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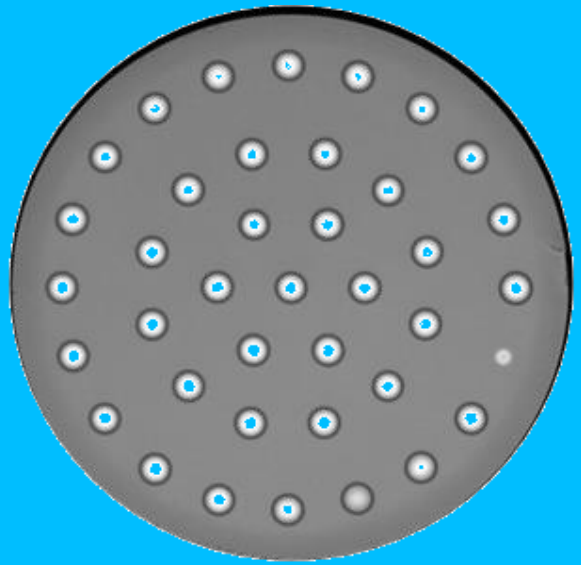
Institute for electrical and optical communications

State of the art of space-division multiplexing transmission systems

Georg Rademacher

ITG Fachtagung Photonische Netze 2023



Content

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- Introduction to space division multiplexing (SDM)
- Field trials using SDM fibers
- High capacity transmission in a 55 mode fiber
- Characterization of a randomly coupled 19-core MCF
- Real time MIMO digital signal processing in a randomly coupled 7-core MCF

Capacity evolution of optical fiber transmission systems

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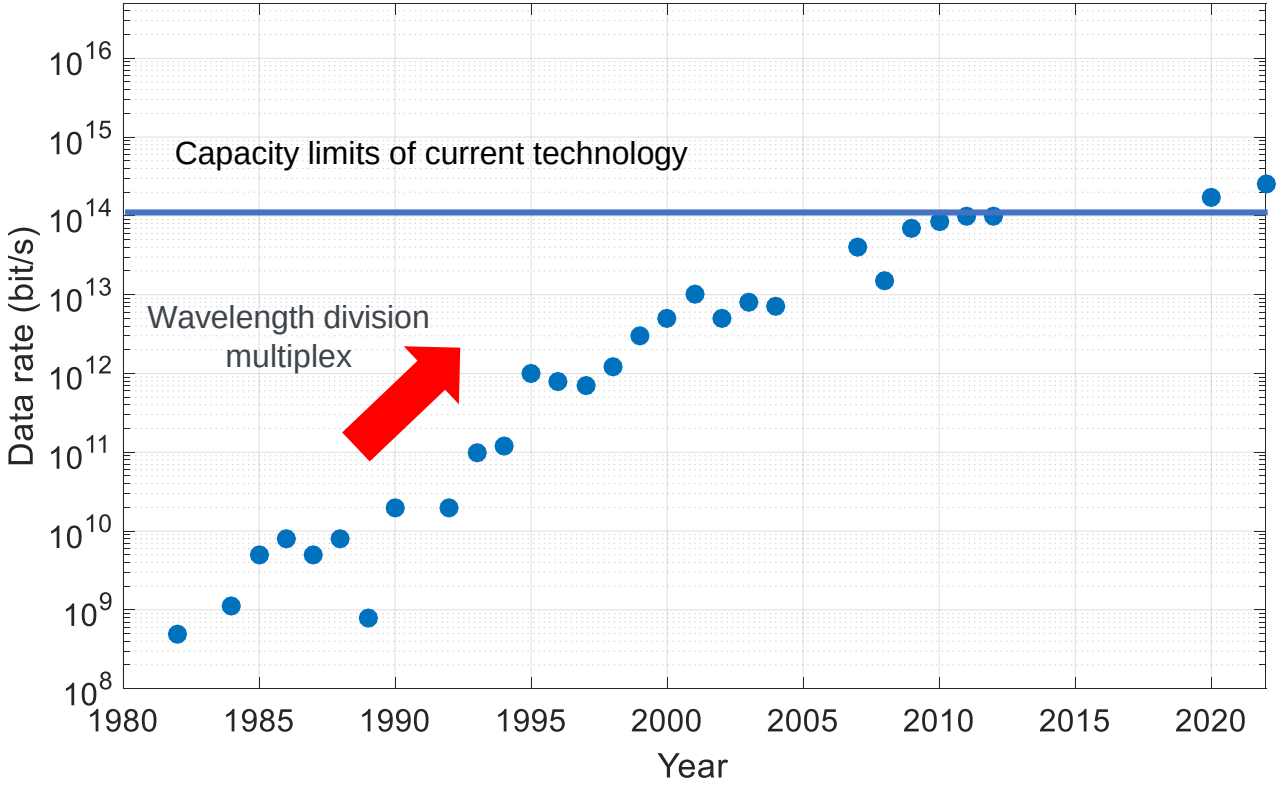
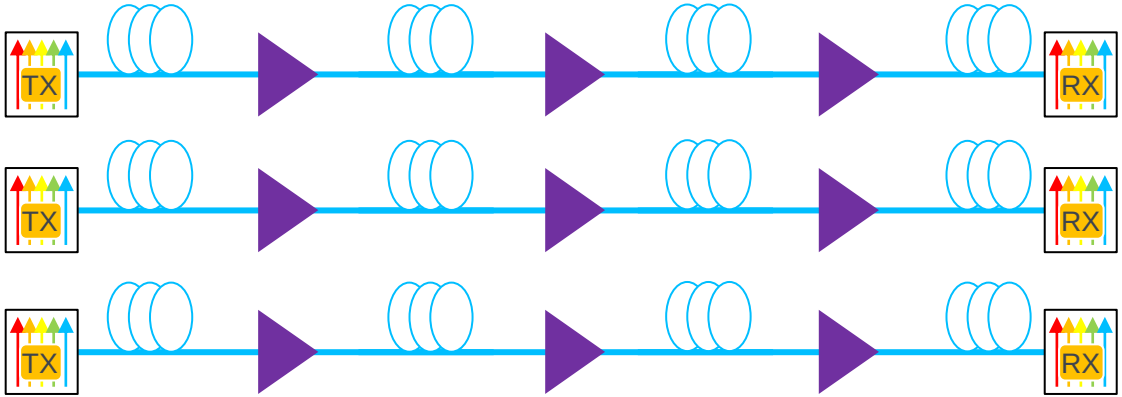
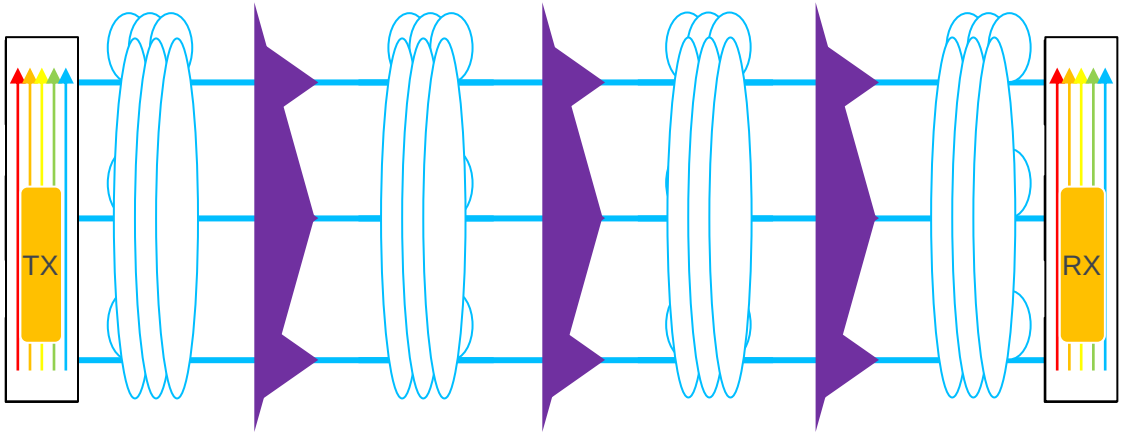


Space-division multiplexing (SDM)



Space-division multiplexing (SDM)



