Emerging Fibre Technology for Optical Communications

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MODE GAP

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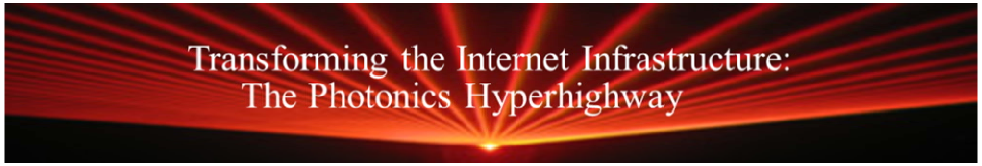


University of Southampton · EPSRC Pioneering research and skills · University of Bristol

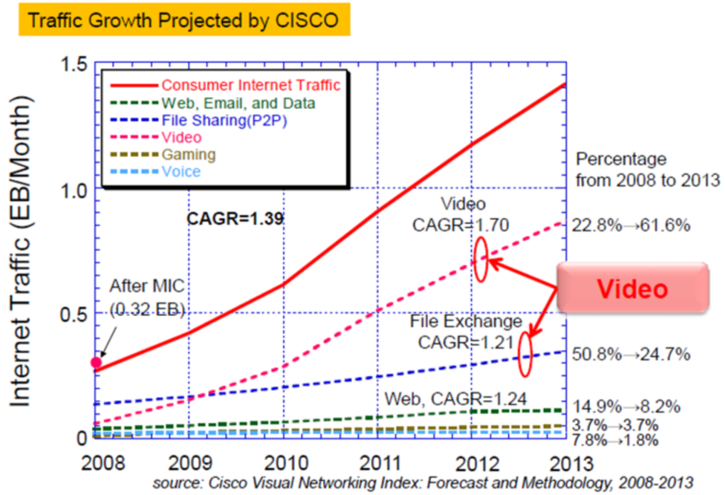
UCL · COMIMO · University of Oxford · University of Southampton · EPSRC Pioneering research and skills · University of Cambridge

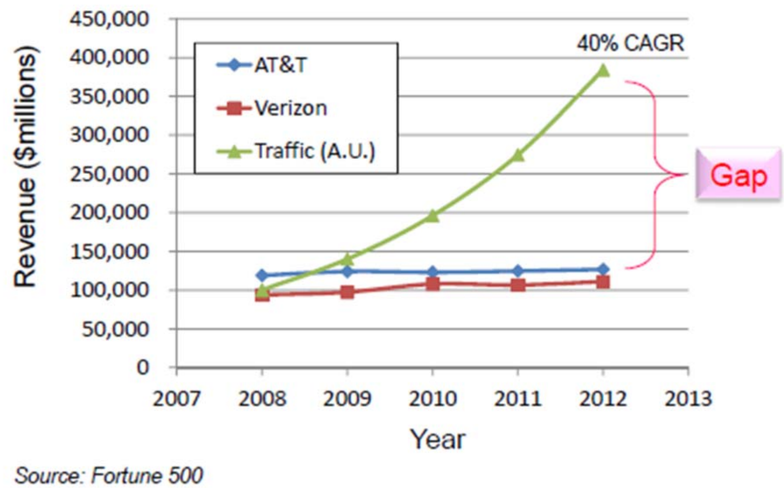
SAFARI

DTU · University of Southampton · Coriant · NTT · Fujikura

COSIGN · Alcatel-Lucent Bell Labs Research · YOFC Delivering Signals Smartly · The Royal Society

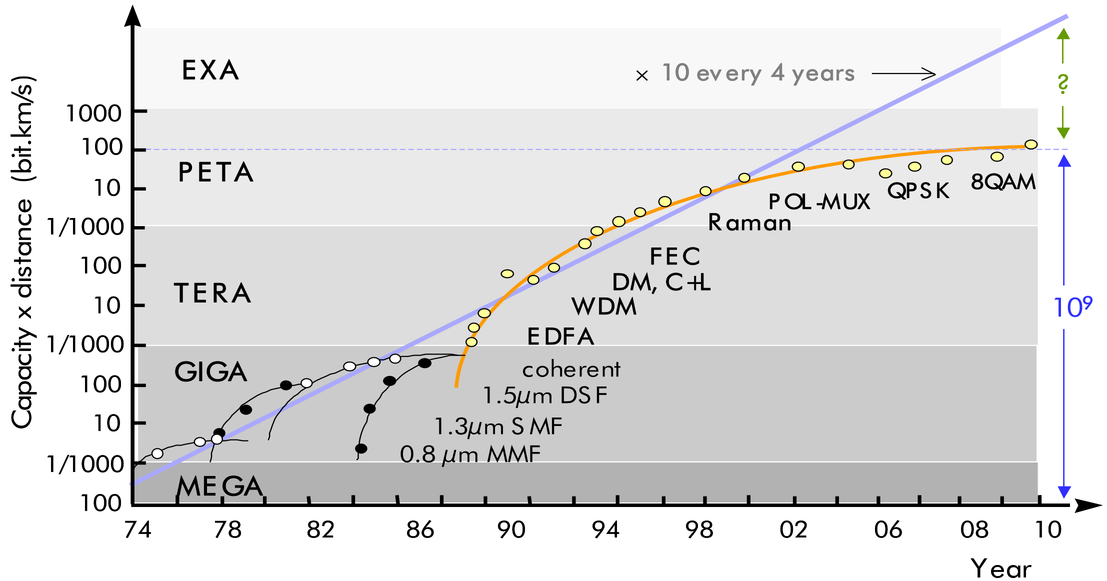
Some Telecom Challenges





Unrelenting demands for increasing internet data traffic (40-50% p.a.)

Increasing costs but flat revenue



Saturation in single-mode fibre transmission capacity looming

Routes to Higher Capacity per Fibre

Overall Fibre Capacity =

Available Bandwidth

x Spectral Efficiency

x Number of Information Channels

Routes to Higher Capacity

Overall Fibre Capacity =

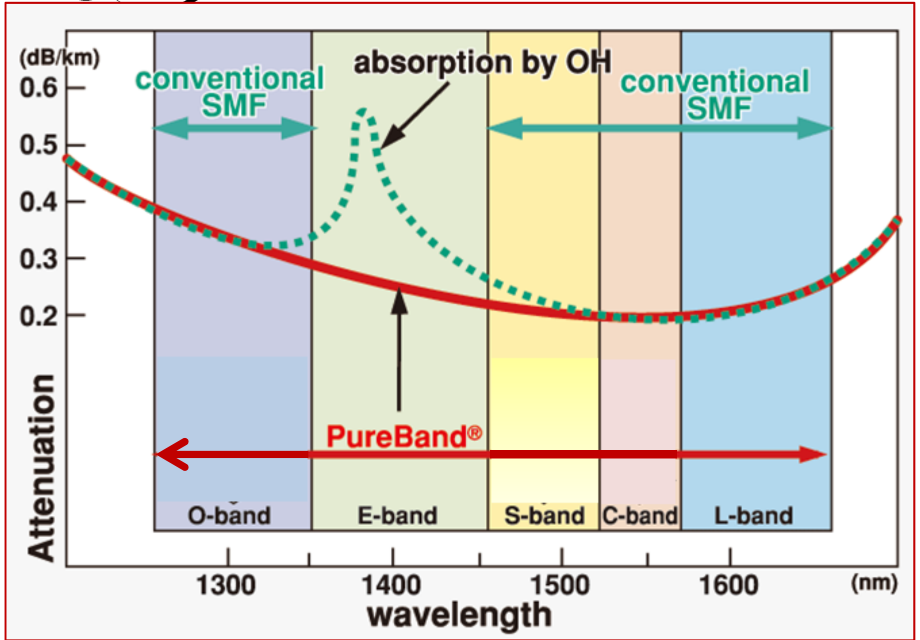
New amplifiers
Extended low loss

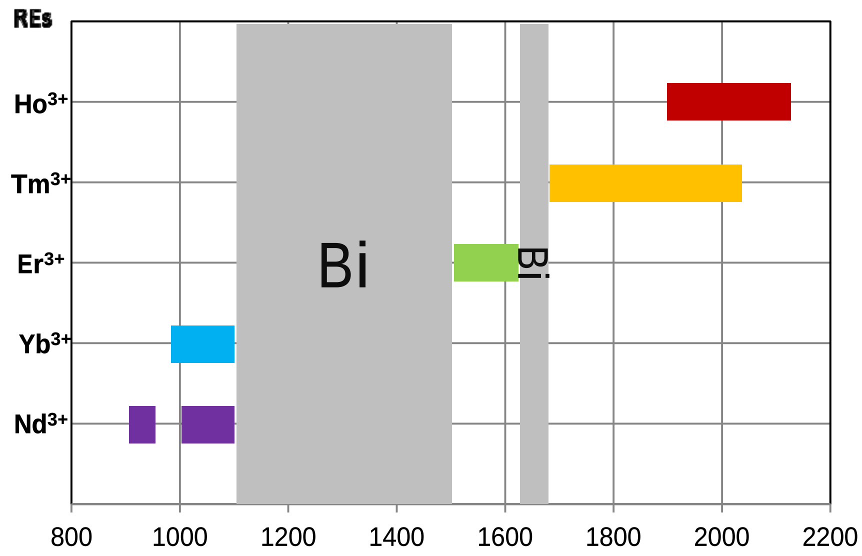
Available Bandwidth

x Spectral Efficiency

x Number of Information Channels

Increasing Bandwidth using Bismuth





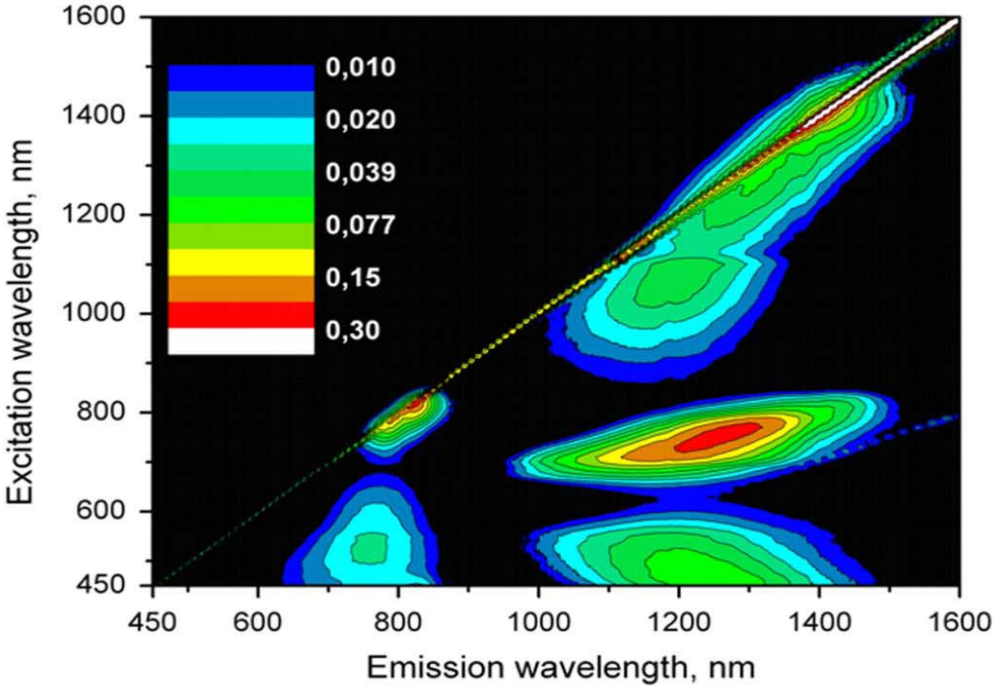
Applications

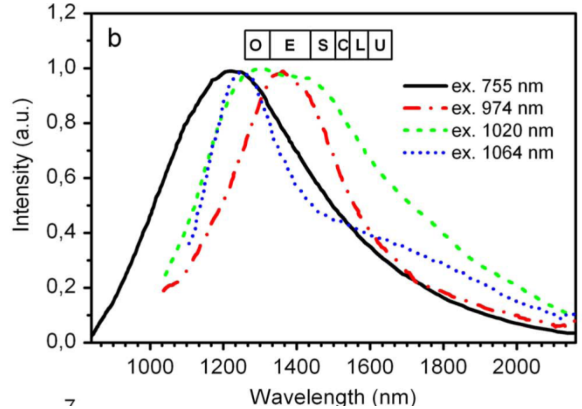
Medicine –Ophthalmology, Dermatology

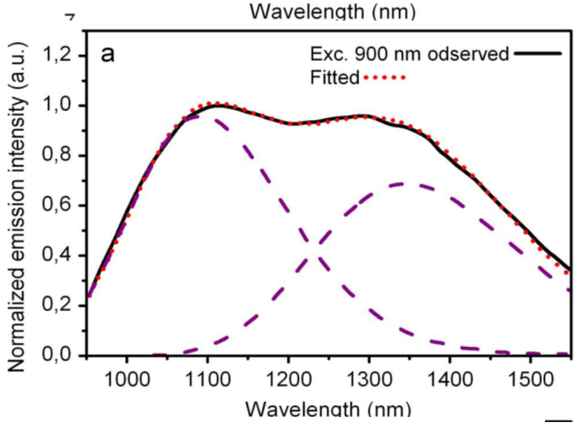
Optical fiber communication

Astronomy-Laser guide star

Spectroscopy of Bismuth



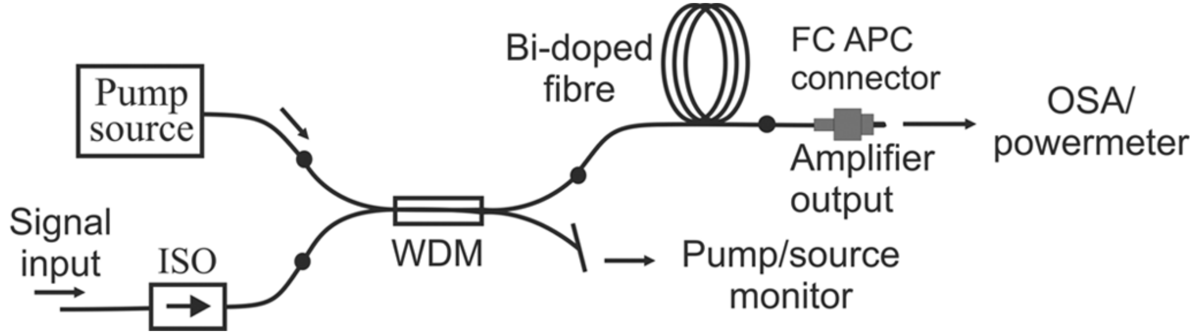


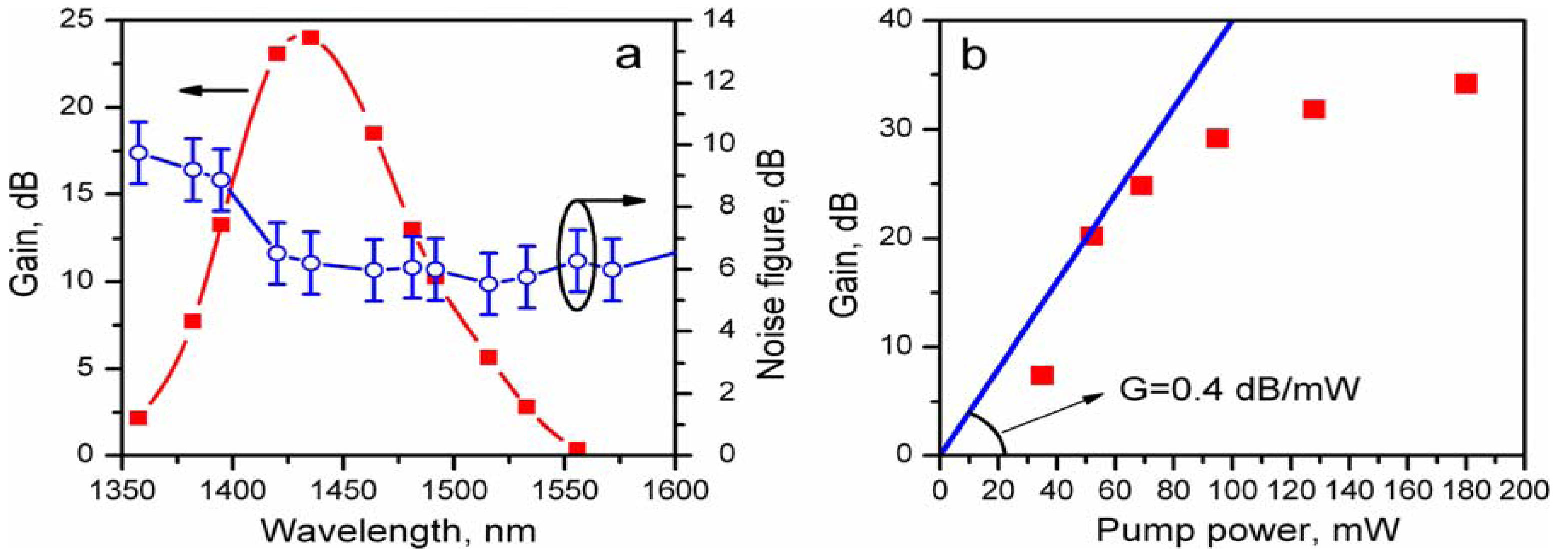


- Bi defect centres in glass produce luminescence from 1100-1600nm
- Spectroscopy complicated and properties depend on glass host, excitation wavelength, fabrication process etc.
- Mechanisms still not well understood, reproducibility a challenge
- Potentially a very interesting gain medium if it can be mastered

E.M. Dianov, JLT, 31, 681-688, (2013).

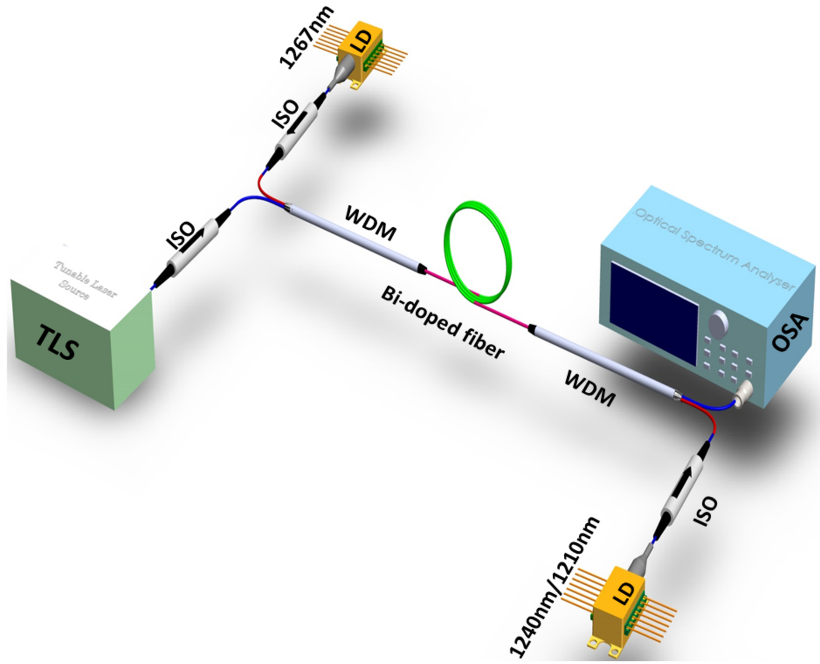
Diode-pumped S-band Bi-amplifier

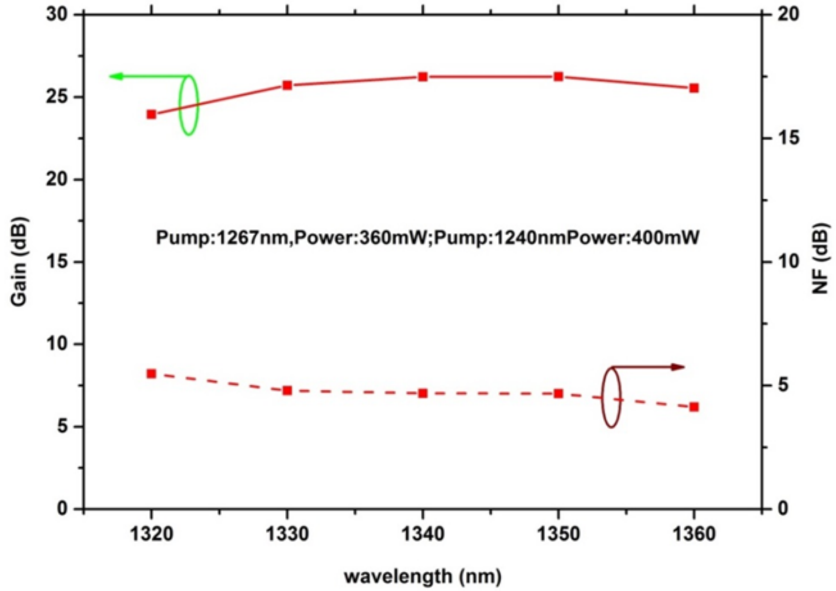




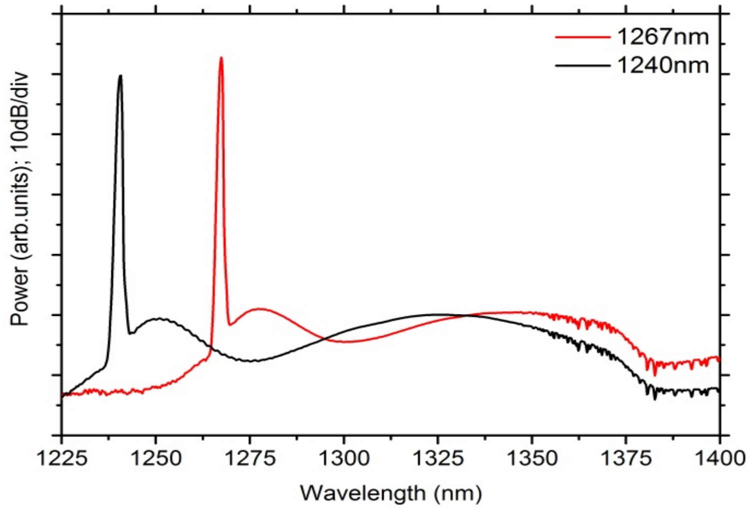
M. A. Melkumov et al. Opt. Letts., 36, 2408-2410, (2011).

1320-1360nm Band BDFA



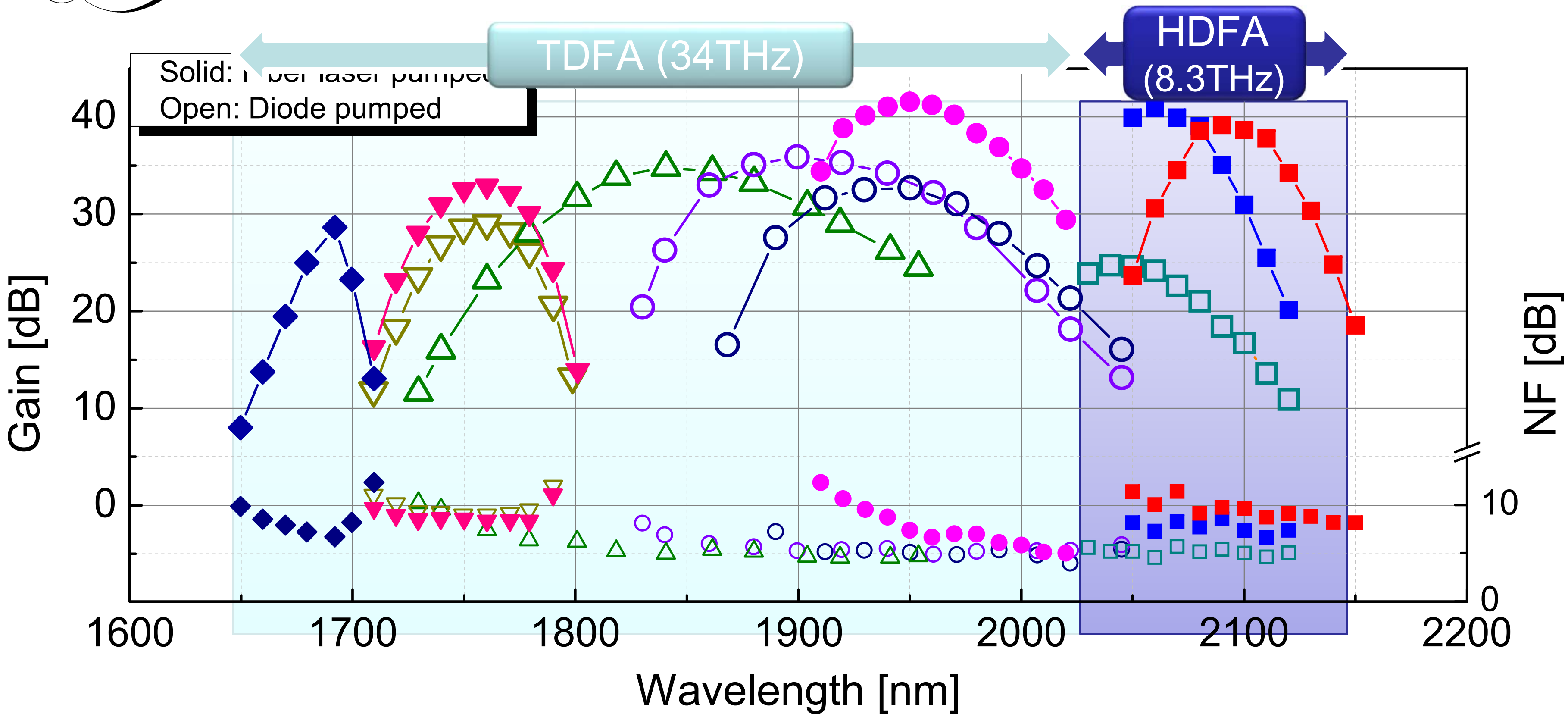


- L=150m
- P_{tot}=760mW (1267nm/1240nm:360mW/400mW)
- G_{max}: 26dB @ 1340nm, NF <5dB
- Gain from 1310-1360nm>20dB



N. K. Thipparapu,etc.al, Opt. Lett. 41, 1518-1521 (2016).

Amplifiers for Beyond the L-Band



- Combined amplification window spans from 1650-2150nm or 500nm which is a factor of ~4 broader than the combined C+L band EDFA in the frequency domain

Z. Li et al. Optics Express 2013

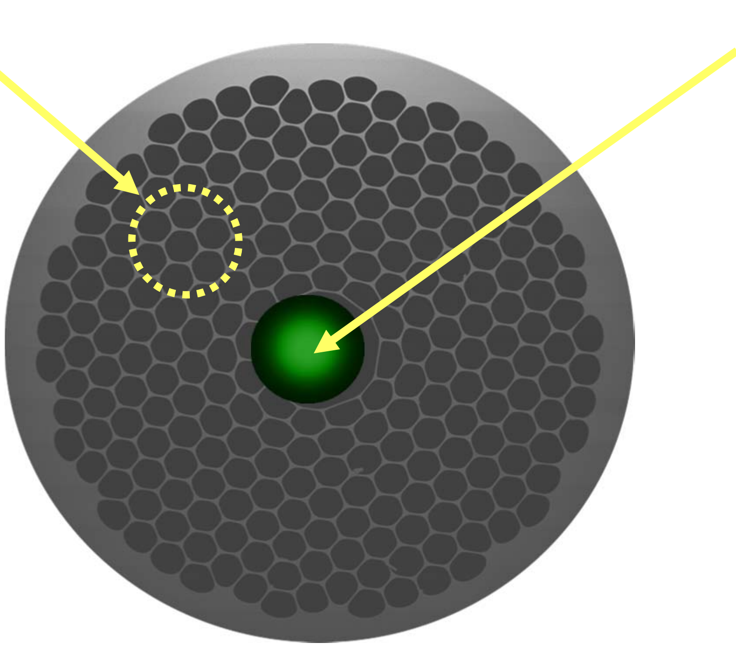
HC-PBGFs for Beyond the L-Band?

