Optica - Optical Communication Technical Group Webinar

6th October 2022

High-Throughput Optical Transmission Experiments with Space-Division Multiplexing

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- **Introduction to SDM and SDM fibers**
- Homogeneous multi-core fibers
  - Long-haul transmission with 19-core EDFA
  - MCF systems and networks
- Wideband transmission in 4-core fiber
  - 1 Pb/s single span transmission
  - 3000 km re-circulating transmission
- 1 Pb/s transmission in a 15-mode fiber
- Conclusions – SDM and Beyond

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Frank Achten

NOKIA Bell Labs

Nick Fontaine
Roland Ryf
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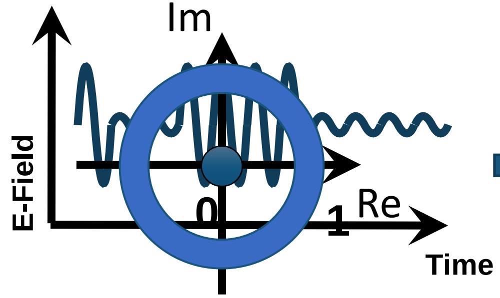
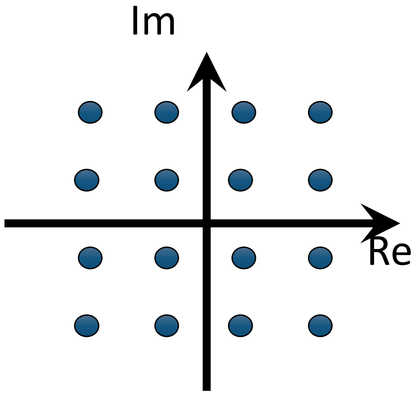
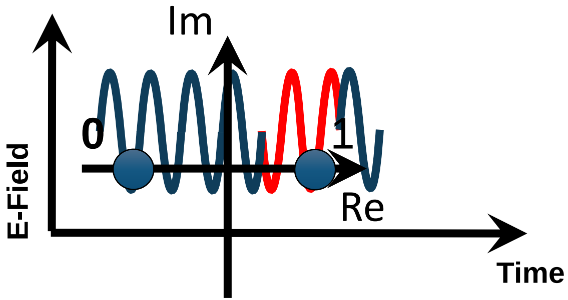
The final frontier



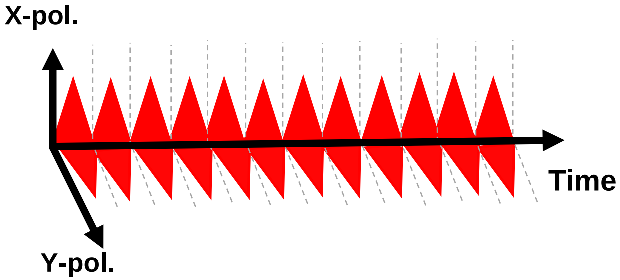
On-Off keying (OOK)

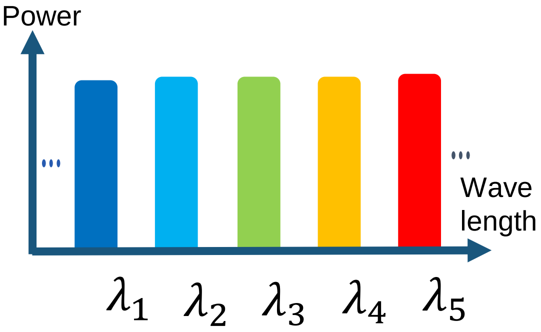


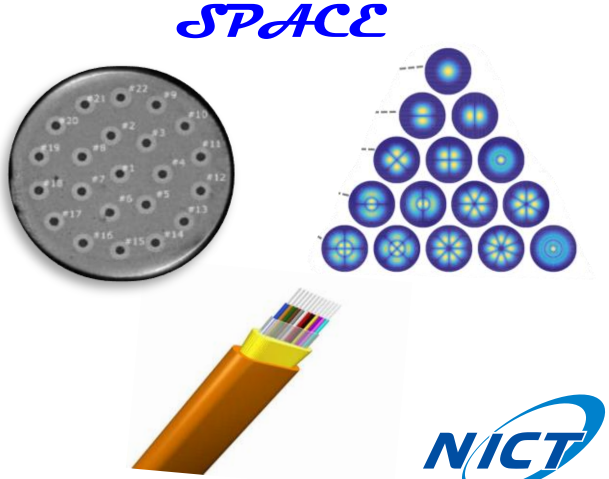
16-Quadrature amplitude modulation (QAM)



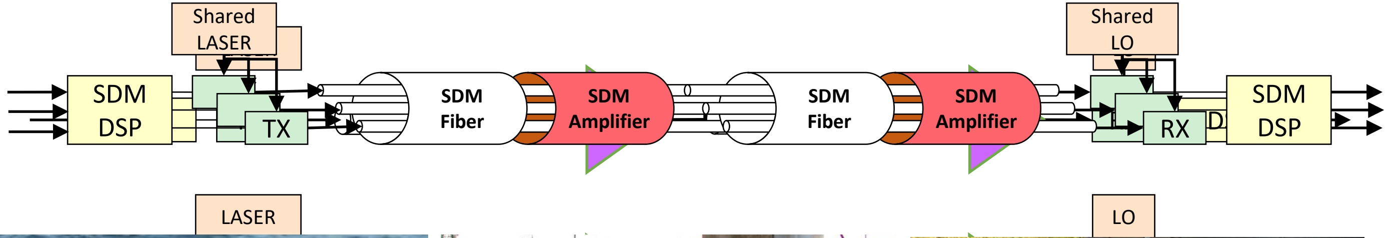
Binary phase-shift keying (BPSK)

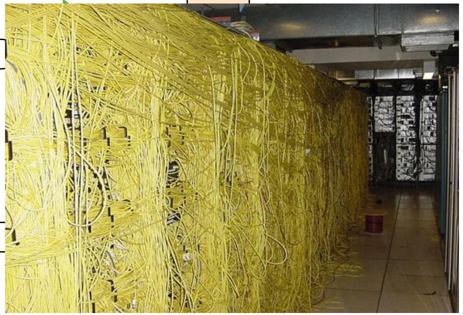






Motivation for space-division-multiplexing





- As demand for fiber transmission grows, SDM is an opportunity to share hardware, power and processing resources over more bits.
- Also as a way to alleviate bottlenecks of physical space:
  - ➢ Submarine cables,
  - ➢ Metro/access networks
  - ➢ Data centres

Spatial skew and crosstalk in SDM Fibers

Independent single-mode fibers

- High skew
- No crosstalk

Heterogeneous multi-core fibers

- High skew
- Very low crosstalk

Homogeneous multi-core fibers

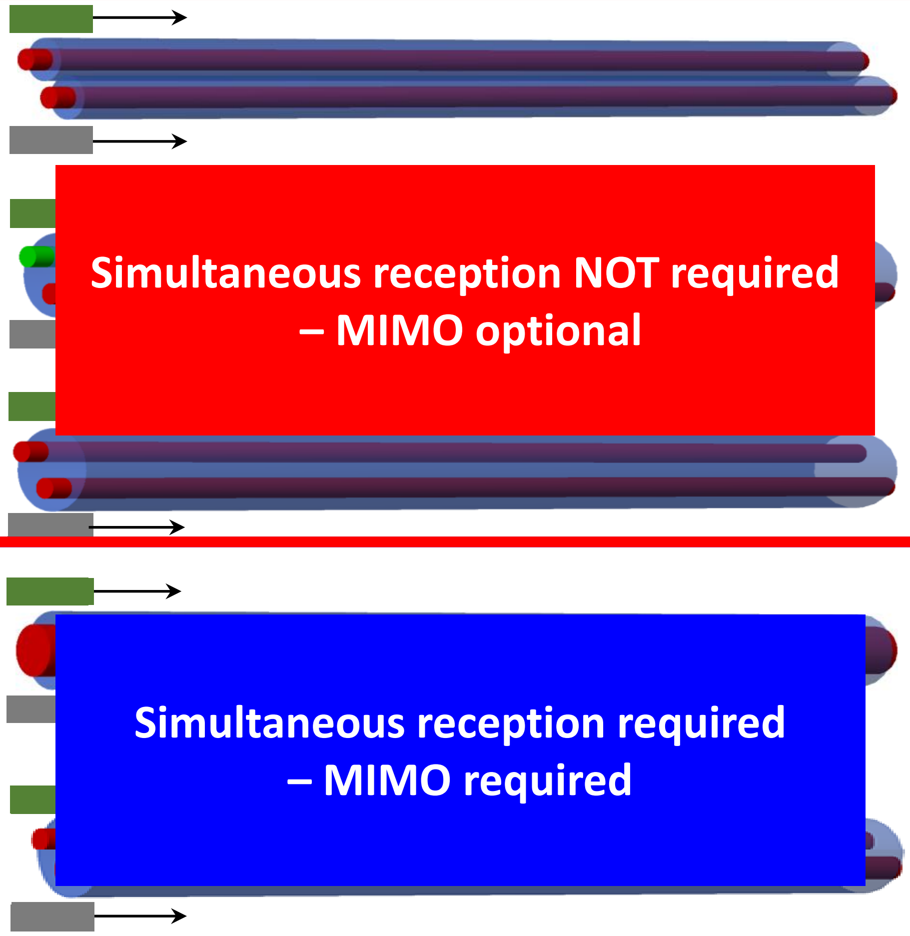
- Low skew
- Low crosstalk

Few/multi-mode fibers

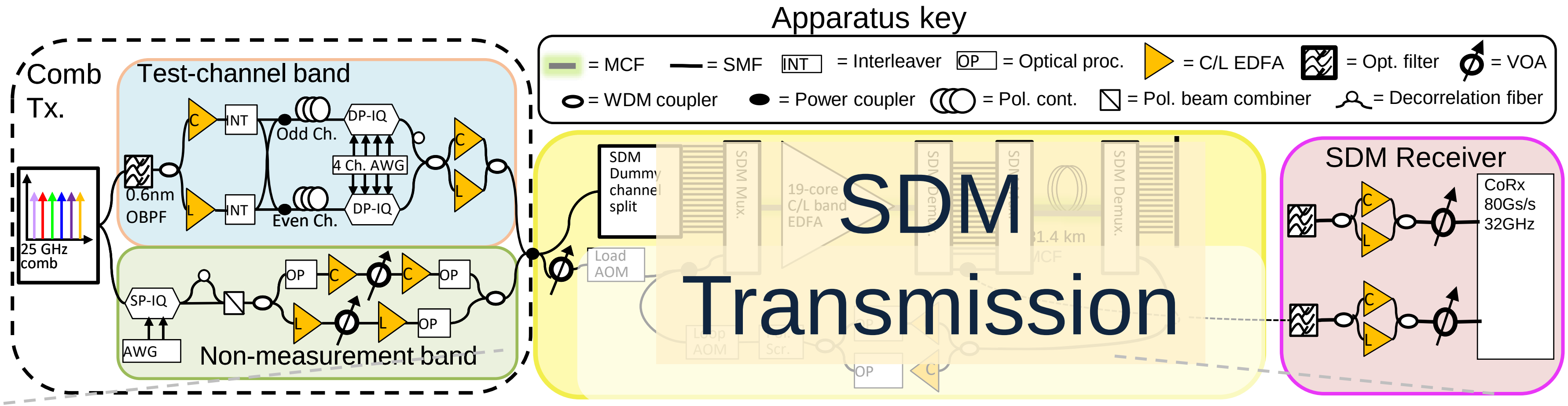
- Low skew (inter mode group)
- Signal mixing (intra mode group)
- Some crosstalk (Inter mode group)

Coupled-core multi-core fibers

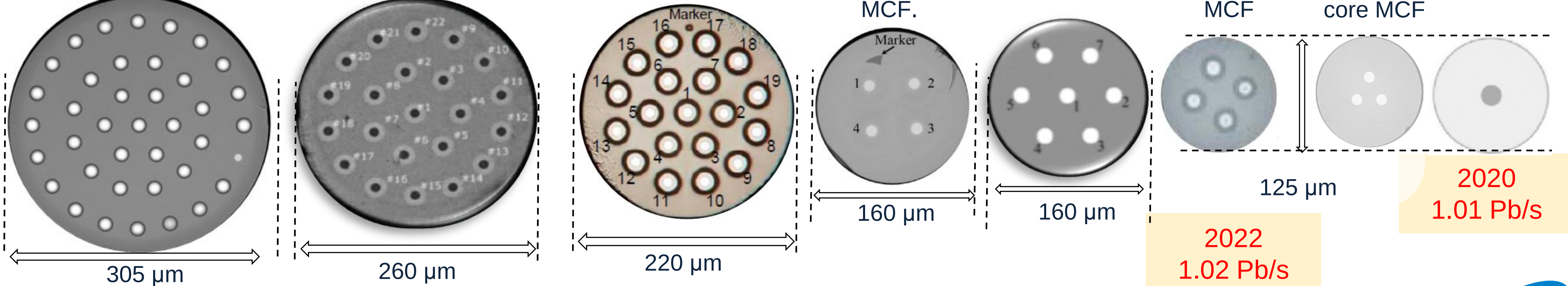
- No skew
- Signal mixing



Transmission experiments with SDM fibers



13 km 38-few-mode multi-core fiber (MCF) | 31.4 km 22-core MCF | 30 km 19-core MCF | 3.5 km 4-core few-mode MCF. | 53.7 km 7-core MCF | 54-100 km 4-core MCF | 60 km 3-coupled core MCF | 28 km 15-mode fiber



2020
10.66 Pb/s

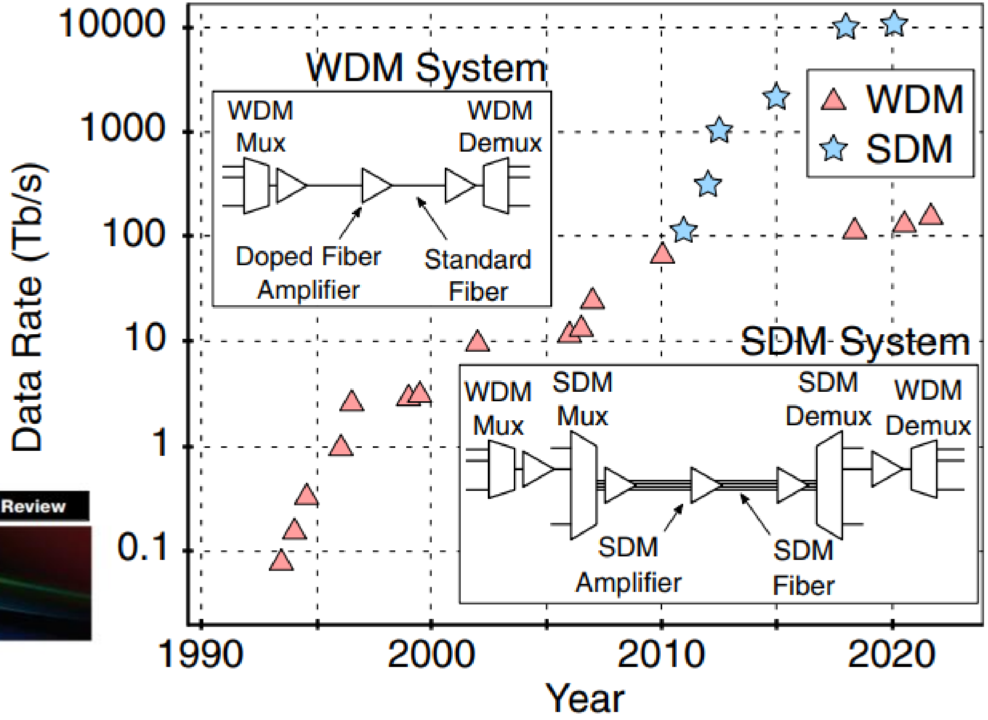
2015
2.15 Pb/s

2018
1.2 Pb/s

2022
1.02 Pb/s

2020
1.01 Pb/s

SDM vs WDM hero experiments



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Space-division multiplexing for optical fiber communications

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Research on space-division multiplexing (SDM) came to prominence in early 2010 being primarily proposed as a means of multiplying the information-carrying capacity of optical fibers at the same time as increasing efficiency through