Capacity evolution of optical fiber transmission systems

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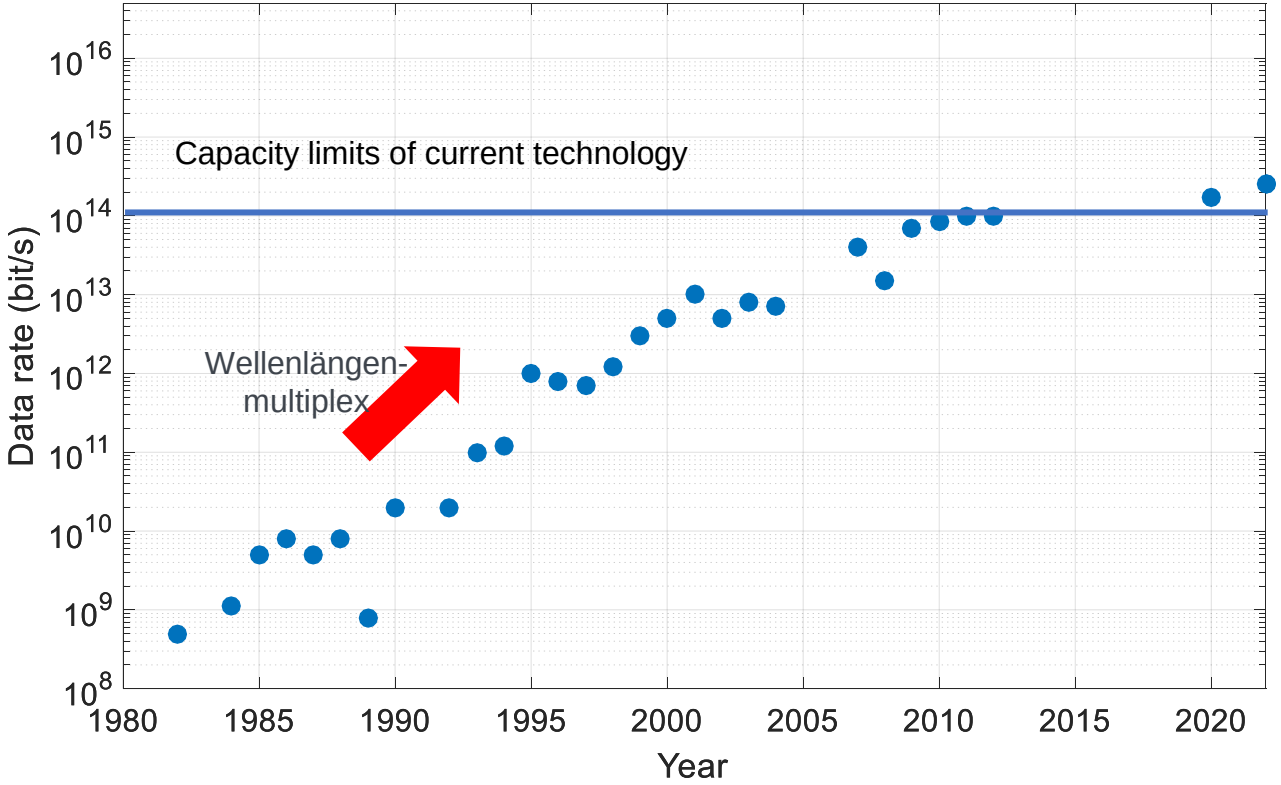

Optical fibers for space-division multiplexing

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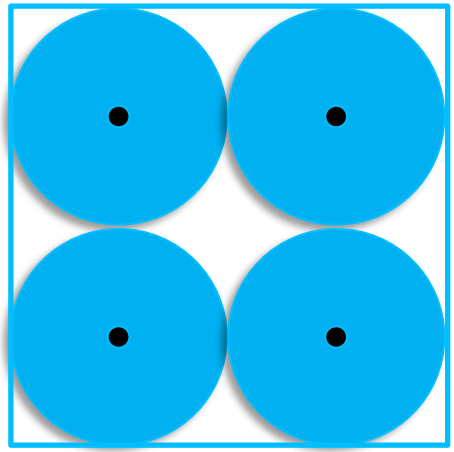
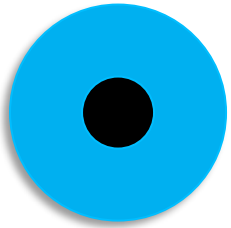
Fiber bundle

$\sim 125\ \mu m$



Few-/ multi-mode fiber

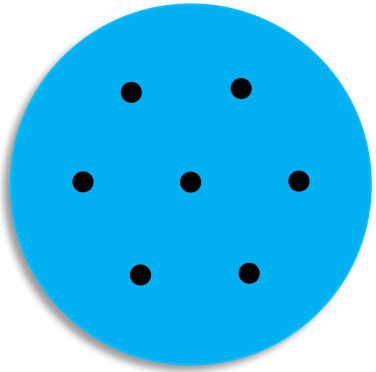
$\sim 125\ \mu m$



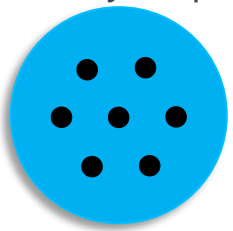
Multi-core fiber

$\sim 125\ -\ 250\ \mu m$

Weakly coupled



Randomly coupled



Few-mode-multi-core fiber

$\sim 160\ -\ 320\ \mu m$

Record SDM fiber demonstrations

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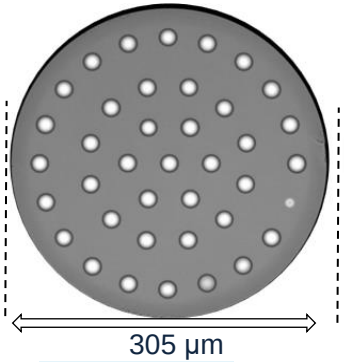
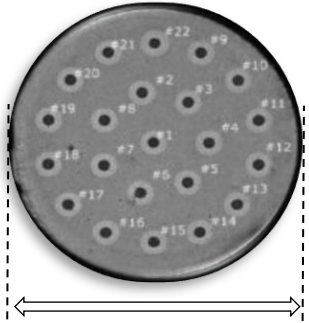
13 km 38-few-mode multi-core fiber (MCF)



305 µm

2020
10.66 Pb/s

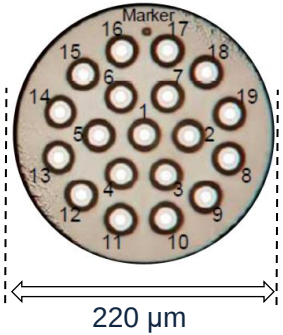
31.4 km 22-core MCF



260 µm

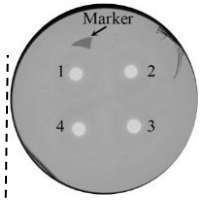
2015
2.15 Pb/s

30 km 19-core MCF



220 µm

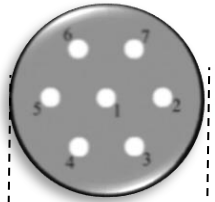
3.5 km 4-core few-mode MCF.



160 µm

2018
1.2 Pb/s

53.7 km 7-core MCF



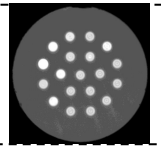
160 µm

54-100 km 4-core MCF

125 µm

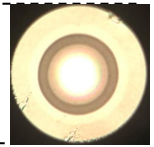
2022
1.02 Pb/s

66 km randomly coupled MCF



2023
1.7 Pb/s

26 km 55-mode fiber



2022
1.53 Pb/s

SDM transmission with a three-mode fiber

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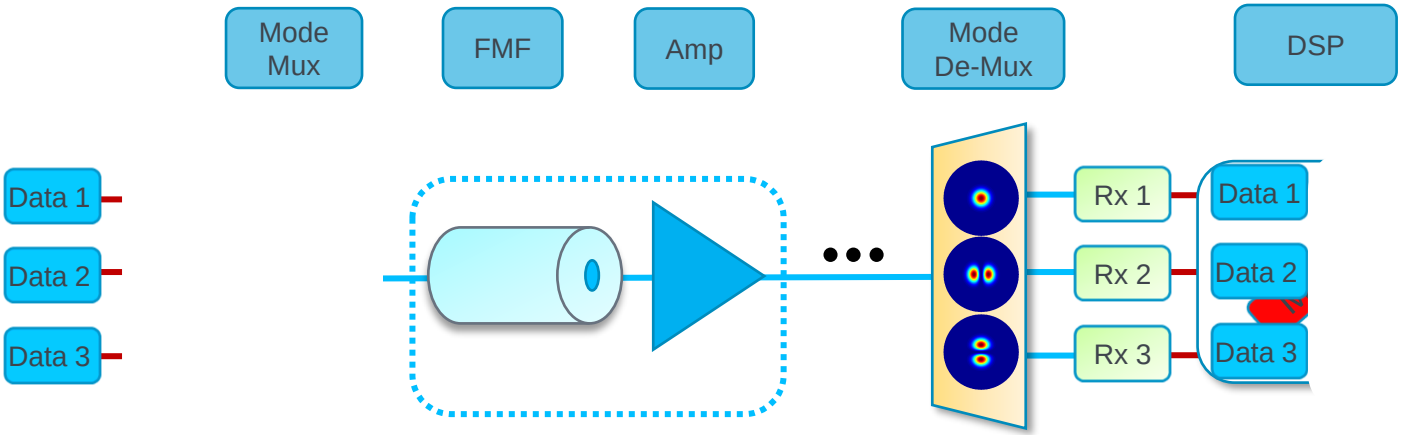