Periodic lattice of holes

Optical bandgap covering a well defined wavelength region

Hollow core

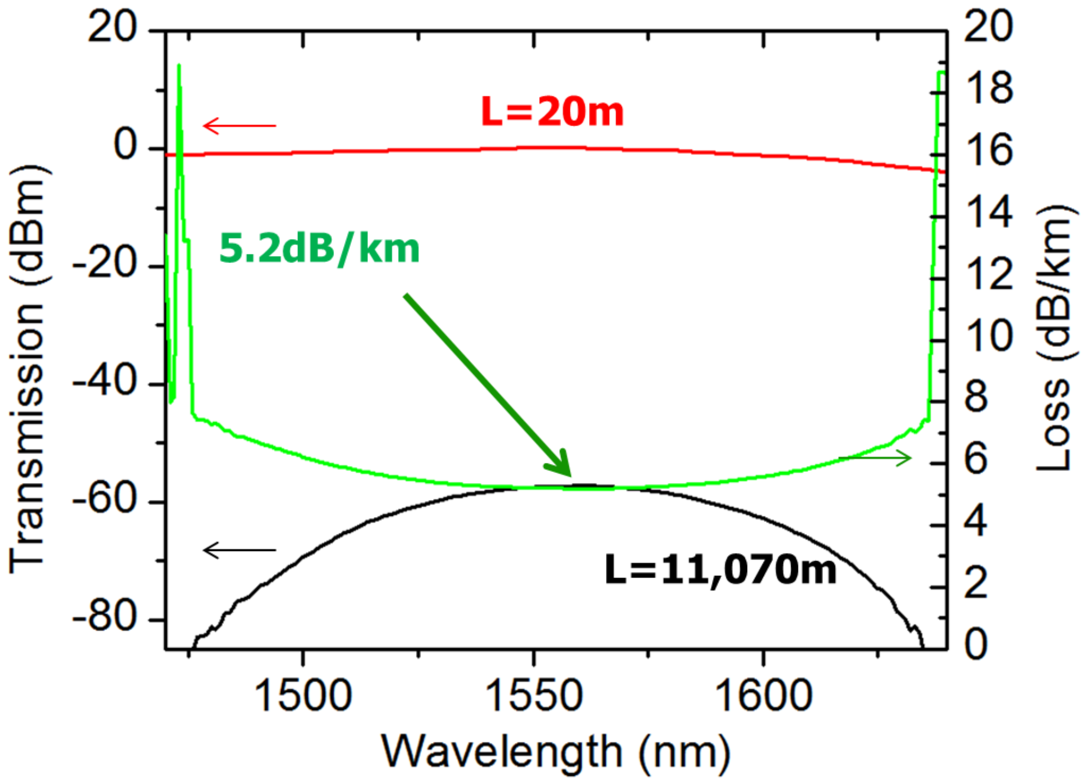
Modes in a low-index core are supported at frequencies within the bandgap

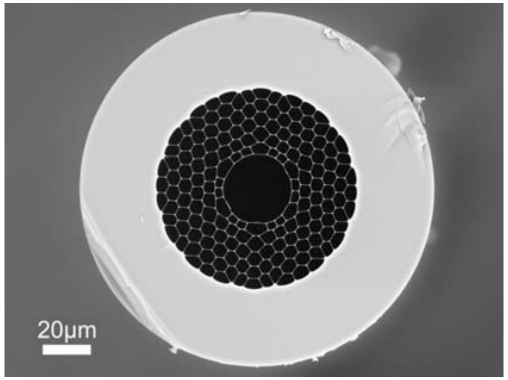


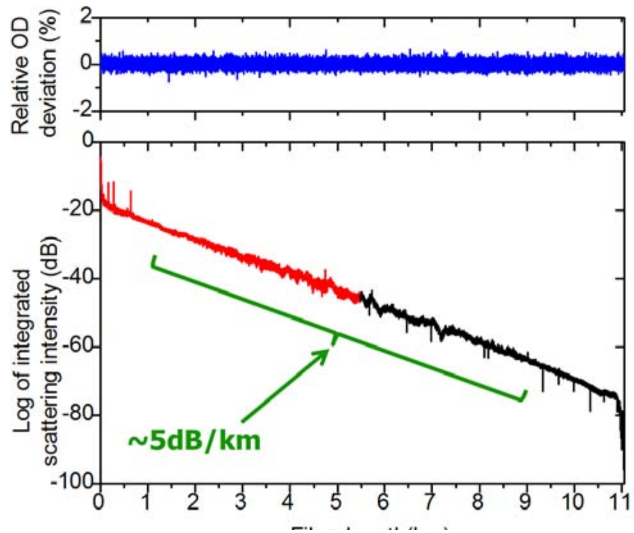
Key Attractions

- Ultralow nonlinearity
- Minimum latency
- Potential for ultralow loss
- Long wavelength transmission
- Radiation hard
- High thermal phase stability

Record 11km length of HC-PBGF



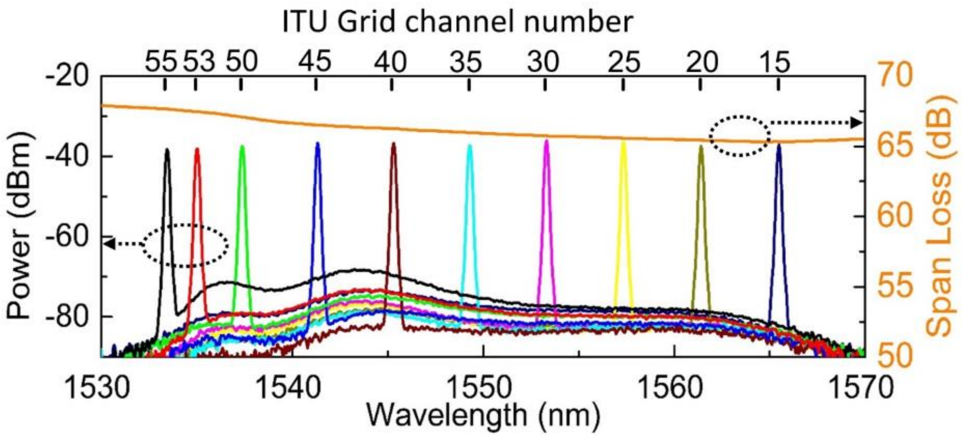


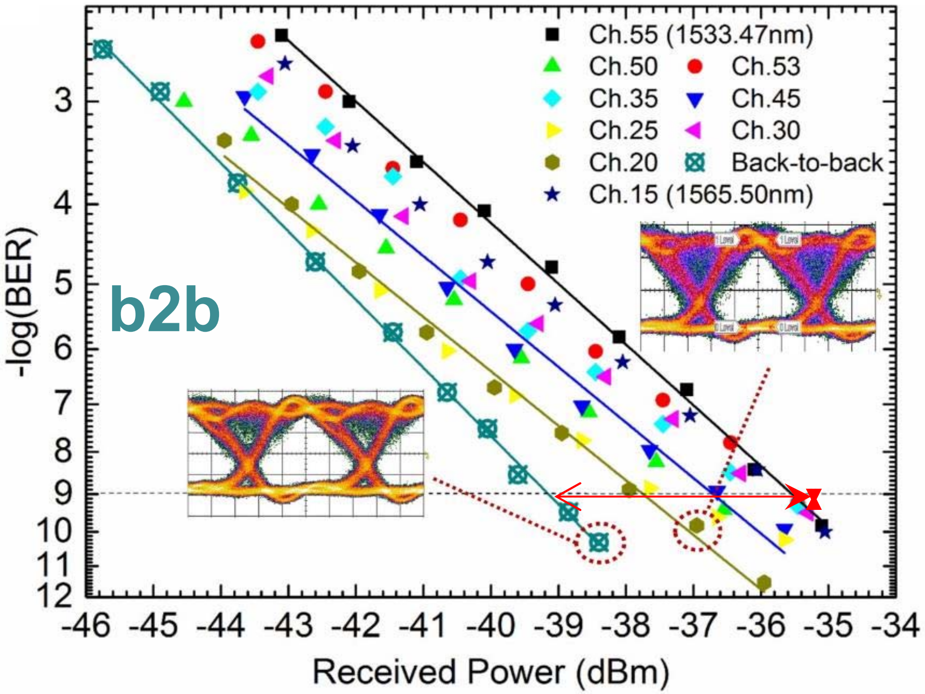


- ~11km long cutback using a SC laser source
- Wide region of low loss (200nm)
- Minimum loss 5.2dB/km @ 1560nm (SOTA losses ~1.7 dB/km)

Y Chen et al. OFC'15 post deadline paper Th5A.1

Low Latency Transmission over 11km





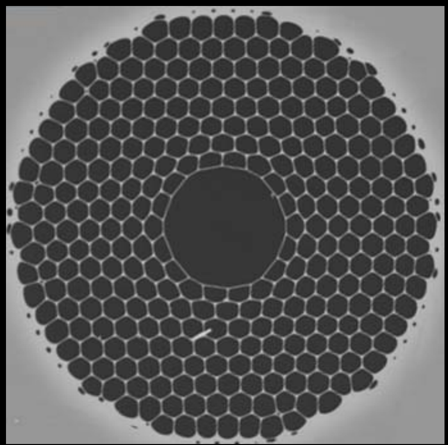
- Simple IM-DD experiment (no DSP, FEC)
- Single channel, 10G RZ, scanned across C band
- Error free transmission, (BER<1e-9) no error floor on all tested channels
- 1.4-3.9dB power penalty likely due to OSNR limitation
- **11km transmission:** **16µs latency reduction** from all-glass equivalent fiber link

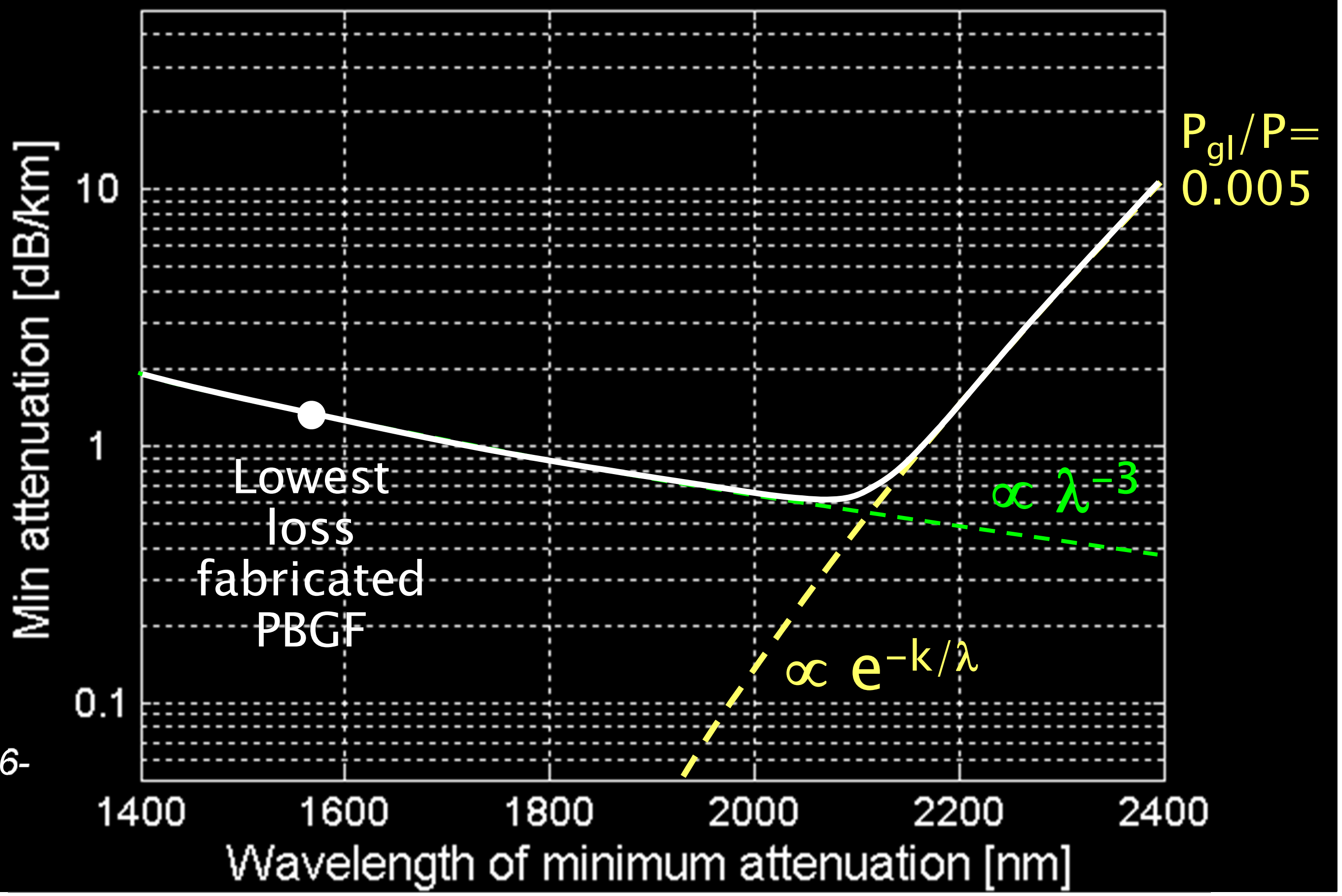
Y Chen et al. OFC'15 post deadline paper Th5A.1

Loss Limits in PBGFs

Main loss contributions

- Rayleigh scattering (always negligible)
- Confinement loss (can be negligible)
- Infrared absorption ($\propto (P_{gl}/P)e^{-k/\lambda}$ → long λ)
- Surface scattering ($\propto \lambda^{-3}$ → short λ)

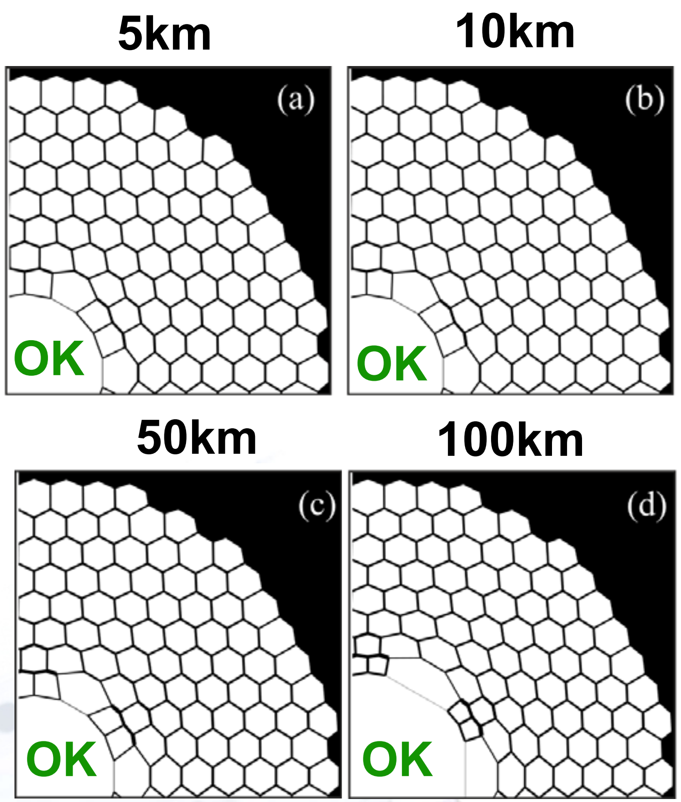




J Roberts et al., OE, 13(1), 236-244, (2005)

Outlook: Yield and Loss

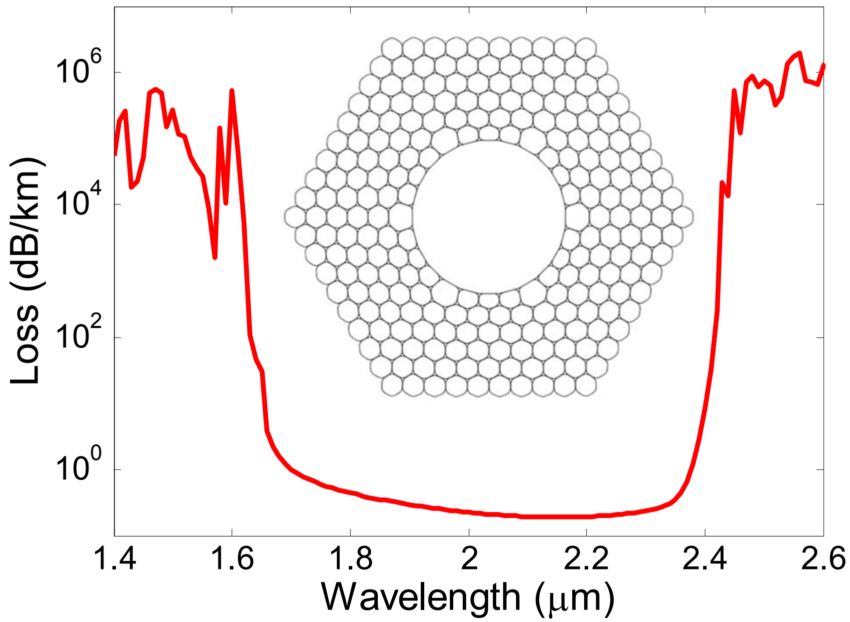
Further yield upscaling



- Modelling indicates current fabrication approach scalable to ~100km/preform

Jasion et al., OFC 2015, paper W2A.37

Further loss reduction

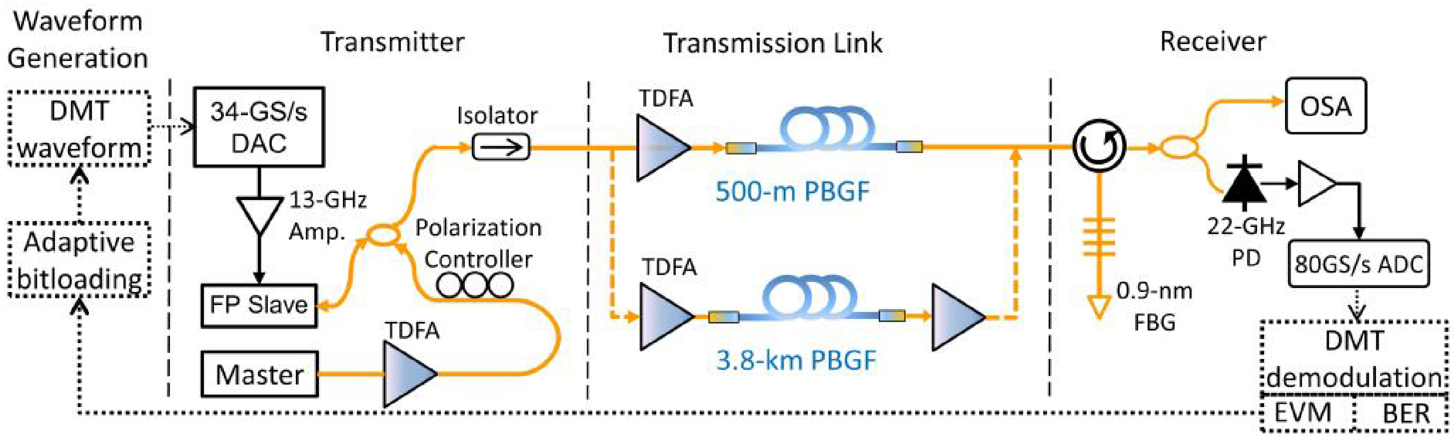


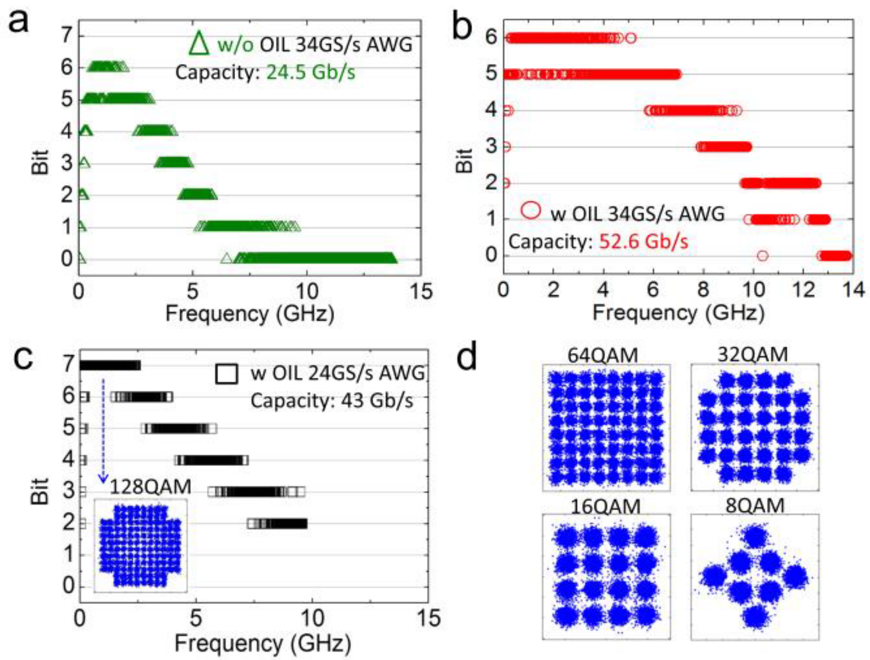
- Loss: <0.2dB/km at 2µm

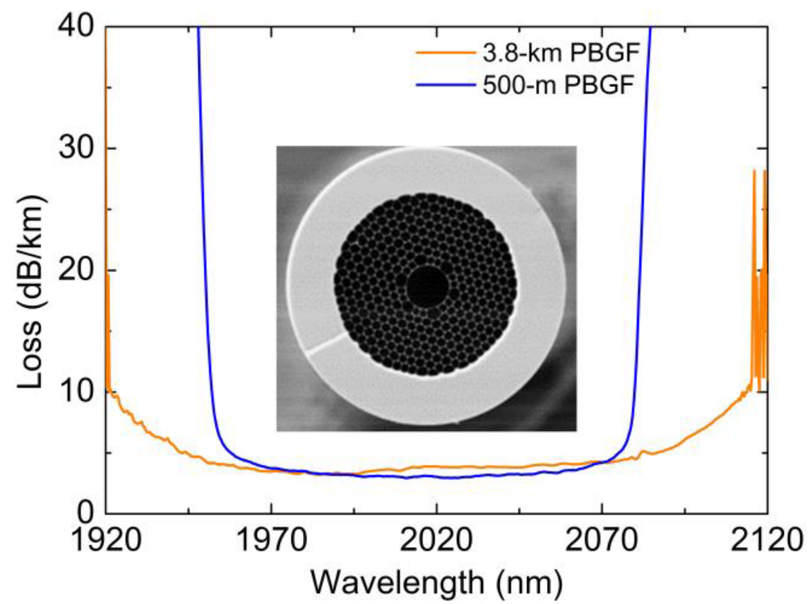
Poletti et al., Nanophotonics 2, 315–340 (2013)