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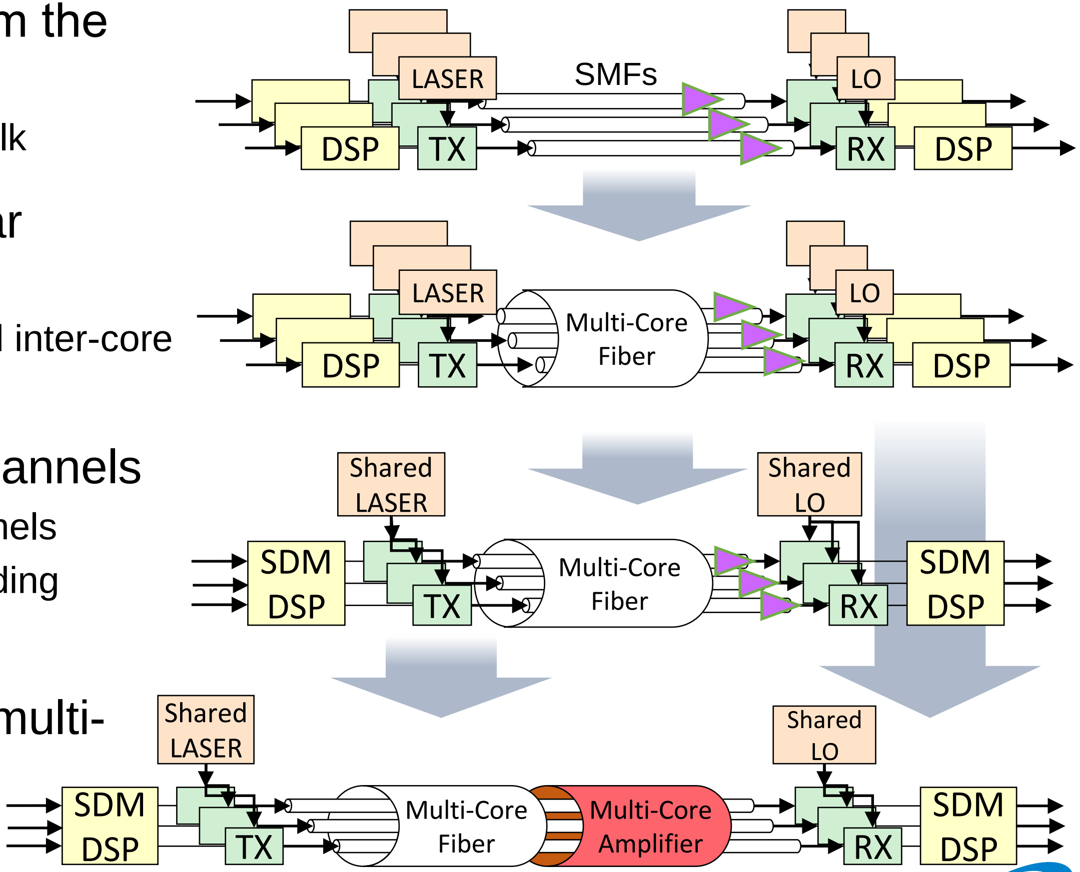
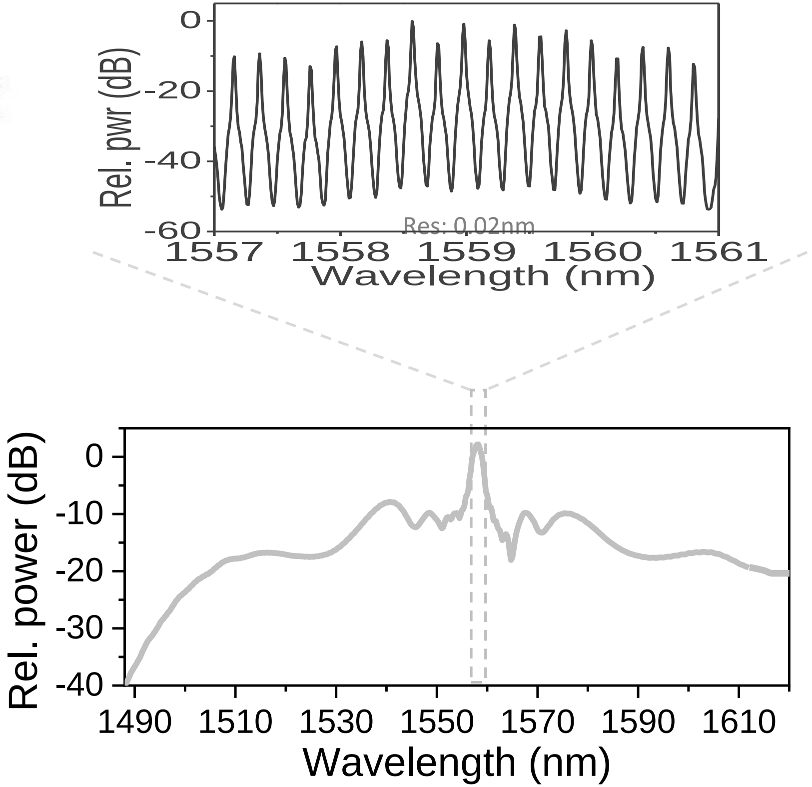
- Conclusions – SDM and Beyond

Homogeneous MCFs

- Light on each core is "uncoupled" from the other cores
  - ➢ Residual coupling yields inter-core crosstalk
- Propagation characteristics are similar amongst all cores
  - ➢ Residual differences in group velocity yield inter-core skew
- Nearly time-aligned Spatial Super-Channels
  - ➢ Simple shared DSP amongst spatial channels
  - ➢ Spatial modulation formats and Spatial coding
  - ➢ Self-Homodyne Detection
- Simple transition from single-core to multi-core fiber systems



Wideband comb



- Custom designed wideband, narrow linewidth comb source*
- > 120nm (15 THz) bandwidth
- Up to 550 lines
- 25GHz line spacing
- >33 dBm Total output power
- Average power 1 dBm/line
- OSNR > 40 dB (1510 nm to 1610 nm)

RAM Photonics

*B. P.-P. Kuo et al., IEEE JLT. 31 (9), 3414-9 (2013)

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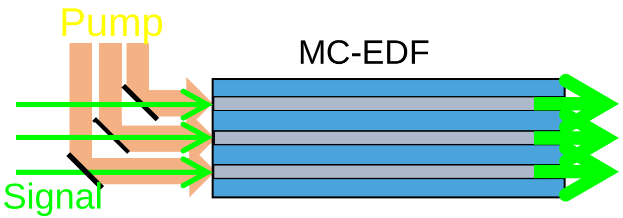
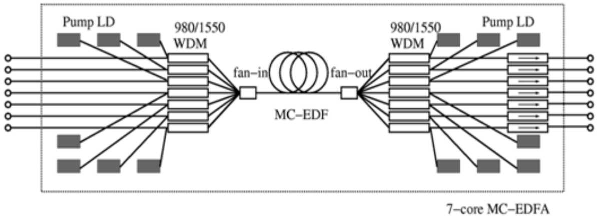
MCF Amplifiers

Core-pumped EDFA

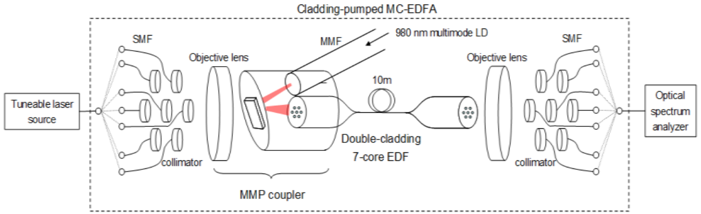




Y. Tsuchida and R. Sugizaki, IEEE Sum. Top. TuC3.1, 2013

- ☺ Excellent gain performance
- ☺ Each core can be switched ON/OFF
- 😐 Pump laser power consumption
- ☹ Number of pump combiners = number of cores

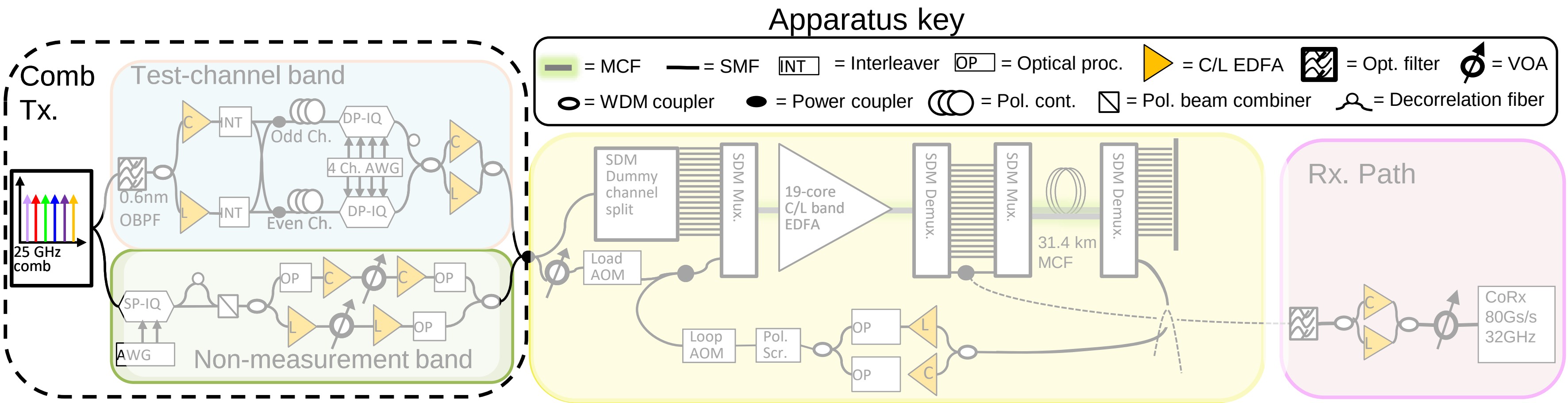
Cladding-pumped EDFA

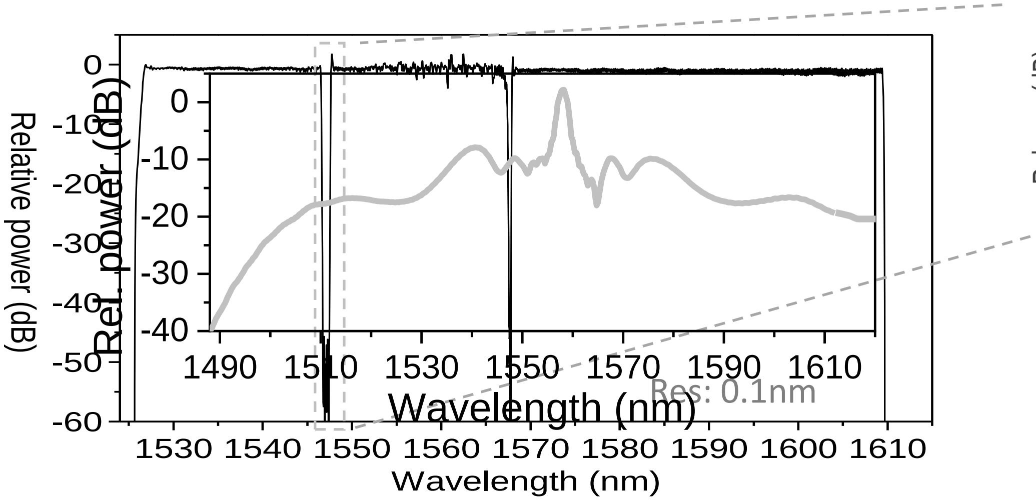


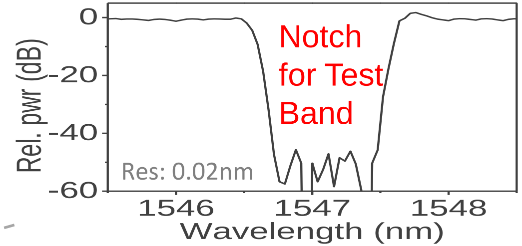
S. Takasaka et al., ECOC 2013, We.4.A.5

- 😐 Performance optimization difficult
- 😐 No independent pump control
- ☺ Pump laser operation (uncooled)
- ☺ Only one pump combiner
- ☹ High pump powers

19 core EDFA Transmission







>40dB to reduce intra-band crosstalk

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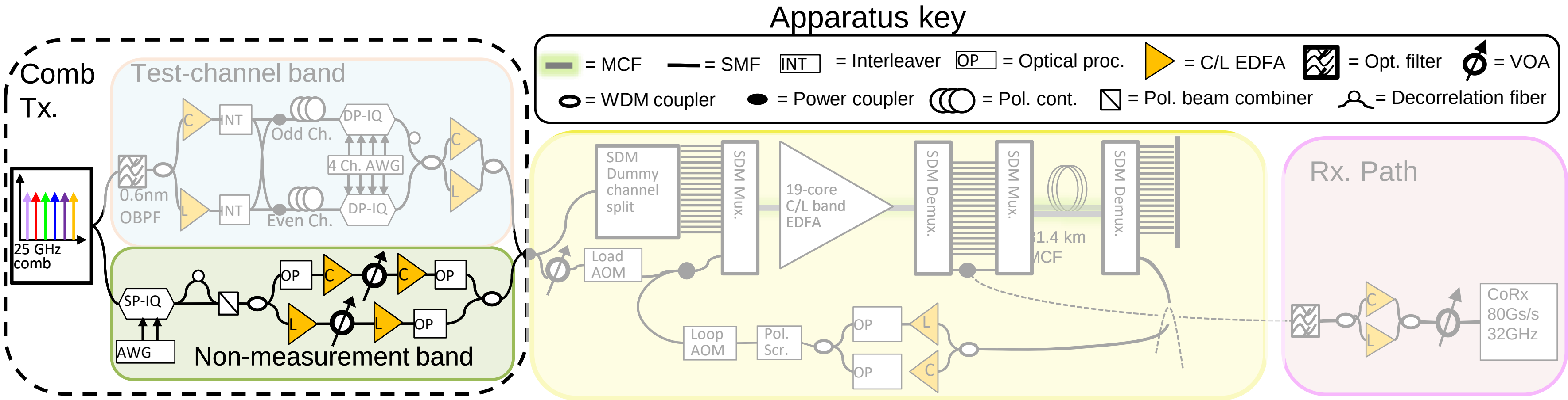
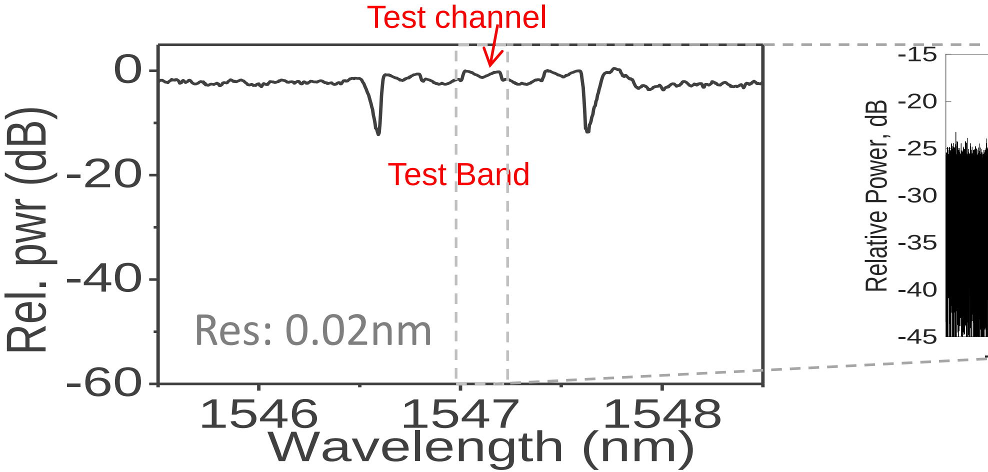
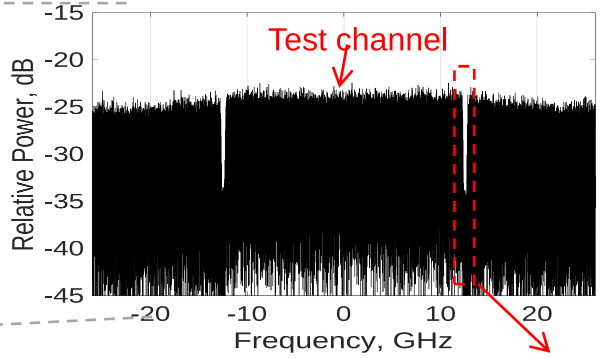
19 core EDFA Transmission