SDM transmission with a three-mode fiber

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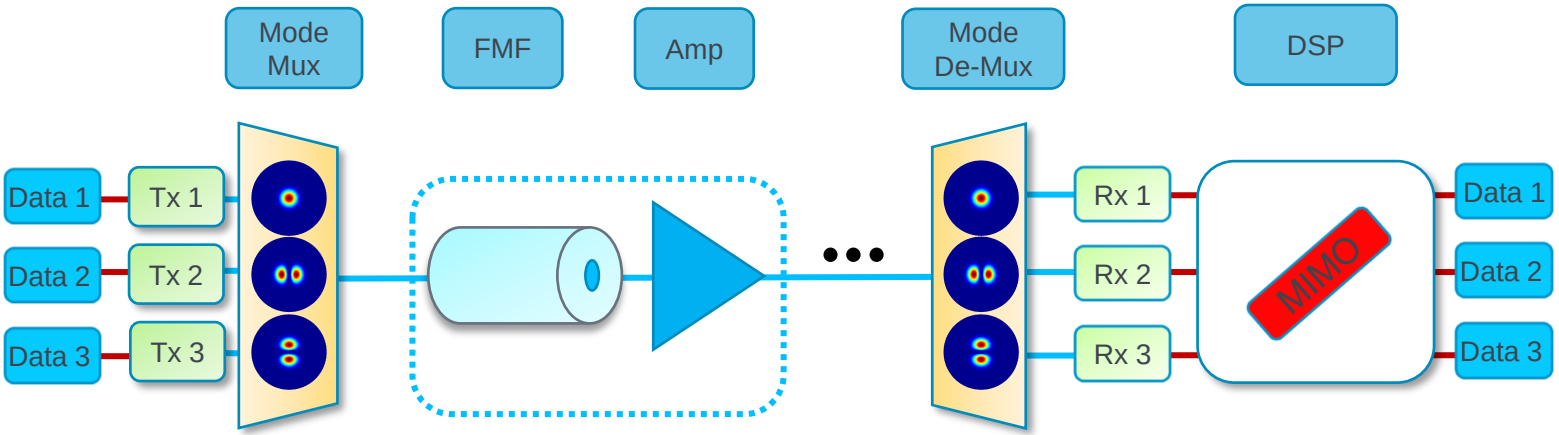

Output Channel matrix Input

$$\begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix}$$

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{pmatrix}^{-1} \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix}$$

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1.53 Peta-bit/s C-Band Transmission in a 55-Mode Fiber

Georg Rademacher, Ruben S. Luís, Ben Puttnam, Nicolas K. Fontaine, Mikael Mazur, Haoshuo Chen, Roland Ryf, David T. Neilson, Daniel Dahl, Joel Carpenter, Pierre Sillard, Frank Achten, Marianne Bigot, Jun Sakaguchi, and Hideaki Furukawa

European Conference on Optical Communication (ECOC), Post-Deadline paper, 2022

NICT

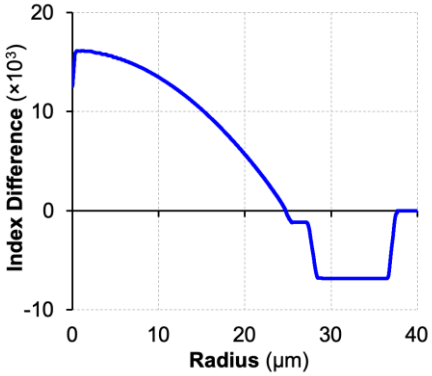
Prysmian Group

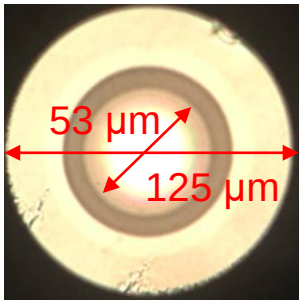
NOKIA Bell Labs

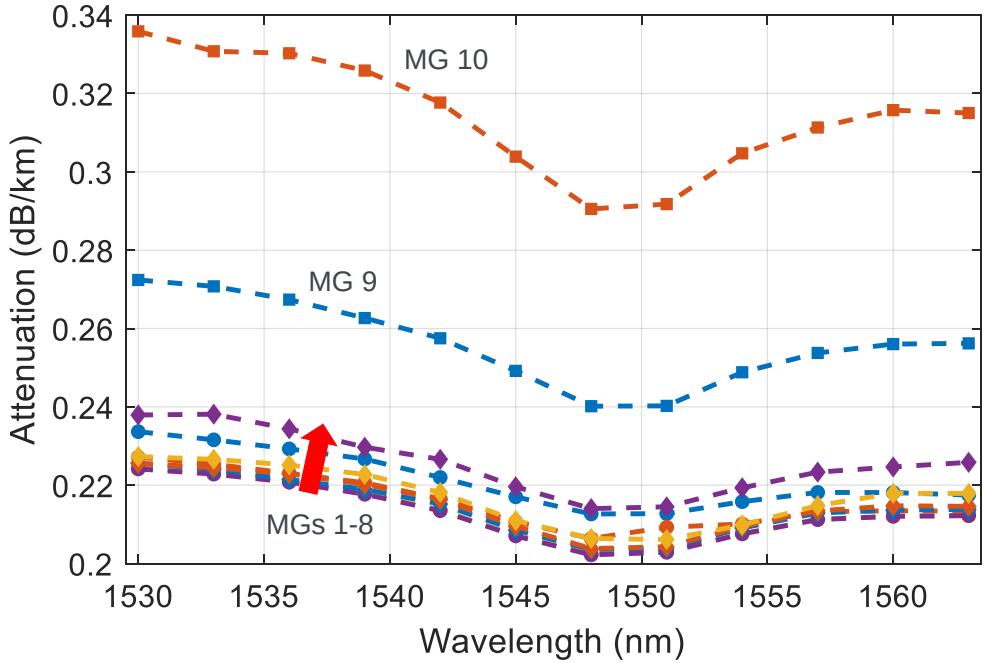
THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

25.9 km long, 55-mode fiber design

55 modes are grouped into 10 mode-groups (MGs)







Mode Multiplexer

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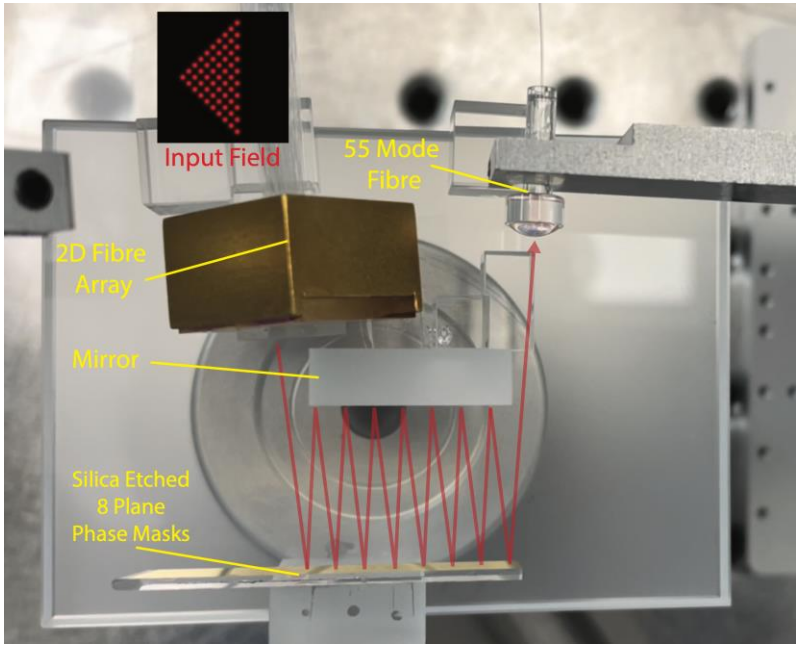

