



UNIVERSITÀ DEGLI STUDI DELL'AQUILA

# *Space-Division-Multiplexed Transmission Setups and Field Trials*

*Hack Your Research @ ECOC 2023*

*October 1<sup>st</sup>, 2023*

**Giammarco Di Sciuolo**

University of L'Aquila



**Giammarco Di Sciuolo**  
PhD student at Università degli Studi  
dell'Aquila.



# Outline

SDM Overview

19-Coupled-Core C+L Transmission Experiment

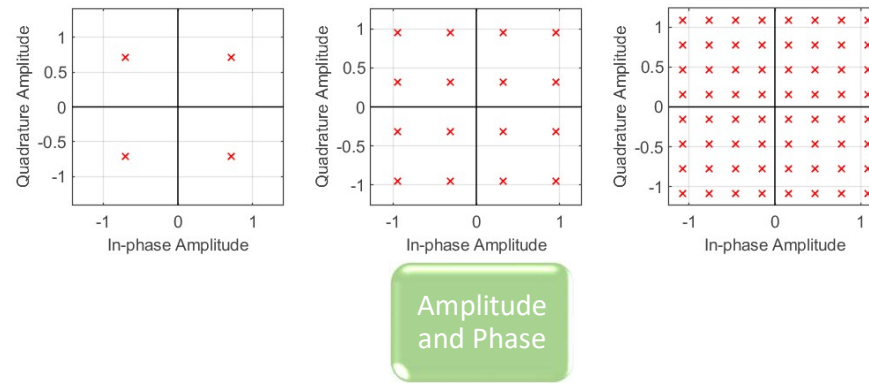
15-Mode Looping Experiments

- Long-distance MMF data transmission
- Impact of Mode Permutation in mitigating Modal Dispersion

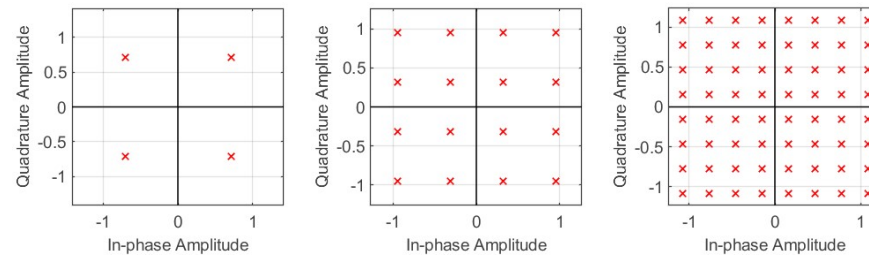
L'Aquila Field-Deployed Testbed

- Introduction
- Recent Experiments

# Physical multiplexing domains

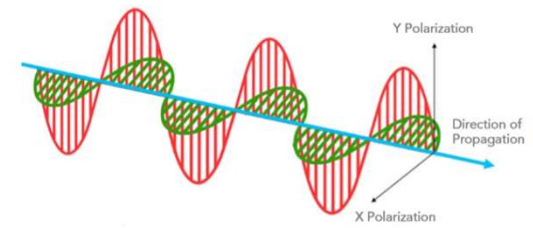


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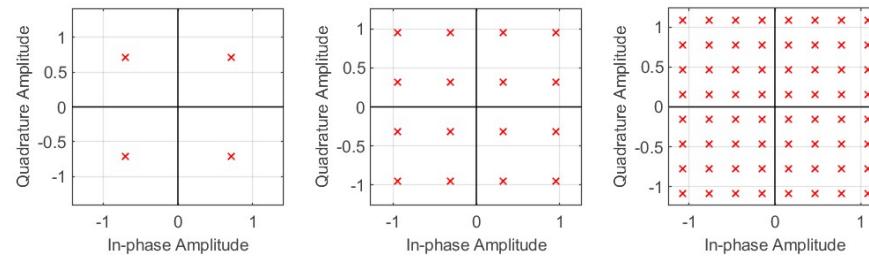


