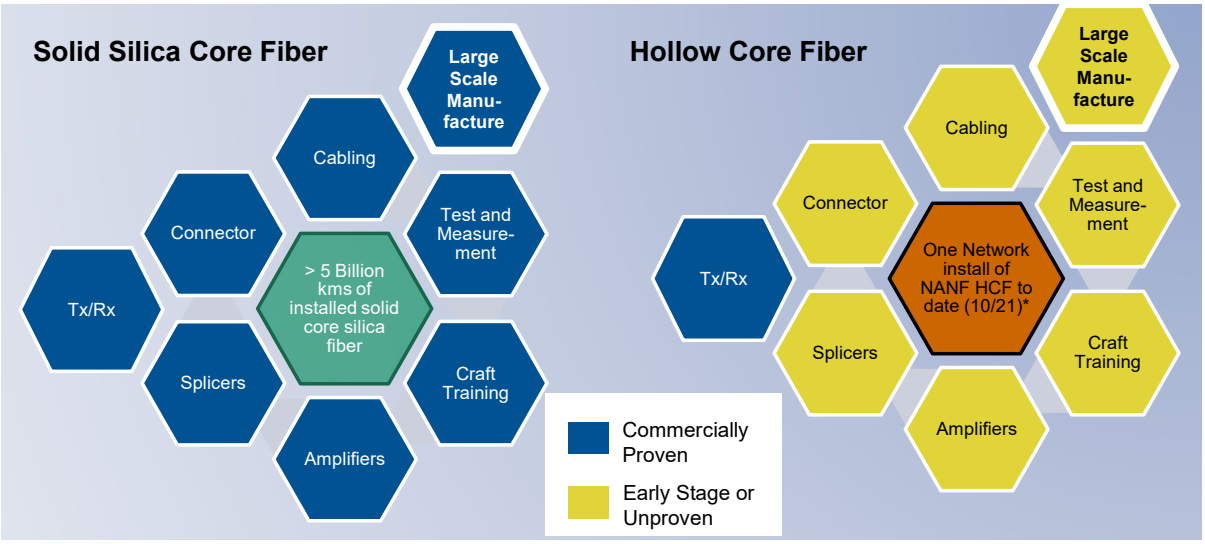
The Installation Ecosystem Challenge

Ecosystem for HCF is still immature, large scale manufacturing unproven: interest likely to remain in specialist, high-value applications for some time



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Agenda

- Today: fibers, systems, networks
- Fiber innovation pathways
- Implications on system and network design

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Further fiber innovations in long-haul applications can be driven by a mix of established and novel pathways

SNR B — Lower Attenuation

SNR — Larger Effective Area

Established ⟷ Novel

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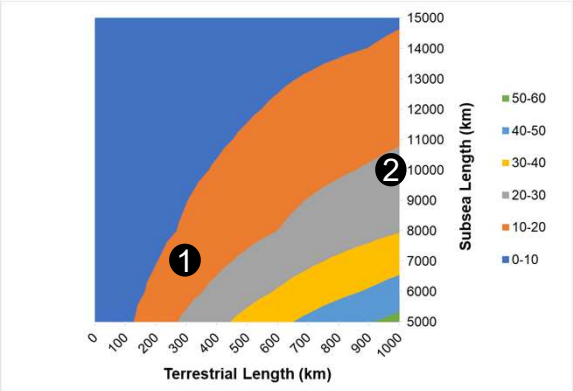
Low attenuation and large A_{eff} require fiber launch power optimization to gain additional performance, but is worth doing

Attenuation ↓	Optical Power ↓		
Effective Area ↑	Optical Power ↑		

Subsea/ Terrestrial Length	7,000km/ 300km	10,000km/ 1,000km
Added system capacity	❶ 14 Tb/s	❷ 23 Tb/s

Extra cable capacity (Tb/s) enabled by using G.654.E vs. G.652.D on land



Source: Makovejs et al, OFC 2022, W2A.17

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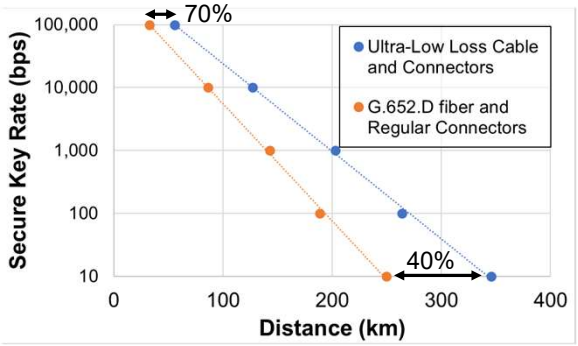
Emerging applications will also favour ultra-low loss fiber