MODE GAP

Amplified 2µm transmission in PBGF

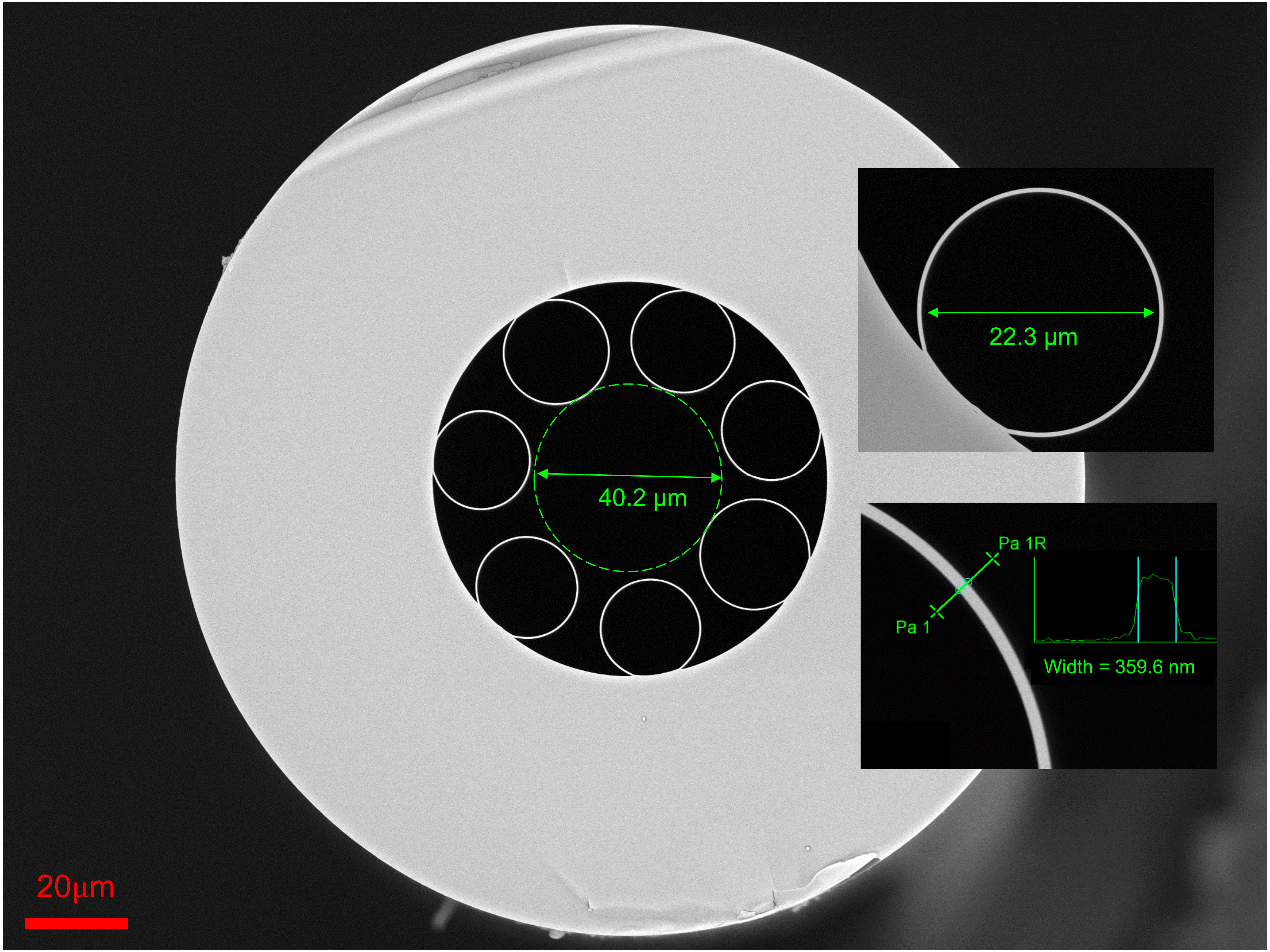




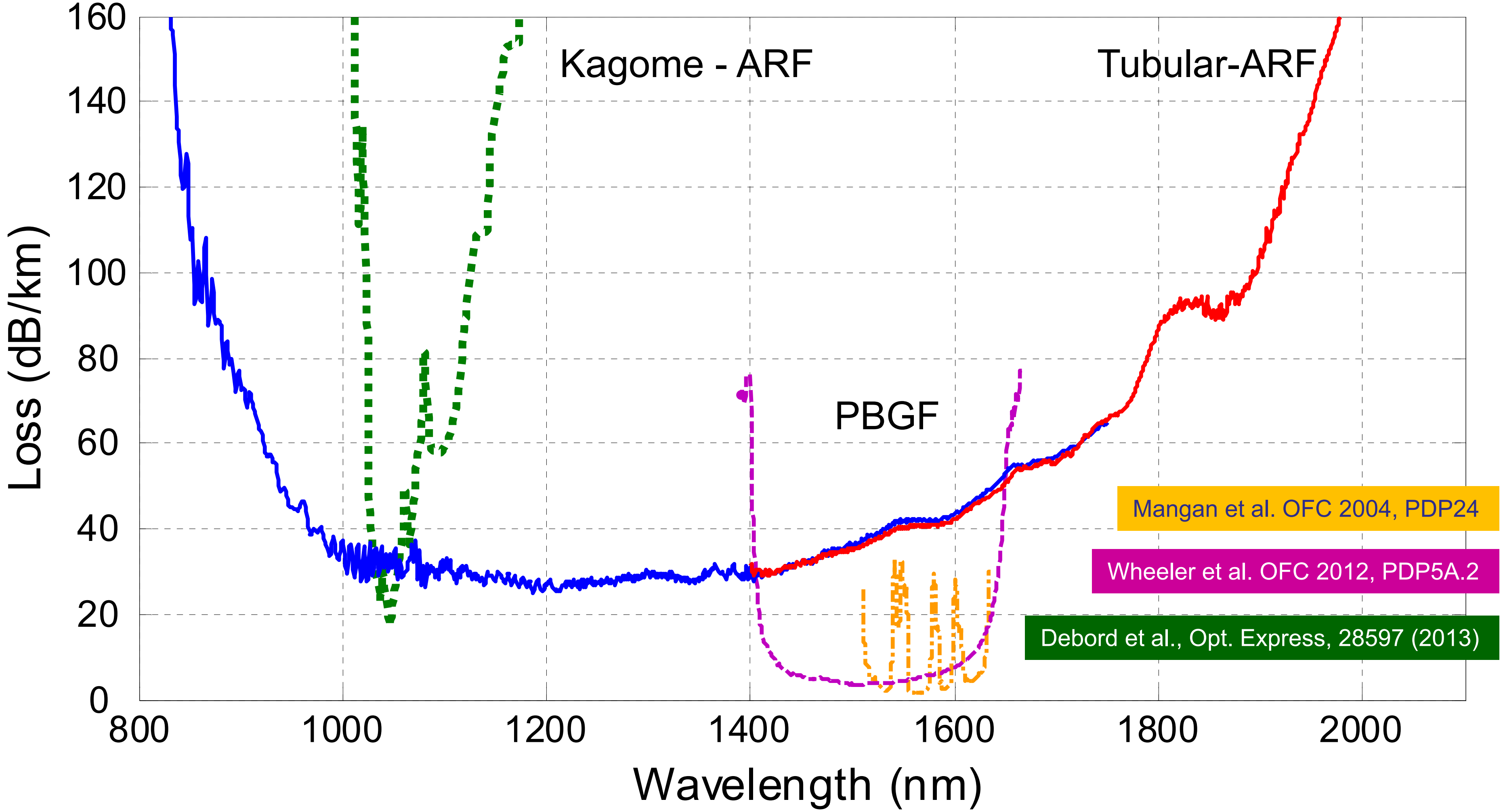


>20 Gbit/s transmission at 2µm over 3.8km PBGF

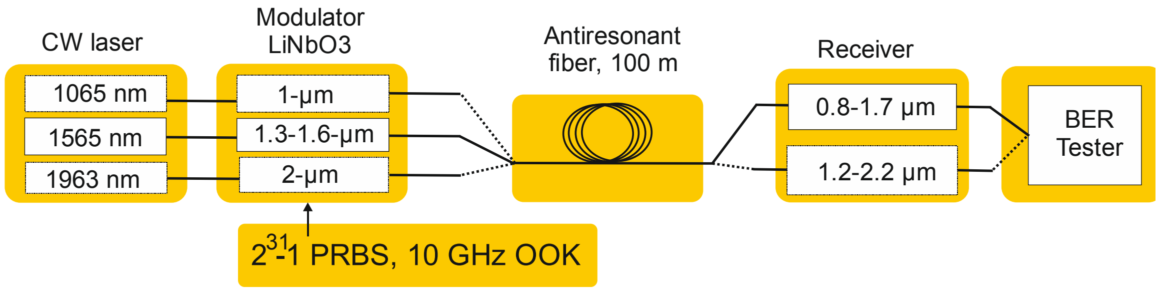
Z.Liu et al. JLT 2015


40.2 μm
22.3 μm
Pa 1R
Pa 1
Width = 359.6 nm
20μm

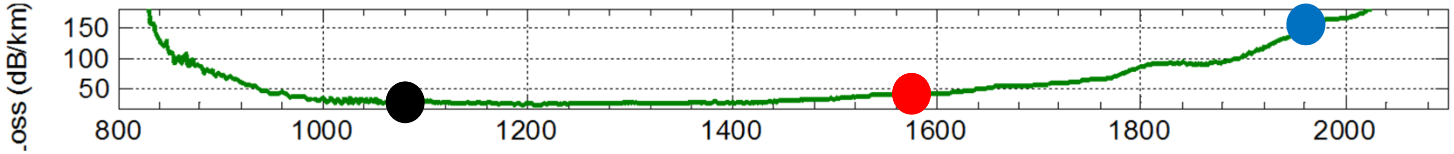
Extended Single Mode Optical Bandwidth

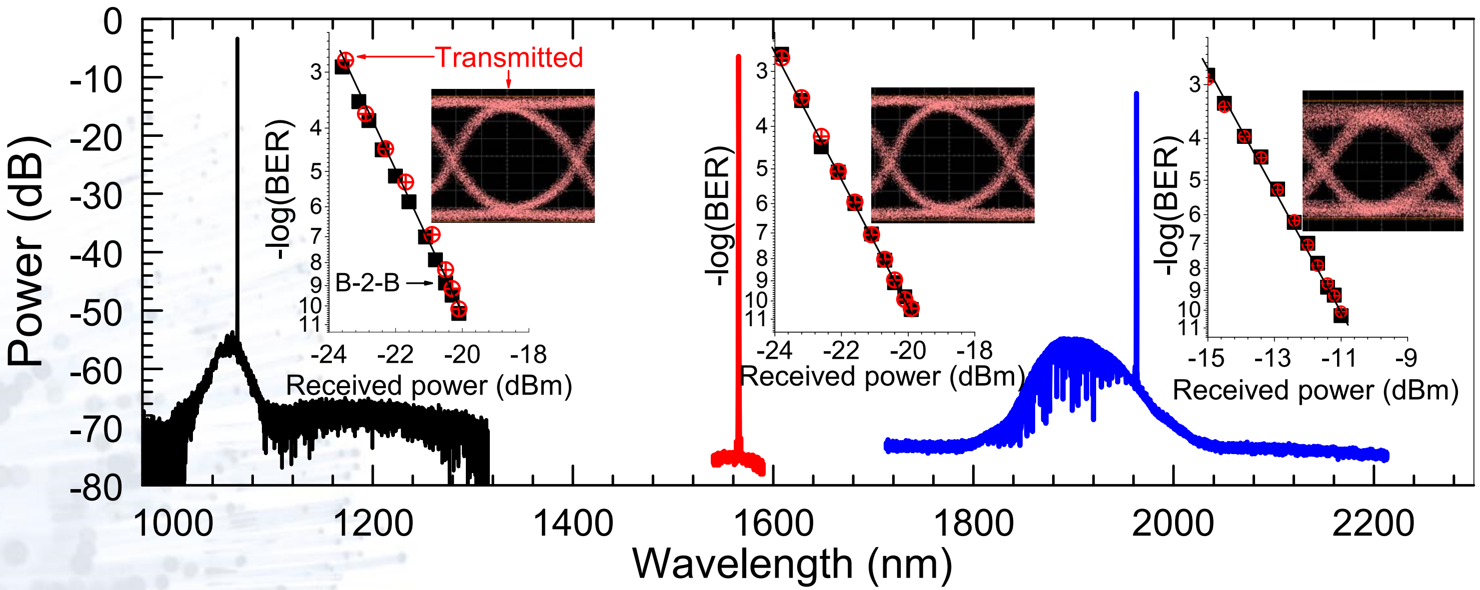


Broadband Transmission Test - 100 m

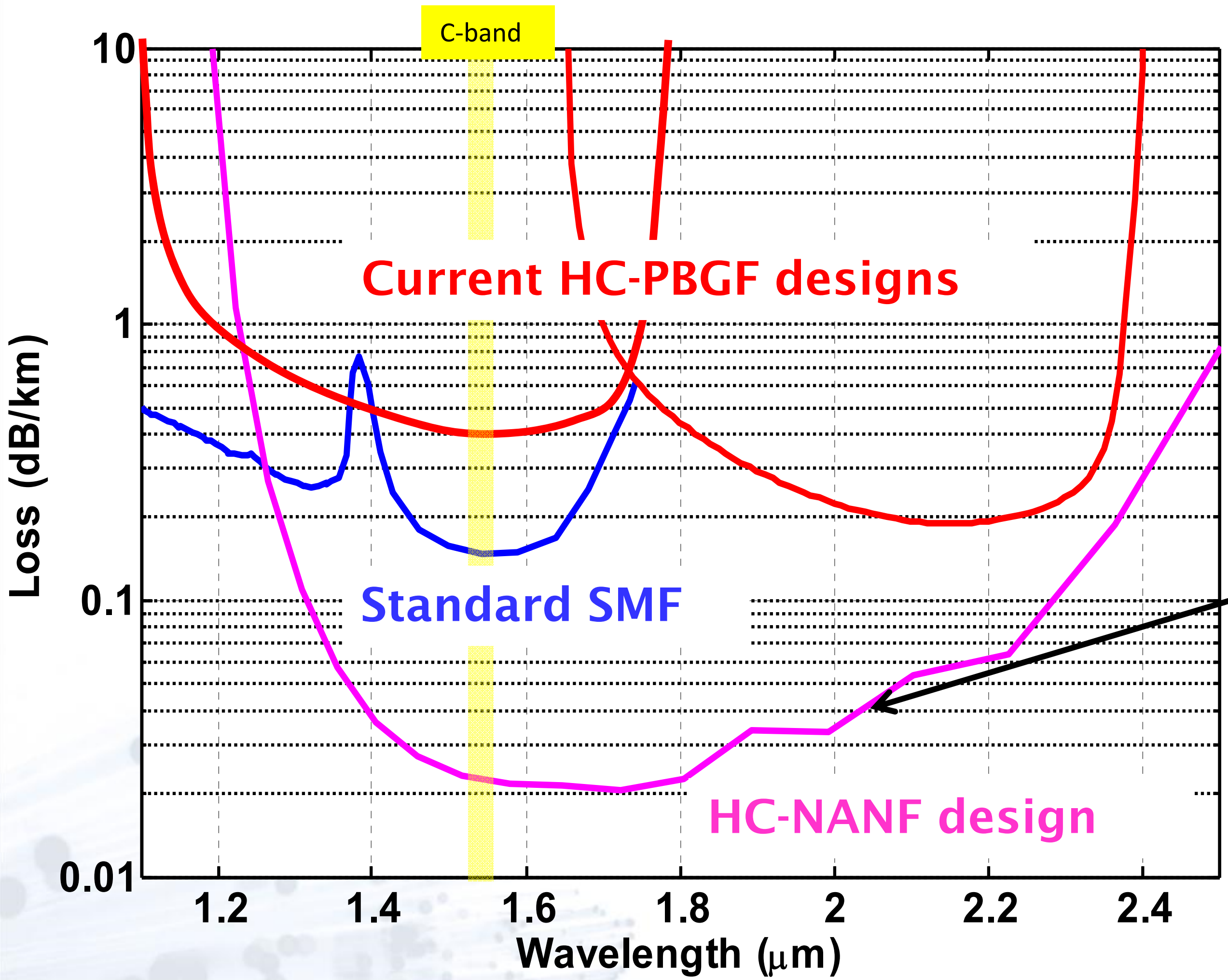


Total 100m link loss: **4.9dB** **6.3dB** **18.5dB**

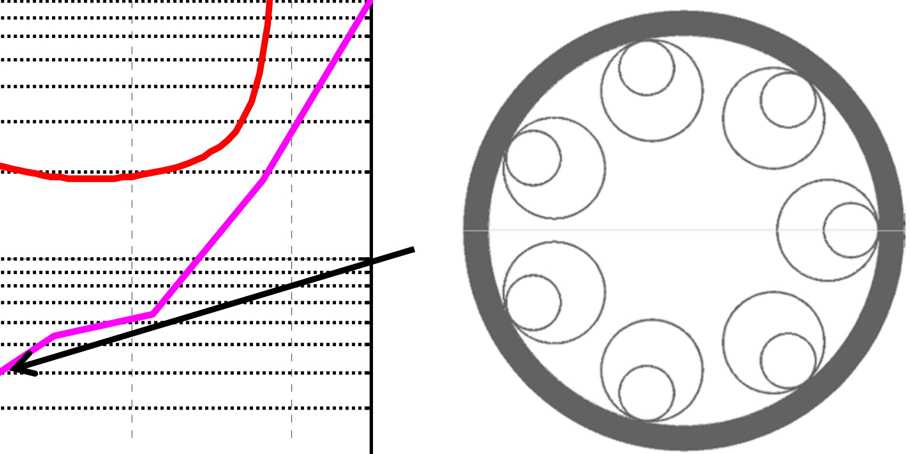




Future Loss Prediction Summary



HC Fibre design phase space is far from being exhausted



Nested Antiresonant Nodeless hollow core fiber

F Poletti, Opt Express 22 (2014)

Routes to Higher Capacity

Overall Fibre Capacity =

Available Bandwidth

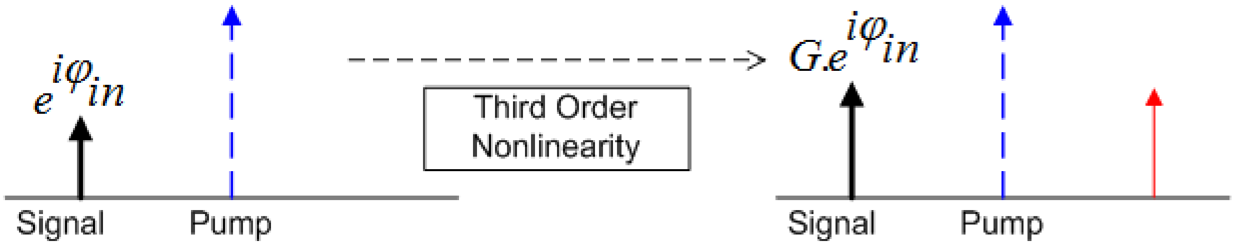
x Spectral Efficiency

Exploit electronics…
Low nonlinearity
Ultralow loss

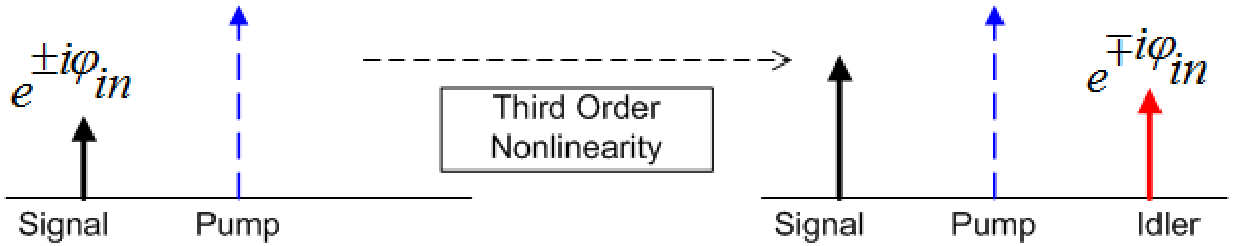
x Number of Information Channels

Nonlinear Vector Processing Toolbox

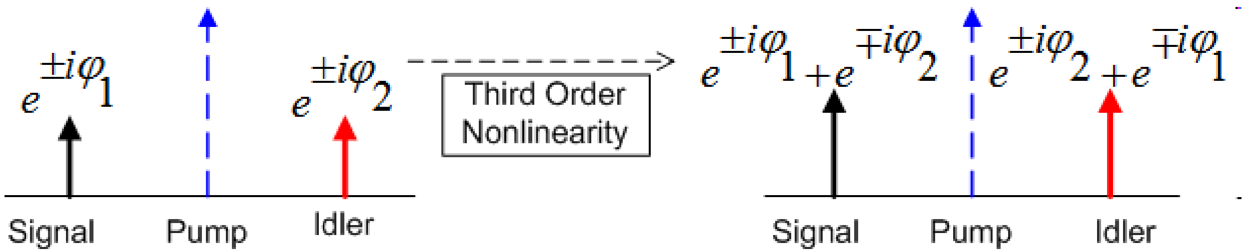
Magnitude Scaling:



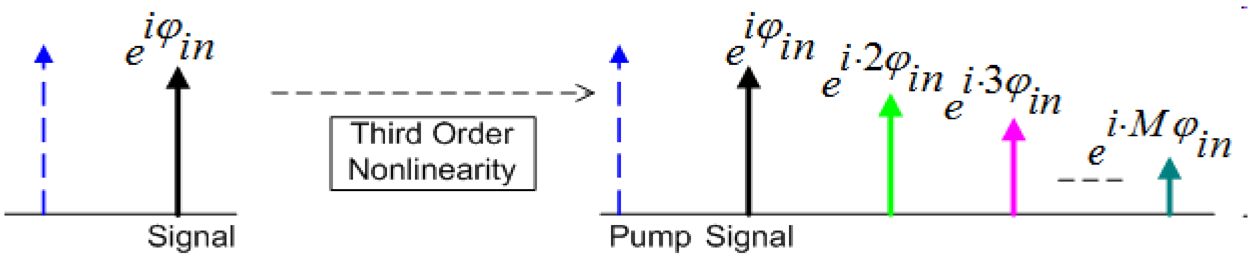
Complex field sign reversal (Phase conjugation)



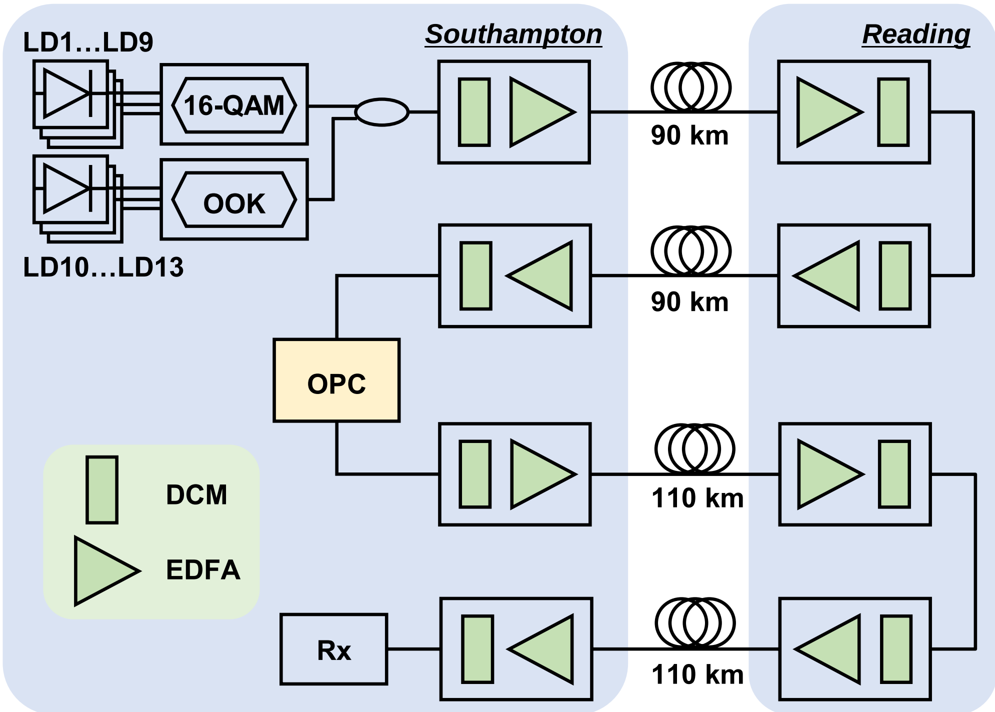
Complex field addition

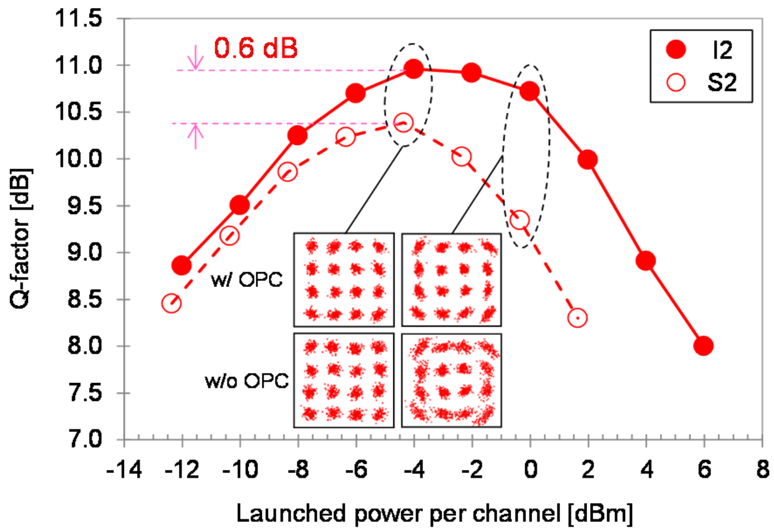


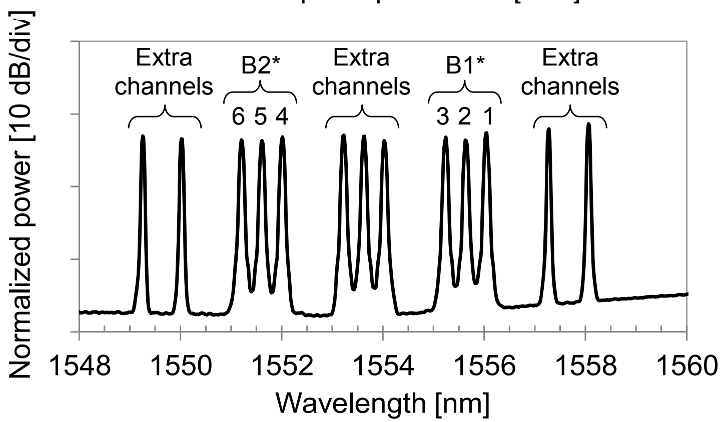
Complex field phase multiplication



Nonlinearity Compensation using OPC







- The two bands, B1 and B2 were each populated with three 10 Gbaud, 16-QAM signals, lying on a 50 GHz grid around centre wavelengths of 1551.72 nm and 1555.75 nm, respectively.
- An additional band (with similar contents to B1 and B2) was added, centred around 1553.73 nm, along with four 10 Gbaud OOK signals.