Amplitude and Phase

Polarization



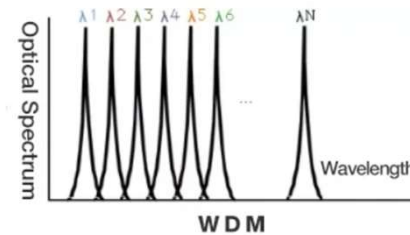
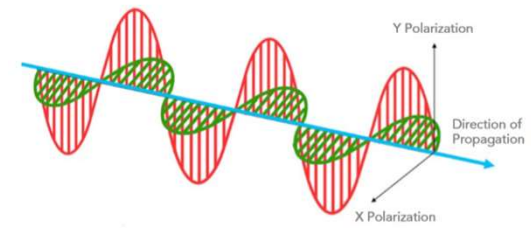
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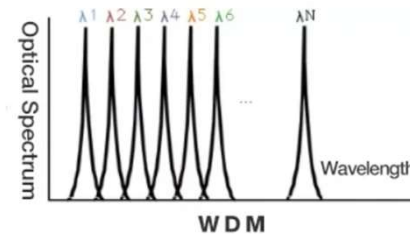
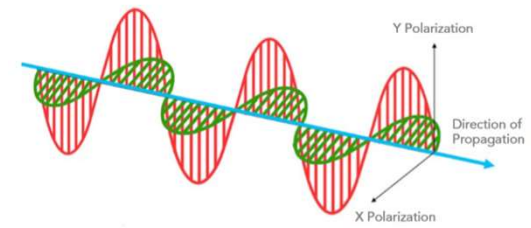
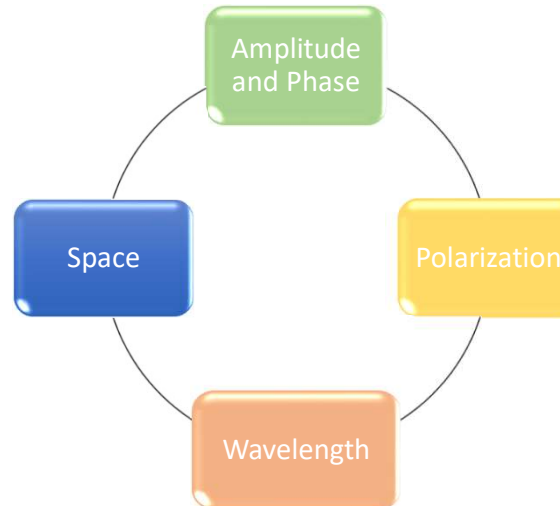
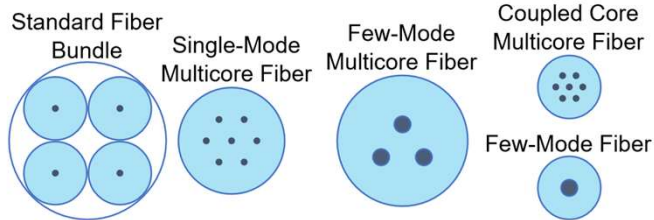
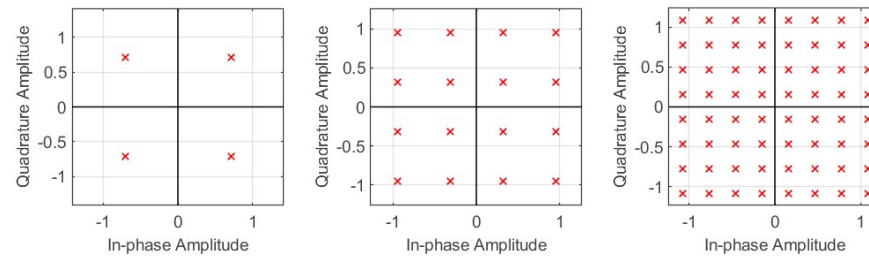
Amplitude and Phase