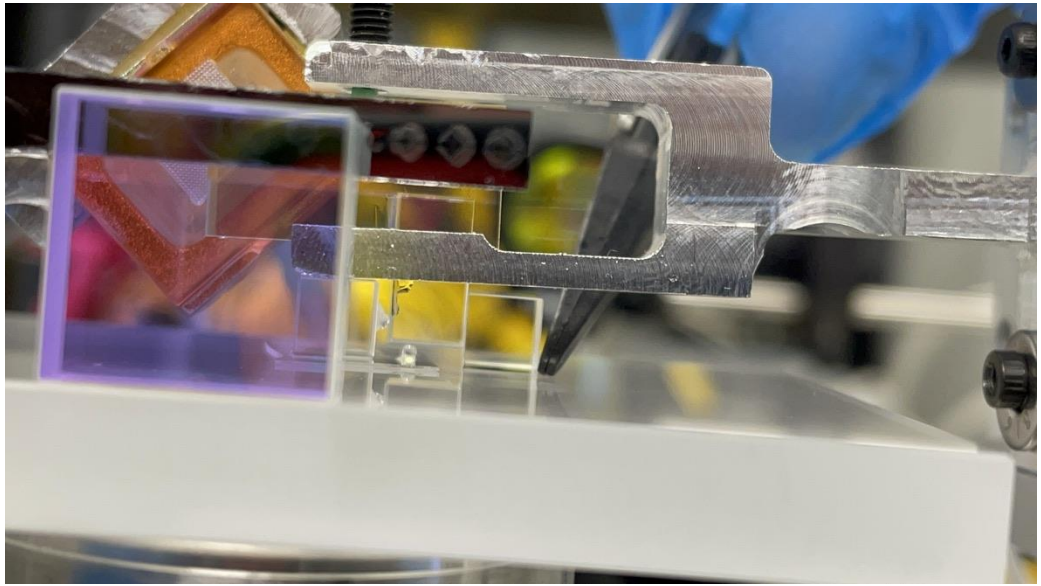

Mode Multiplexer

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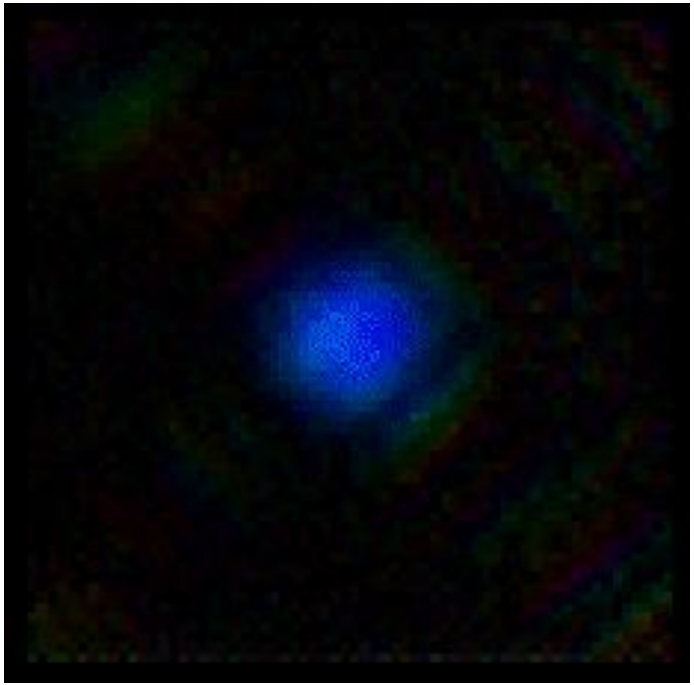
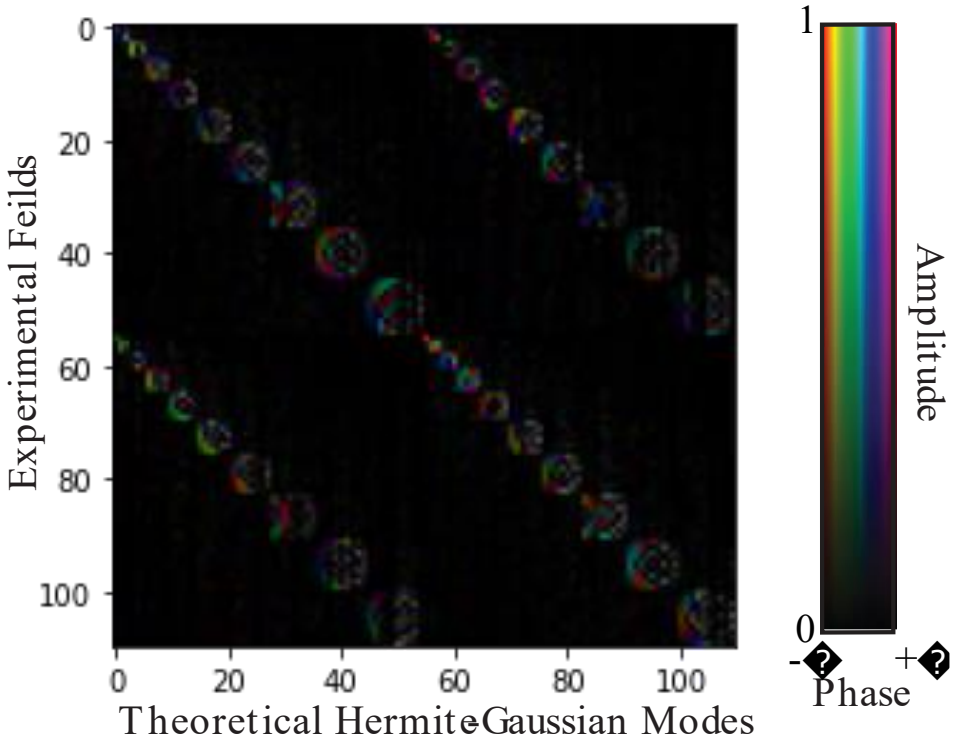
Germany





Experimental Setup

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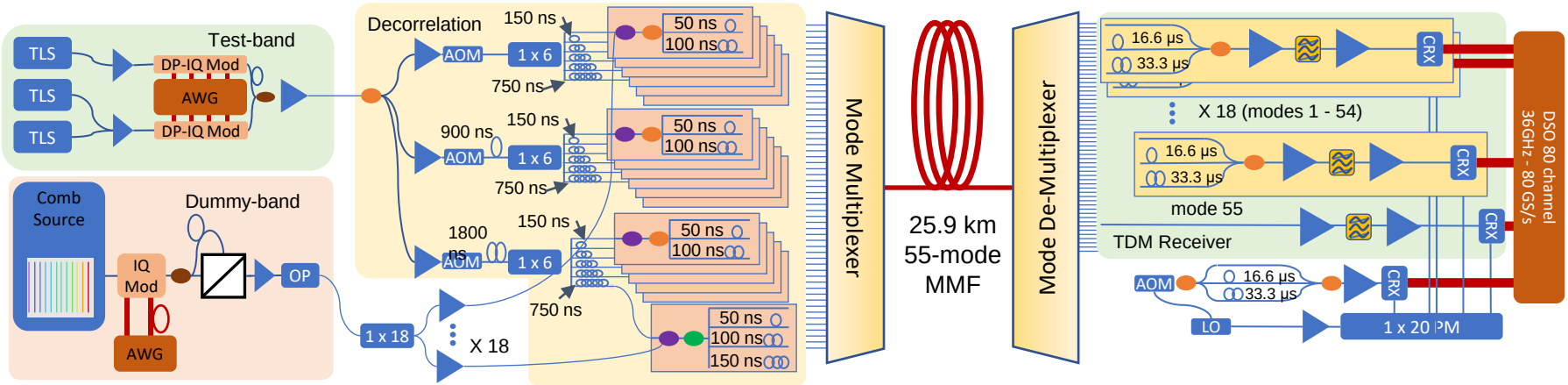