Be Quantum Key Distribution (QKD)-ready



Connector	Cable attenuation
0.5 dB - Regular	0.210 dB/km - Regular
0.03 dB – Ultra-Low Loss	0.157 dB/km – Ultra-Low Loss

- What should be the target secure key rate?
- QKD over the same or separate fiber?
- If same fiber, will 1310nm work (Raman scattering)?

Source: adapted from K. Wei, "High-speed measurement-device-independent quantum key distribution with integrated silicon photonics", Phys. Rev. X 10, 31030, 2020

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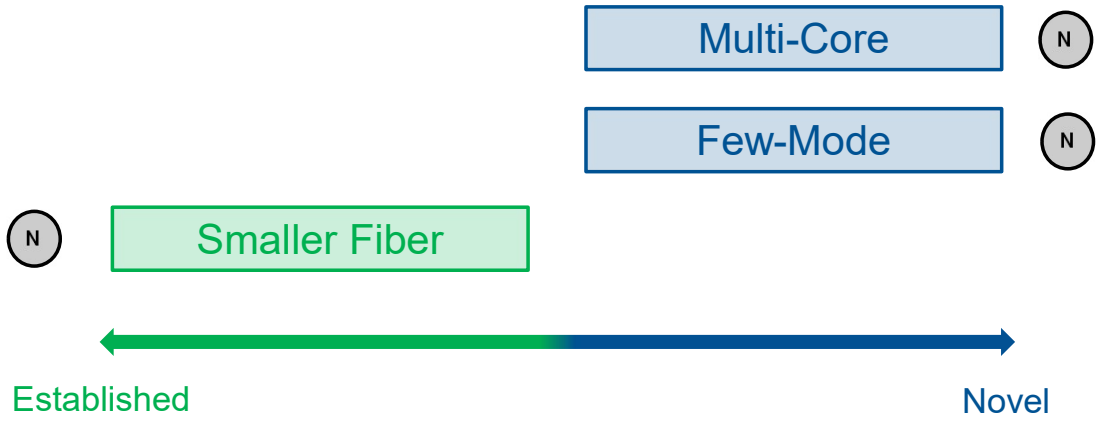
Further fiber innovations in long-haul applications can be driven by a mix of established and novel pathways



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Higher "N" may require more electrical power in subsea

Power feed equipment (PFE) voltage increase or cable impedance decrease

$$V_{PFE} = I \cdot R_C + n_R \cdot n_{EDFA} \cdot \frac{P_{EDFA}}{I}$$

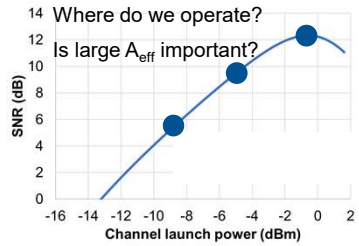
Current; More fibers / more amplifiers; Reduce EDFA ***electrical*** power dissipation (channel launch power)

Voltage; Cable impedance; Number of repeaters, EDFAs; Power dissipated per EDFA

V_{PFE}: 15 kV → 18 kV[1,2] → ?

R_C: 1 Ω/km → 0.7 Ω/km[3] → ?

Cable design limitations ?



[1] HMN Press Release, "HMN Tech launches 18 kV power feeding solution", 2021
[2] SubCom Press Release, "SubCom announces contract-in-force for Firmina; a new undersea cable connecting North and South America, 2021
[3] M. Spalding, "Vision for next generation undersea optical networks", Tu2E-1, ECOC 2020

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Further fiber innovations in long-haul applications can be driven by a mix of established and novel pathways