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Wavelength

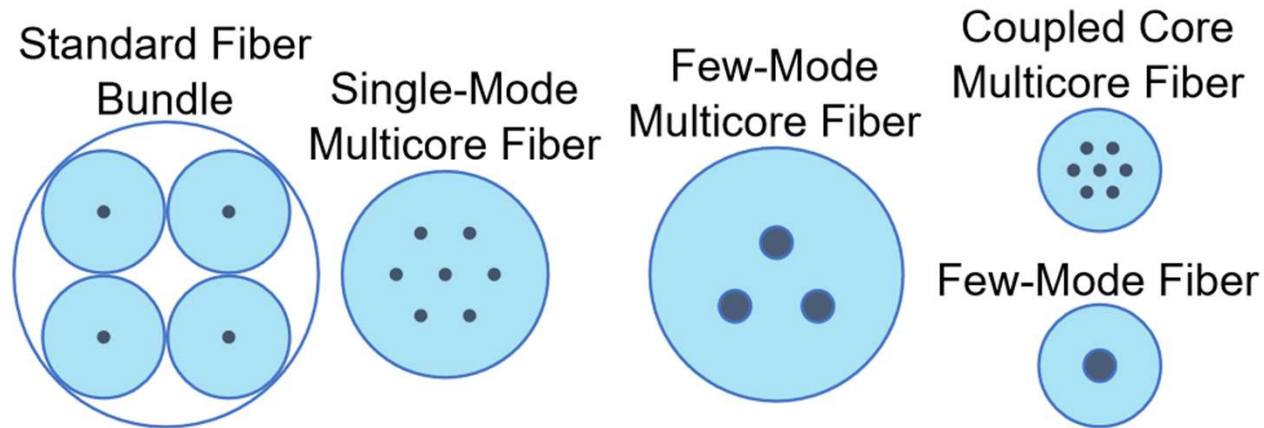


# Physical multiplexing domains



# Space-division multiplexing overview

Space division multiplexing (SDM) is a promising technology to increase the per-fiber capacity in optical fiber transmission systems.

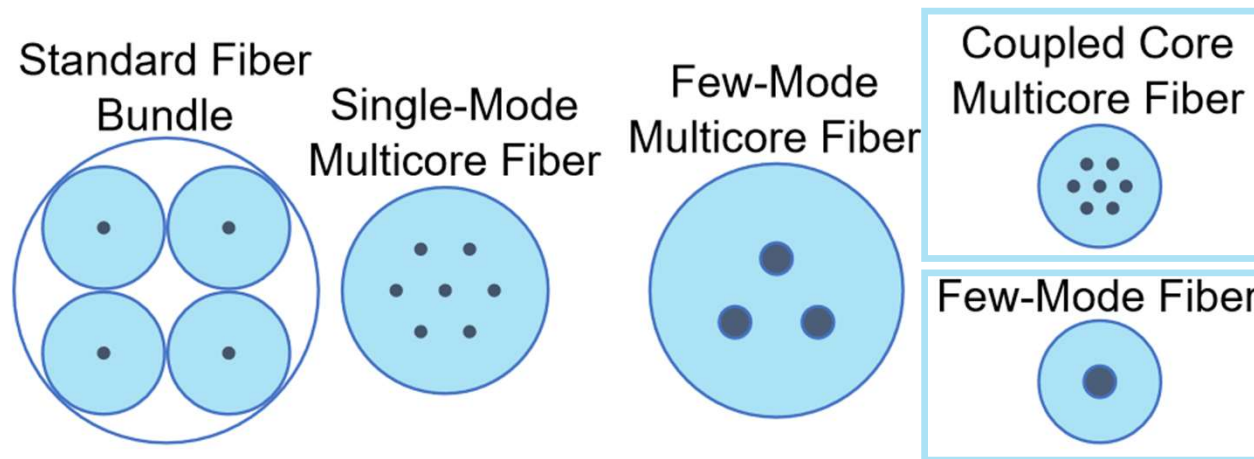


[B. Puttnam *et al.*, *Optica*, vol. 8, no. 9, pp. 1186–1203 (2021)]



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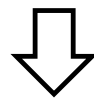
[S. Matsuo *et al.*, JLT, vol. 34, no. 6, pp. 1464-1475, (2016)]



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Limitations to the number of spatial channels!