255 MHz

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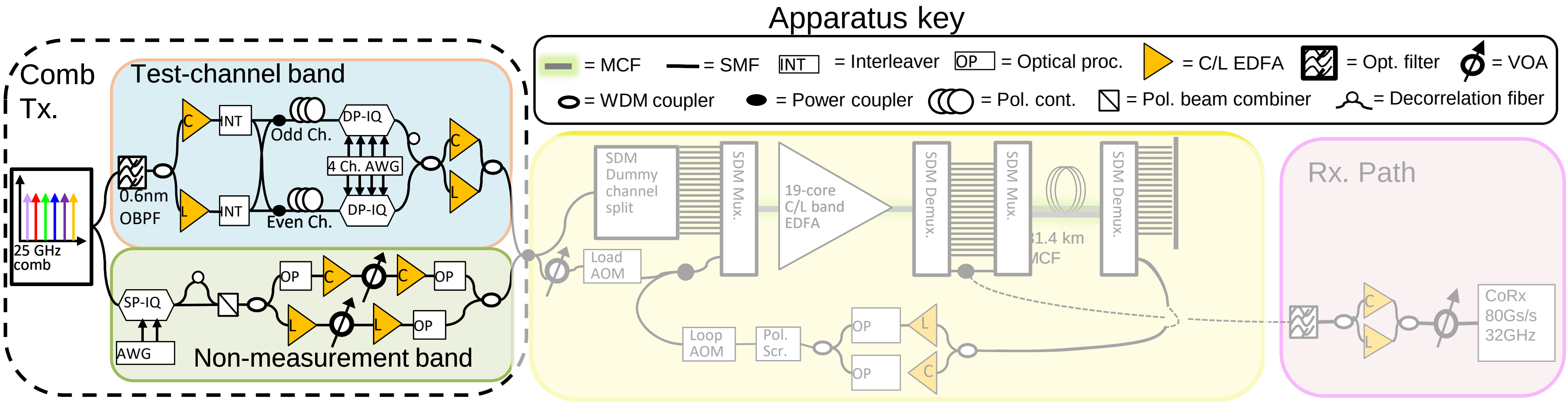
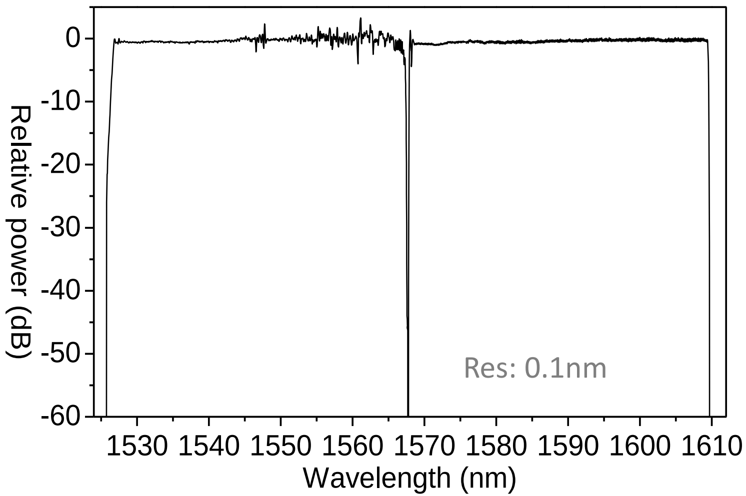
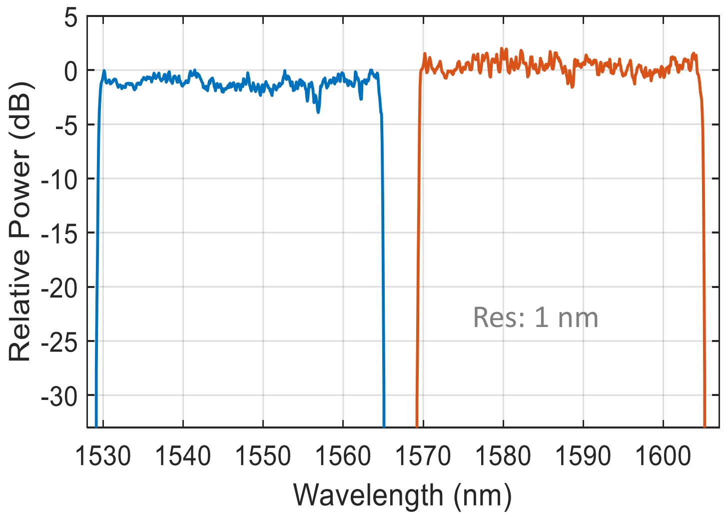
19 core EDFA Transmission







- Q-factor/BER
- GMI
- Decoded throughput

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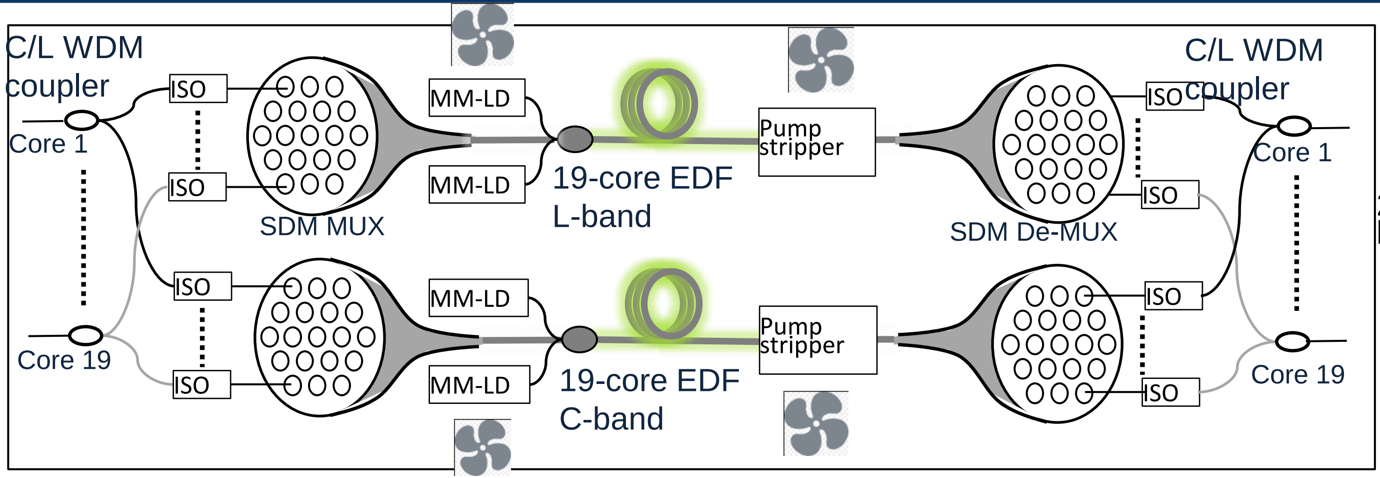
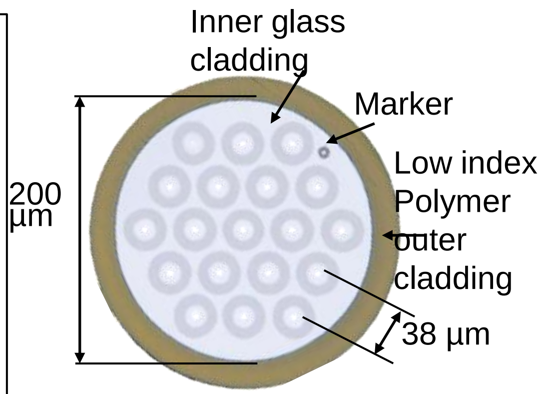
19-core cladding pumped EDFA

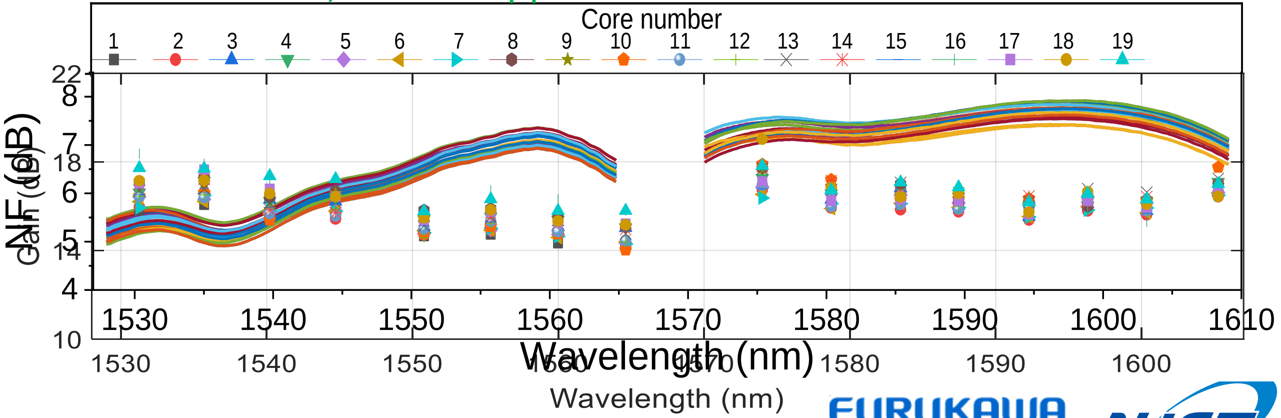




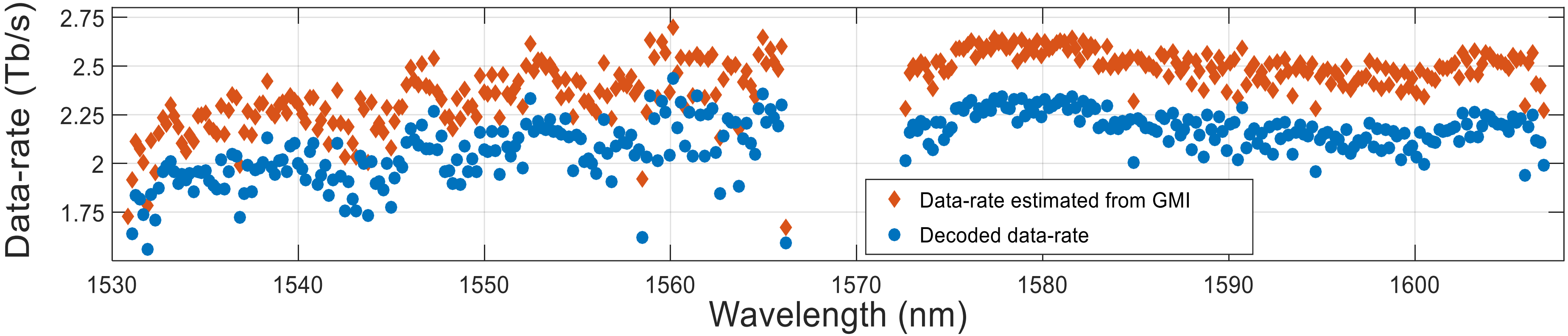
Hexagonal double cladding structure EDF

S. Takasaka et al., ECOC'17 pp TH.2.D

Parameter	C-band	L-band
Clad. diameter (µm)	200	200
Core pitch (µm)	38	38
MFD (µm)	7.3	7.3
EDF length (m)	8	55
Optical pw. (W)	43.5	13.7
Electrical pw. (W)	104	34
XT (dB)	<-40	<-40



19-core EDFA – 2000km PDM 16-QAM transmission



- Total throughput after decoding 715 Tb/s after 2009.6 km
  - (64 recirculations, 345 wavelength channels)
- Decoded data throughput approximately 90% of GMI estimate

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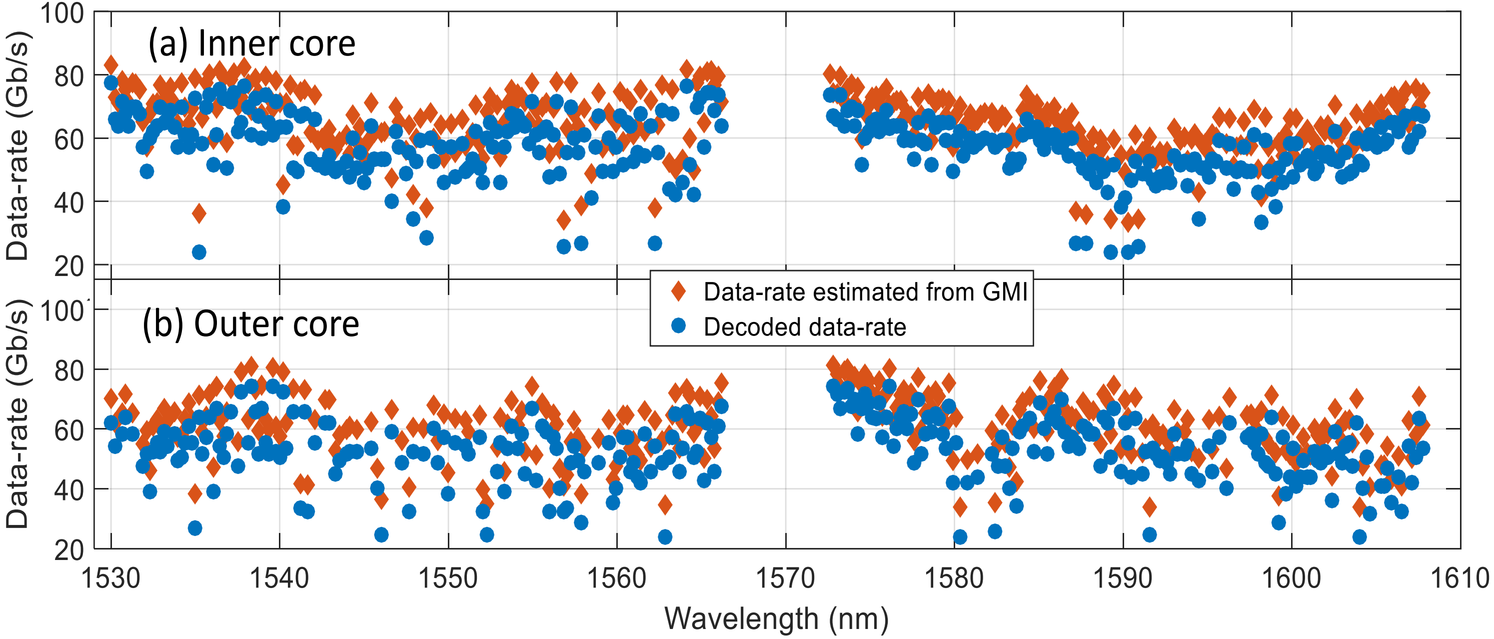
8000km Summary – PDM-QPSK



- Per-core throughput after decoding 18.5 Tbit/s and 14.5 Tbit/s in low and high XT cores after 8007 km
  - – 255 Recirculations
- Decoded data throughput also ≈ 90% of GMI estimate

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Spatial super-channels

- Spatial super-channels were proposed to exploit the relative uniformity of parallel spatial channels to allow joint digital signal processing (DSP) and simplify switching in multi-core fiber (MCF)

  M .D. Feuer et al. PTL, 24, 1957–1960 (2012)
  M. D. Feuer et al., OFC 13 PDP5B.8

- SSCs allow multi-dimensional modulation across spatial channels

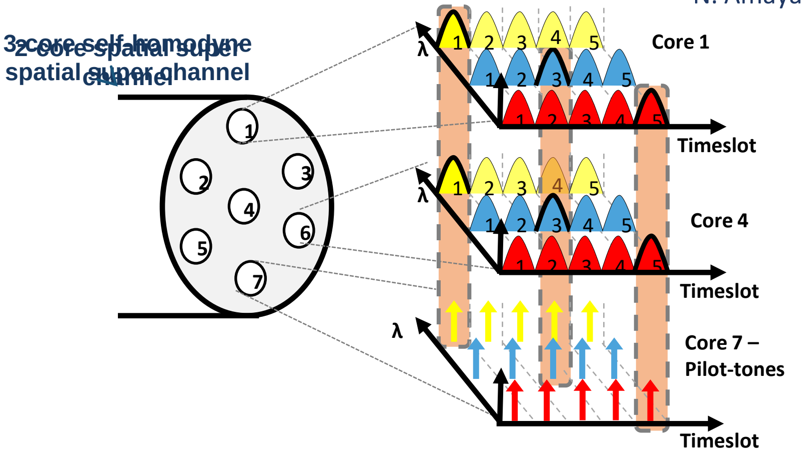
  B. J. Puttnam et al. OPEX 22 (26), pp. 32457-69, 2014