S. Yoshima, ECOC'15; S. Yoshima, OFC'16

Routes to Higher Capacity

Overall Fibre Capacity =

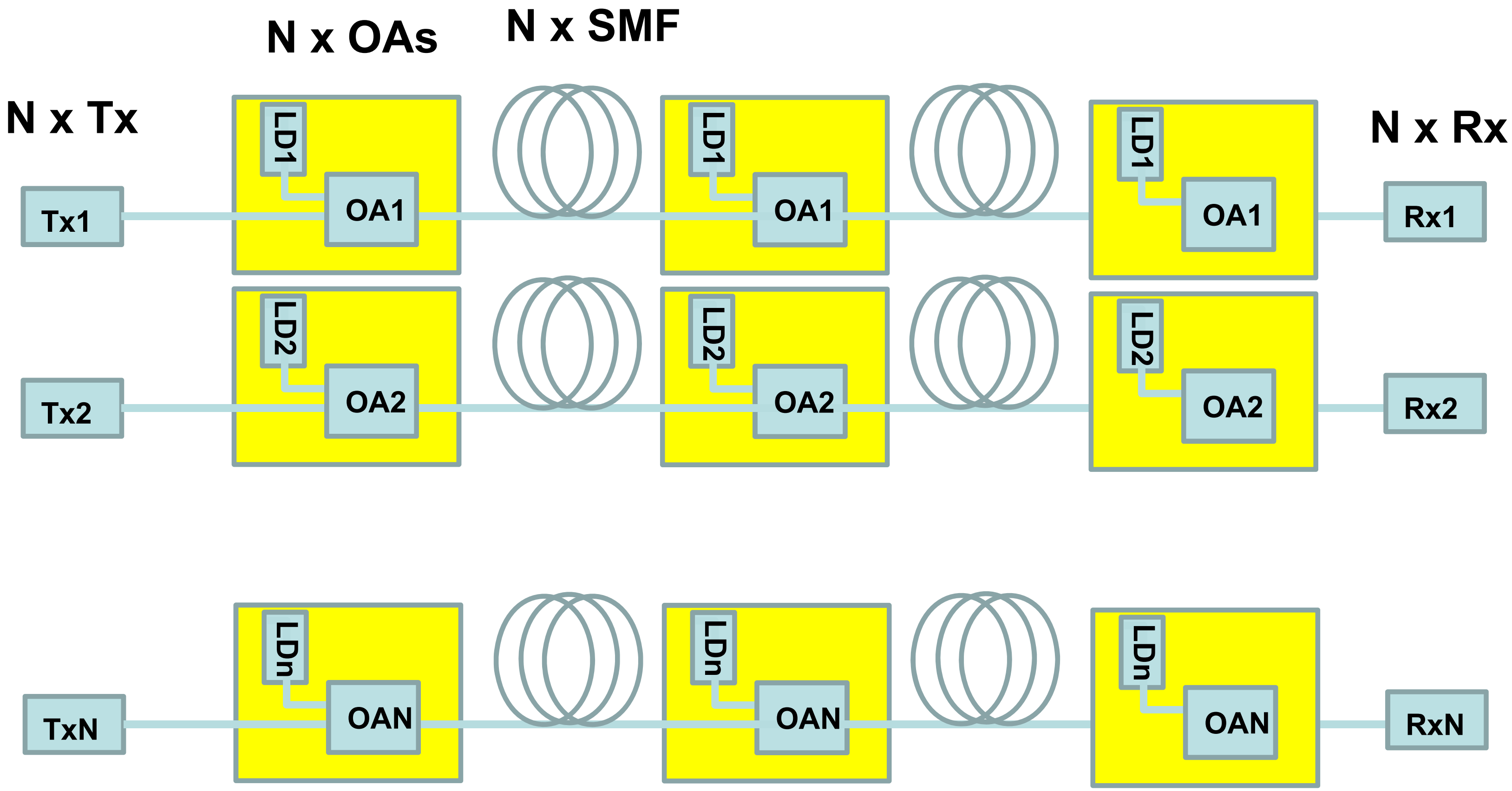
Available Bandwidth

x Spectral Efficiency

x Number of Information Channels

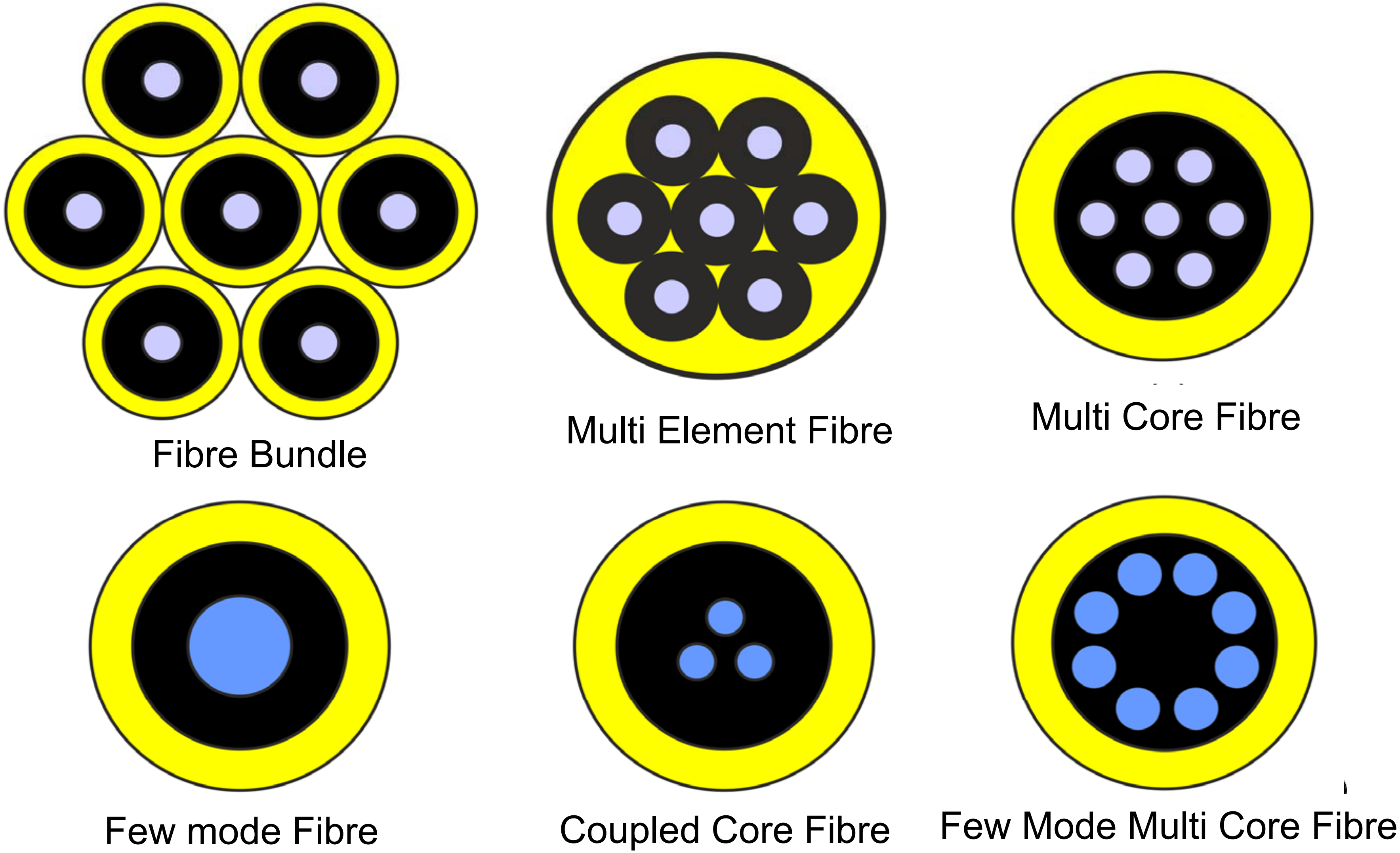
Multi core fibre
MM fibre

Scaling Capacity: N x SMF Systems



Once optimised transmitters/receivers adopted further capacity scaling can only be achieved by lighting new fibers at an effectively fixed cost per bit

Contender Fiber Solutions



D.J. Richardson, J.M. Fini and L.E. Nelson, Nature Photonics, 7,354–362, (2013)

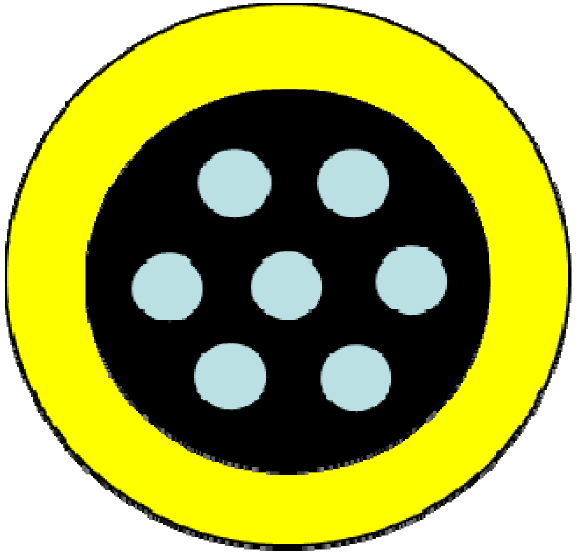
Some Key Common Issues

- Channel Mux:Demux
- Fundamental propagation characteristics
- Channels per unit area
- Channel coupling
- Amplification
- Practicality / cabling / interconnection

Possible applications in both long-haul, short-haul systems

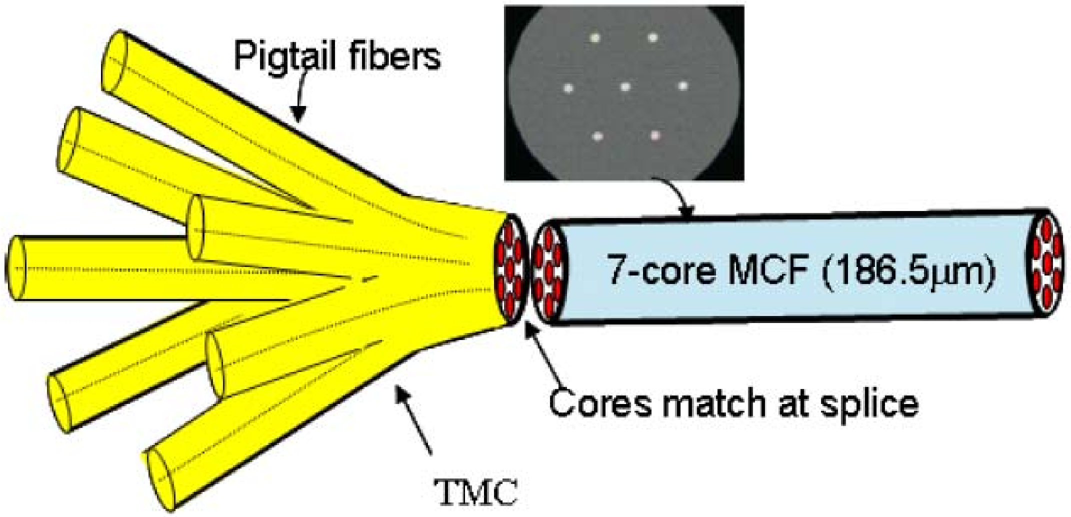
The Promise of SDM

- Higher transmission capacity per individual fiber strand
- Higher spatial path densities than possible within SMF/SMF-bundles
- Potential for greater transmitter/receiver integration with reduced interconnection costs.
- Potential for multi-spatial channel devices providing cost savings through sharing of components e.g. amplification, switching, isolation, filtering, etc

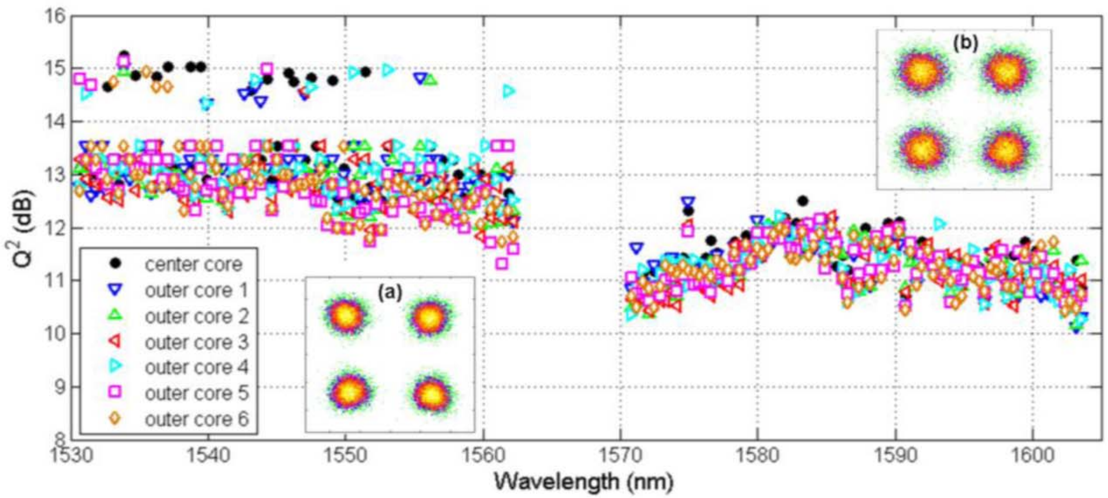


Multicore Fiber

56 Tbit/s over 76.8km of 7-C MCF



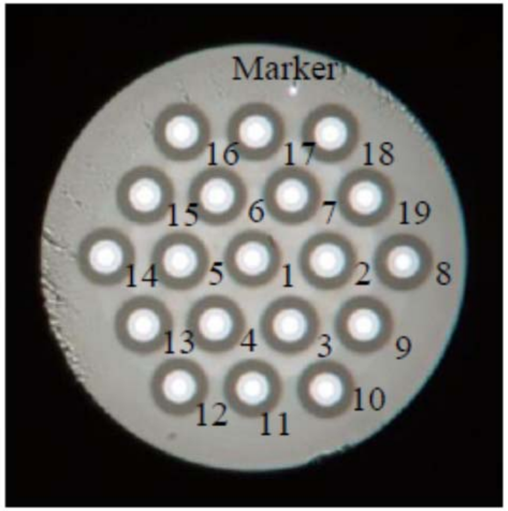
	TMC#1		TMC#2	
Core #	Loss (dB)	Crosstalk (dB)	Loss (dB)	Crosstalk (dB)
Center core	1.11		0.55	
Outer core1	0.75	-48.0	2.10	-49.0
Outer core2	2.77	-47.5	0.90	-46.5
Outer core3	1.95	-45.0	0.45	-46.0
Outer core4	0.98	-48.0	1.13	-47.0
Outer core5	1.42	-48.0	2.05	-48.5
Outer core6	1.37	-47.8	1.61	-45.5
average	1.48	-47.4	1.26	-47.1

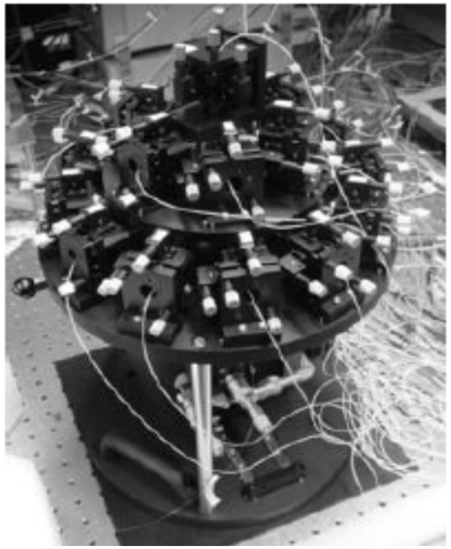


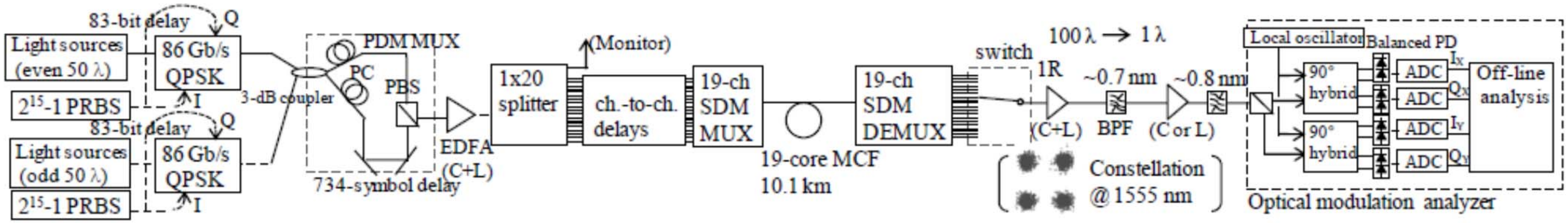
- 9/47µm core diameter/spacing
- Fiberised Mux:Demux with low loss and X-talk
- 76.8km length (1 in-line splice)
- Total X-talk<30 dB (centre core)
- SE=14 bit/s/Hz

B. Zhu et al. OFC 2011 PDPB7

Early19-core Transmission Experiment



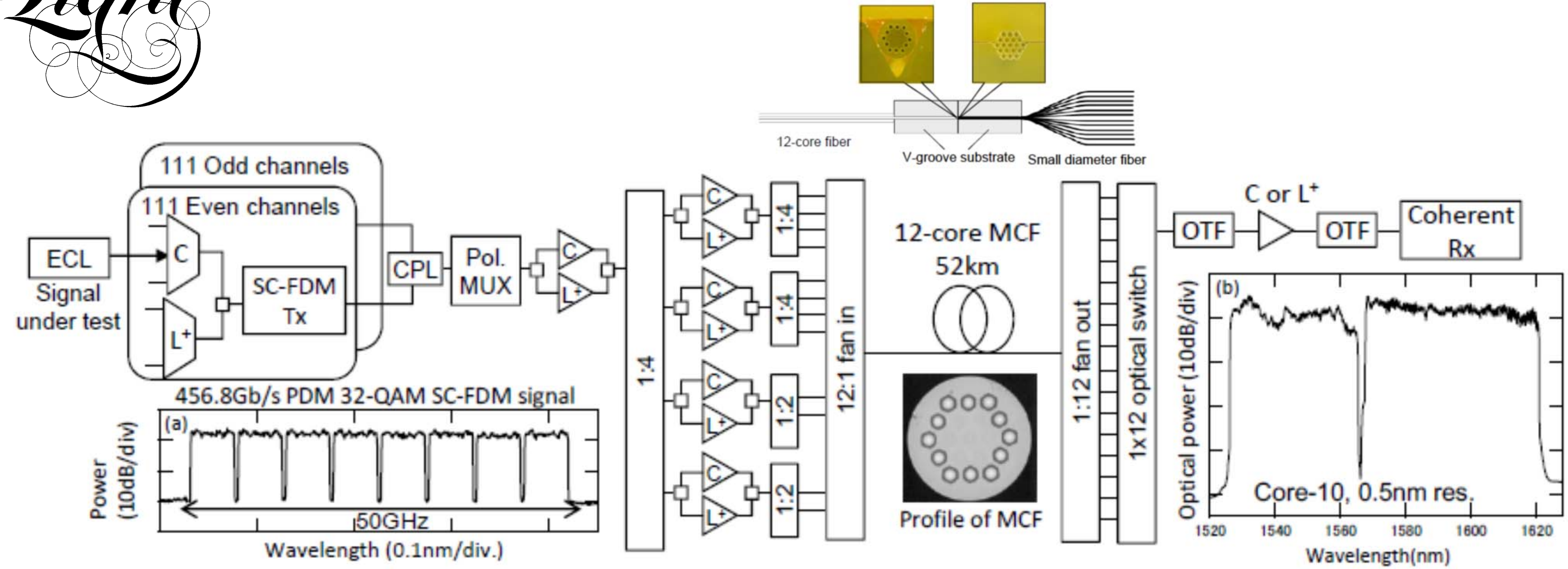


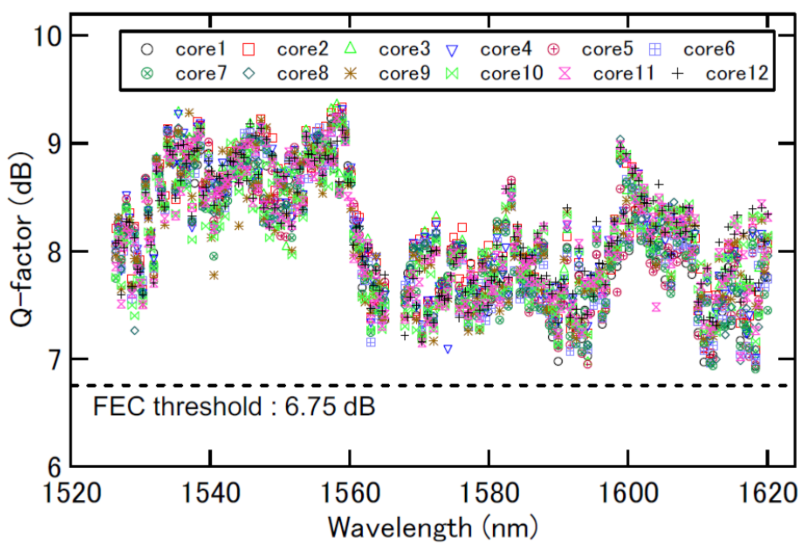


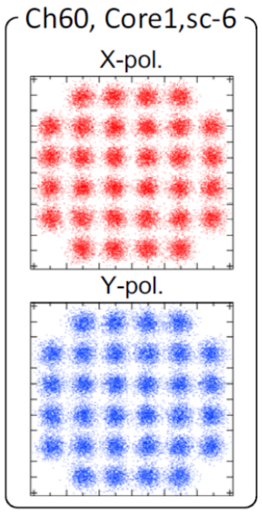
- Bulk Optic Launch Assembly
- SDM(19 core) x WDM(100ch) x PDM-QPSK (2×86 Gb/s) signals
- 305 Tbit/s total capacity
- 10.1 km span

J. Sakaguchi, et al., OFC 2012, paper PDP5C.1.

1 Pbit/s Transmission in 12C Fiber



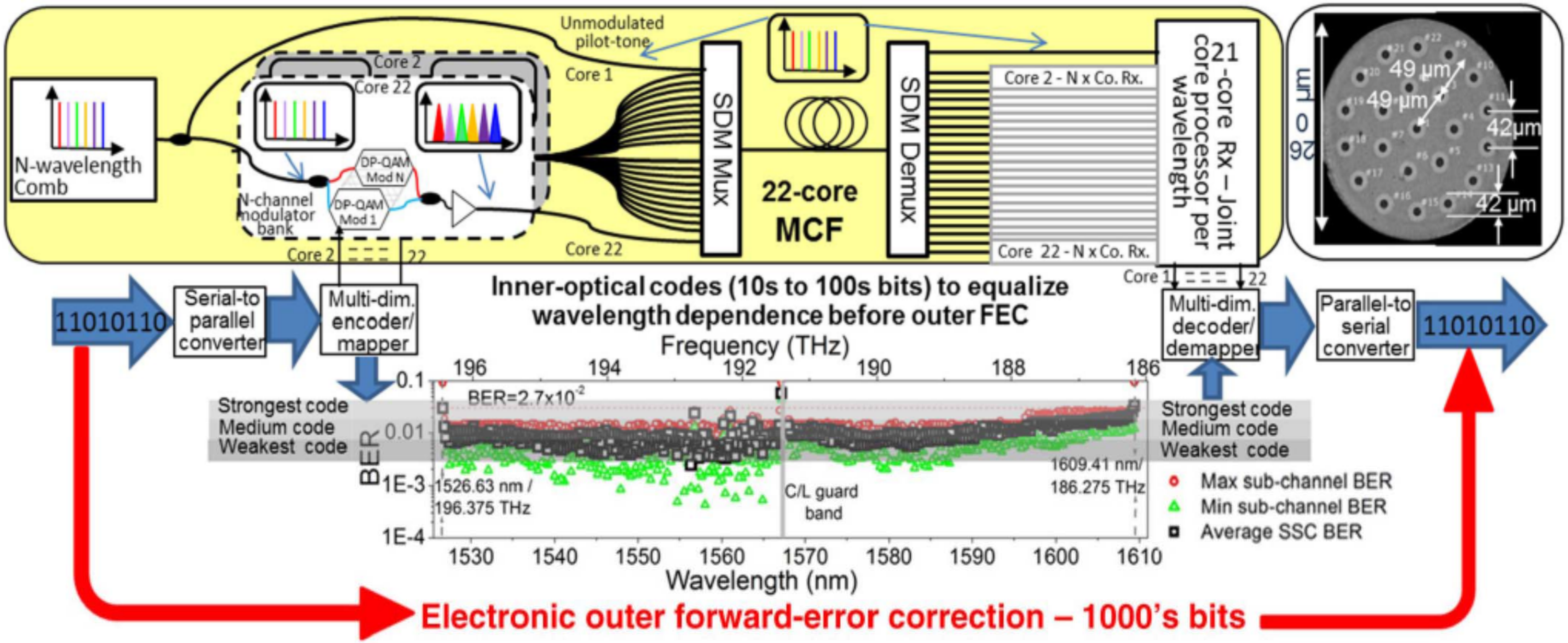




- 222 (WDM) x 12(SDM) x 486 Gbit/s (PDM 32-QAM SC-FDM)
- Total Capacity = 1.01PBit/s
- SE=91.4 bit/s/Hz
- L= 52km