Hollow-Core

SNR B

Established → Novel

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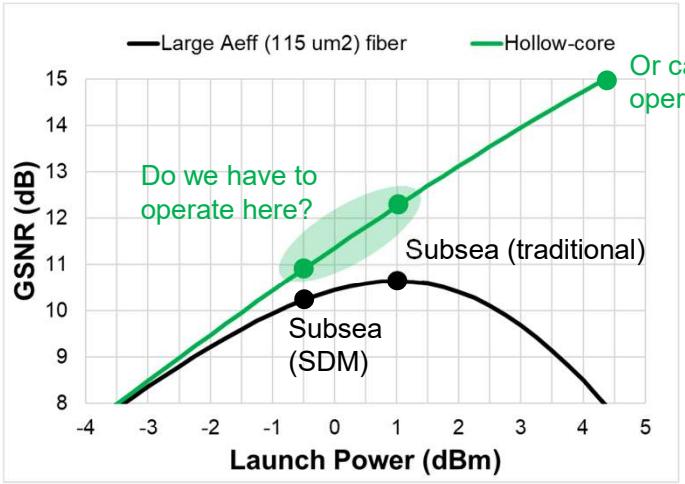
Hollow-core fiber: can we leverage its super-low nonlinearity?

10,000km with 90km spans



(+) Higher fiber pair capacity

(-) Need more powerful EDFAs
(-) Need more electrical power in subsea

Source: Corning

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Further thoughts and predictions…

- Increase in transmission capacity will happen differently in subsea vs. terrestrial networks
  - *Route* capacity is getting more important than *fiber pair* capacity
- No easy fiber solutions beyond the ones used today
  - Will cable innovations play a more central part?
- Next-generation solutions may present themselves organically (path of least resistance) or unexpectedly
  - Will we find the next big step in cost/bit reduction?
  - Will other metrics come to play (e.g. low power consumption)?

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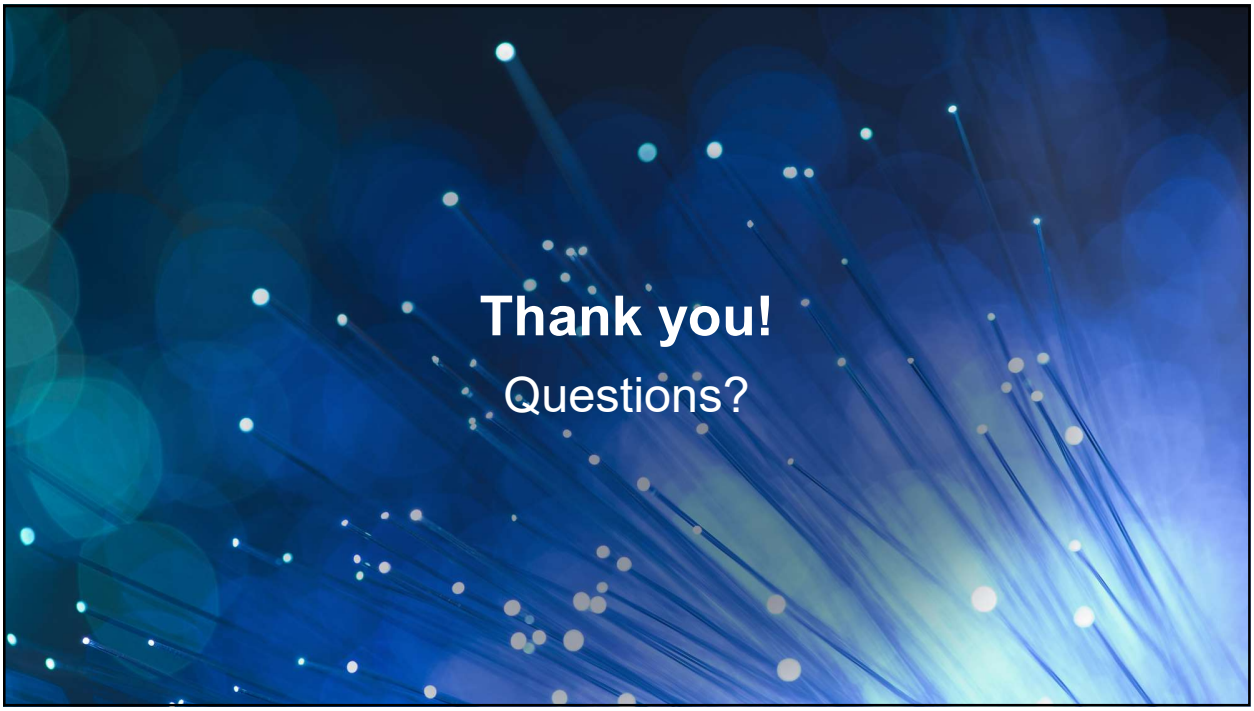

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