EDFA | 1 x 3 coupler | 1 x 4 coupler | 10 / 90 coupler | 50 / 50 coupler | Optical band pass filter | Pol. Beam combiner

Snapshot of lab system

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Transmission channel characteristics:

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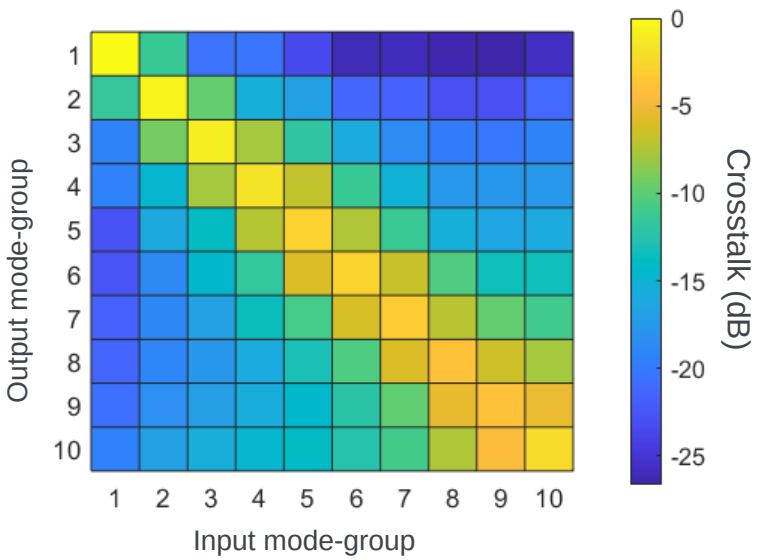
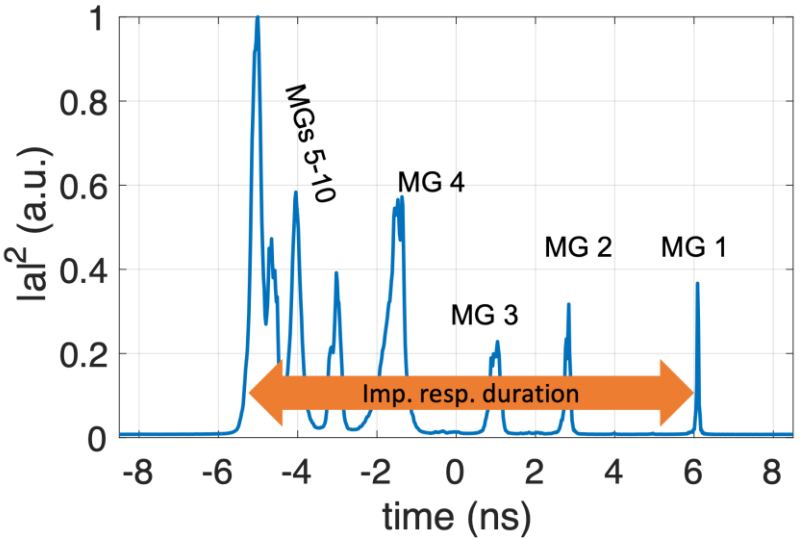
Wavelength channel at 1543 nm





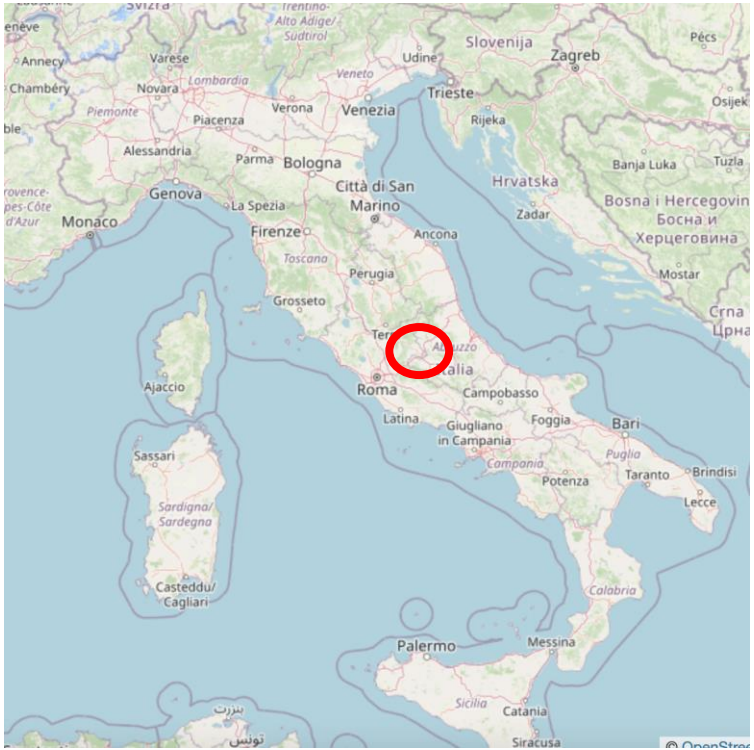
National Institute of
Information and Communications Technology

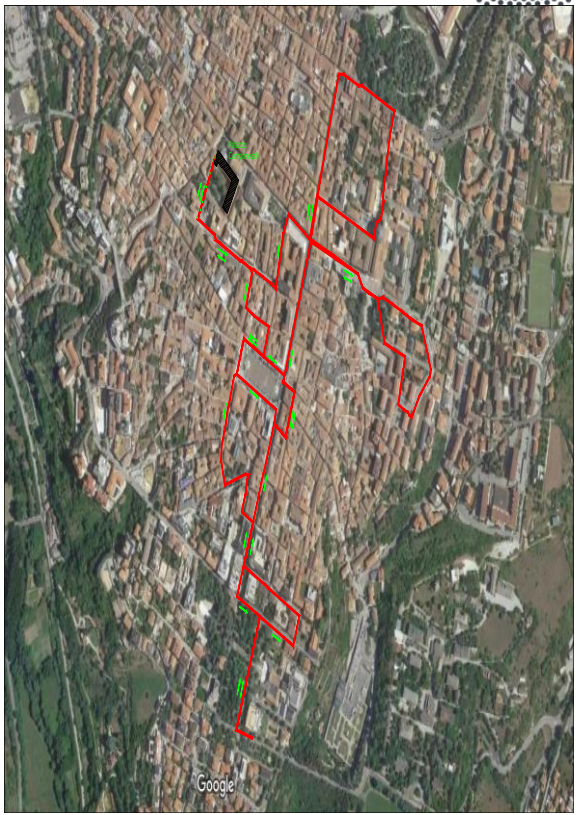
Characterization of the First Field-Deployed 15-Mode Fiber Cable for High Density Space-Division Multiplexing

Georg Rademacher, Ruben S. Luís, Ben Puttnam, Giammarco Di Sciullo, Robert Emmerich, Nicolas Braig-Christophersen, Andrea Marotta, Lauren Dallachiesa, Roland Ryf, Antonio Mecozzi, Colja Schubert, Pierre Sillard, Frank Achten, Giuseppe Ferri, Jun Sakaguchi, Cristian Antonelli, Hideaki Furukawa