- They are also compatible with other transmission schemes requiring correlated transmission paths such as self-homodyne detection or shared carrier reception for further simplified DSP

  J-M Delgado Mendinueta. OFC, JTh2A.48 (2013)
  E. Le Taillandier de Gabory. OFC, OM2C.2 (2013)

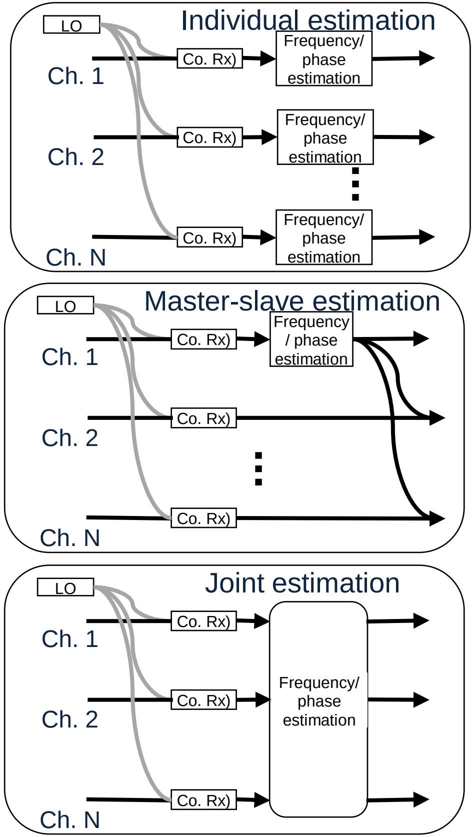
- They have also been used in networking experiments in combination with self-homodyne detection in an MCF for further simplified DSP

  N. Amaya et al. OPEX 22 (3), 3638–47 (2014)



An MCF/SDM system may carry multiple spatial-super- channels (SSC)s using variable numbers of cores and wavelengths

Strategies for shared and joint DSP



- Individual estimation equivalent to N x conventional receivers
- Master-slave estimation uses a single core and applies updates to other spatial channels
- Joint processing uses the signals from all cores to try and improve on single core estimation

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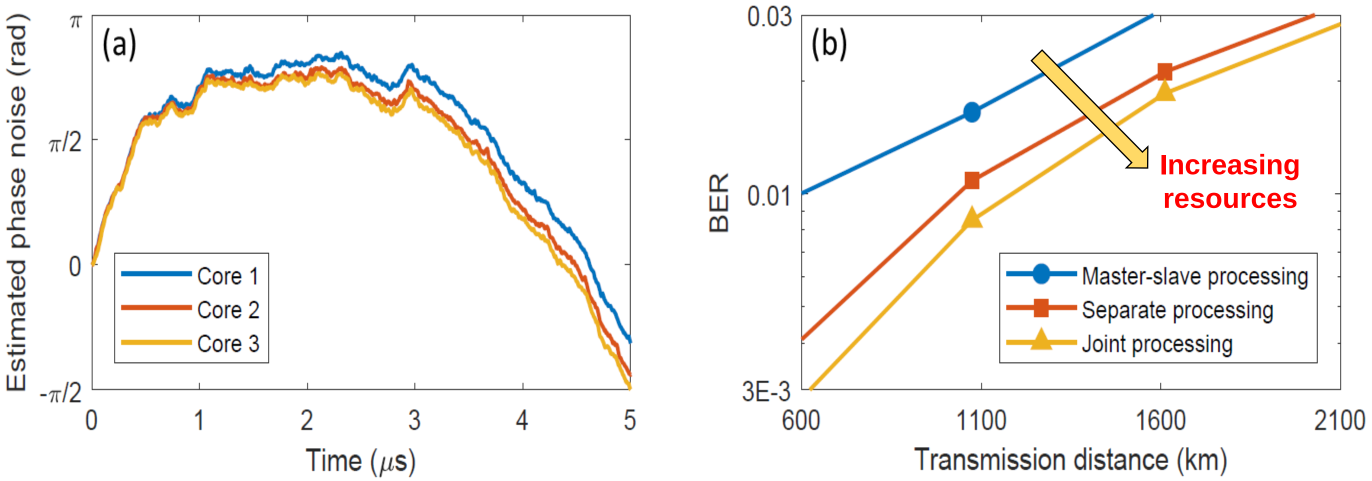
Joint Phase Estimation



- Estimated phase noise and BER vs distance for different phase-noise estimation strategies in 3-core MCF PDM-16QAM transmission
- Common transmitter gives correlated receiver phase noise in different spatial channels
- Joint processing can improve performance over individual core processing
- Master-slave can divide required resources as a trade-off to transmission distance

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APL Photonics 4 (2), pp. 22804 (2019)

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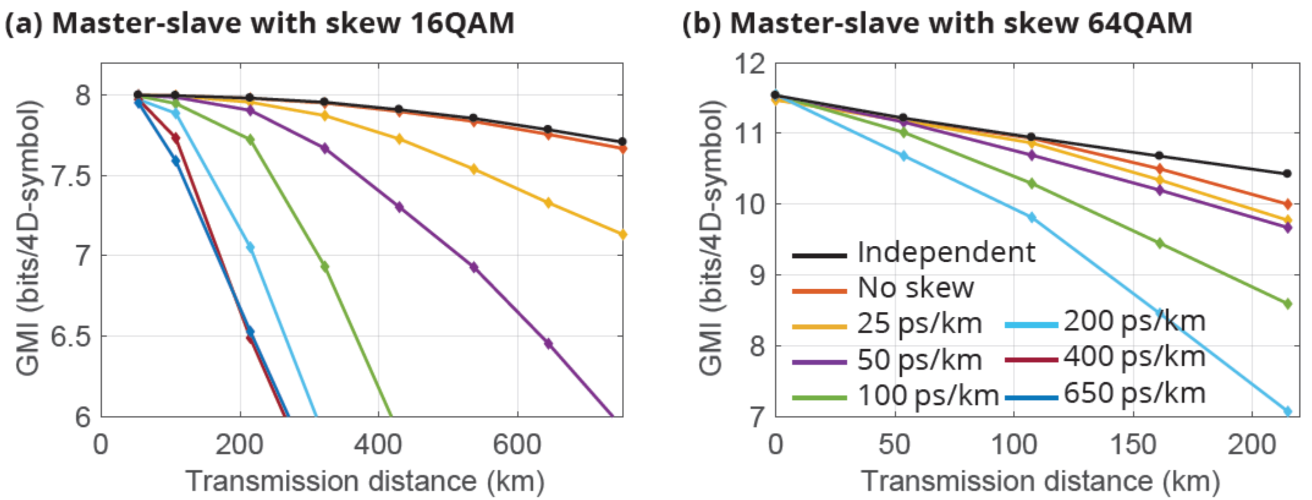
Impact of skew on joint processing



- Skew (Time delay) between spatial channels will have impact of performance of joint processing
- This was investigated with master-slave processing for 16-QAM and 64QAM experiments
- Distance penalty increases strongly with skew

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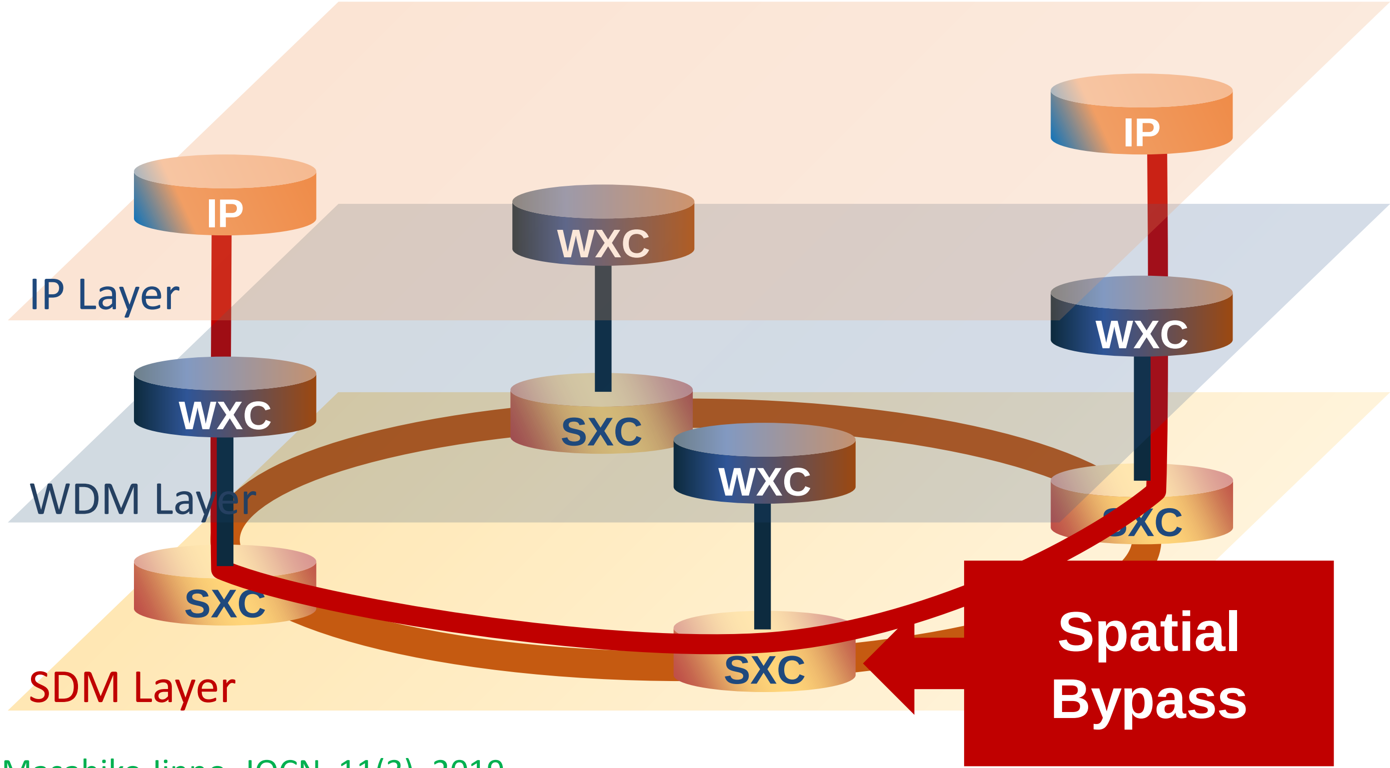
Spatial dimension in networking



Masahiko Jinno, JOCN, 11(3), 2019

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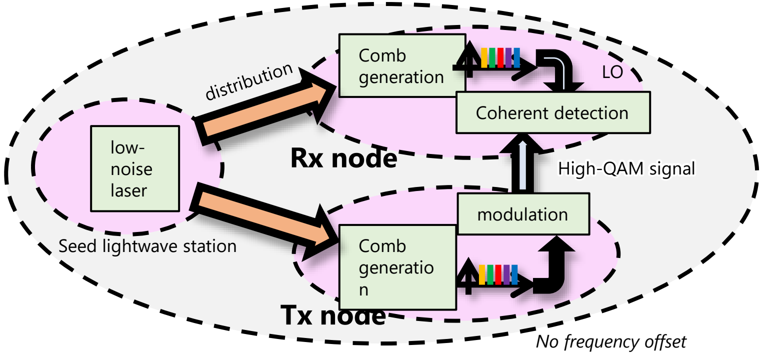
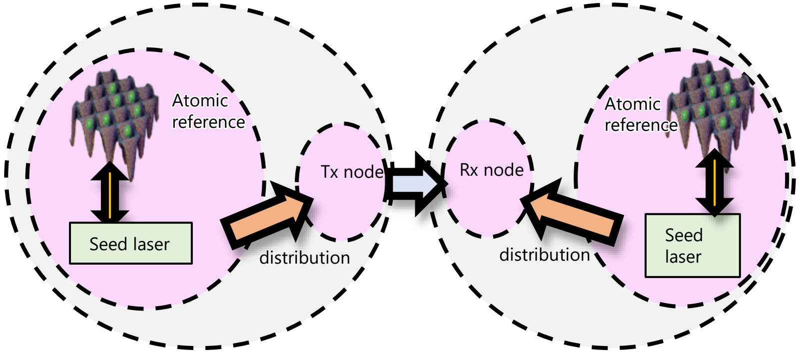
Comb seed distribution in SDM networks

Single coverage-area system



Multiple coverage-area system



Frequency offset ~ 1 Hz would be achievable

Remote comb sources can be spectrally synchronised by transmission of comb seed through spatial channels enabling simplified DSP and networking advantages

Correlated Tx and LO combs allow elimination of carrier-phase estimation and frequency offset estimation

MCF and few-mode fiber seed transmission already demonstrated for WDM 64QAM signals

Jun Sakaguchi et al., Proc. ECOC 2016, W.4.P1.SC5.57
Proc. ECOC 2017, M.1.E.4,

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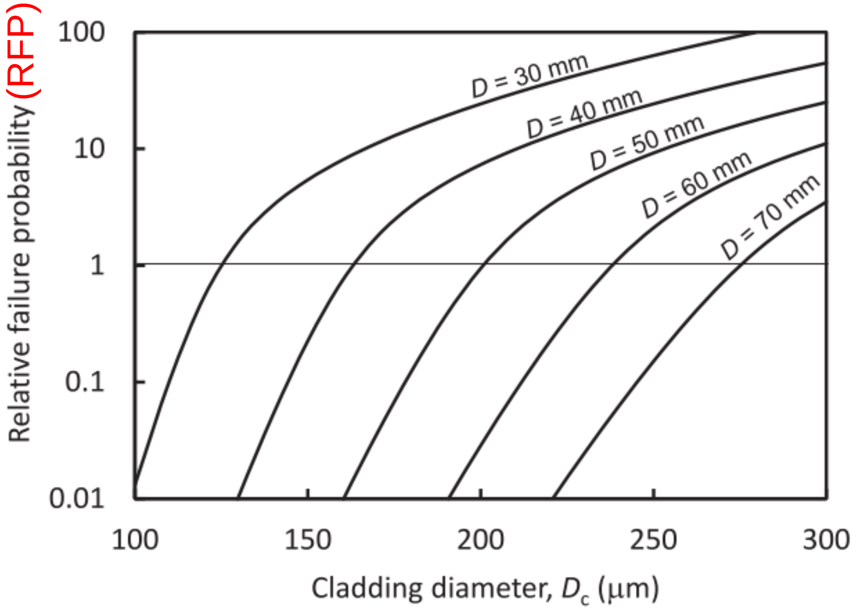
Impact of enlarged cladding diameter fibers

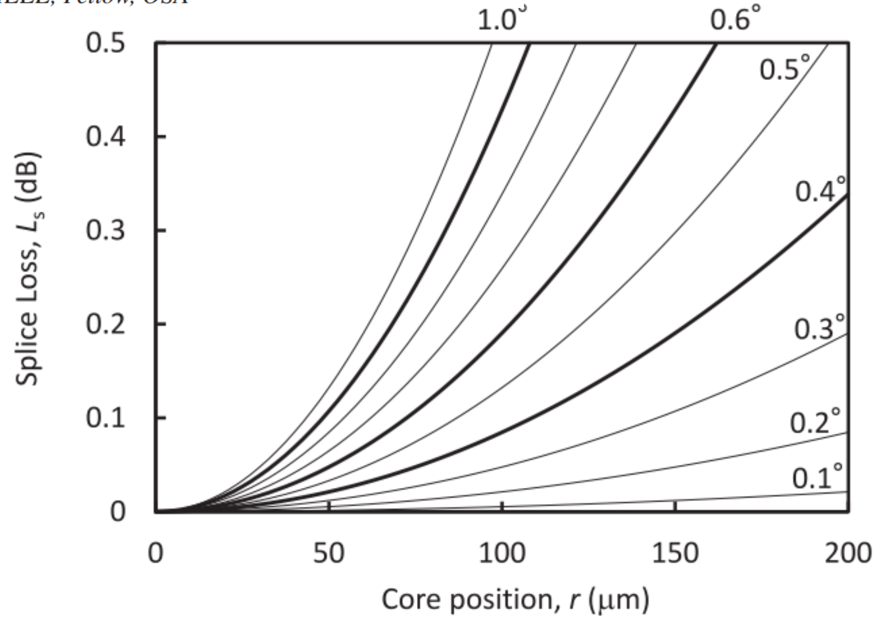
JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 34, NO. 6, MARCH 15, 2016