H. Takara et al. ECOC2012 PDP Th3.C.1

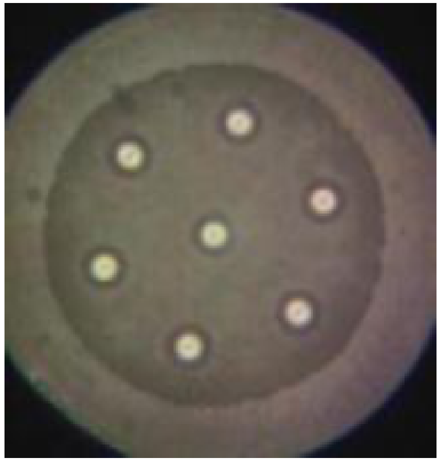
2 Pbit/s Transmission in 22C Fiber

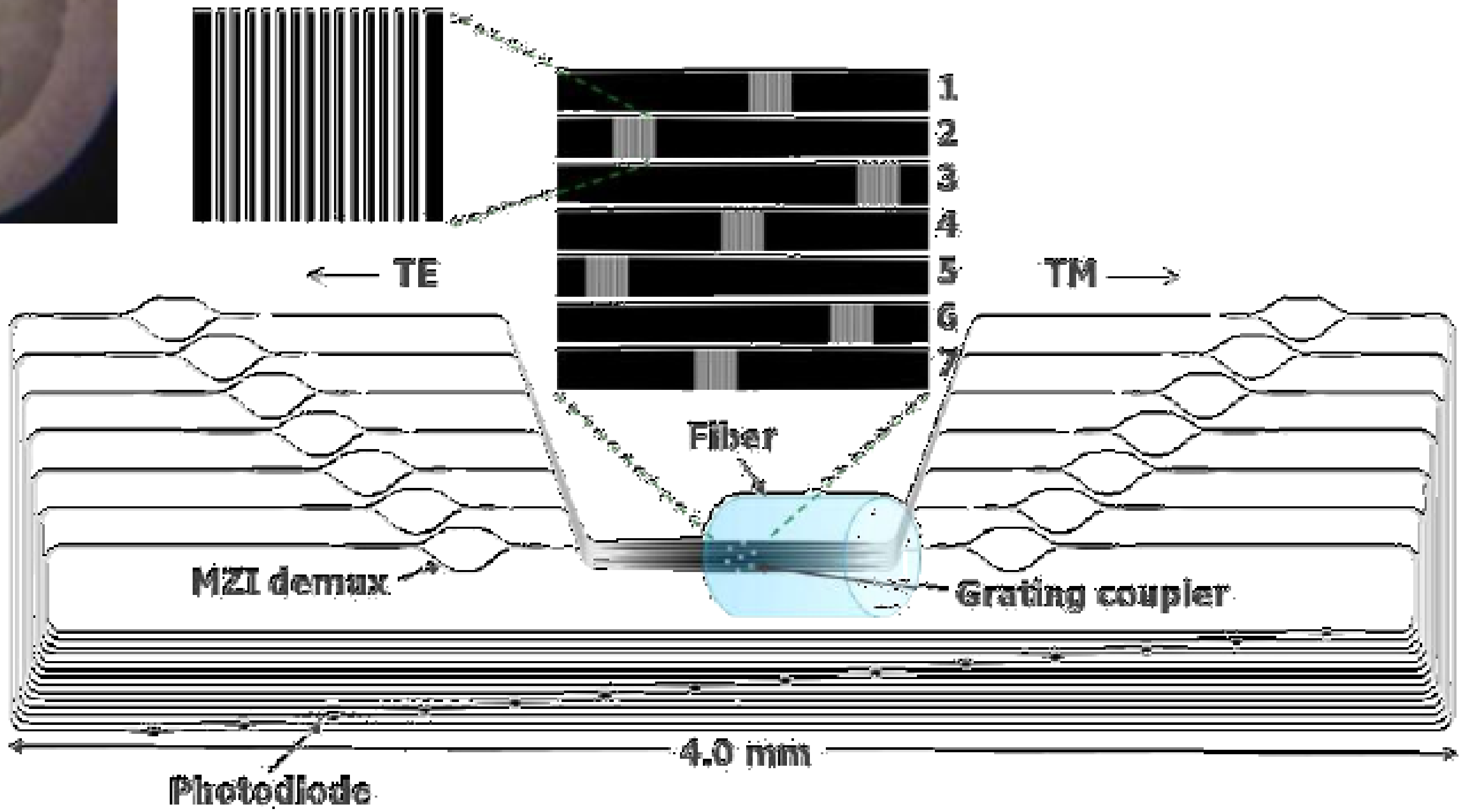


- 399 (WDM) x 22 (SDM) x 24.5 Gbaud, PDM 64-QAM
- Total Capacity = 2.15 PBit/s.
- L= 31.4 km

BJ Puttnam et al. ECOC2015 PDP 3-1

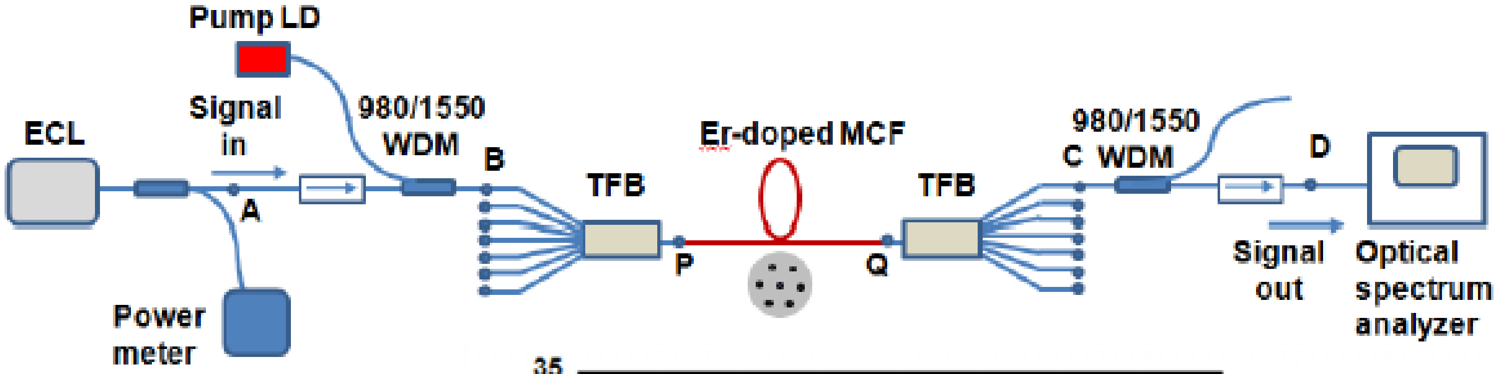
TRANSPONDER INTEGRATION
MULTI-CORE FIBER INTERFACING

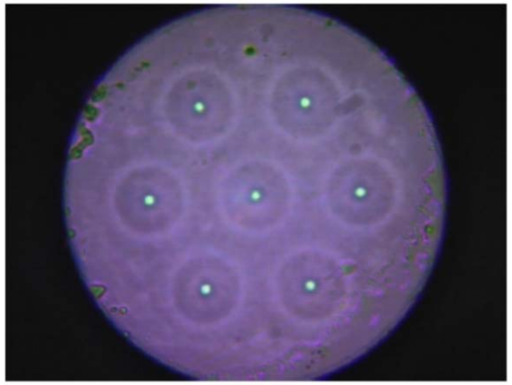


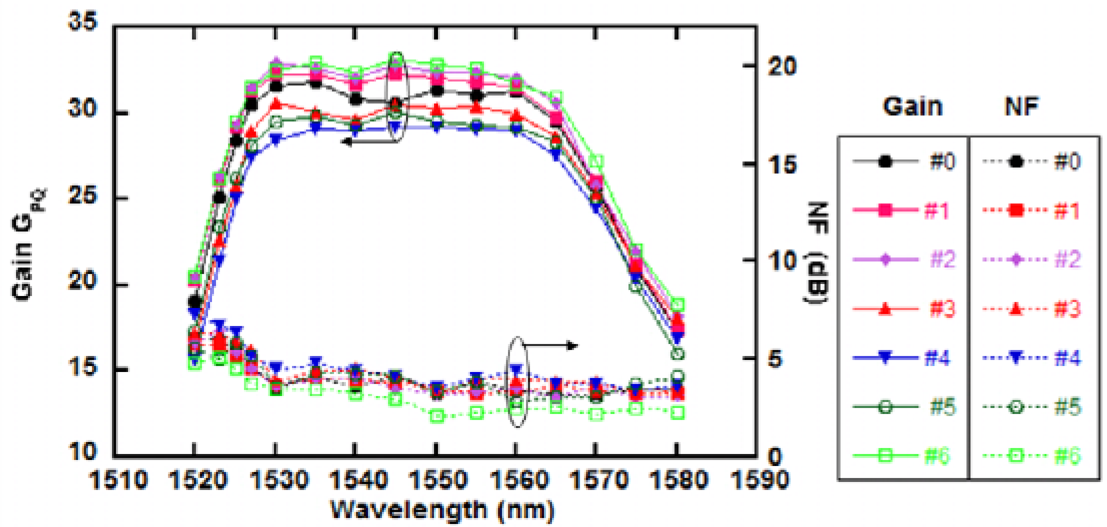


[C. R. Doerr et al., Photon. Technol. Lett. 23(9), 597-599 (2011)]

Core-pumped MCF Amplifier



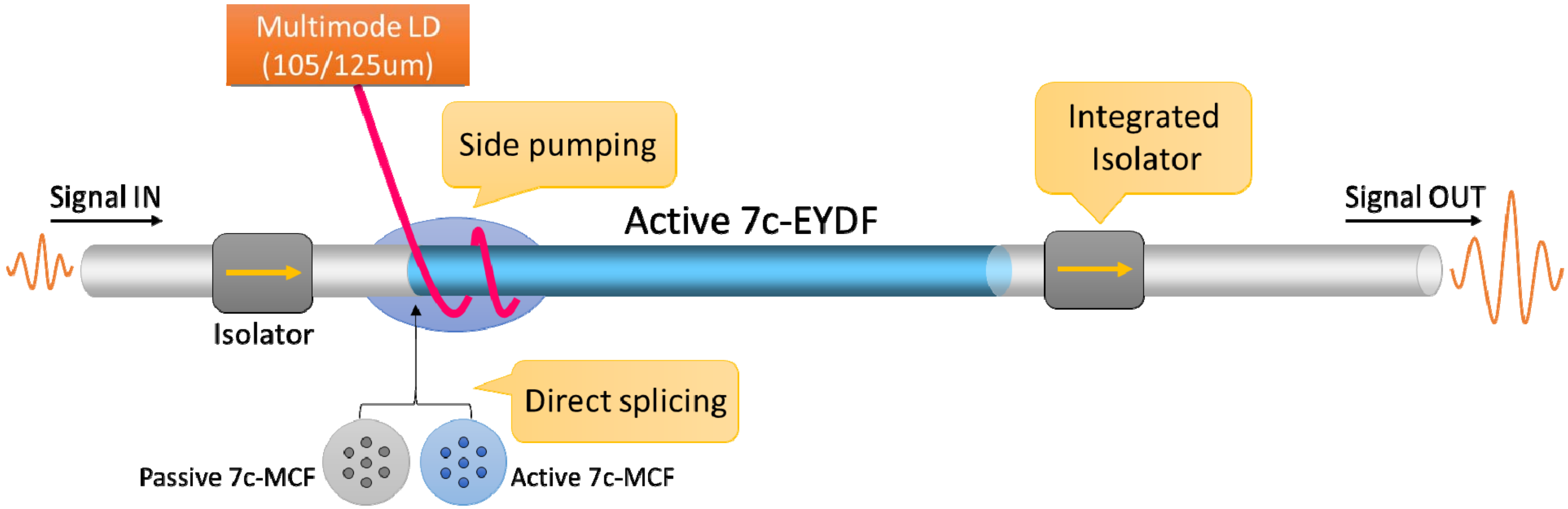




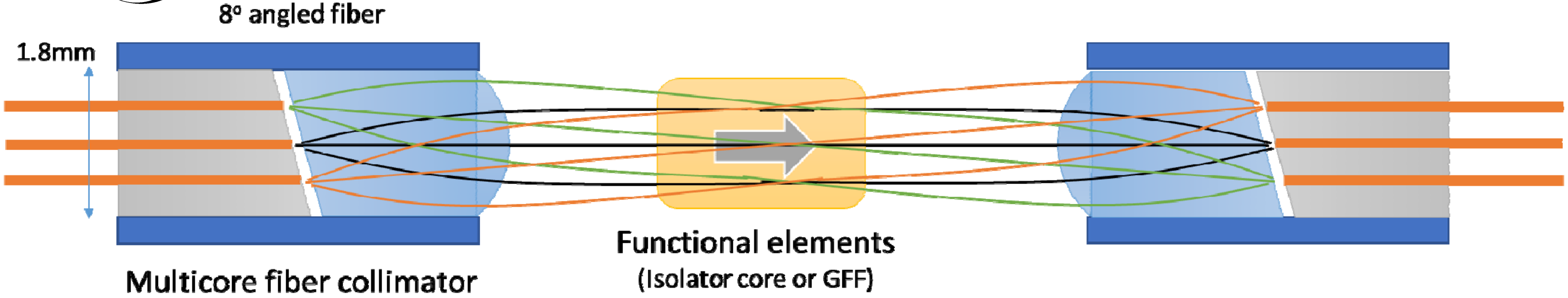
- Signal cross-talk<30dB
- Low cross coupling of ASE
- Internal NF~4dB
- Passive losses ~ 5dB
- Net external gain ~ 25dB

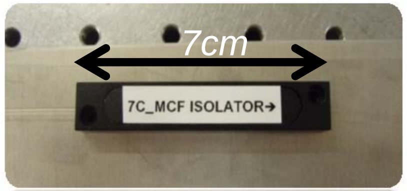
K. Abedin et al. OE 19(17), 16715-16721, 2011

Cladding-pumped MCF-EDFA

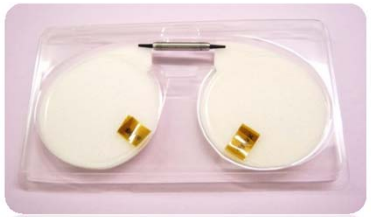


Inline MCF Components

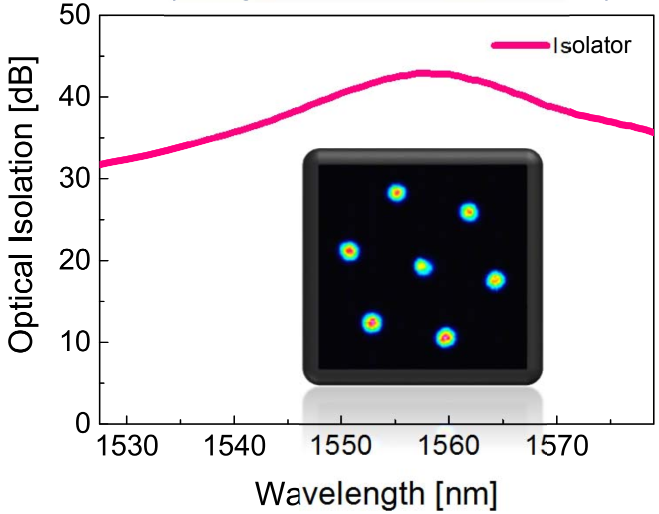


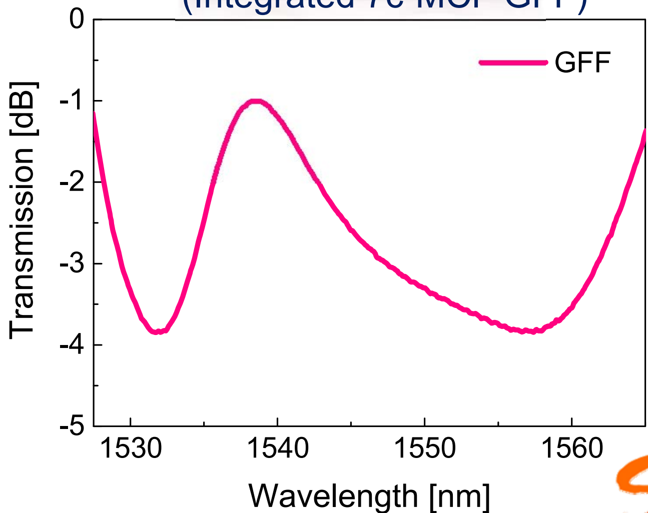


(Integrated 7c-MCF isolator)

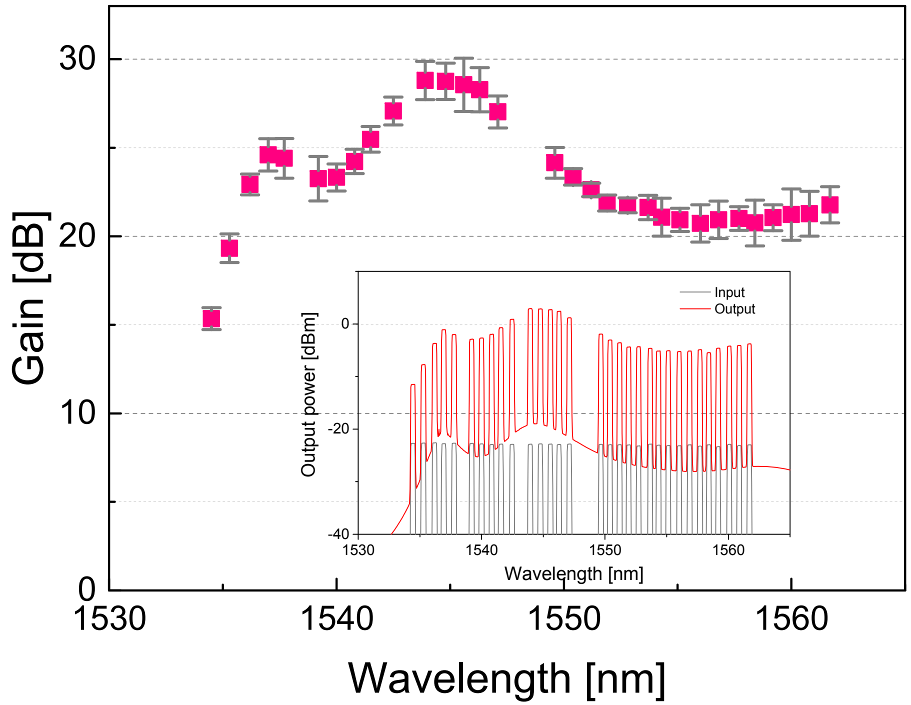


(Integrated 7c-MCF GFF)





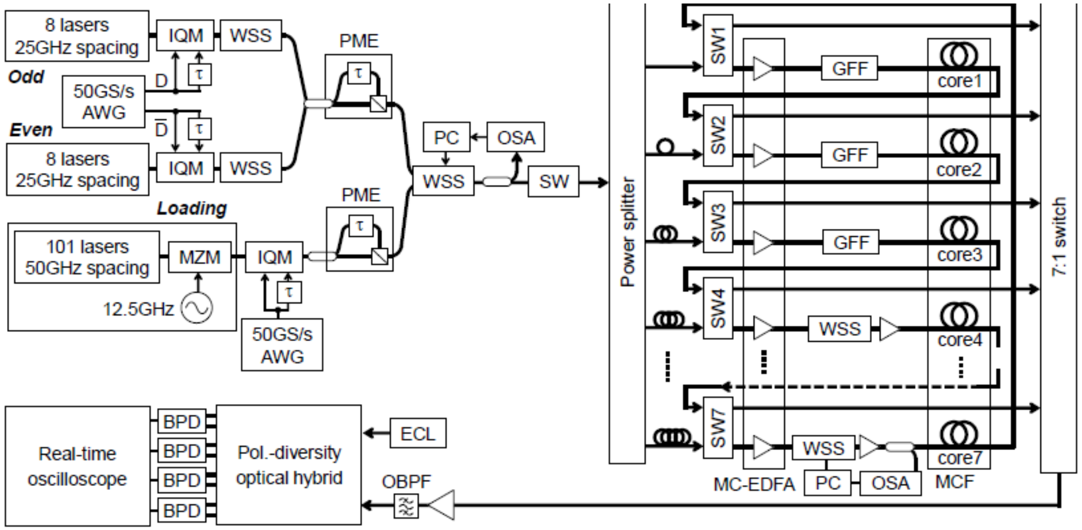
Cladding-pumped MCF-EDFA

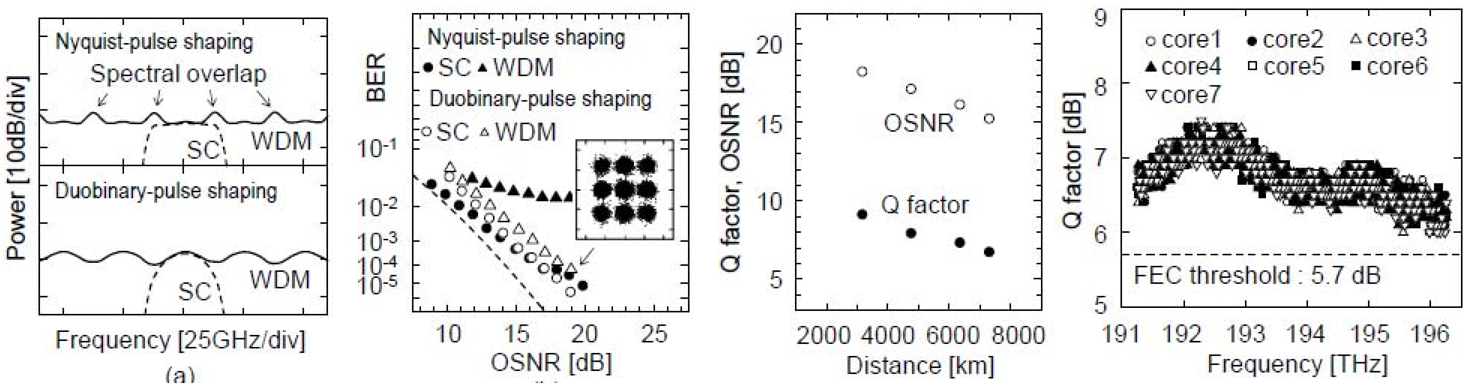


Optical Parameters	Typical
Number of cores	7
Wavelength range	1538-1563 (C-band)
Input signal power range	-15 to 0 dBm per core
Small signal gain	> 20dB
Maximum output power	> 20dBm
Core-to-core gain variation	< 3dB
Typical noise figure	5-7dB
Crosstalk between cores	< -40dB

- Fully-fiberized boxed optical amplifiers (including 7-core MCF isolators)
- ~20dB average modal gain and <3dB core-to-core gain variation

1.03 Exabit/s.km MCF Transmission

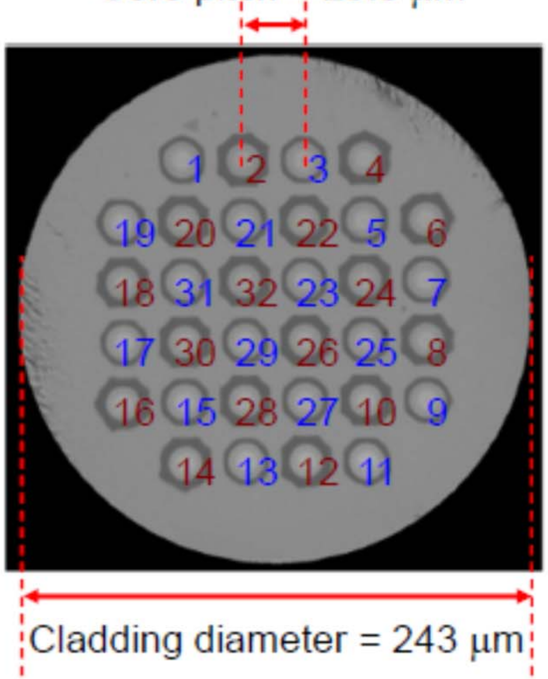




- 140.7-Tbit/s, 7,326-km transmission
- 7 x 201-channel 25-GHz-spaced Super-Nyquist-WDM 100-Gbit/s (30 Gbaud DP-QPSK)

K. Igarashi et al. ECOC PD3.E.3 (2013)

Heterogeneous 32-core fibre

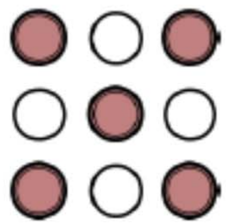


Odd number: higher Δ core
Even number: lower Δ core

Fiber length = 51.4 km

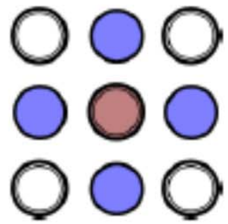
Low inter-core crosstalk

- Trench-assisted profile
- Square lattice arrangement with two types of core with different β placed next to each other