ECOC 2022 PDP

Field-deployed Fiber cable





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First

MIMO equalizer: mode-group averaged crosstalk matrix

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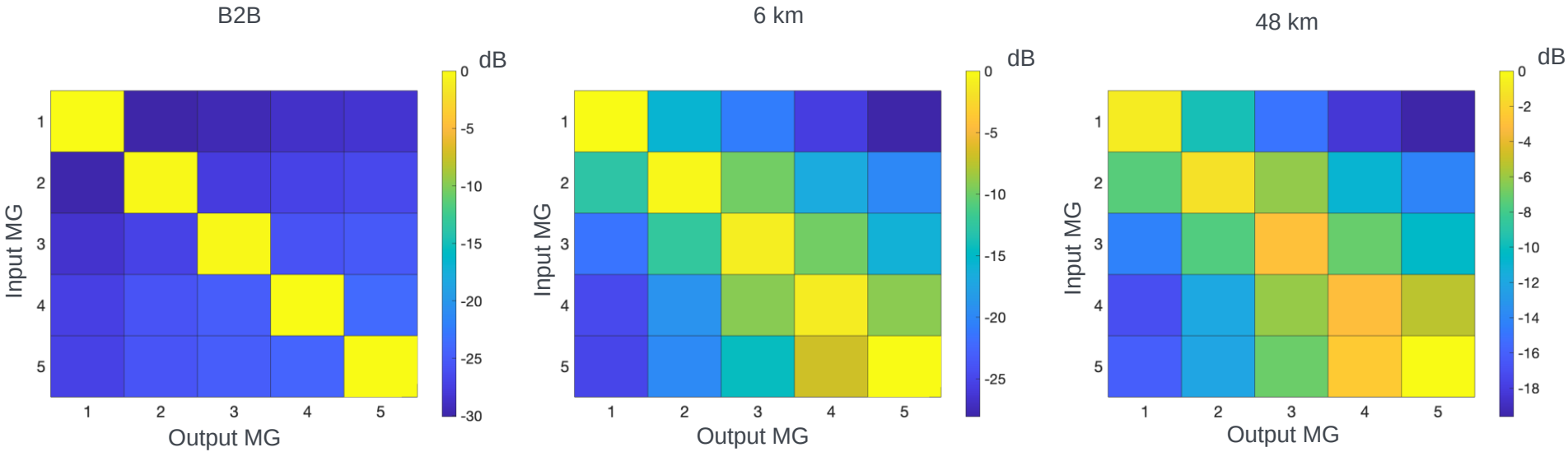

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Information & Communications Technologies

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Fiber-optic infrastructure for space-division multiplexed transmission

University of Stuttgart
Germany

Randomly Coupled 19-Core Multi-Core Fiber with Standard Cladding Diameter

Georg Rademacher, Menno van den Hout, Ruben S. Luís, Ben Puttnam, Giammarco Di Sciullo, Tetsuya Hayashi, Ayumi Inoue, Takuji Nagashima, Simon Gross, Andrew Ross-Adams, Michael J. Withford, Cristian Antonelli, Chigo Okonkwo, Jun Sakaguchi, and Hideaki Furukawa

Optical fiber communications conference (OFC), Post-Deadline paper, 2023

NICT

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

SUMITOMO ELECTRIC

MACQUARIE University
SYDNEY·AUSTRALIA
MQ Photonics Research Centre

Motivation – SDM fibers with 125 µm cladding diameter

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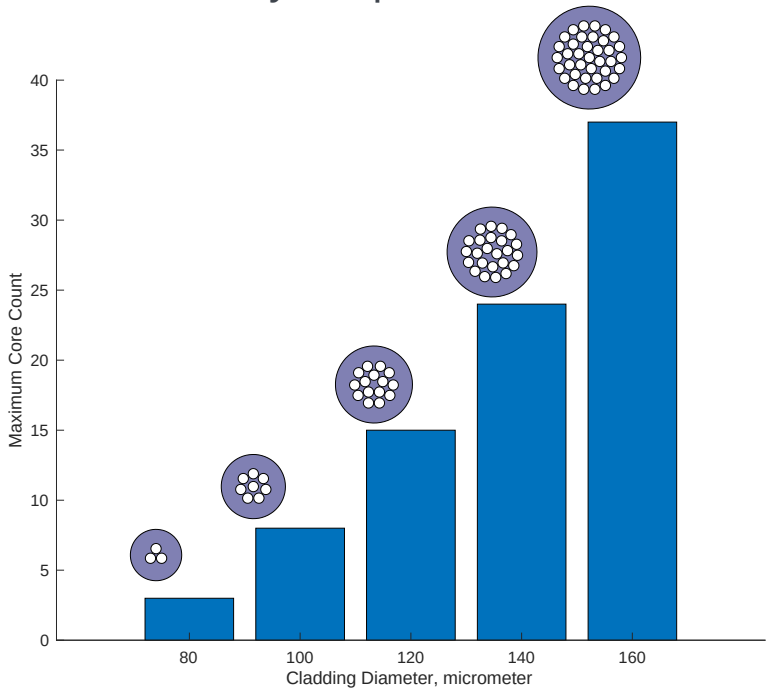
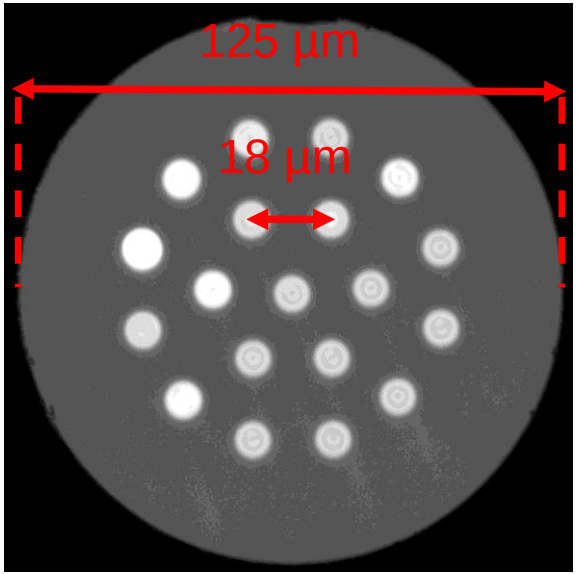
- Weakly-coupled MCF can be made with ~4 cores at 1550 nm (crosstalk)
- MMF can be made with many spatial channels (>=55), but the channel characterisitics may not be favorable for long-haul transmission (MDL, DMD)
- RC-MCF are sweet spot of high spatial density and high quality transmission characteristics
- RC-MCFs have been shown with 2,3,4,7 and 12 cores