High-Spatial-Multiplicity Multicore Fibers for Future Dense Space-Division-Multiplexing Systems

Shoichiro Matsuo, *Member, IEEE, Member, OSA*, Katsuhiro Takenaga, Yusuke Sasaki, Yoshimichi Amma, Shota Saito, Kunimasa Saitoh, *Member, IEEE, Member, OSA*, Takashi Matsui, Kazuhide Nakajima, *Member, IEEE*, Takayuki Mizuno, *Member, IEEE*, Hidehiko Takara, *Member, IEEE*, Yutaka Miyamoto, *Member, IEEE*, and Toshio Morioka, *Member, IEEE, Fellow, OSA*

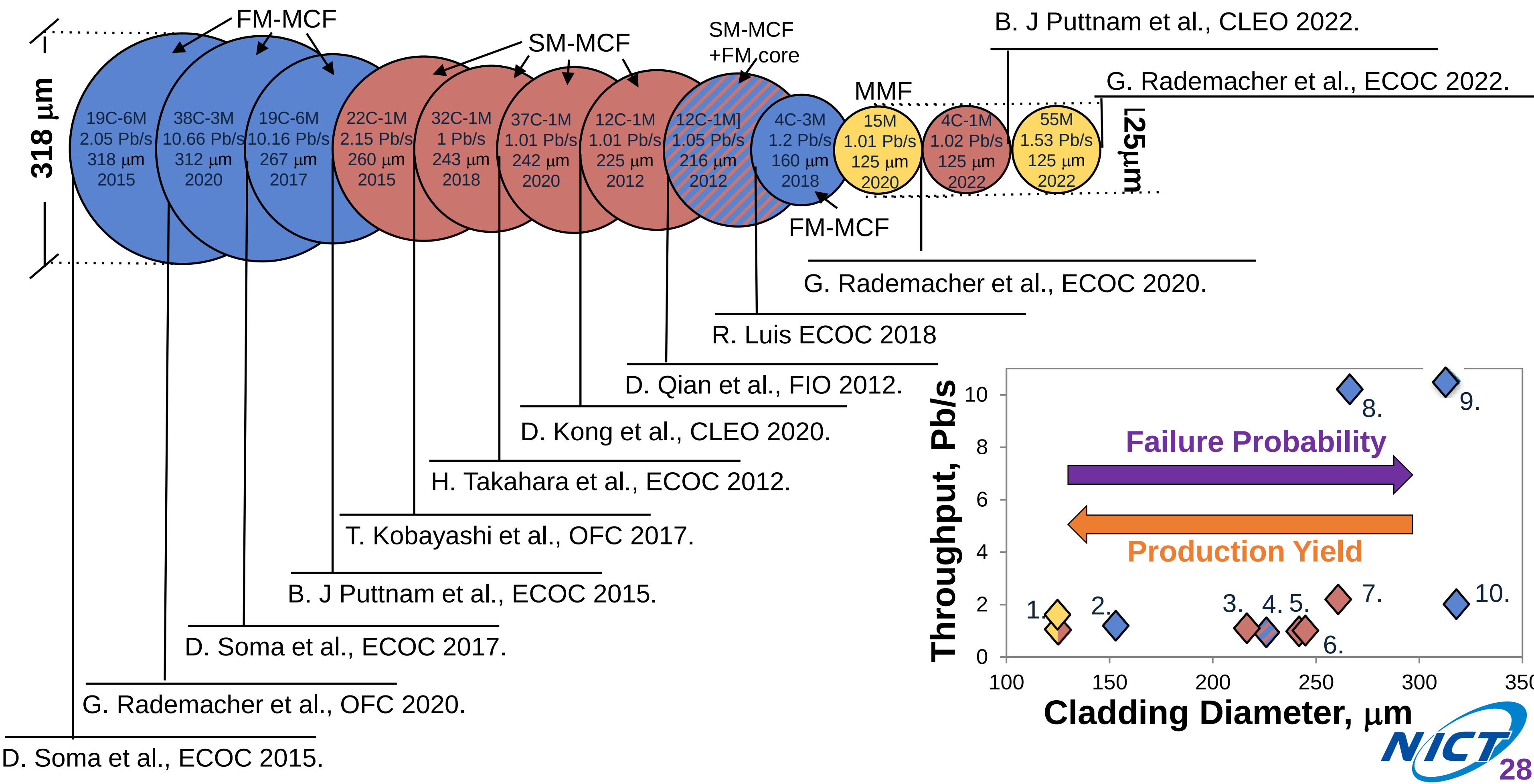


RFP is the failure ratio compared to fiber with cladding diameter (D_c) = 125 μm and bending diameter (D) = 30 mm



Splice loss (L_s) varies with distance from cladding center and angle alignment error

Fiber diameters in large SDM experiments



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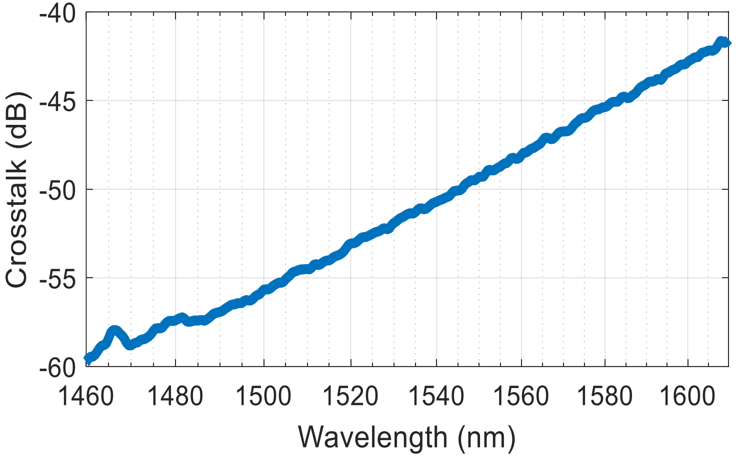
Amplifier combinations for S, C + L-band transmission

- Recently S + C + L band demonstrations have led to new transmission records with various amplifier technologies adopted

- S-band exploitation can also attractive to boost throughput in low-core count MCF systems or to take advantage of lower crosstalk



SMF - Hybrid Raman + SOA amplifiers – 107 Tb/s

J. Renaudier et al., '107 Tb/s Transmission of 103-nm Bandwidth over 3×100 km SSMF using Ultra-Wideband Hybrid Raman/SOA Repeaters',OFC'19 Tu3F.2.1

SMF - EDFA + distributed Raman – 150.3 Tb/s

F. Hamaoka et al.,'150.3-Tb/s Ultra-Wideband (S, C, and L Bands) SMF Transmission over 40-km Using >519Gb/s/A PDM-128QAM Signals', ECOC'18 Mo4G.1

4-core MCF - TDFA + EDFA – Ave. 152.5 Tb/s/core

B.J. Puttnam et al., '0.61 Pb/s S, C, and L-Band Transmission in a 125μm Diameter 4-core Fiber Using a Single Wide-band Comb Source' , IEEE JLT 39(4) pp. 1027-32.

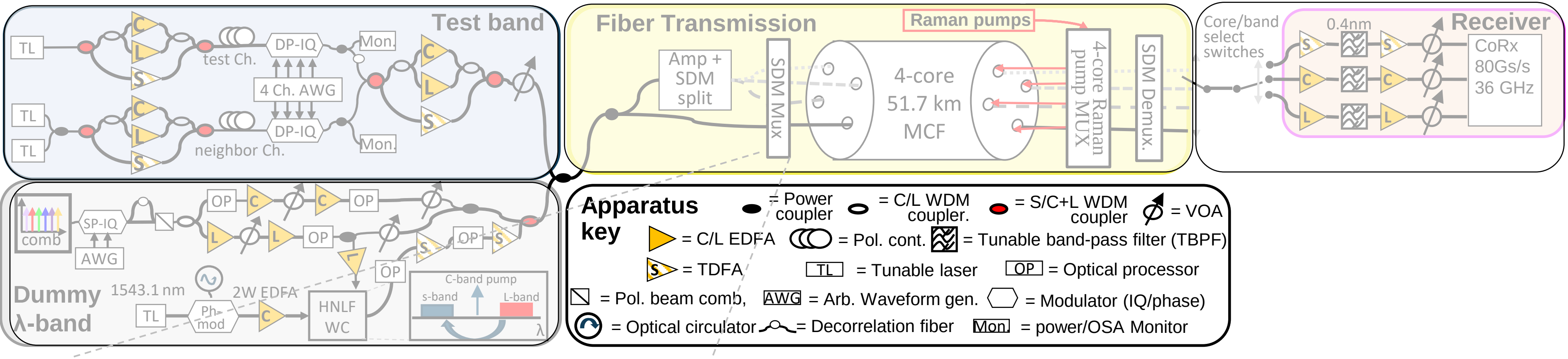
SMF - TDFA, EDFA + lumped Raman amplifier– 178 Tb/s (GMI)

L. Galdino et al., 'Optical Fibre Capacity Optimisation via Continuous Bandwidth Amplification and Geometric Shaping', IEEE PTL 32(17), pp. 1021-24, 2020

SMF - TDFA, EDFA + distributed Raman amplifier– 190.1 Tb/s

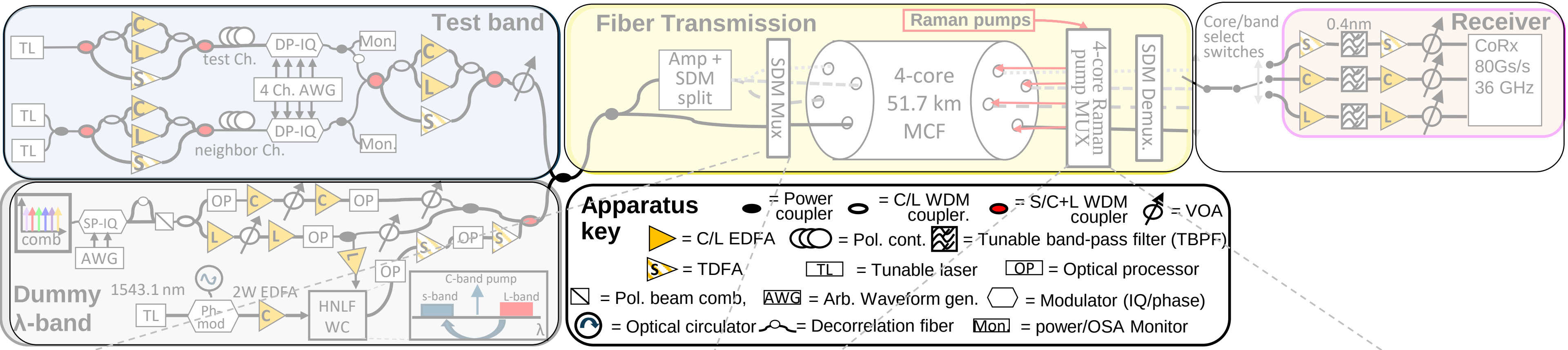
B.J. Puttnam et al., 'S, C and Extended L-Band Transmission with Doped-Fiber and Distributed Raman Amplification' , OFC'21 Th4C.2

Transmission set-up



- 3 channel test-band with highest quality PDM-256-QAM modulation
- Dummy wavelength channels modulated in single pol. modulators with PDM emulation
- S-band dummy channels wavelength converted from L-band in flat dispersion HNLF
- 801 wavelength channels over > 20 THz bandwidth measured after 51.7 km transmission
- 5 x 40 mW Raman pumps (1424.3 to 1452 nm) 2 x 80 mW pumps (1410.8 + 1417.5 nm) and 1 x 400 mW pump at 1385 nm added in multi-core pump combiner
- Signal digitized in 80Gs/s 36 GHz scope for offline processing after coherent reception

Transmission set-up



- 3 … ty PDM
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  nm … n adde
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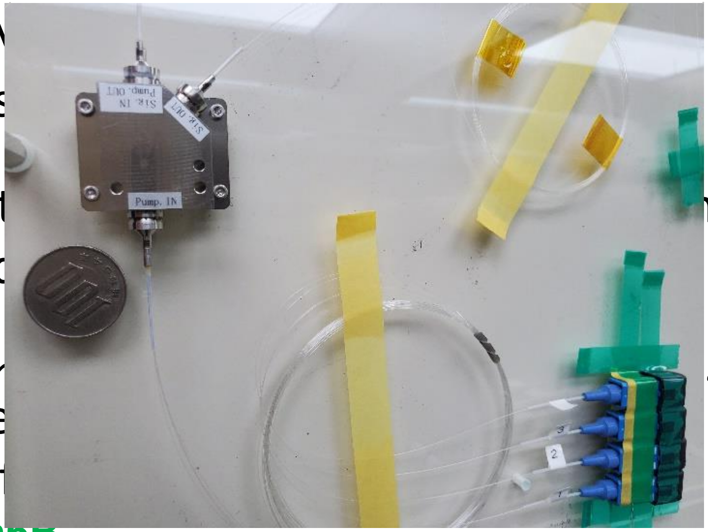
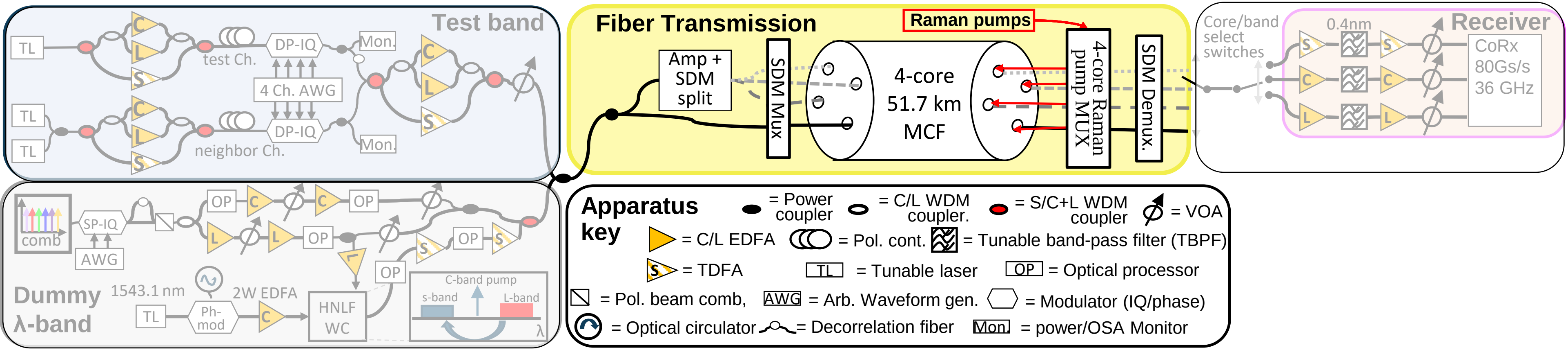
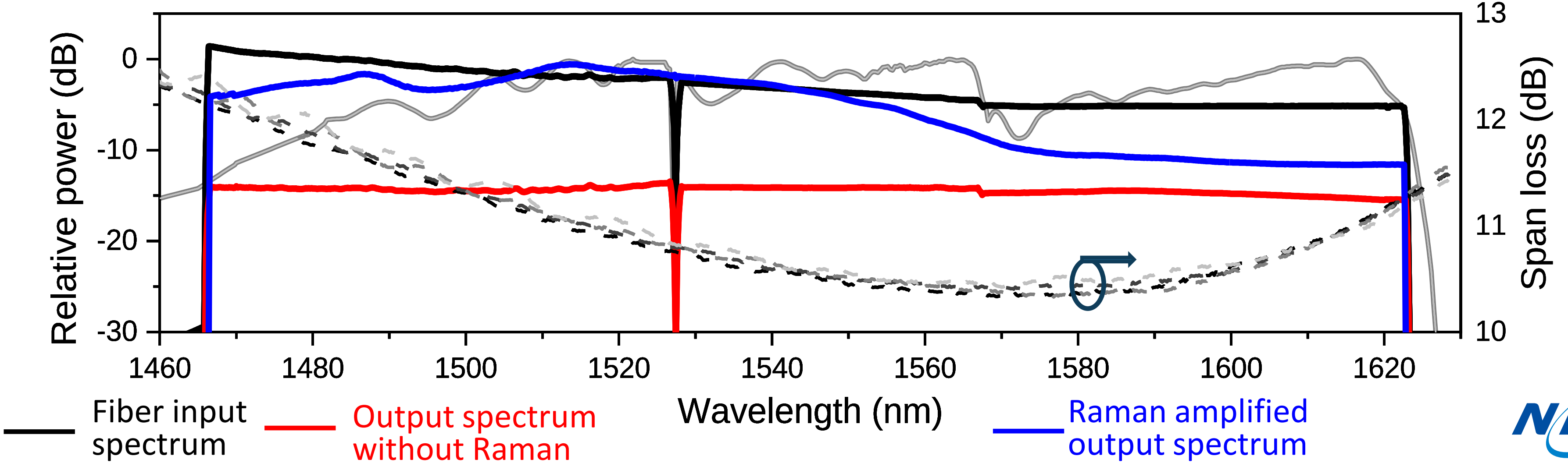
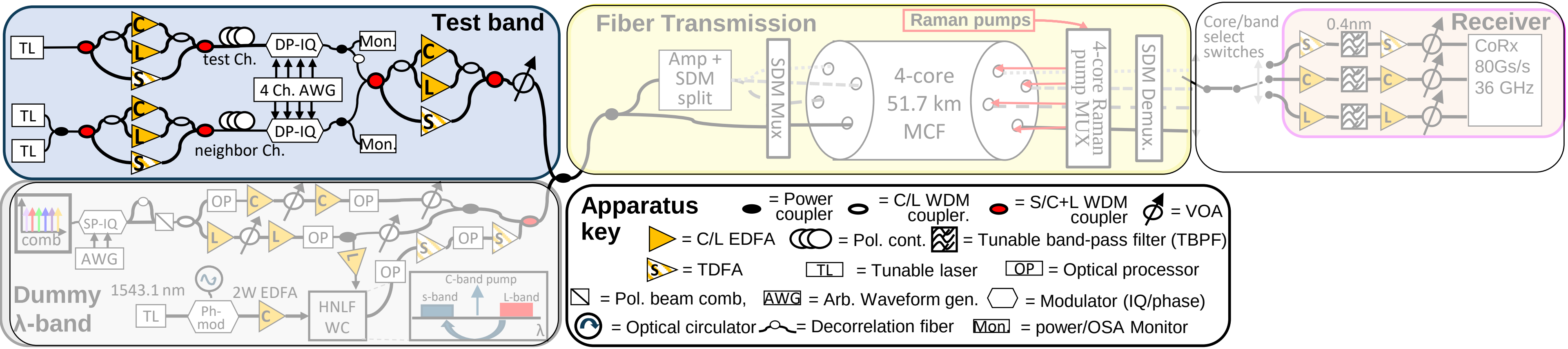