# 19-Coupled-Core C+L transmission experiment

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

**Georg Rademacher<sup>(1)</sup>, Menno van den Hout<sup>(1,2)</sup>, Ruben S. Luís<sup>(1)</sup>, Benjamin J. Puttnam<sup>(1)</sup>, Giammarco Di Sciullo<sup>(1,3)</sup>, Tetsuya Hayashi<sup>(4)</sup>, Ayumi Inoue<sup>(4)</sup>, Takuji Nagashima<sup>(4)</sup>, Simon Gross<sup>(5)</sup>, Andrew Ross-Adams<sup>(6)</sup>, Michael J. Withford<sup>(6)</sup>, Jun Sakaguchi<sup>(1)</sup>, Cristian Antonelli<sup>(3)</sup>, Chigo Okonkwo<sup>(2)</sup>, Hideaki Furukawa<sup>(1)</sup>**

<sup>(1)</sup> NICT, 4-2-1, Nukui-Kitamachi, Koganei, Tokyo, 184-8795, Japan,

<sup>(2)</sup> Eindhoven University of Technology, High Capacity Optical Transmission Lab, Eindhoven, The Netherlands

<sup>(3)</sup> University of L'Aquila and CNIT, 67100, L'Aquila, Italy

<sup>(4)</sup> Sumitomo Electric Industries, Ltd., 1 Taya-cho, Sakae-ku, Yokohama 244-8588, Japan

<sup>(5)</sup> MQ Photonics Research Centre, School of Engineering, Macquarie Univ., Sydney, Australia.

<sup>(6)</sup> MQ Photonics Research Centre, School of Math. and Physical Sciences, Macquarie Univ., Sydney, Australia.

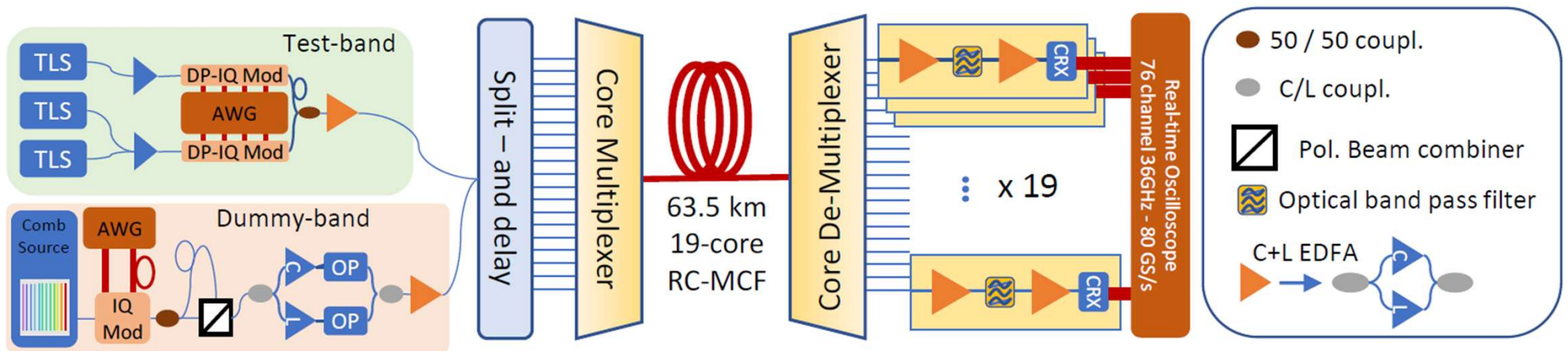
[georg.rademacher@nict.go.jp](mailto:georg.rademacher@nict.go.jp)