Four adjacent cores of the same Δ type

< – 39.4 dB/span



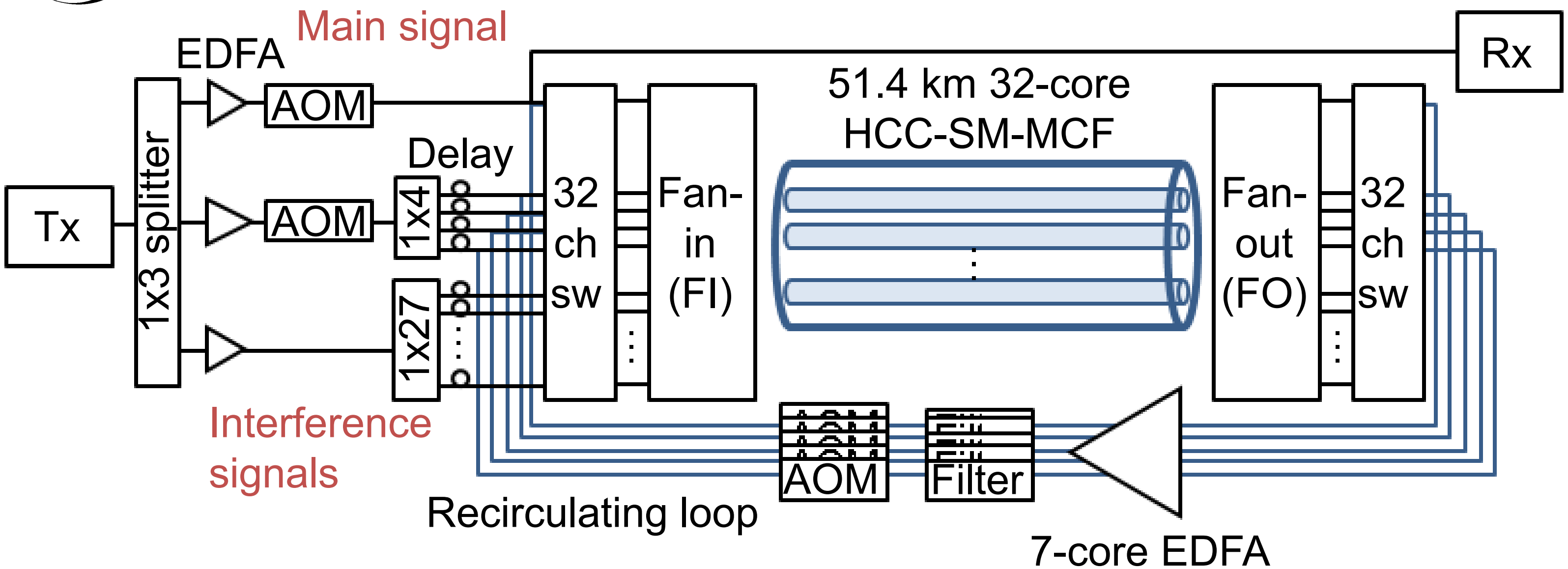
Four adjacent cores of the different Δ type

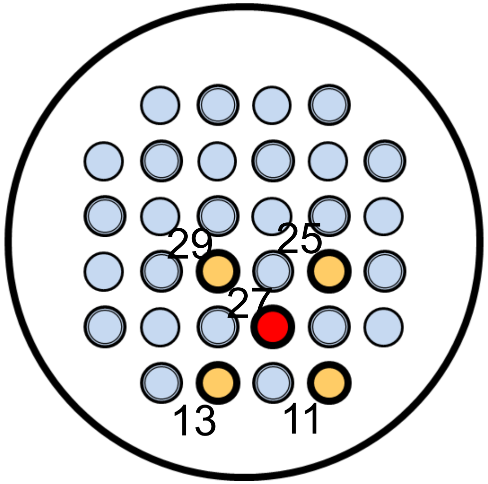
< – 54.0 dB/span

Attenuation at 1550 nm	< 0.24 dB/km
A_{eff} at 1550 nm	> 80.3 μm²
Cutoff wavelength of 1-km	< 1530 nm

T.Mizuno et al. OFC 2016 PDP paper Th5C.3

Long Haul 32-ch MCF Transmission

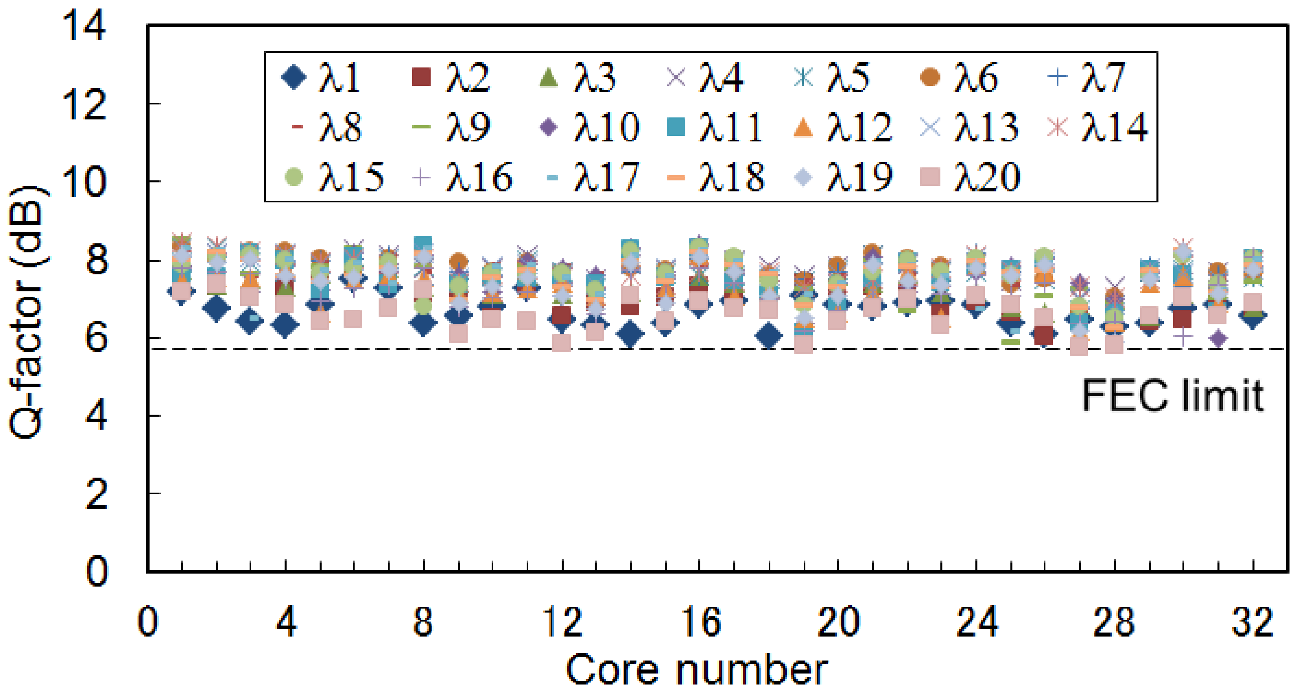




Example signal allocation for core #27 measurement

- Core under measurement (core #27)
- Cores loaded with recirculating signals (#11, #13, #25, #29)
- Cores loaded with non-recirculating signals (all other cores)

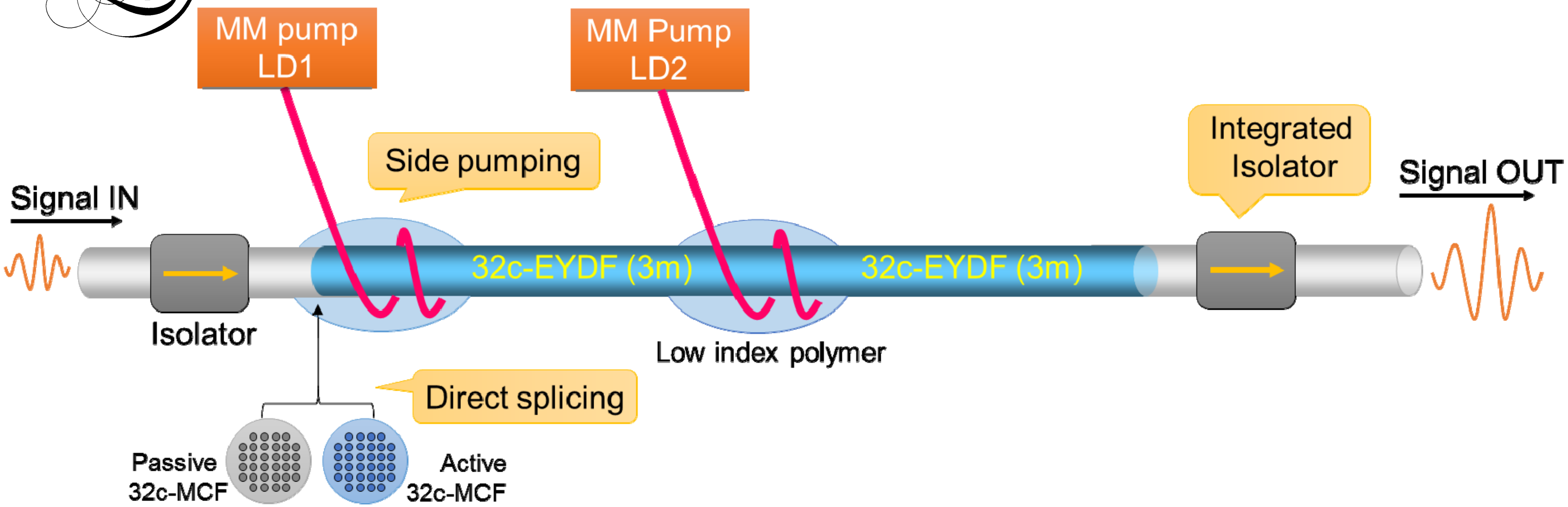
Long Haul 32-ch MCF Transmission



- Q-factors of PDM-16QAM signals for all 640 channels (20 DWDM x 32 DSDM) exceeded the FEC limit after 1644.8 km transmission
- First demonstration of a long-distance DSDM transmission exceeding 1000 km

T. Mizuno et al., OFC 2016, Postdeadline paper Th5C.3

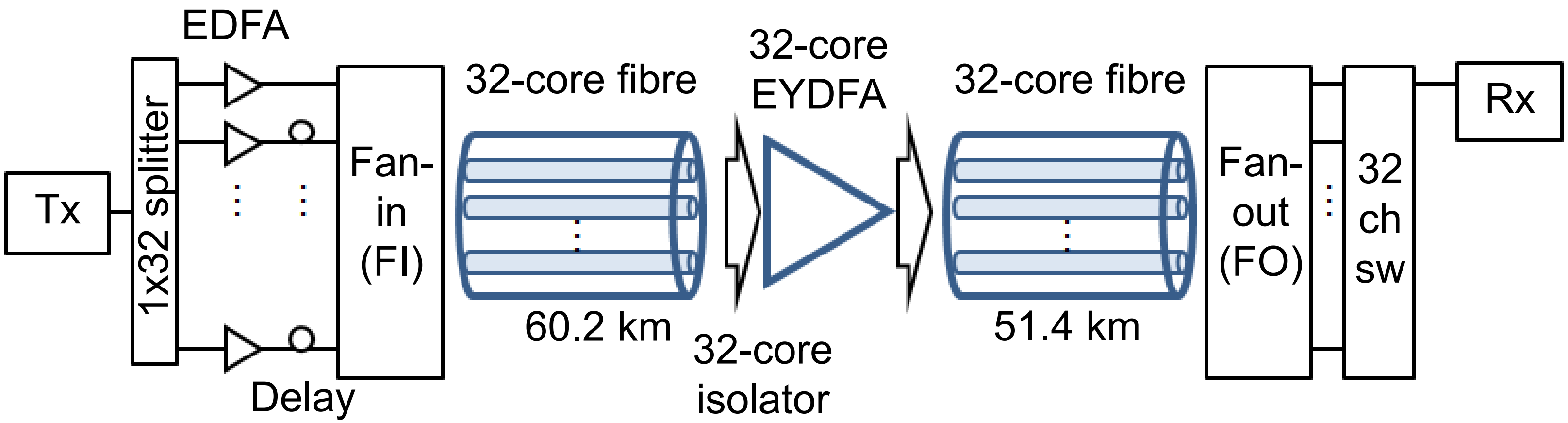
32-core fully Integrated EDFA



- Direct splicing between all passive and active fibres
- MM pump laser radiation was coupled into the fibre via side coupling in a co-directional pumping arrangement
- Two side-couplers (beginning & middle) to better balance the population inversion level along the 7m device length.
- Two 32-core MCF isolators spliced at input and output ends of the amplifier to suppress any potential reflections

S. Jain et al., ECOC'16 PDP, Th3.A1

Amplified 32c,113km transmission

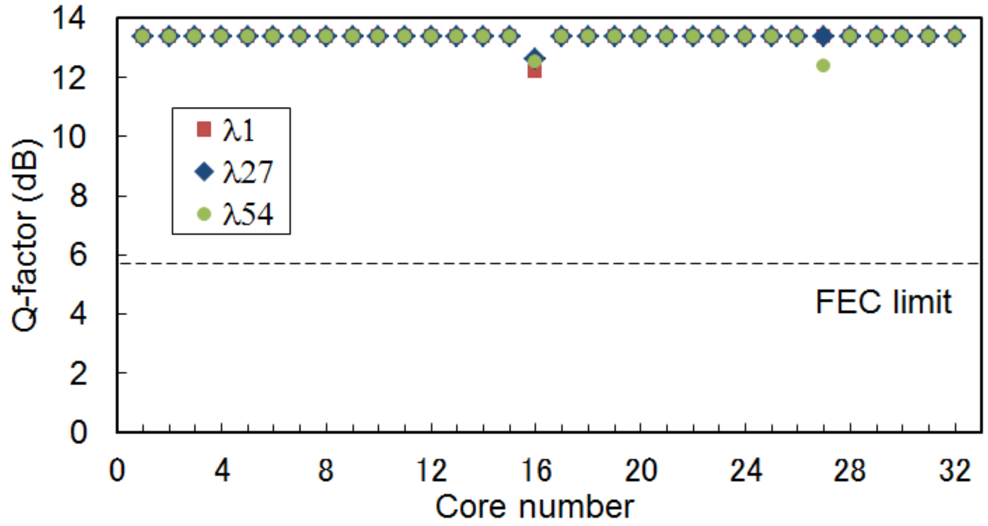


- 50 GHz-spaced 54 WDM channels
- Transmission line incorporating long-length 32-core fibres and a 32-core MC-EYDFA with in-line isolators
- Measurement #1: 32 Gbaud PDM-QPSK at $\lambda 1$, $\lambda 27$, and $\lambda 54$
- Measurement #2: 32 Gbaud PDM-16QAM at $\lambda 27$

S. Jain et al., ECOC'16 PDP, Th3.A1

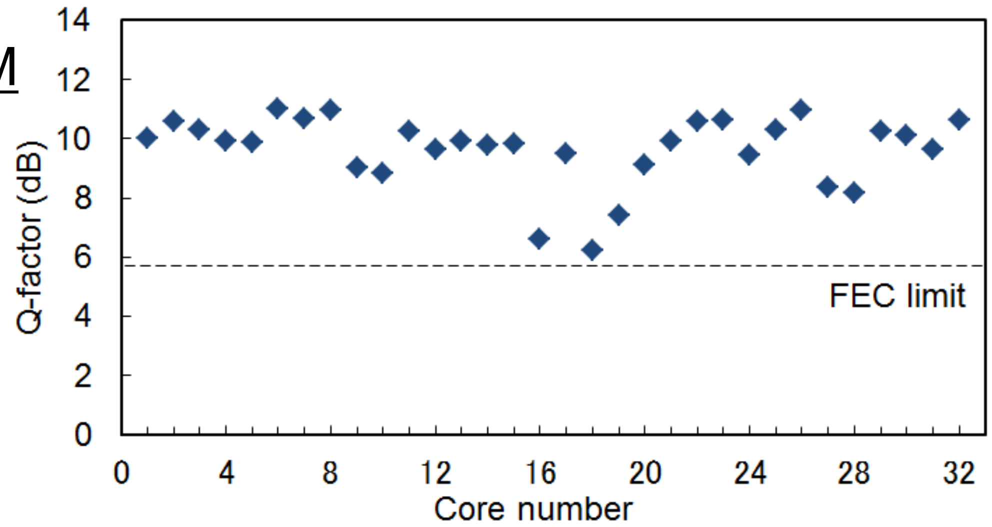
Amplified 32c,113km transmission

PDM-QPSK



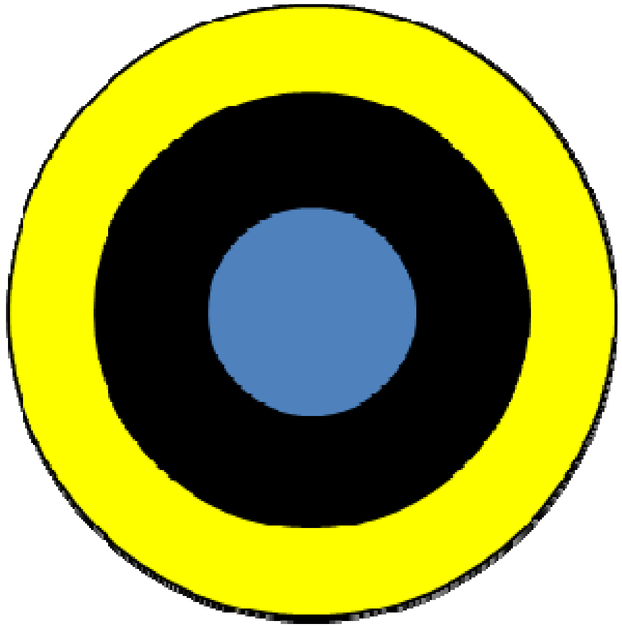
Almost had no errors

PDM-16QAM



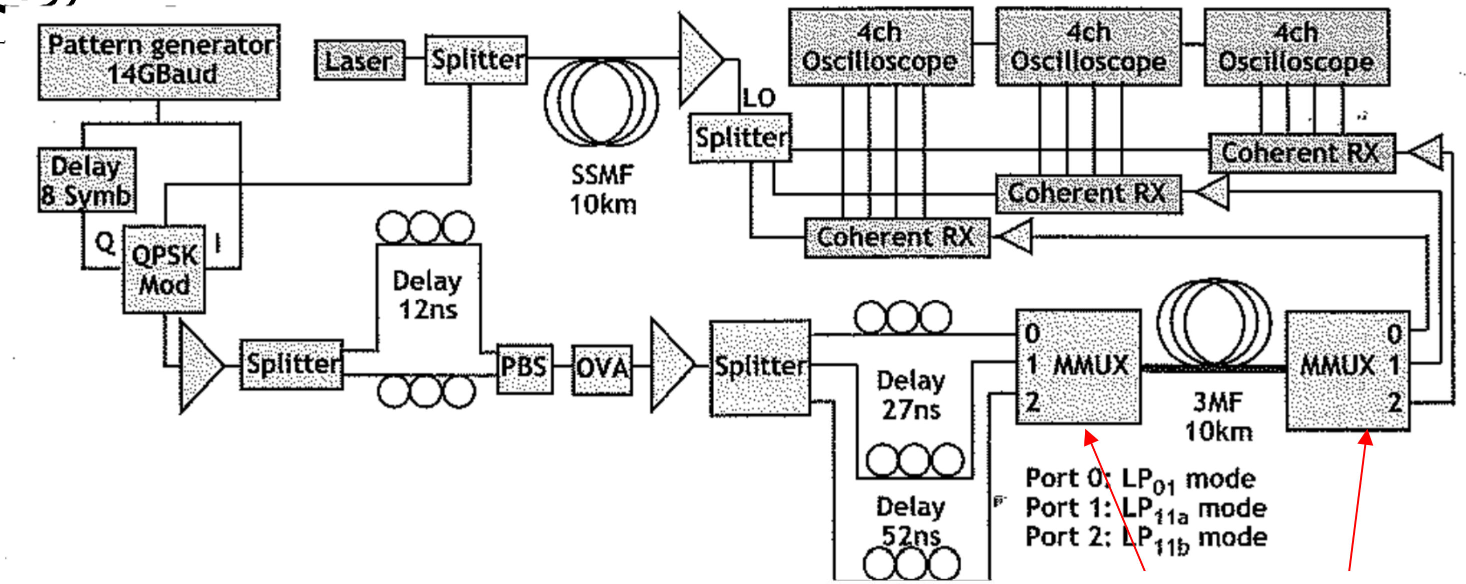
Q-factors exceeded the FEC limit of 5.7 dB

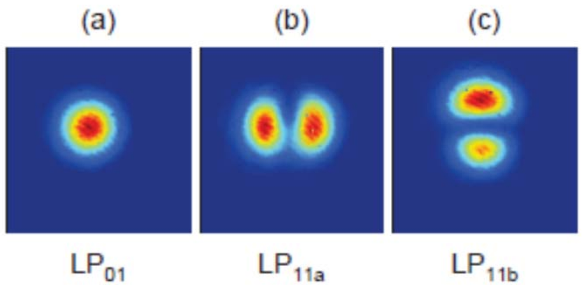
S. Jain et al., ECOC'16 PDP, Th3.A1

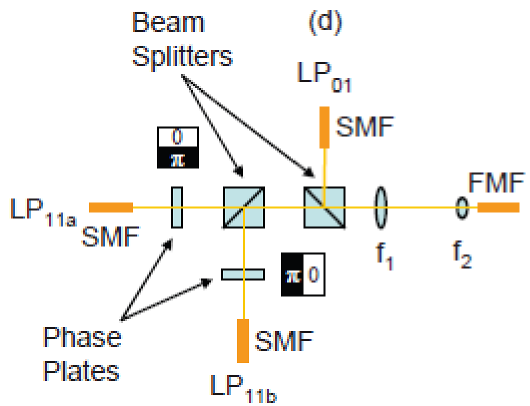


Few Mode Fiber

MDM over 10km TMF with MIMO DSP





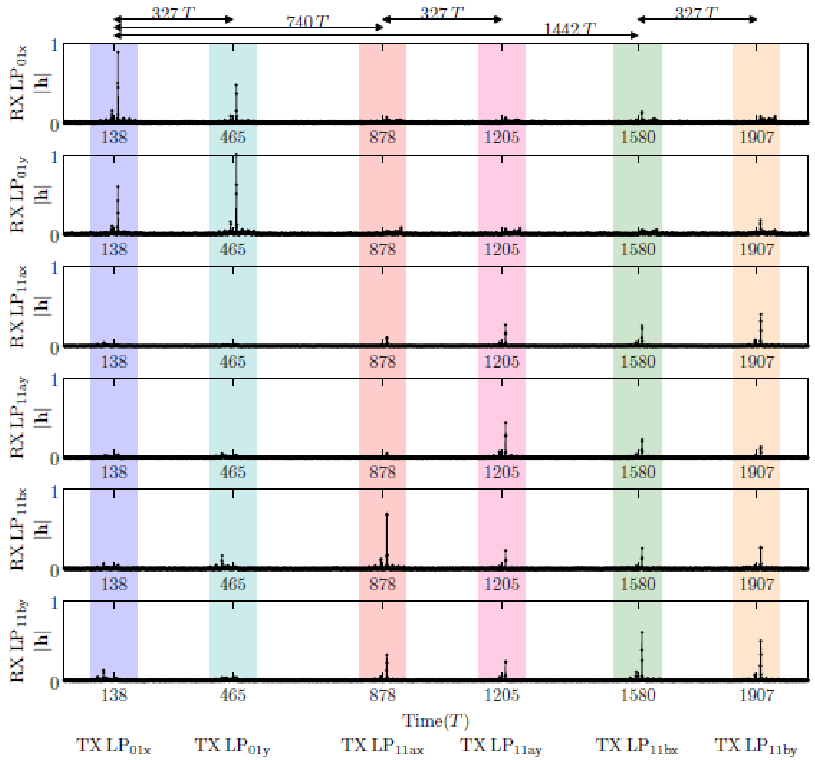


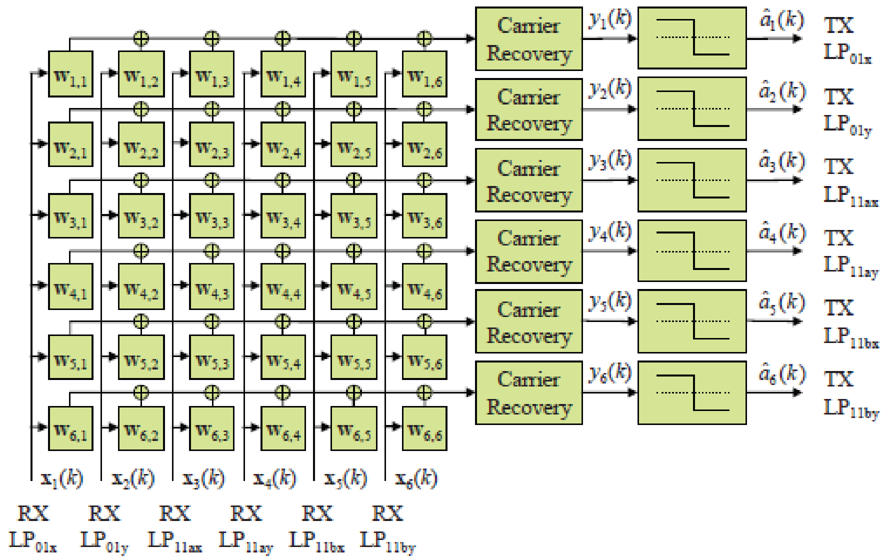
- 6-channel MDM over 10 km three mode fiber (3 modes/2 polarisations)
- Phase plate/bulk optic excitation
- MIMO correction of mode coupling effects
- Offline processing (computationally intensive)

R Ryf et al., OFC 2011 PDPB10

(A. Li et al., OFC 2011, PDPB8)