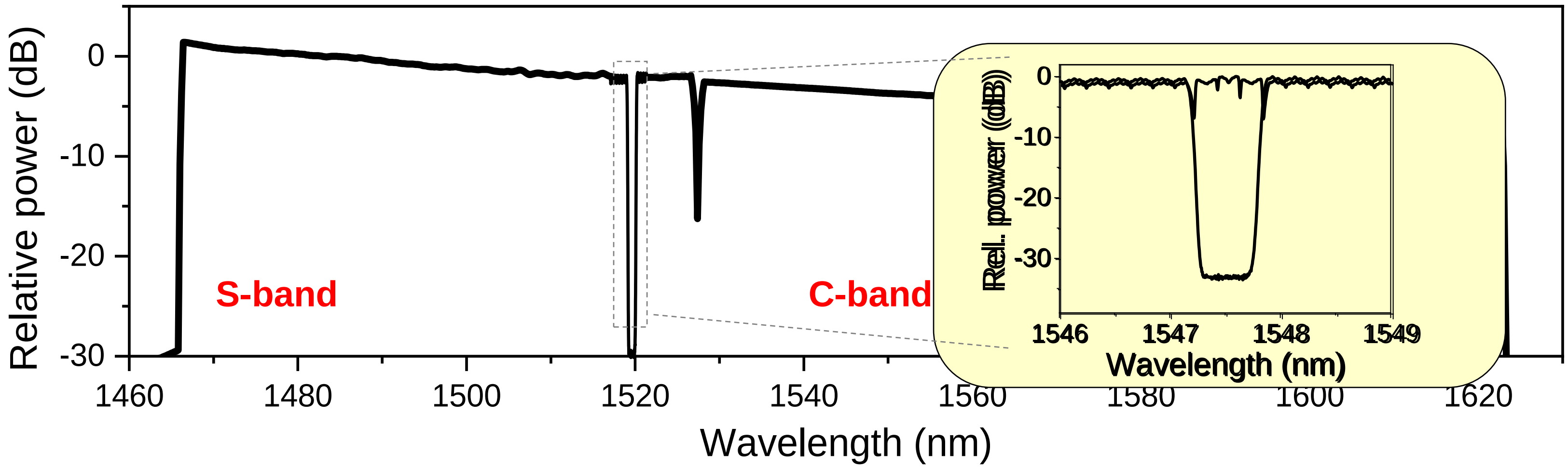
Wideband spectra and Raman gain



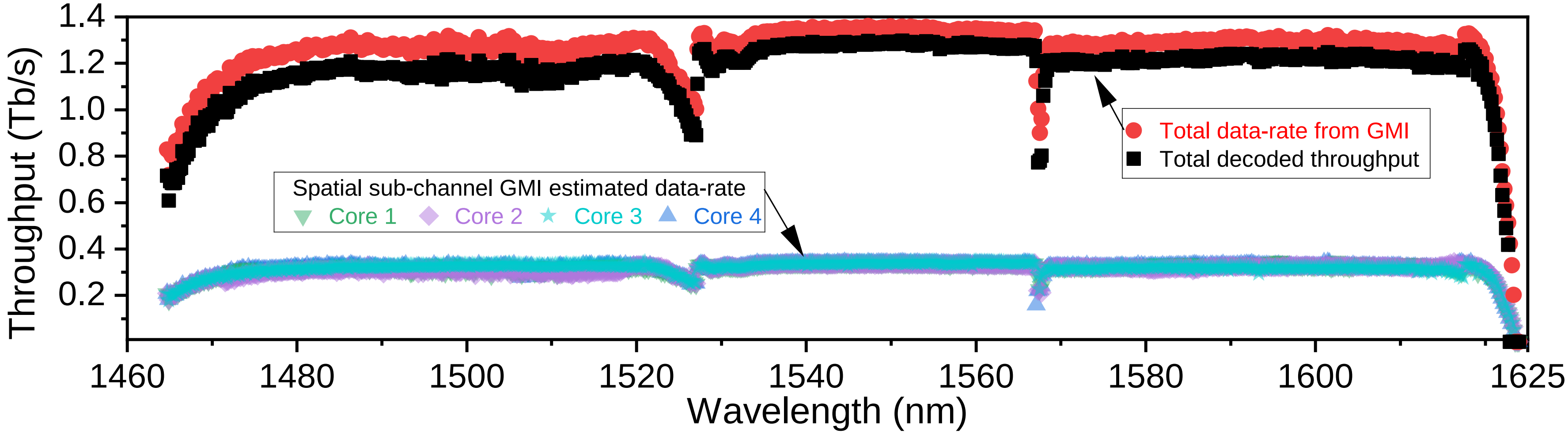


Notch and test-band



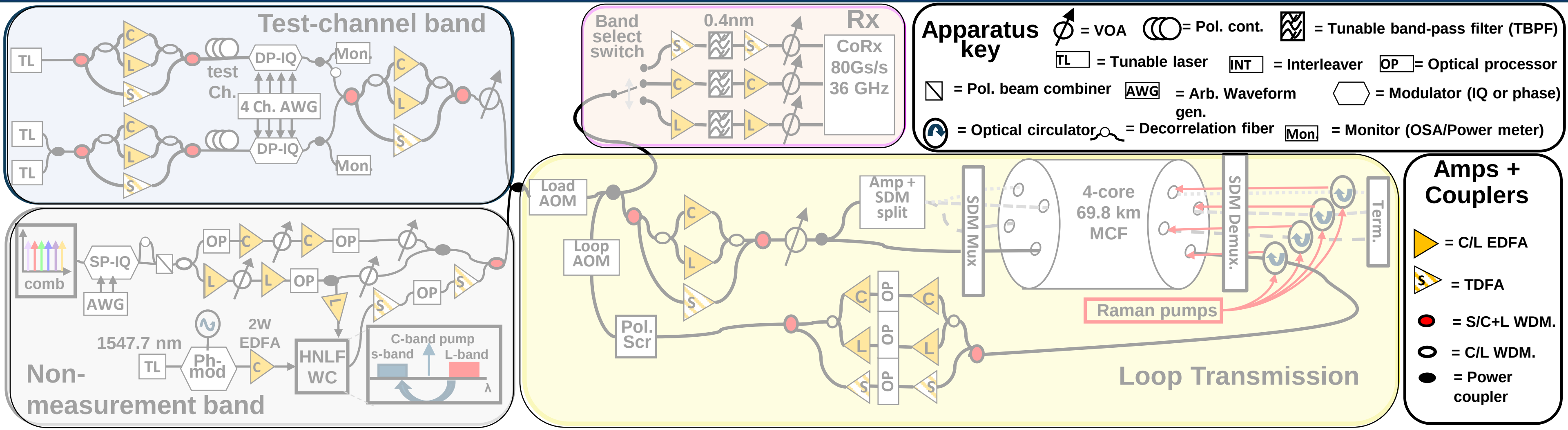


Quality of received channels



- 801 x 24.5 GBd PDM-256QAM channels over near-continuous 20 THz or 158.6 nm bandwidth
  - 335 S-band, 200 C-band and 266 in L-band
- Total GMI estimated data-rate was 1.02 Pb/s
  - 408.5 Tb/s in S-band, 266.9 Tb/s in C-band and 334.6 Tb/s in L-band
- Decoded data-rate 0.96 Pb/s
- Best quality channels in C-band, but S-band contributes most to the data-rate
- Inter-band and long wavelength passband limited by TDFA and EDFAs

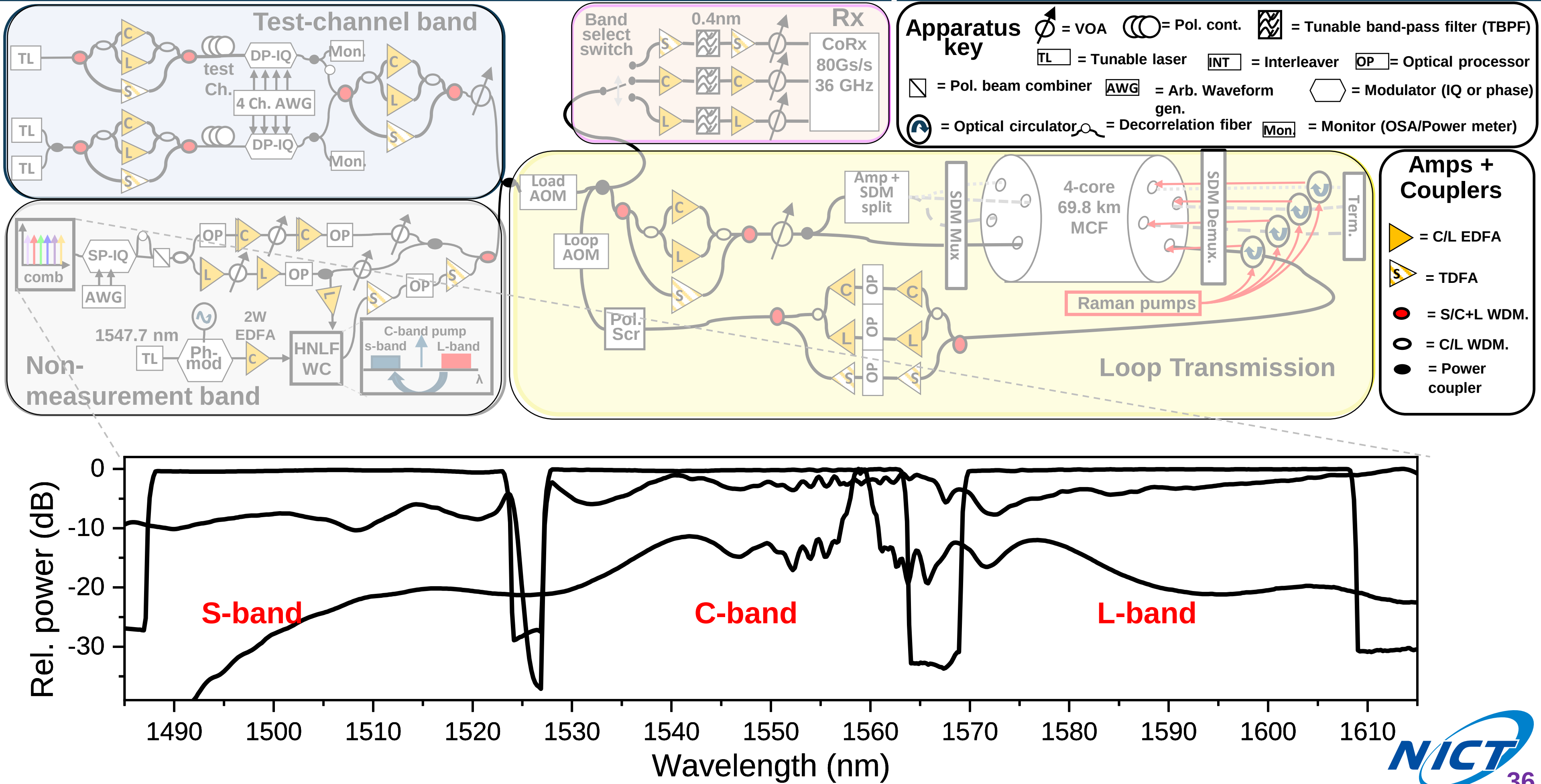
3000 km wideband transmission



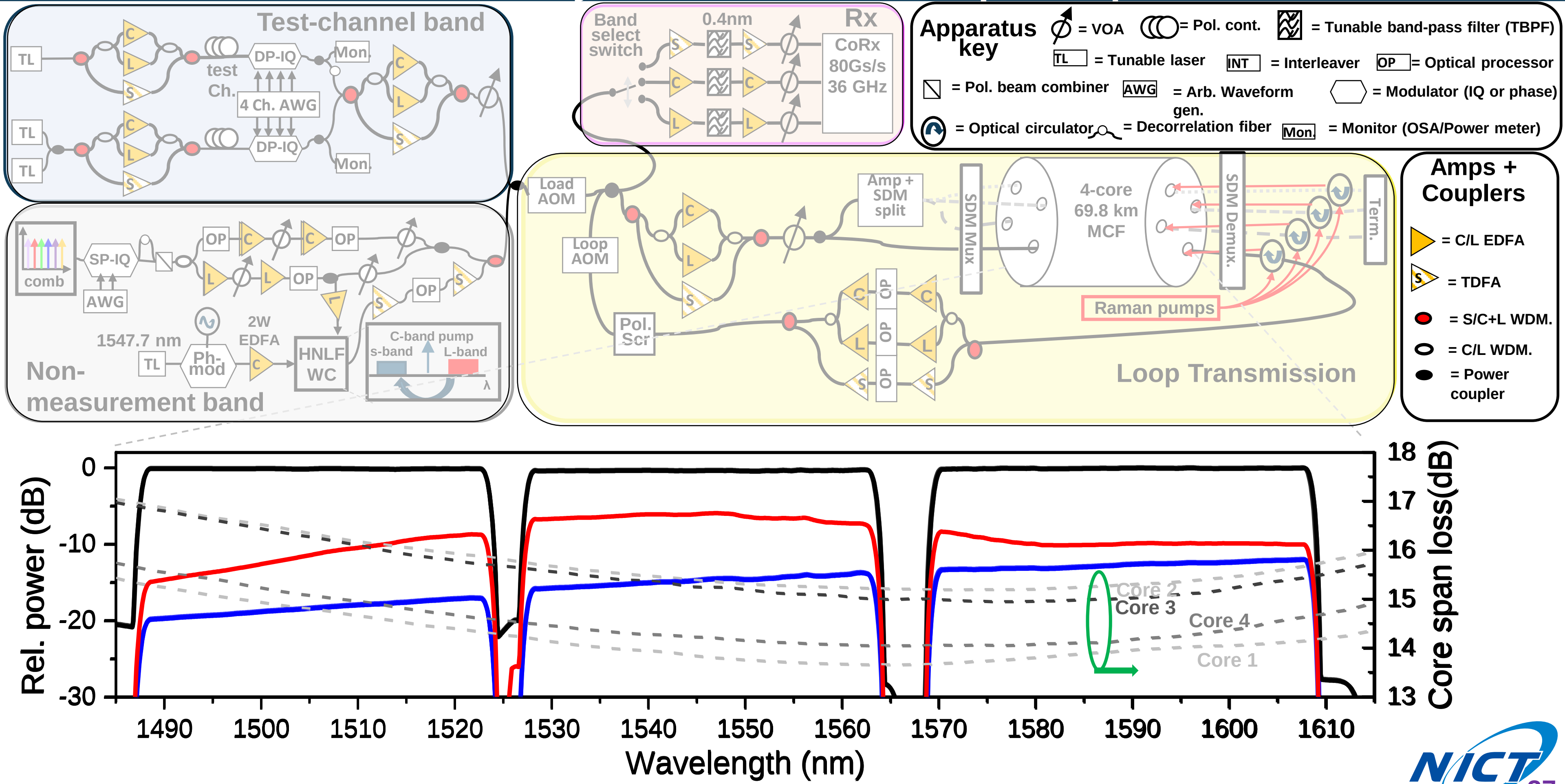
OFC’21 F3B.3

- 3 channel test-band with highest quality PDM-16QAM modulation
- Dummy wavelength channels modulated in single pol. modulators with PDM emulation
- S-band dummy channels wavelength converted from L-band in flat dispersion HNLF
- 552 WDM launched in to recirculating transmission loop based on low-loss 4-core MCF
- Spatial dummy channels tapped and amplified from recirculated core at fiber input
- 8 Raman pumps (1410.8 nm,1417.5 nm, 1424.3 nm, 1431 nm, 1437.9 nm, 1444.8 nm, 1451.6 nm and 1558.8 nm) added in optical circulator after FI/FO
- Standard coherent Rx – Signal digitized in 80Gs/s 36 GHz scope, offline processing