[G. Rademacher *et al.*, *Optica*, OFC 2023, Th4A.4 (2023)]



**MACQUARIE**  
University  
SYDNEY · AUSTRALIA

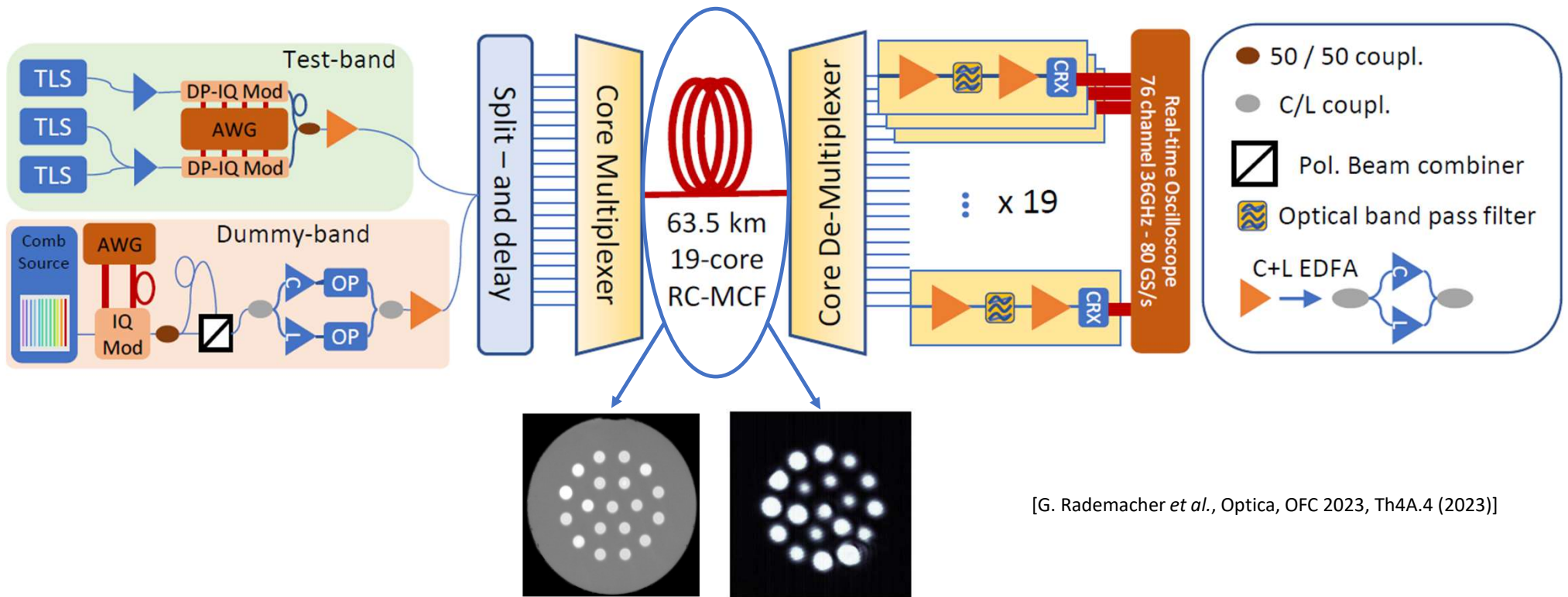
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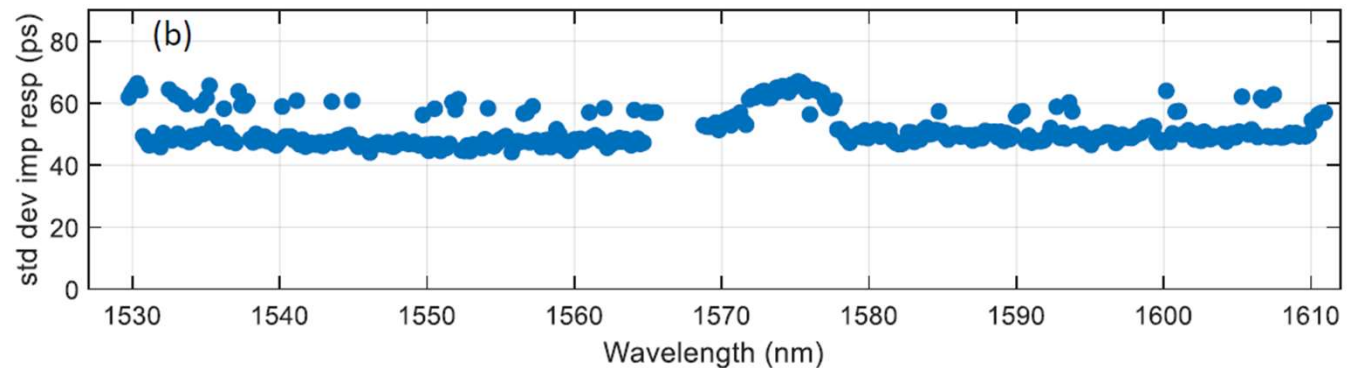
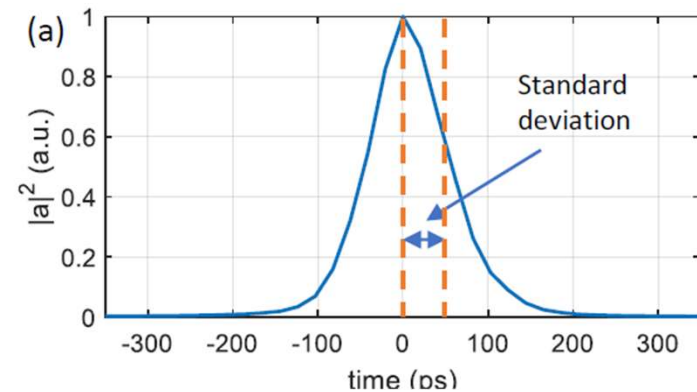