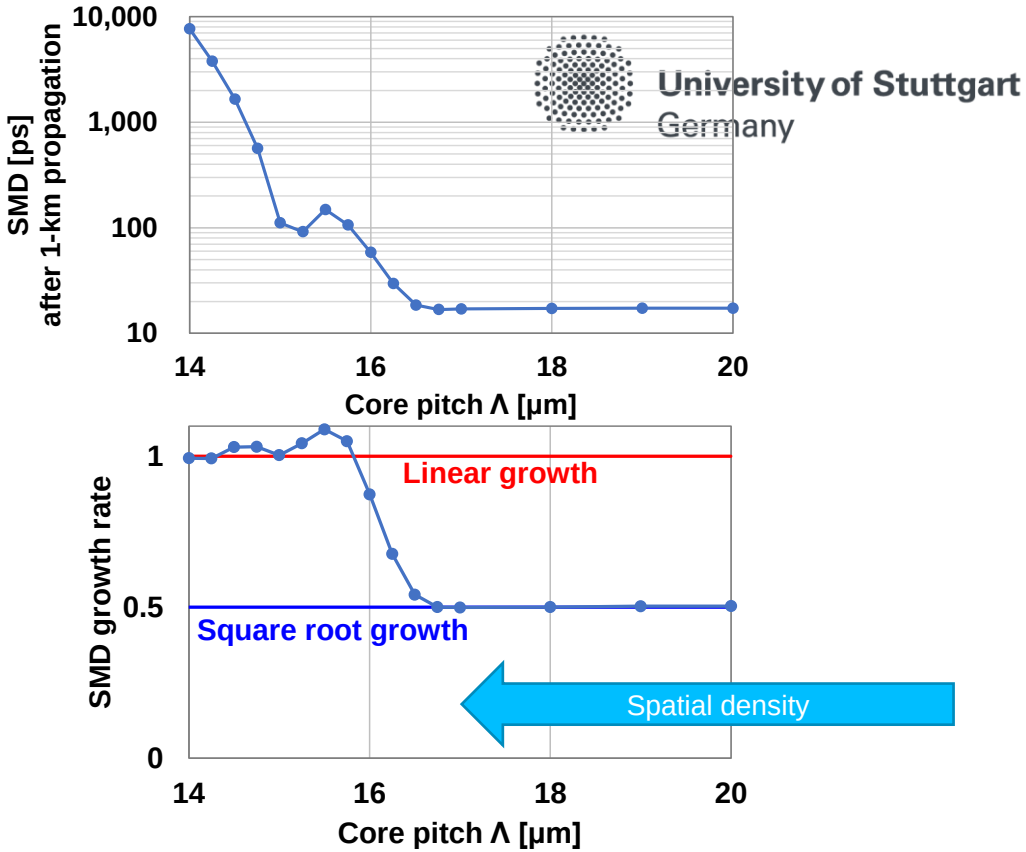
Randomly-coupled MCF



Fiber Design

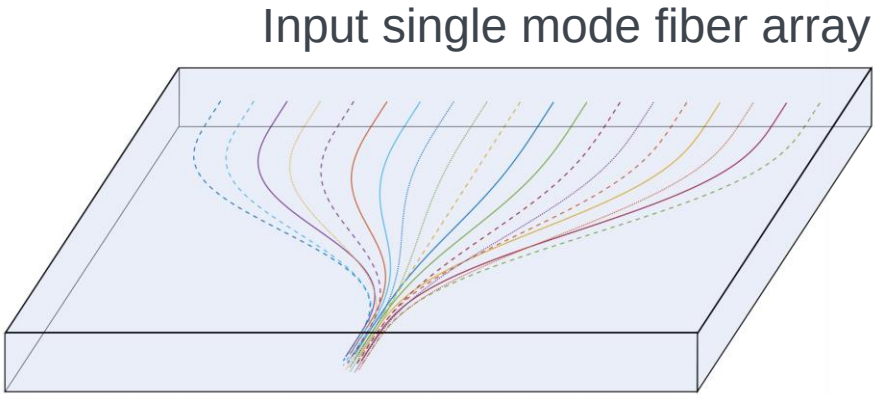


- Pure silica cores
- Effective area 62 µm²
- 0.215 dB/km attenuation at 1550 nm



Hayashi *et al.*, "Randomly-Coupled Multi-Core Fiber Technology", Proc. IEEE, 110 (11) , pp. 1786 – 1803 (2022)

Core Multiplexer



S. Gross and M.J. Withford, ”Ultra fast-laser-inscribed 3D integrated photonics,” Nanophotonics 4 (1) (2015)

Transmission Channel Characteristics

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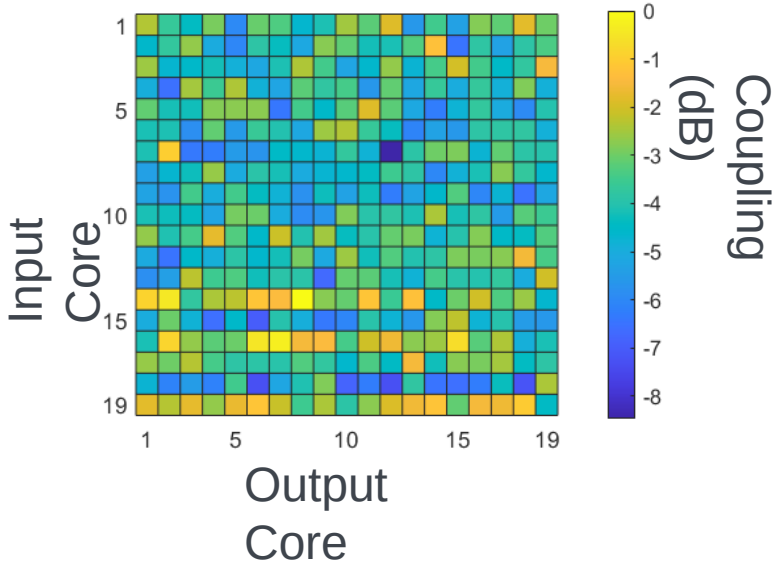
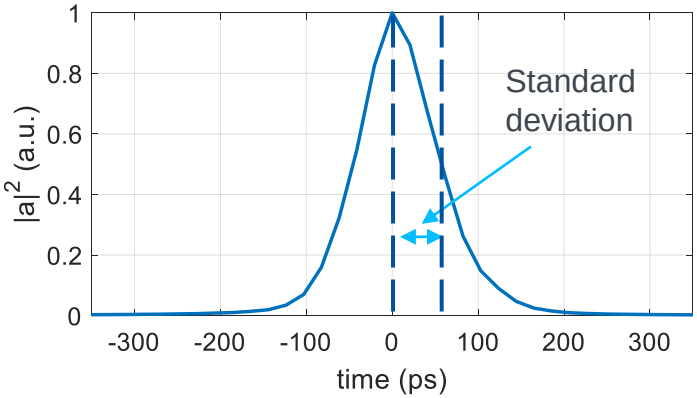
Coupling characteristics



Impulse response



Wavelength dependence of Impulse Response duration

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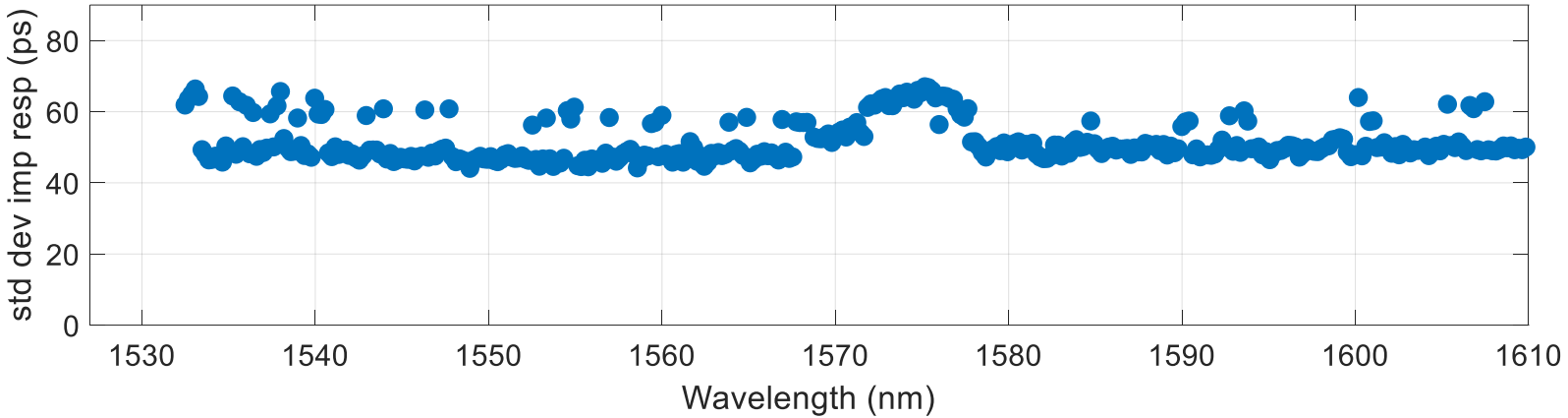