MIMO Processing

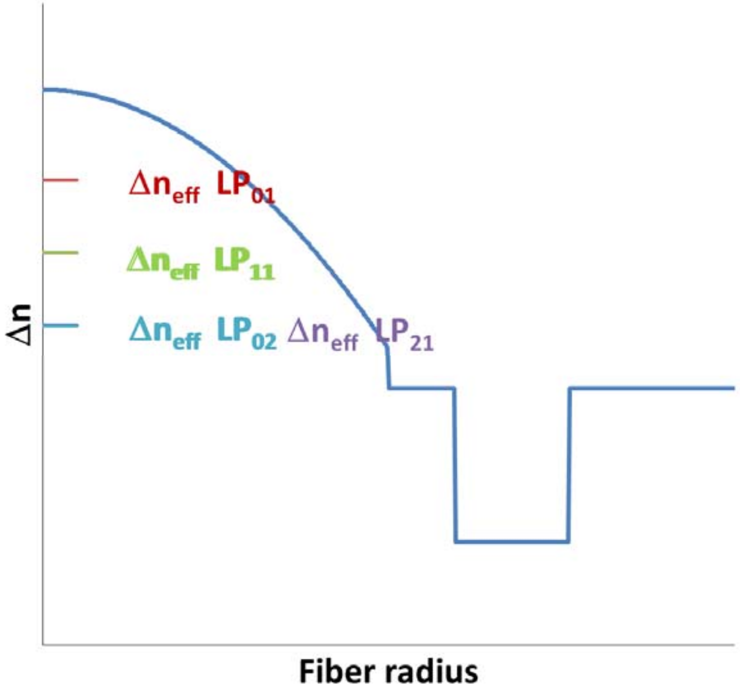




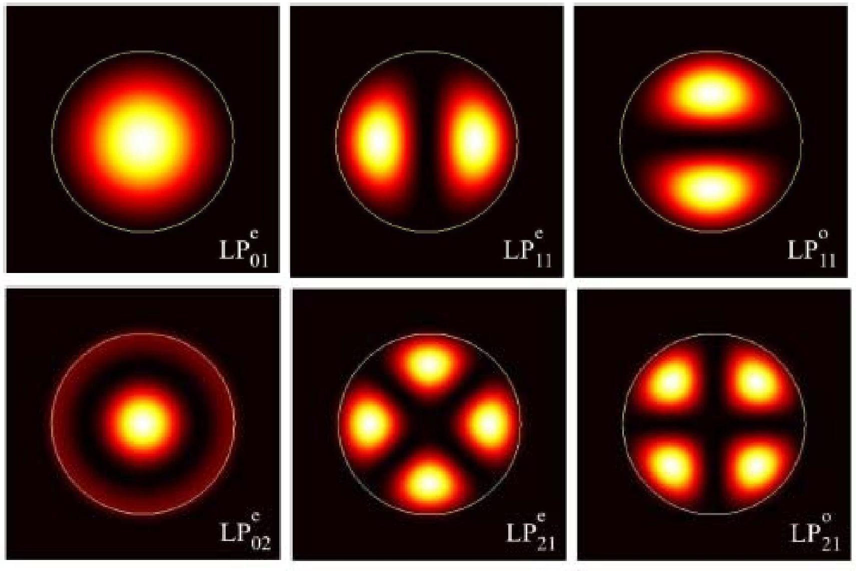
- Linear properties of system characterised by 6x6 impulse response matrix
- Need to use an N-tap DSP filter to retrieve data where N determined by the impulse response spread.
- Need to reduce fiber DGD to reduce N and complexity of processing.
- MDL/MDG ideally also needs to be small

S. Randel et al., OE,19,16697-16707, (2011)

OFS graded index four LP mode fiber

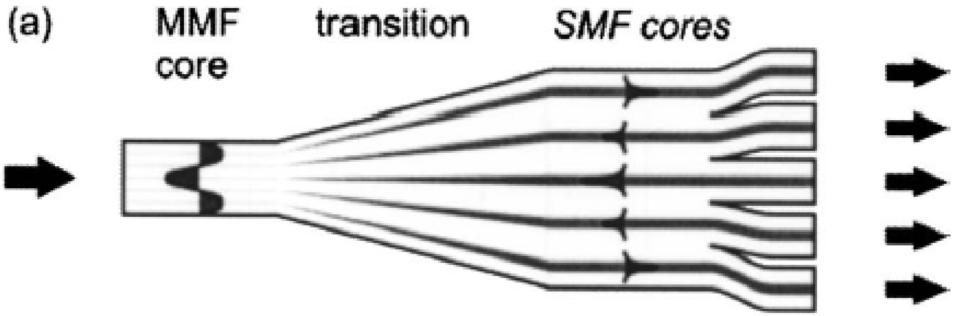


Refractive index profile

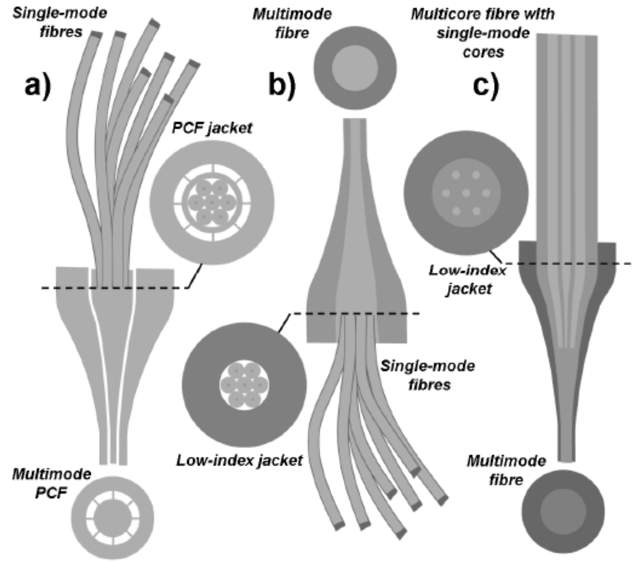


Four LP mode
Six spatial modes

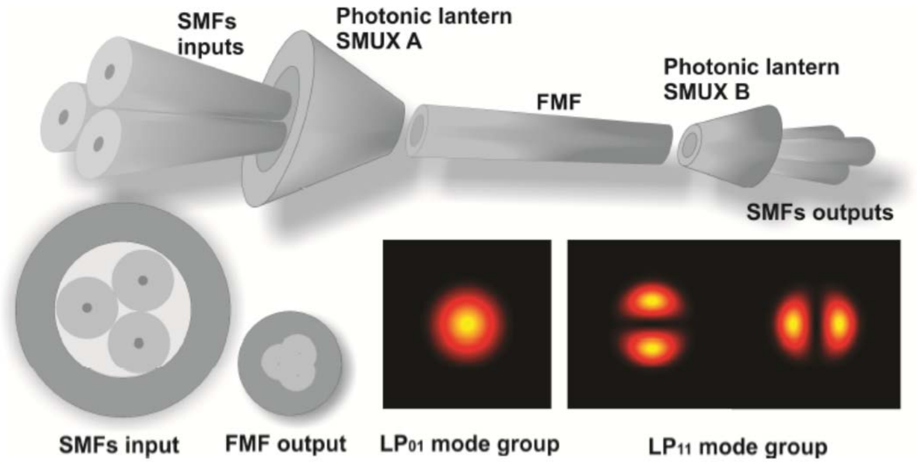
Photonic Lanterns



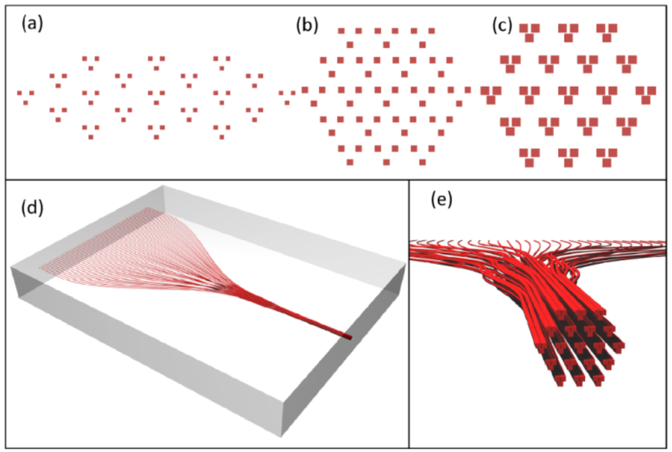
Leon-Saval et al. Opt. Letts. 30, (2005).



Leon-Saval et Opt. Exp, 18, 8435, (2010)

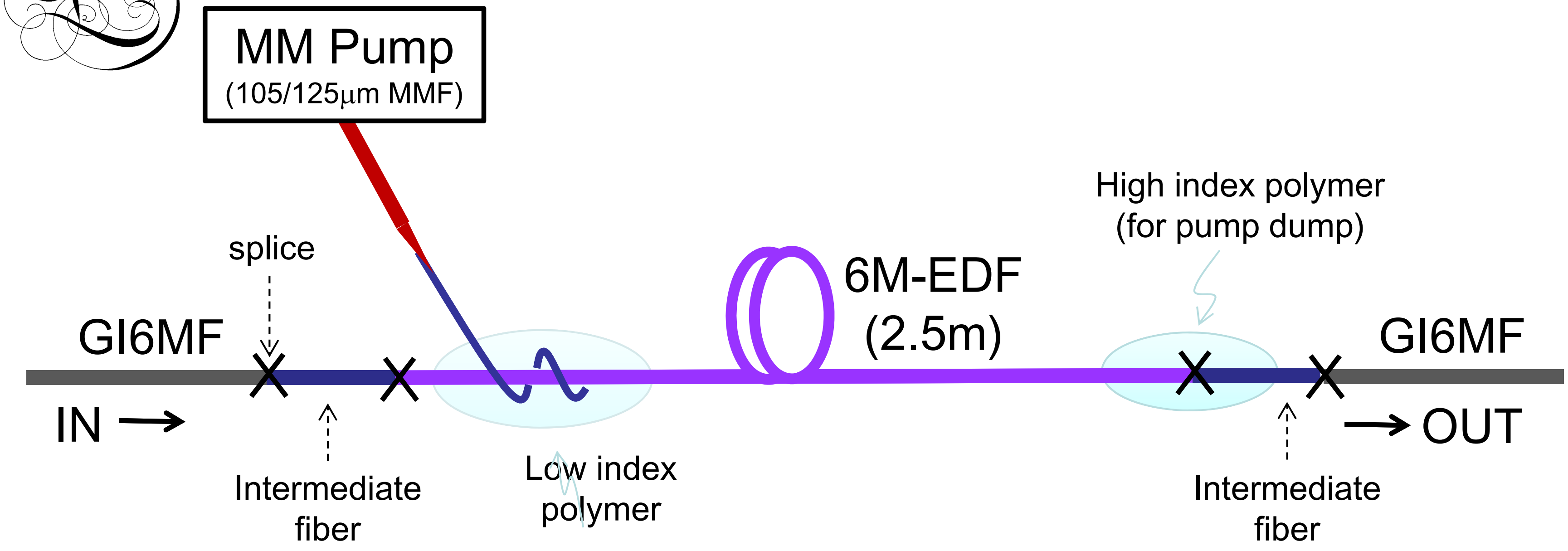


Leon-Saval et al. Opt. Exp., 22, 3 (2014).

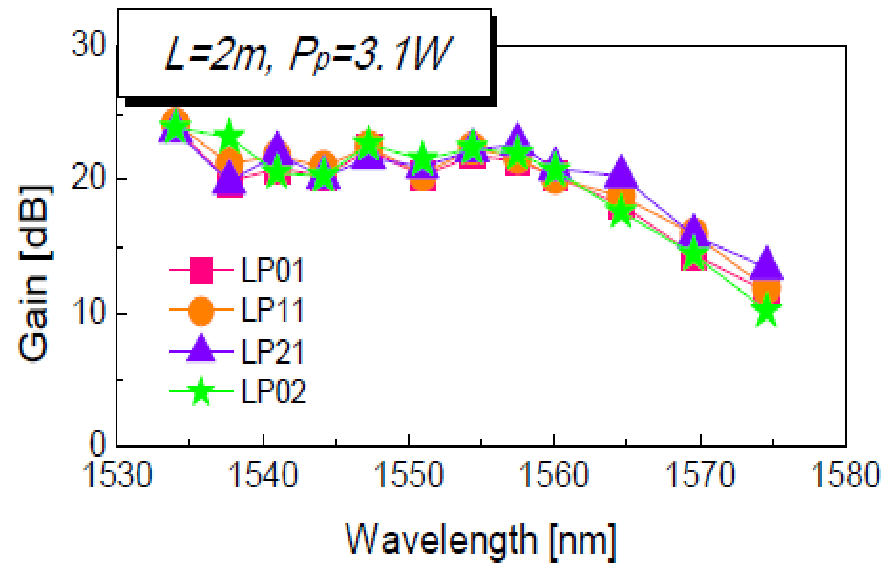


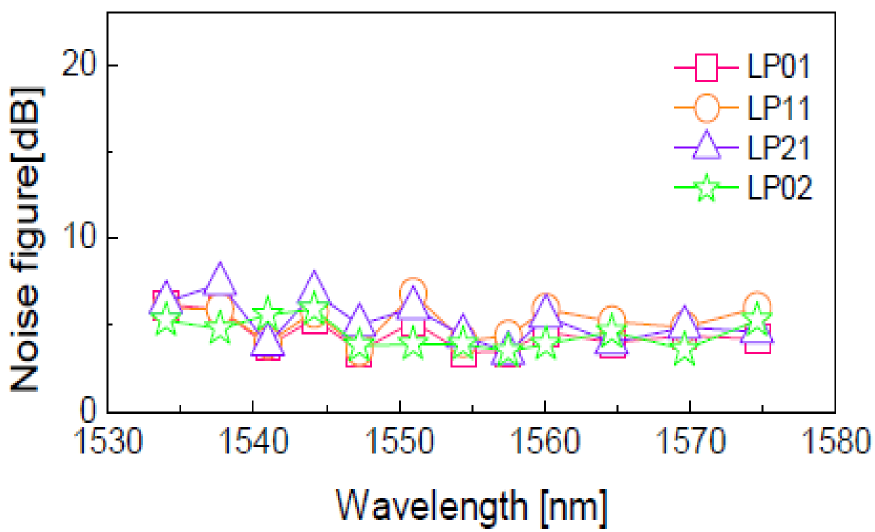
P Mitchell at al. OFC 2014 paper M3K.5

Fully Fiberized Cladding-Pumped 6M-EDFA

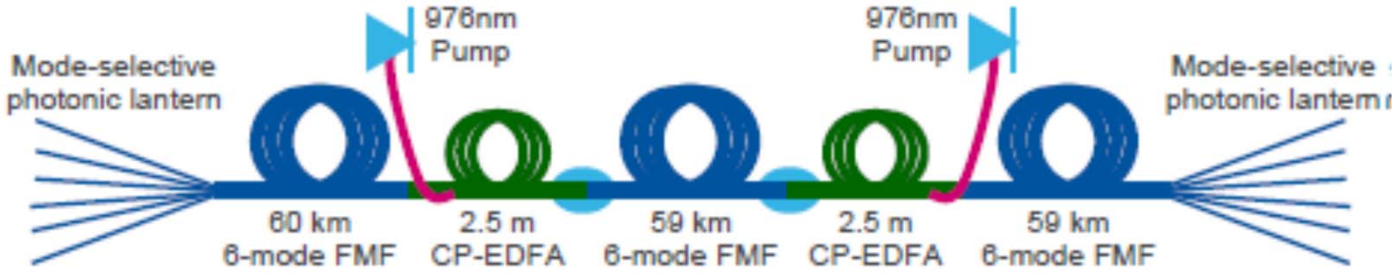


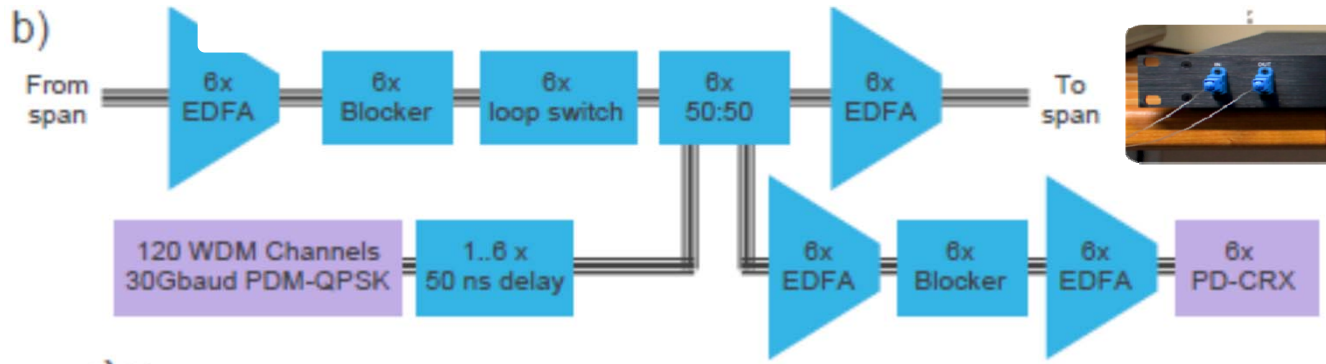
Y. Jung et al., Opt. Exp. 23, 29011 (2014)





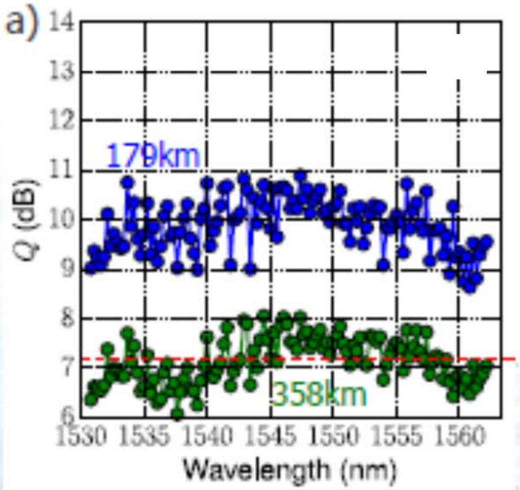
Recirculating loop experiment with 6M-EDFA





Single 1"X19"x11" rack mountable unit

(Fully integrated SDM amplifier)



c)

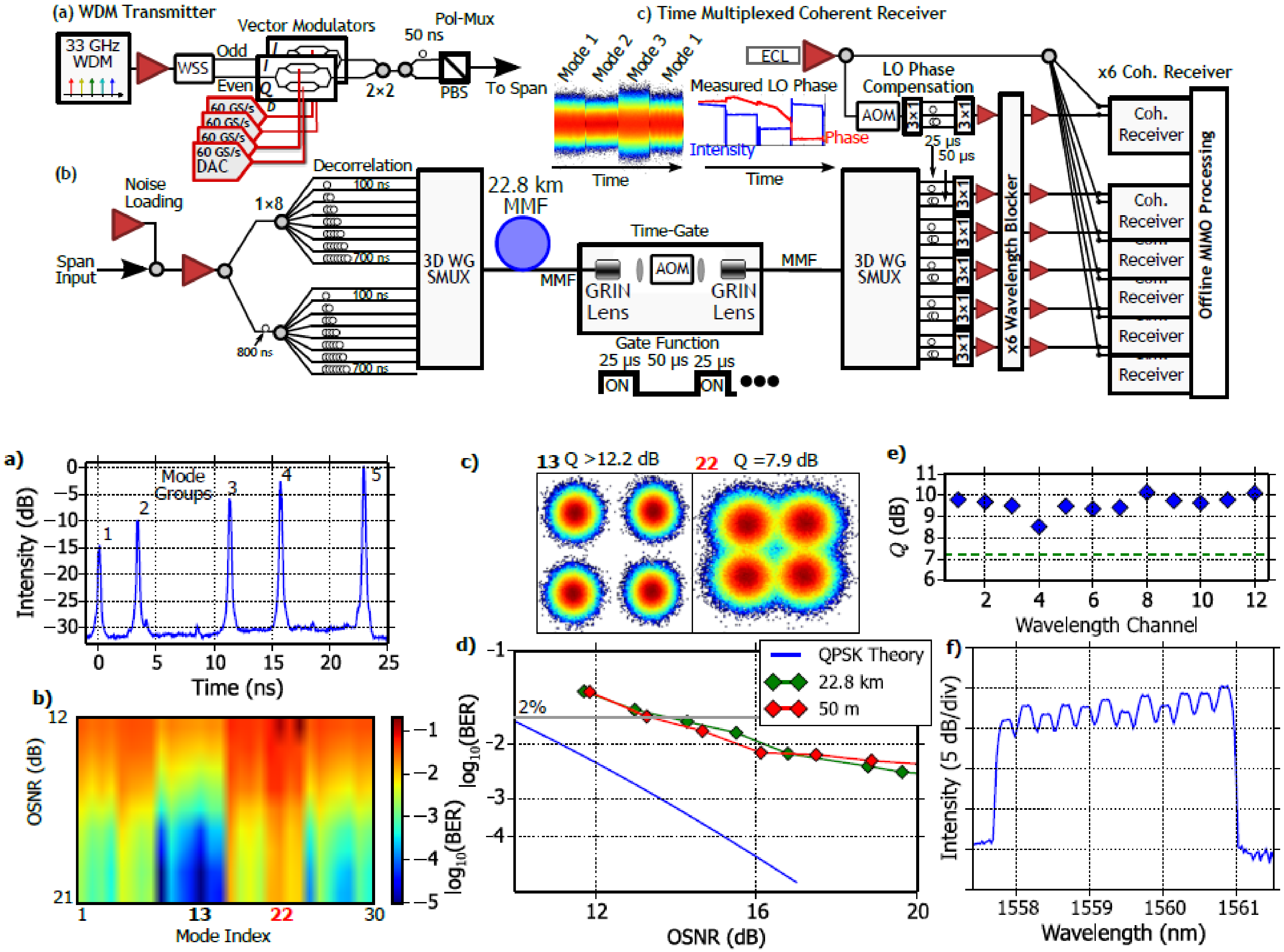
	Distance (km)	120 Ch, 33.3 GHz Q_{min} (dB)	Q_{max} (dB)	Q_{avg} (dB)	40 Ch, 100GHz Q_{min} (dB)	Q_{max} (dB)	Q_{avg} (dB)
FMF6 179km	179	8.0	10.9	9.9	10.0	11.9	11.2
	358	6.1	8.1	7.2	7.0	8.7	7.9

- 12 x 6 Modes, 30 Gbaud PDM-QPSK
- Low DGD fiber
- Cladding-pumped EDFAs
- Spectral efficiency – 18 bit/s/Hz