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# 19-Coupled-Core C+L transmission experiment

- We evaluated the standard deviation of the impulse response for all 381 measured WDM channels.
- High uniformity of the spatial mode dispersion was observed.

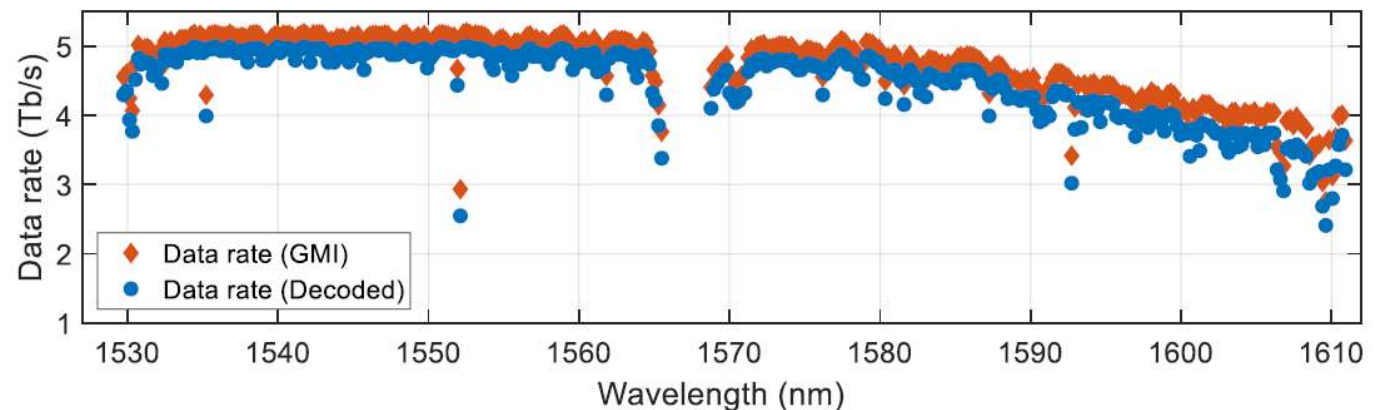
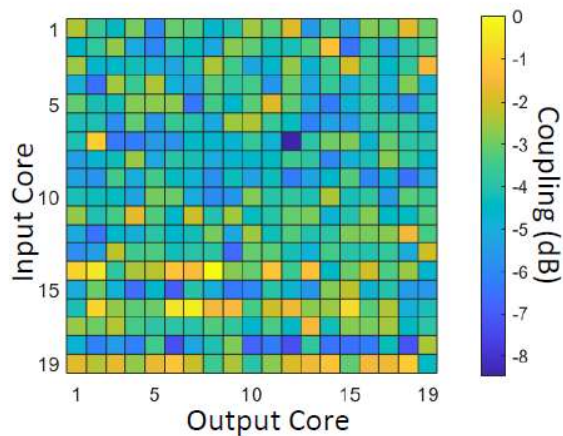