Real time MIMO Digital Signal Processing

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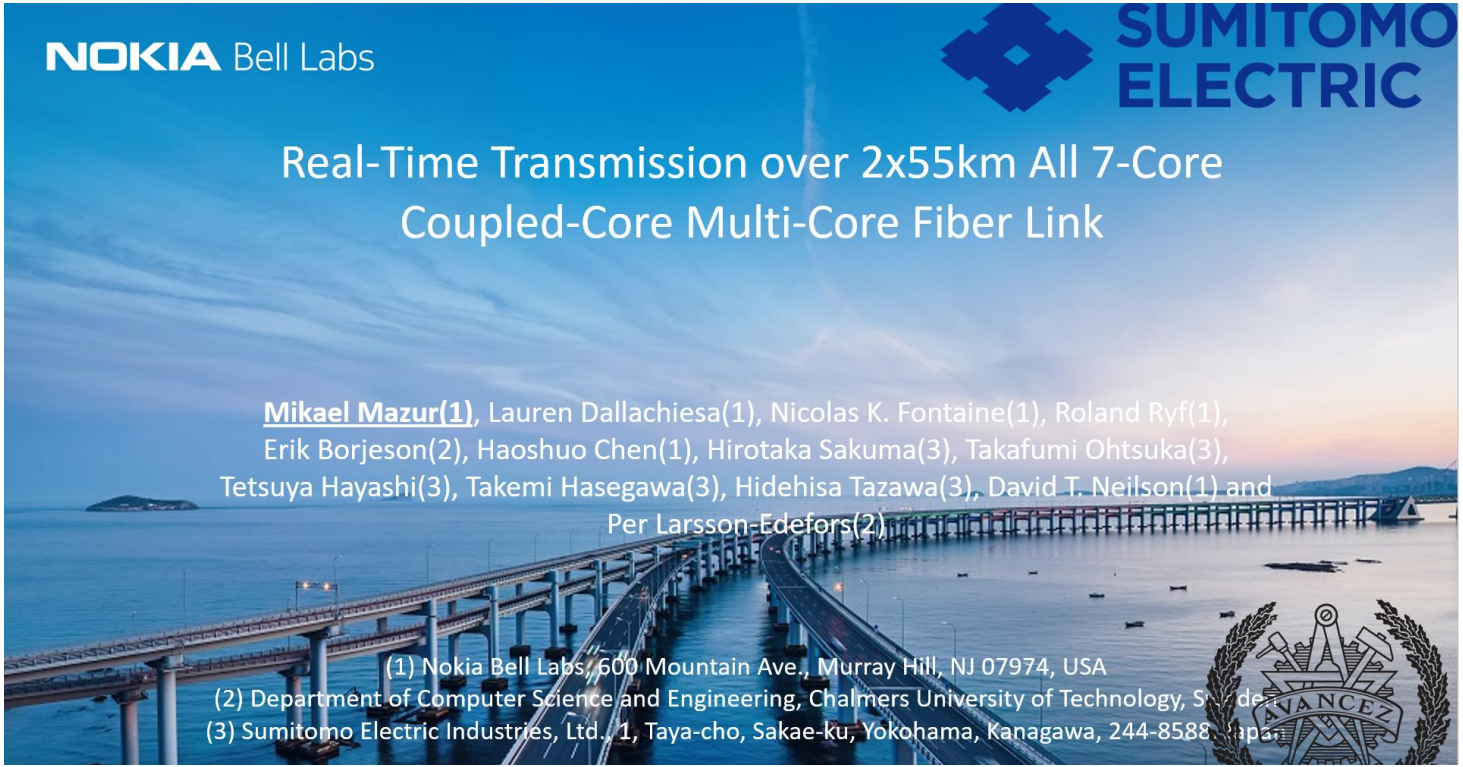
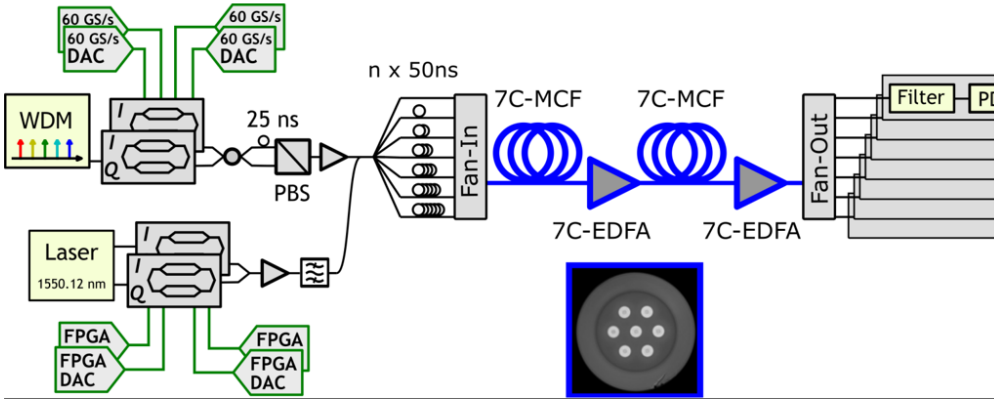
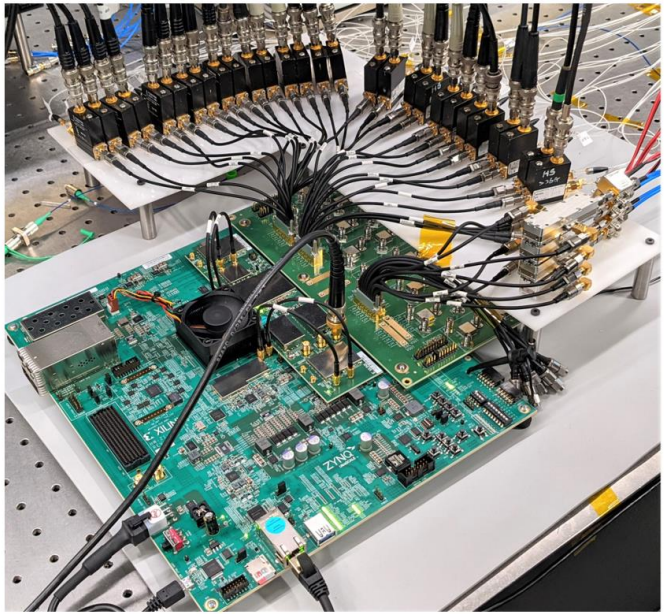


Setup



- Heterodyne receiver
  - 14 input modes (2 pols and 7-cores)
  - 14 differential output BPDs built using 28x3GHz PDs



- 4x4GS/s DACs and 14x2.5GS/s ADCs
- 625MBd SSB signal with 1.25GHz IF offset
- Comon 10MHz clock reference
- Complete transceiver on a single FPGA

Results – MIMO DSP

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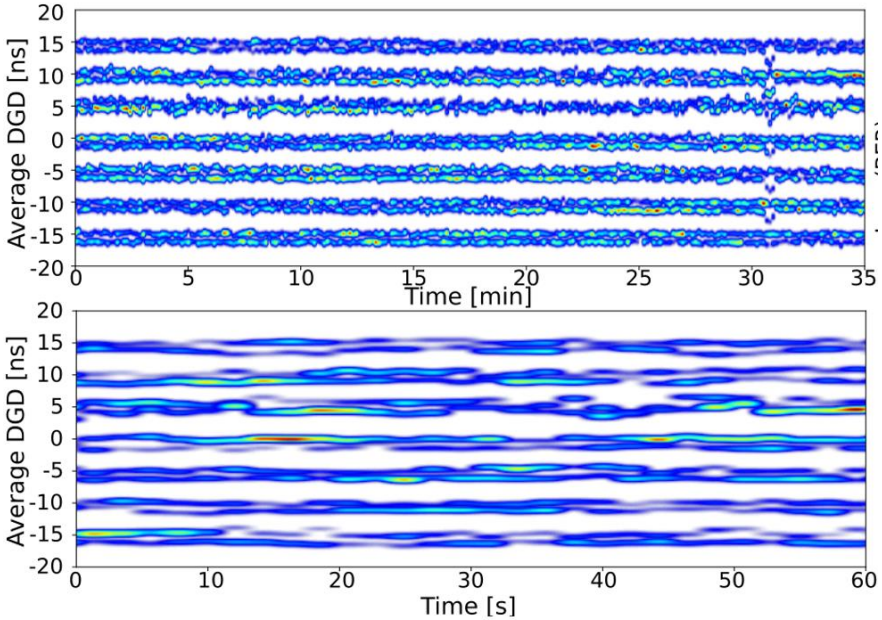

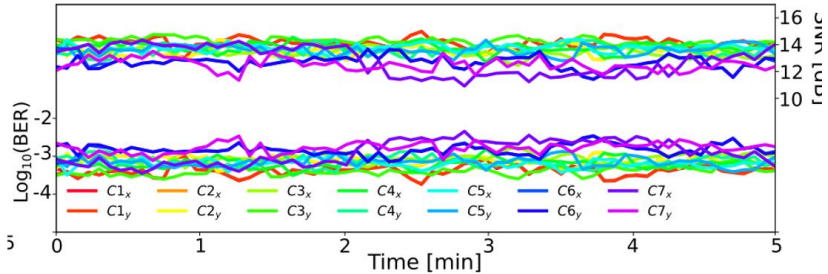

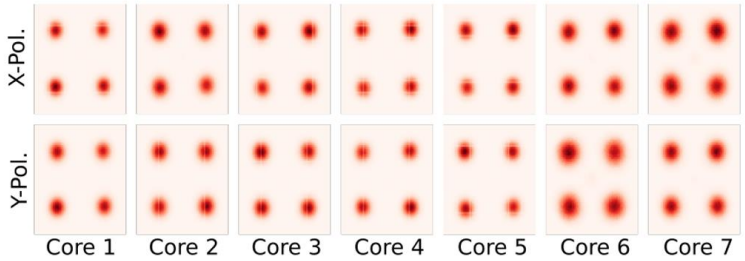

Conclusion

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- SDM is a technology that can dramatically increase the per-fiber data rate
- SDM field trials have demonstrated maturity of SDM fiber technology
- Max. number of coupled mode SDM transmission was 55 in a MMF with 1.5 Pb/s data rate
- Max. number of randomly coupled cores was 19 with record data rate of 1.7 Pb/s
- Real time MIMO DSP has been demonstrated on 7 coupled cores, however at lower data rate

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Institute for electrical and optical communications

Thank you!

Prof. Dr. Georg Rademacher

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Space-division multiplexing for optical fiber communications

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