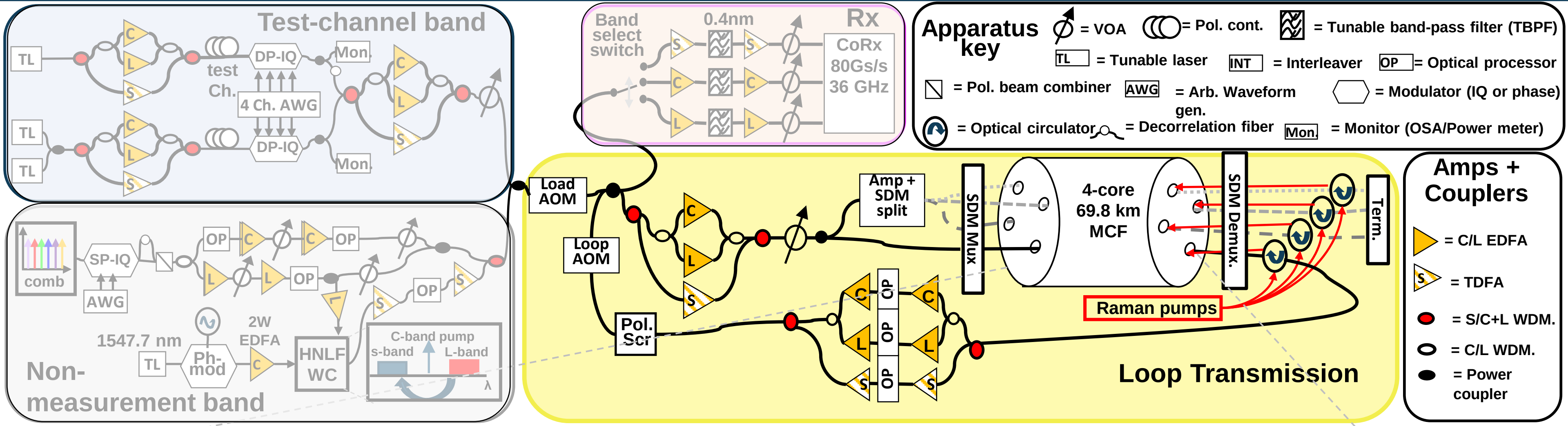
Transmission spectra

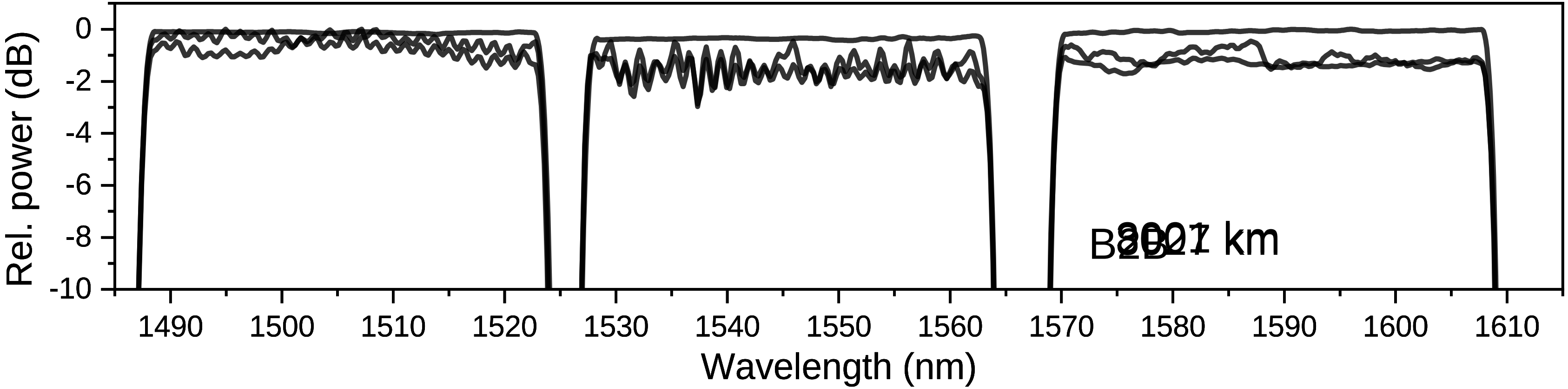


Raman adjusted fiber output spectrum

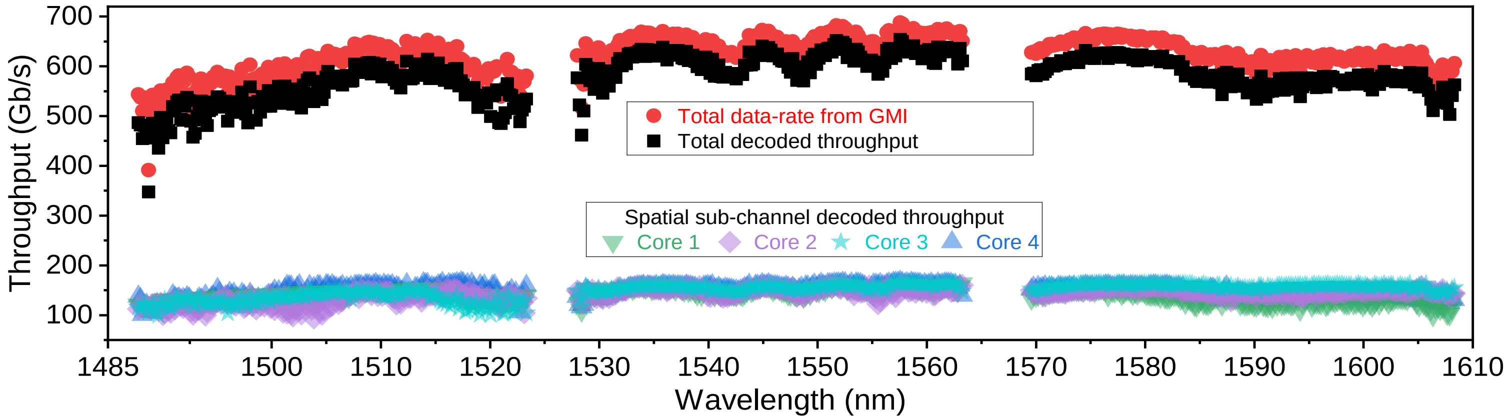


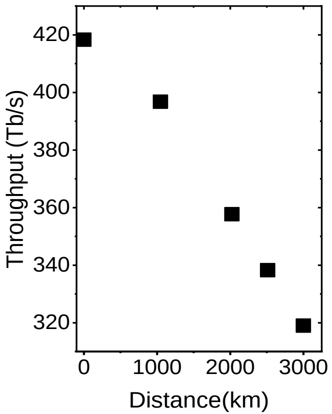
Spectrum evolution over distance





Quality of received channels – 3001 km





- 552 x 24.5 Gbd PDM-16QAM channels spanning > 120 nm bandwidth
  - 189 S-band, 178 C-band and 185 L-band channels
- 319 Tb/s total decoded data-rate at 3001 km
  - 102.5 Tb/s (S), 108.7 Tb/s (C) and 107.7 Tb/s in L-band channels
- GMI estimated data-rate was 342.8 Tb/s at 3001 km
- Measurements at 1047 km 2024 km and 2513 km show potential for distance/throughput trade-off over shorter distances

Contents

- Introduction to SDM and SDM fibers
- Homogeneous multi-core fibers
  - Long-haul transmission with 19-core EDFA
  - MCF systems and networks
- Wideband transmission in 4-core fiber
  - 1 Pb/s single span transmission
  - 3000 km re-circulating transmission
- **1 Pb/s transmission in a 15-mode fiber**
- Conclusions – SDM and Beyond

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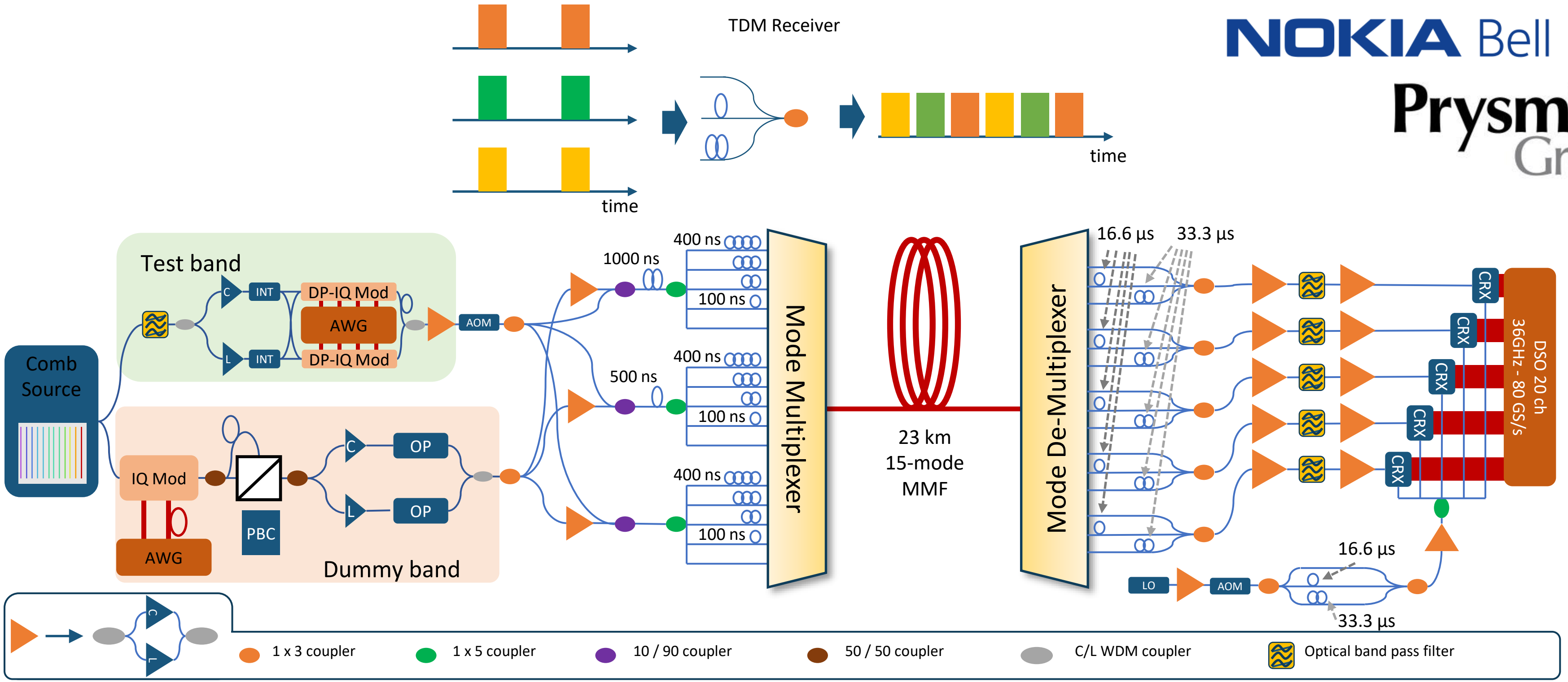
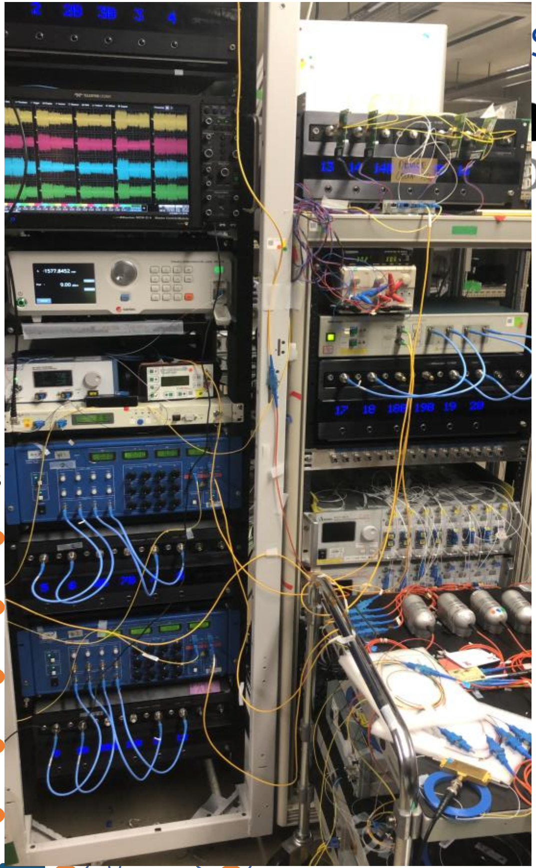
15-mode transmission experimental set-up

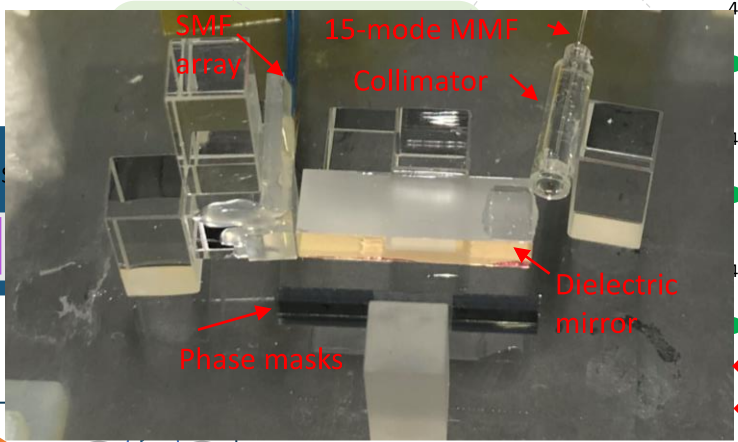


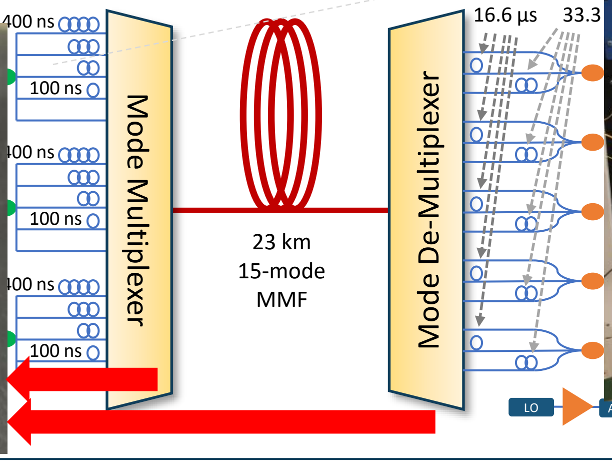
- All 15 mode input signals 100 ns decorrelated copies of C + L - band spectrum
- Time division multiplexed receiver needed to receive 15 modes in 5 coherent Rxs