[G. Rademacher *et al.*, *Optica*, OFC 2023, Th4A.4 (2023)]



# 19-Coupled-Core C+L transmission experiment

We transmitted 19x381x24.5 GBd PDM-64-QAM resulting in a decoded data rate of 1.7 Pb/s, the highest reported data rate in any standard cladding diameter optical fiber.



[G. Rademacher *et al.*, *Optica*, OFC 2023, Th4A.4 (2023)]



# Multi-mode fiber

- MMFs can accommodate a large number of spatial channels within the standard 125  $\mu\text{m}$  cladding diameter (55 modes already demonstrated!).

[G. Rademacher *et al.*, ECOC 2022, Th3C.3 (2022)]



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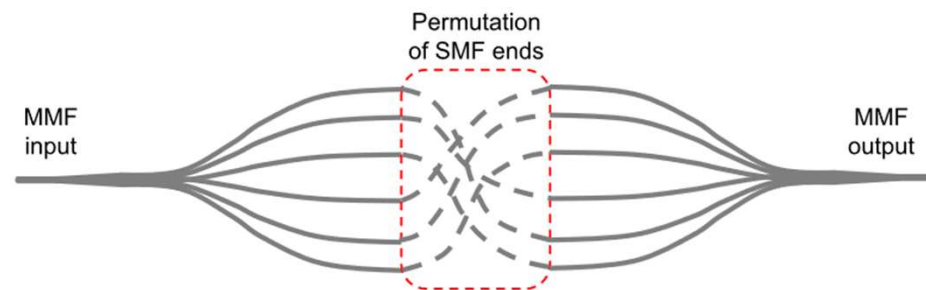


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[G. Rademacher *et al.*, ECOC 2022, Th3C.3 (2022)]

- DMD can be mitigated by implementing mode permutation.



[S. Arik *et al.*, JLT, vol. 34, no. 11, pp. 2867-2880, (2016)]



# 15-Mode looping experiments

## Reduction of Modal Dispersion in a long-haul 15-Mode Fiber link by means of Mode Permutation

Giammarco Di Sciullo<sup>(1,2)</sup>, Menno van den Hout<sup>(1,3)</sup>, Georg Rademacher<sup>(1,4)</sup>, Ruben S. Luís<sup>(1)</sup>, Benjamin J. Puttnam<sup>(1)</sup>, Nicolas K. Fontaine<sup>(5)</sup>, Roland Ryf<sup>(5)</sup>, Haoshuo Chen<sup>(5)</sup>, Mikael Mazur<sup>(5)</sup>, David T. Neilson<sup>(5)</sup>, Pierre Sillard<sup>(6)</sup>, Frank Achten<sup>(6)</sup>, Jun Sakaguchi<sup>(1)</sup>, Chigo Okonkwo<sup>(3)</sup>, Antonio Mecozzi<sup>(2)</sup>, Cristian Antonelli<sup>(2)</sup>, and Hideaki Furukawa<sup>(1)</sup>.