Alcatel·Lucent

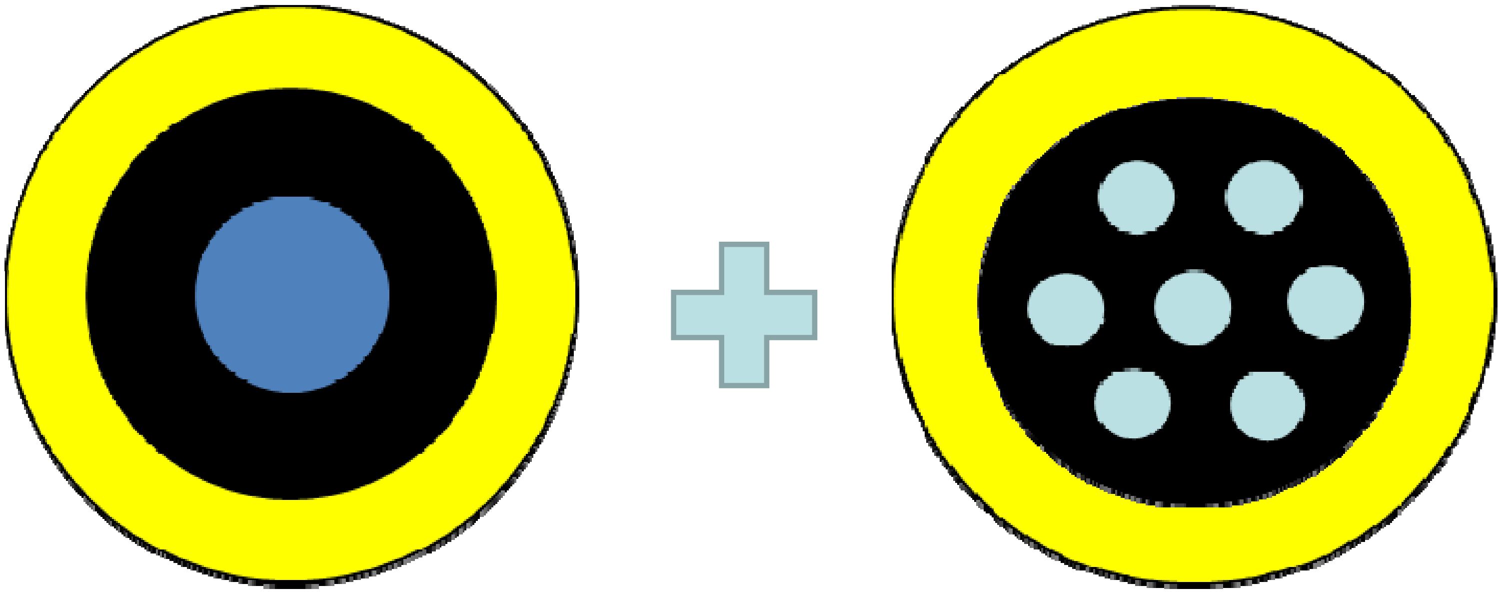
MODE GAP

15-mode 22.8 km Transmission in 9 LP-Mode Fibre

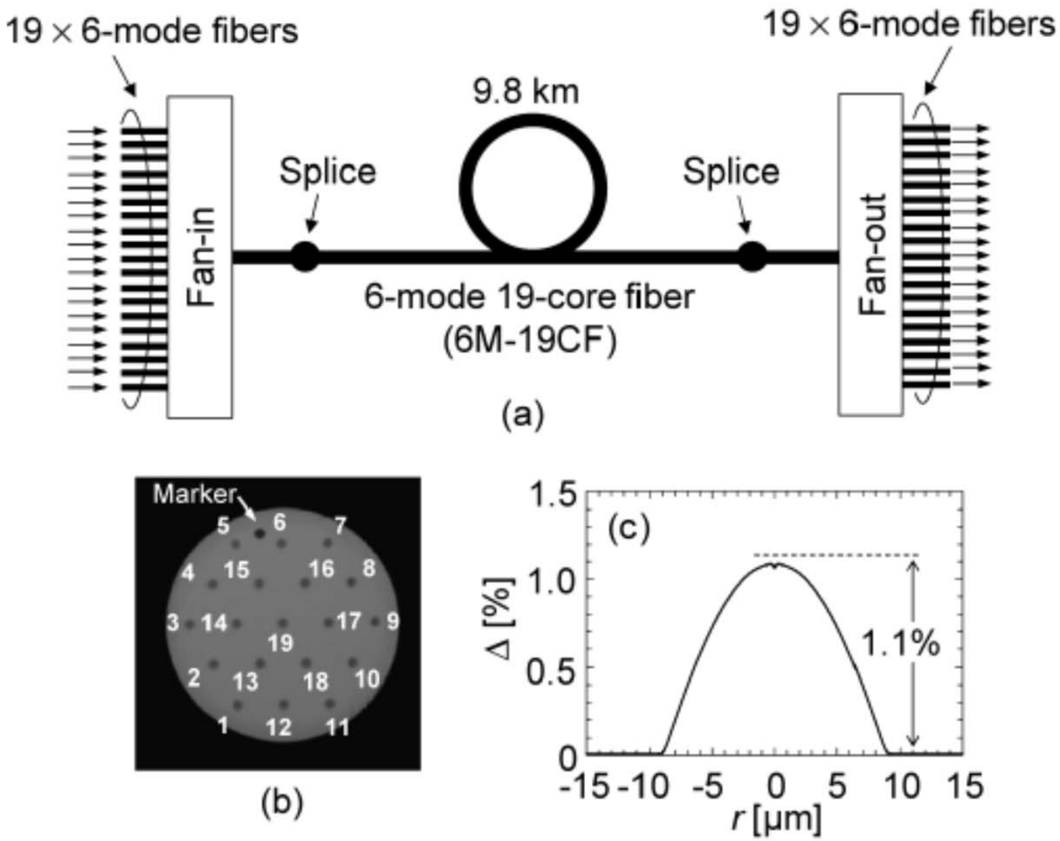


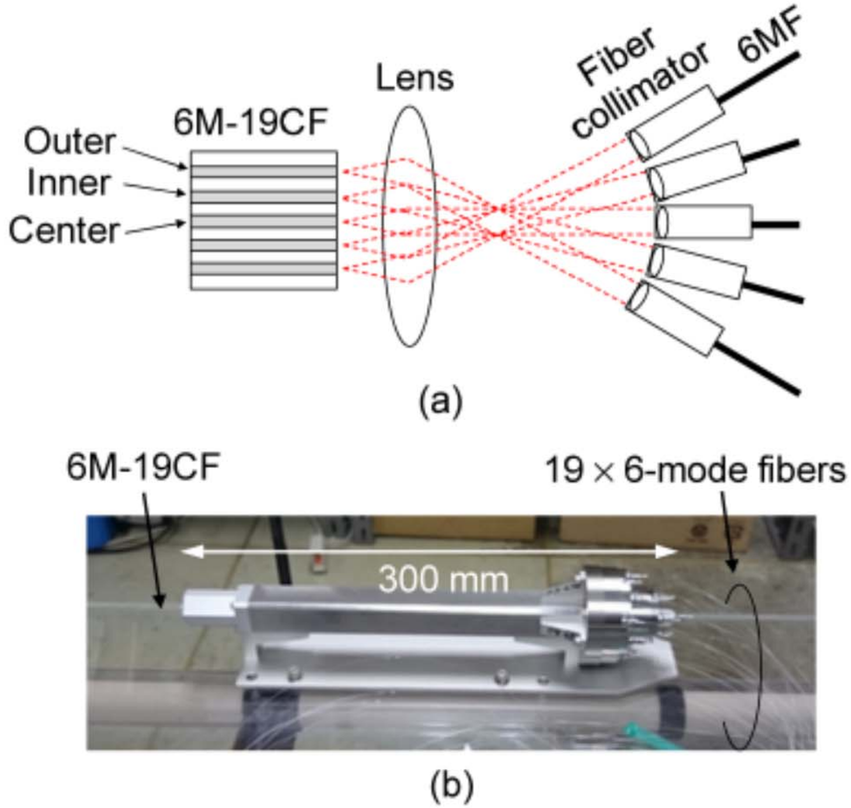
N. Fontaine OFC'15 post deadline paper Th5C.1

Ultimate Channel Scalability



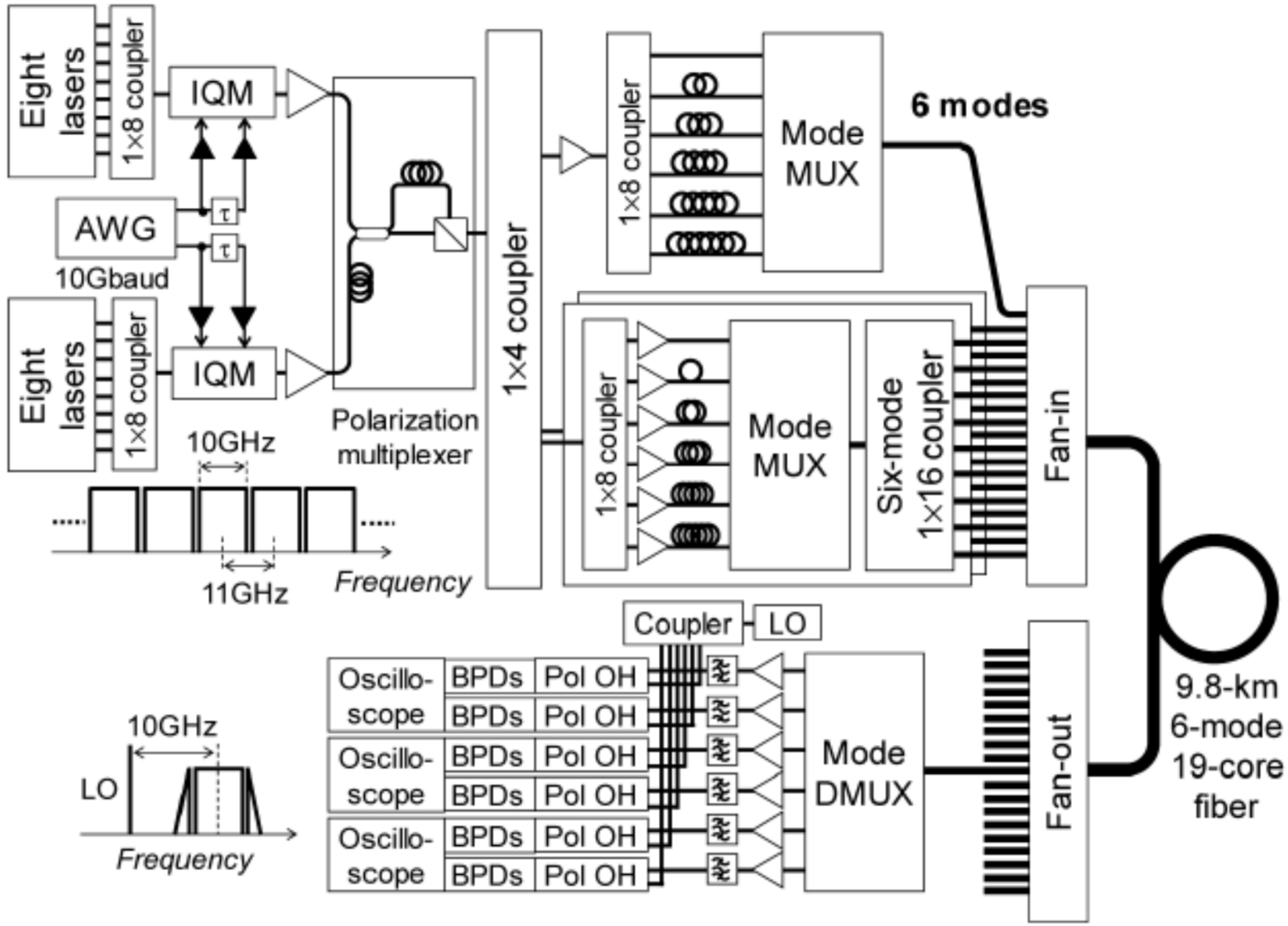
19Cx6M Fiber with 114 Spatial Channels





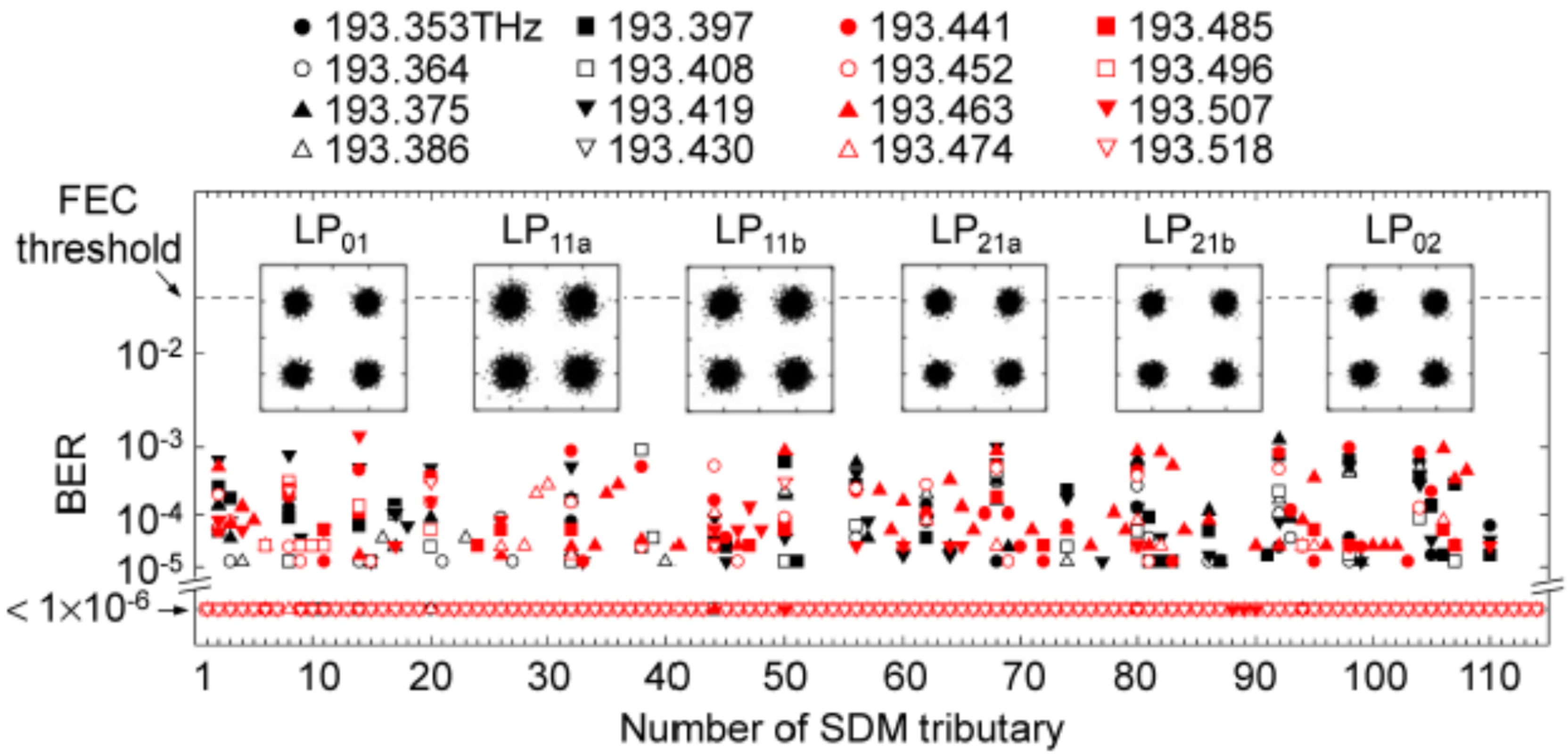
D. Soma et al. ECOC 2015 PDP 3-2

2.05 Pbit/s transmission experiment



D. Soma et al. ECOC 2015 PDP 3-2

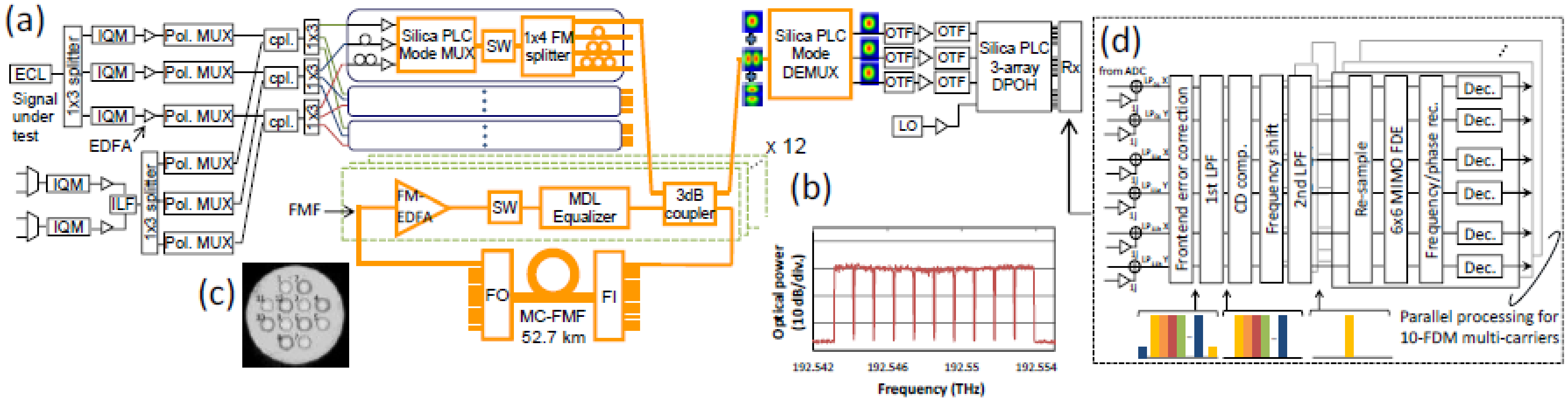
2.05 Pbit/s transmission experiment

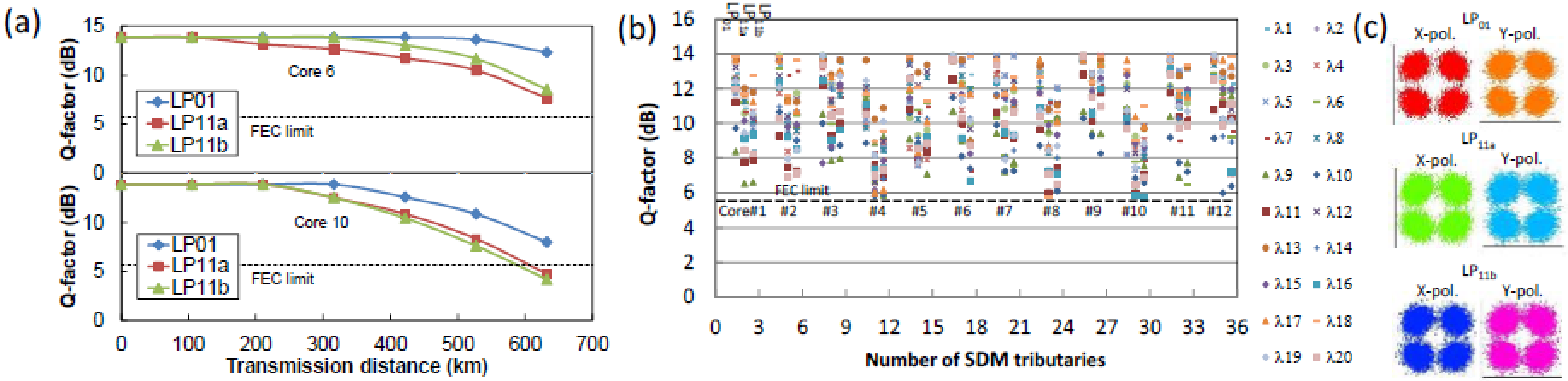


- 360 (super Nyquist WDM) x 114 (SDM) x 15 Gbaud, DP-QPSK
- Total Capacity = 2.05 PBit/s
- SE= 456 bit/s/Hz
- L= 9.6 km

D. Soma et al. ECOC 2015 PDP 3-2

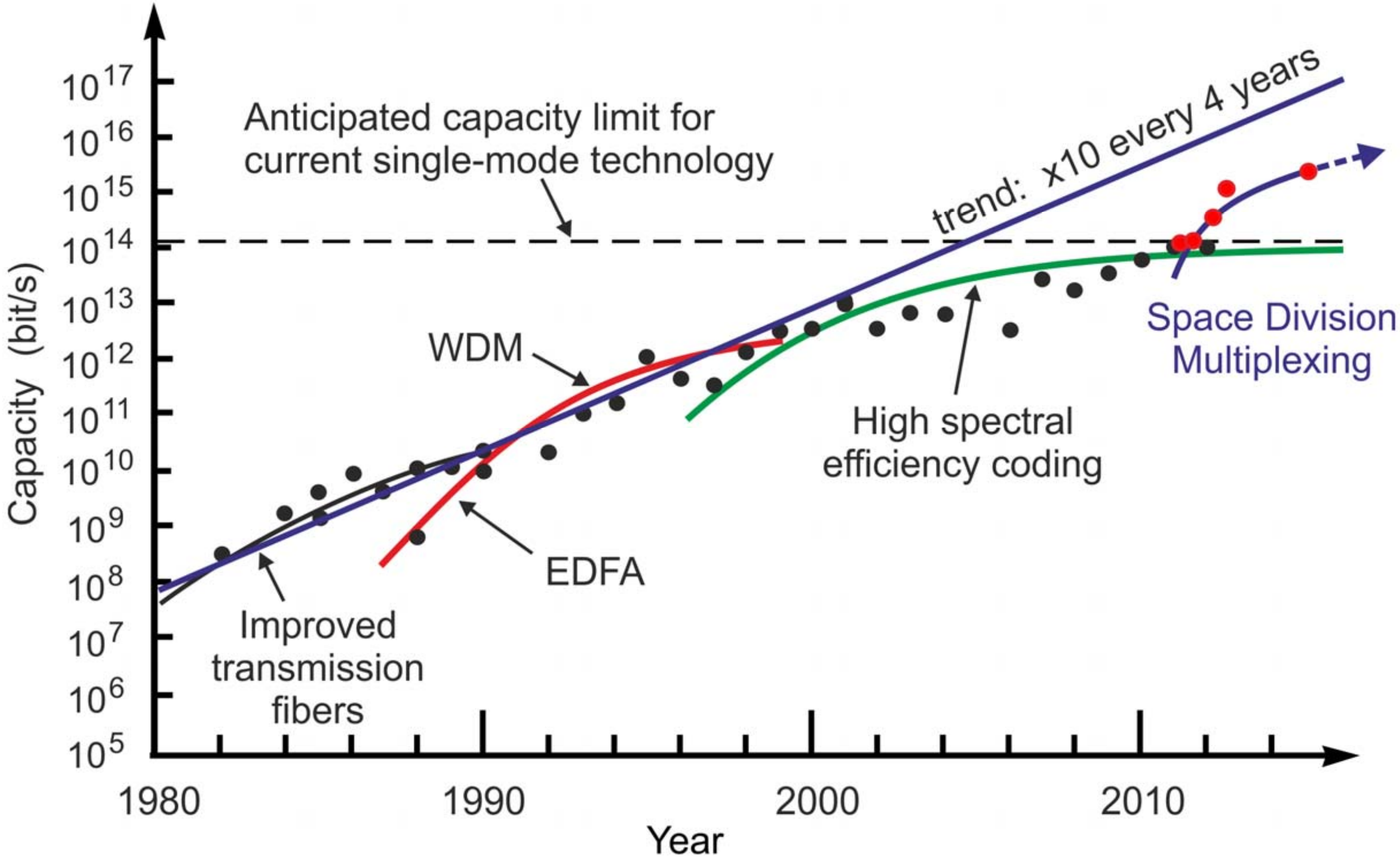
12C x 3M amplified transmission over 527km





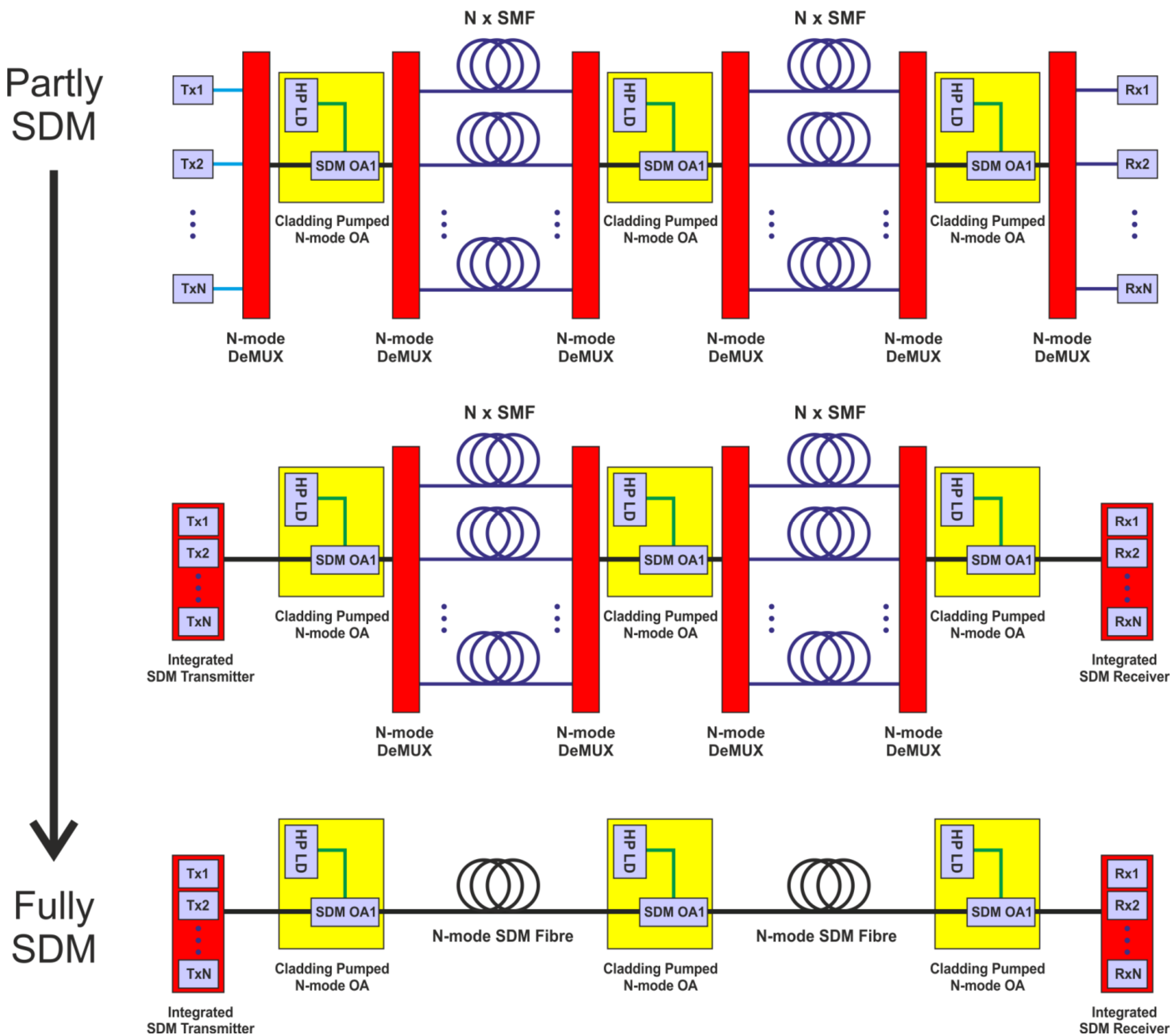
K. Shibahara et al. OFC 2015 PDP paper Th5C.3

SDM Progress to Date

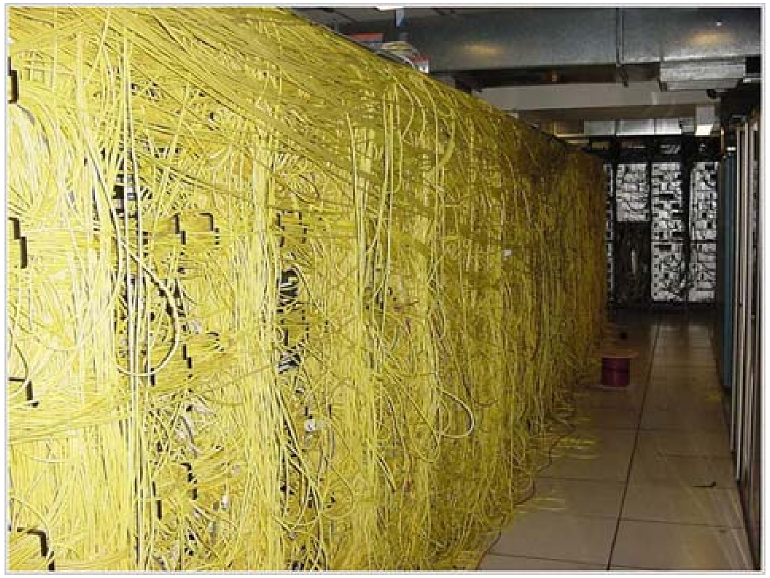


- Transmission records as derived from OFC PDPs
- ECOC PDPs also included since 2010

Possible Upgrade Scenarios



Data Centre Interconnection



Information flow per unit area and latency key in supercomputers and datacenters

New high capacity and high spatial density fibers required

Conclusions

- Gross technological feasibility demonstrated (x20 capacity, x10 capacity length product, x100 spatial multiplicity) but many open questions remain in terms of control, reliability, practicality, …
- Device integration (e.g. transponders, amplifiers etc.) is critical to the value proposition, as is ultimate manufacturability
- Interoperability key
- Commercial case for SDM in long haul telecoms is still to be proven

A long way to go before we are likely to a see full SDM system deployment.
A graceful adoption of "SDM components" is far more likely

"SDM technology" likely to appear commercially elsewhere first