R. Van Uden et al. "Time domain multiplexed spatial division multiplexing receiver", Optics express, 22, (10), pp. 12,668–77, 2014

15-mode transmission experimental set-up

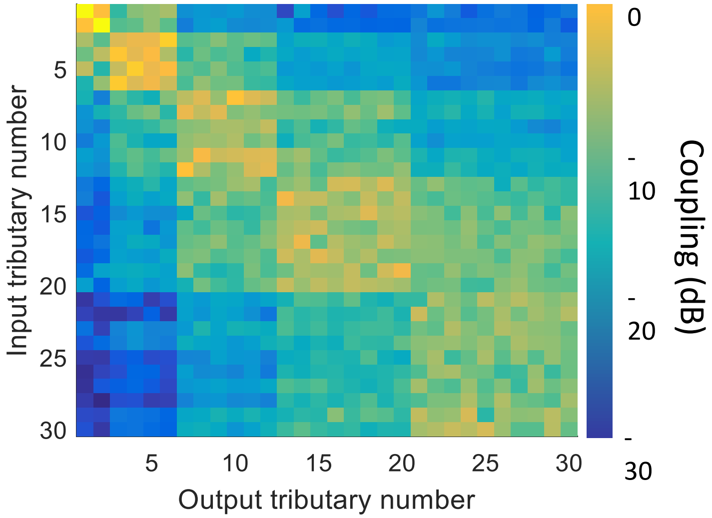


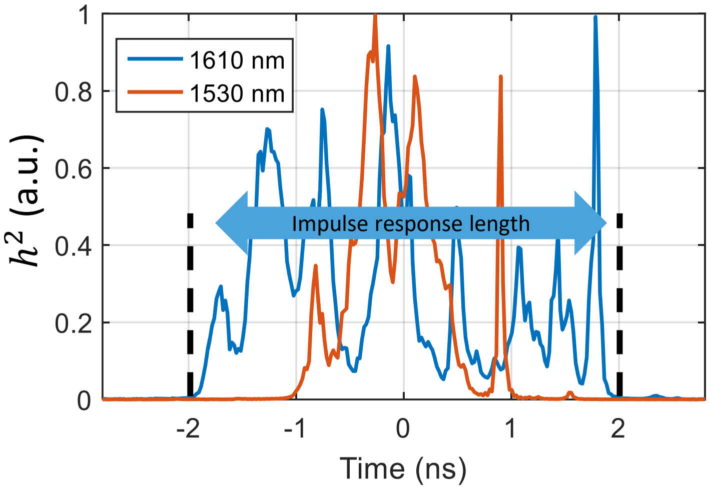




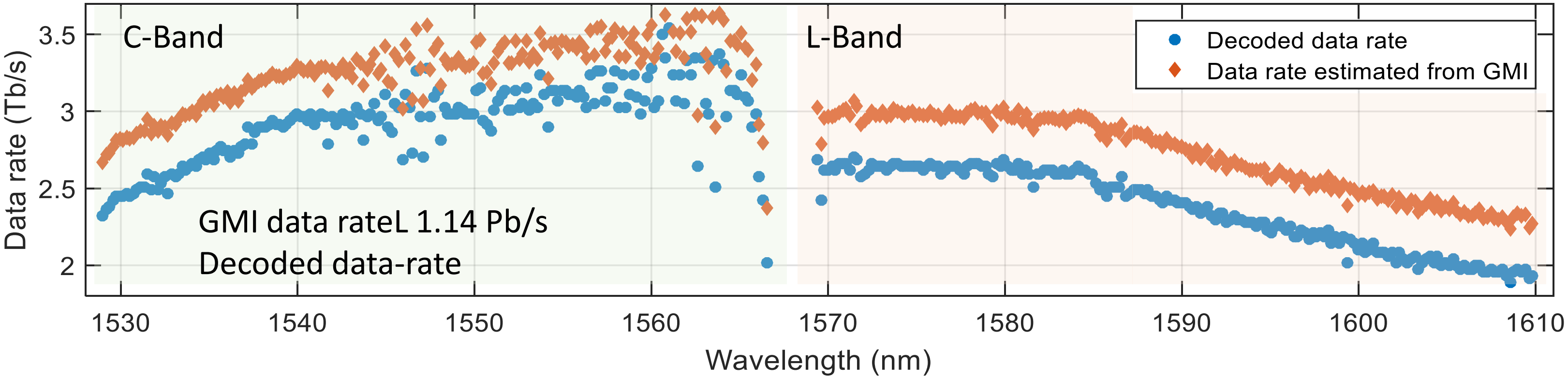
1 x 3 coupler 1 x 5 coupler 10 / 90 coupler 50 / 50 coupler C/L WDM coupler Optical band pass filter

Transmission link characteristics





- Fiber designed for minimum DMD at 1530
- Longer impulse response at furthest L-band wavelengths



Conclusions

- SDM systems can increase data-rates and efficiency in many areas of optical communications
- Weakly or un-coupled SDM systems (MCFs, SMF bundles) offer simplest migration path for transmission and networking, but if mechanical reliability limits cladding diameter, may not solve critical space issues, submarine, data-center panels etc.
- Coupled SDM systems (MMF, FMF, Coupled core MCF) can offer these benefits plus drastic improvements in spatial spectral efficiency, but require high uniformity between spatial channels.
- Low MDL/MDG fibers and amplifiers yet to be convincingly demonstrated, possibly only for short P2P links
- Coupled-core fibers have shown improved non-linear tolerance for long-haul transmission, but may be hard to exploit in submarine systems where electrical power to EDFAs is key limitation.
- In addition to optical Comms, SDM fibers are also finding application in other areas of photonics…

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5G and Microwave Signal Processing

434 IEEE TRANSACTIONS ON BROADCASTING, VOL. 65, NO. 2, JUNE 2019

High-Capacity 5G Fronthaul Networks Based on Optical Space Division Multiplexing

Simon Rommel, *Member, IEEE*, Diego Perez-Galacho, Josep M. Fabrega, *Senior Member, IEEE*, Raul Muñoz, *Senior Member, IEEE*, Salvador Sales, *Senior Member, IEEE*, and Idelfonso Tafur Monroy, *Senior Member, IEEE*

***Abstract*—The introduction of 5G mobile networks, bringing multi-Gbit/s user data rates and reduced latency, opens new opportunities for media generation, transport and distribution,**

use cases for mobile communications and to fundamentally re-shape many of the traditional use cases. As networks become ever faster and coverage reaches unprecedented levels

SCIENTIFIC REPORTS

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Spatial Division Multiplexed Microwave Signal processing by selective grating inscription in homogeneous multicore fibers

Received: 31 August 2016
Accepted: 03 January 2017
Published: 30 January 2017

Ivana Gasulla, David Barrera, Javier Hervás & Salvador Sales

The use of Spatial Division Multiplexing for Microwave Photonics signal processing is proposed and experimentally demonstrated, for the first time to our knowledge, based on the selective inscription of Bragg gratings in homogeneous multicore fibers. The fabricated devices behave as sampled true

Imaging/Adaptive optics

IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 26, NO. 4, JULY/AUGUST 2020 4501209

Astronomical Applications of Multi-Core Fiber Technology

Nemanja Jovanovic, Robert J. Harris, and Nick Cvetojevic

Abstract—**Optical fibers have altered astronomical instrument design by allowing for a complex, often large instrument to be mounted in a remote and stable location with respect to the telescope. The fibers also enable the possibility to rearrange the signal from a focal plane to form a psuedo-slit at the entrance to a spectrograph, optimizing the detector usage and enabling the**

spectrograph allowing it to be located remote to the telescope, but it wasn't until the late 1970's when multi-mode fibers (MMF) had matured that they were seriously considered for such astronomical applications. Soon after, the first fiber-fed spectrographs were demonstrated [1], [2].

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Light: Science & Applications (2017) 6, e16208; doi:10.1038/lsa.2016.208
Official journal of the CIOMP 2047-7538/17
www.nature.com/lsa

ORIGINAL ARTICLE

Shaping the light amplified in a multimode fiber

Raphael Florentin[1], Vincent Kermene[1], Joel Benoist[1], Agnès Desfarges-Berthelemot[1], Dominique Pagnoux[1], Alain Barthélémy[1] and Jean-Pierre Huignard[2]

nature COMMUNICATIONS

ARTICLE

Received 8 May 2012 | Accepted 27 Jul 2012 | Published 28 Aug 2012 DOI: 10.1038/ncomms2024

Exploiting multimode waveguides for pure fibre-based imaging

Tomáš Čižmár[1] & Kishan Dholakia[2]

Spectroscopy and Bio-medical Imaging

nature COMMUNICATIONS

ARTICLE

Received 13 Mar 2015 | Accepted 7 Jun 2015 | Published 23 Jul 2015

DOI: 10.1038/ncomms8762

High-resolution optical spectroscopy using multimode interference in a compact tapered fibre

Noel H. Wan[1,2], Fan Meng[1,3], Tim Schröder[1], Ren-Jye Shiue[1], Edward H. Chen[1] & Dirk Englund[1]

nature photonics

ARTICLES

https://doi.org/10.1038/s41566-017-0053-8

Three-dimensional holographic optical manipulation through a high-numerical-aperture soft-glass multimode fibre

Ivo T. Leite[1,2,3], Sergey Turtaev[1,3,4], Xin Jiang[5], Martin Šiler[6], Alfred Cuschieri[2], Philip St. J. Russell[5] and Tomáš Čižmár[1,3,6*]

Holographic optical tweezers (HOT) hold great promise for many applications in biophotonics, allowing the creation and measurement of minuscule forces on biomolecules, molecular motors and cells. Geometries used in HOT currently rely on bulk optics, and their exploitation in vivo is compromised by the optically turbid nature of tissues. We present an alternative HOT approach in which multiple three-dimensional (3D) traps are introduced through a high-numerical-aperture multimode optical fibre, thus enabling an equally versatile means of manipulation through channels having cross-section comparable to the size of a single cell. Our work demonstrates real-time manipulation of 3D arrangements of micro-objects, as well as manipulation inside otherwise inaccessible cavities. We show that the traps can be formed over fibre lengths exceeding 100 mm and positioned with nanometric resolution. The results provide the basis for holographic manipulation and other high-numerical-aperture techniques, including advanced microscopy, through single-core-fibre endoscopes deep inside living tissues and other complex environments.

Quantum Communications

COMMUNICATIONS PHYSICS

ARTICLE

https://doi.org/10.1038/s42005-018-0105-5 OPEN

Wavelength division multiplexing of continuous variable quantum key distribution and 18.3 Tbit/s data channels

Tobias A. Eriksson[1], Takuya Hirano[2], Benjamin J. Puttnam[1], Georg Rademacher[1], Ruben S. Luís[1], Mikio Fujiwara[1], Ryo Namiki[2], Yoshinari Awaji[1], Masahiro Takeoka[1], Naoya Wada[1] & Masahide Sasaki[1]

COMMUNICATIONS PHYSICS

REVIEW ARTICLE

https://doi.org/10.1038/s42005-019-0269-7 OPEN

Quantum information processing with space-division multiplexing optical fibres

Guilherme B. Xavier[1*] & Gustavo Lima[2,3*]

Multidimensional Entanglement Generation with Multicore Optical Fibers

E.S. Gómez,[1,2,*] S. Gómez,[1,2] I. Machuca,[1,2] A. Cabello,[3,4] S. Pádua,[5] S.P. Walborn,[1,2] and G. Lima[1,2]

[1] *Departamento de Física, Universidad de Concepción, Concepción 160-C, Chile*

[2] *ANID—Millennium Science Initiative Program—Millennium Institute for Research in Optics, Universidad de Concepción, Concepción 160-C, Chile*

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(Received 31 May 2020; revised 9 November 2020; accepted 3 December 2020; published 9 March 2021)

Trends in photonic quantum information follow closely the technical progress in classical optics and

SCIENTIFIC REPORTS

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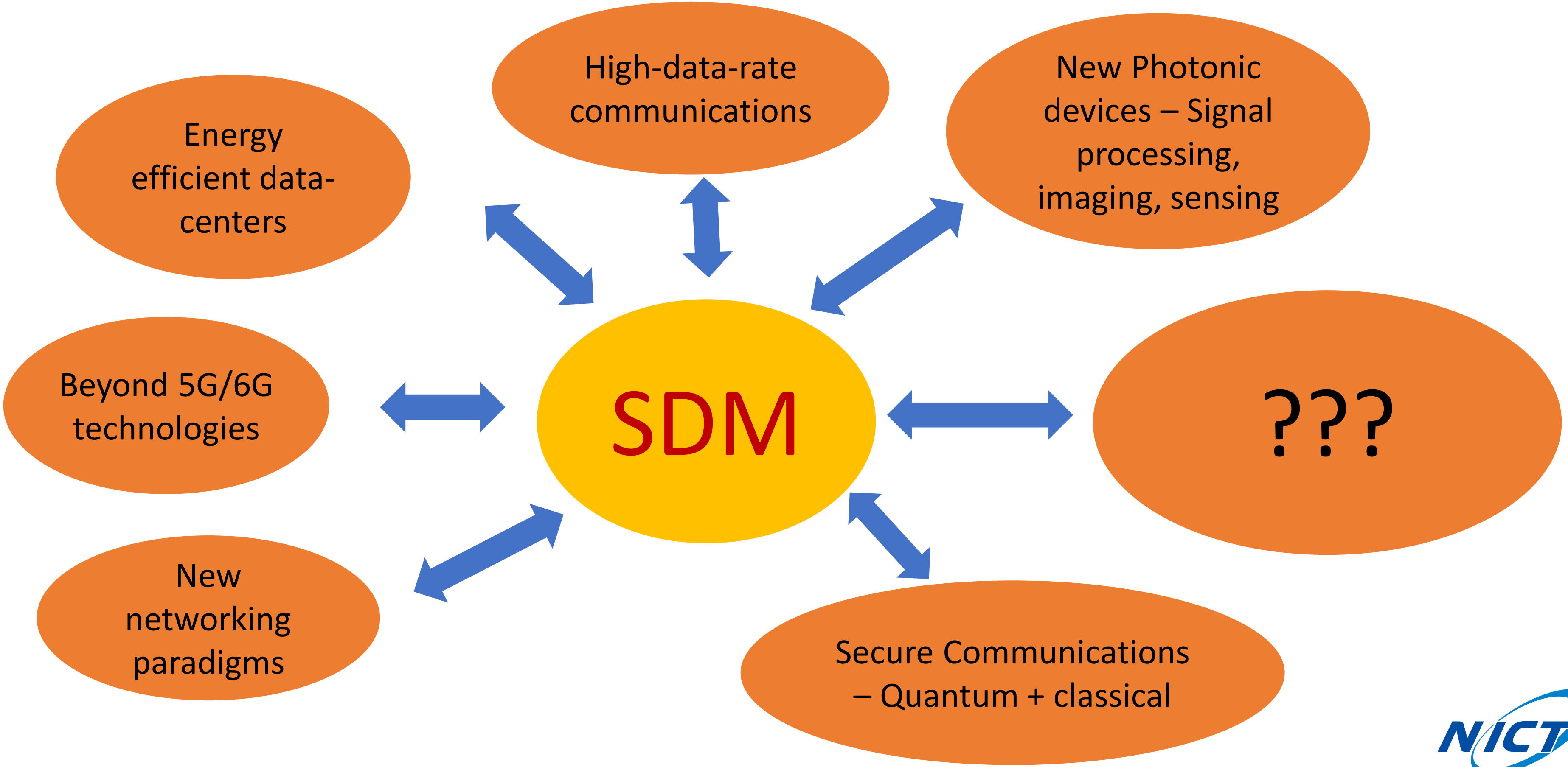
Published online: 29 September 2017

Space division multiplexing chip-to-chip quantum key distribution

Davide Bacco, Yunhong Ding, Kjeld Dalgaard, Karsten Rottwitt & Leif Katsuo Oxenløwe

Quantum cryptography is set to become a key technology for future secure communications. However, to get maximum benefit in communication networks, transmission links will need to be shared among several quantum keys for several independent users. Such links will enable switching in quantum network nodes of the quantum keys to their respective destinations. In this paper we present an experimental demonstration of a photonic integrated silicon chip quantum key distribution protocols based on space division multiplexing (SDM), through multicore fiber technology. Parallel and independent quantum keys are obtained, which are useful in crypto-systems and future quantum network.

SDM and beyond



Thanks for listening!