- (1) NICT, Koganei, Tokyo, Japan, [giammarco.disciullo@graduate.univaq.it](mailto:giammarco.disciullo@graduate.univaq.it)
- (2) University of L'Aquila and CNIT, L'Aquila, Italy,
- (3) High Capacity Optical Transmission Lab, Eindhoven University of Technology, The Netherlands,
- (4) INT, University of Stuttgart, Stuttgart, Germany,
- (5) Nokia Bell Labs, New Providence, NJ, USA,
- (6) Prysmian Group, France and The Netherlands.

**We.A.1.2 – 9:45-10:00, Wednesday, 4 October 2023, Lomond Auditorium**



# 15-Mode looping experiments

## 273.6 Tb/s Transmission Over 1001 km of 15-Mode Fiber Using 16-QAM C-Band Signals

**Menno van den Hout<sup>(1,2)</sup>, Giammarco Di Sciullo<sup>(1,3)</sup>, Georg Rademacher<sup>(1)</sup>,  
Ruben S. Luís<sup>(1)</sup>, Benjamin J. Puttnam<sup>(1)</sup>, Nicolas K. Fontaine<sup>(4)</sup>, Roland Ryf<sup>(4)</sup>,  
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<sup>(5)</sup> Prysmian Group, 644 Boulevard Est, Billy Berclau, 62092 Haisnes Cedex, France

<sup>(6)</sup> Prysmian Group, Eindhoven, 5651 CA, The Netherlands

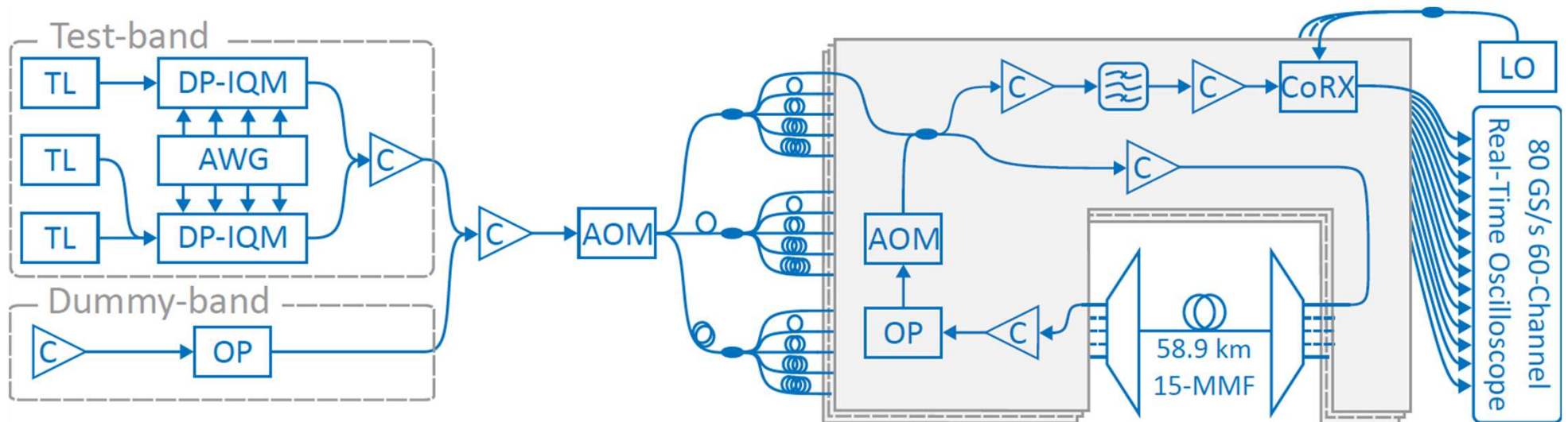
[m.v.d.hout@tue.nl](mailto:m.v.d.hout@tue.nl)

[M. van den Hout *et al.*, *Optica*, OFC 2023, Th4B.5 (2023)]



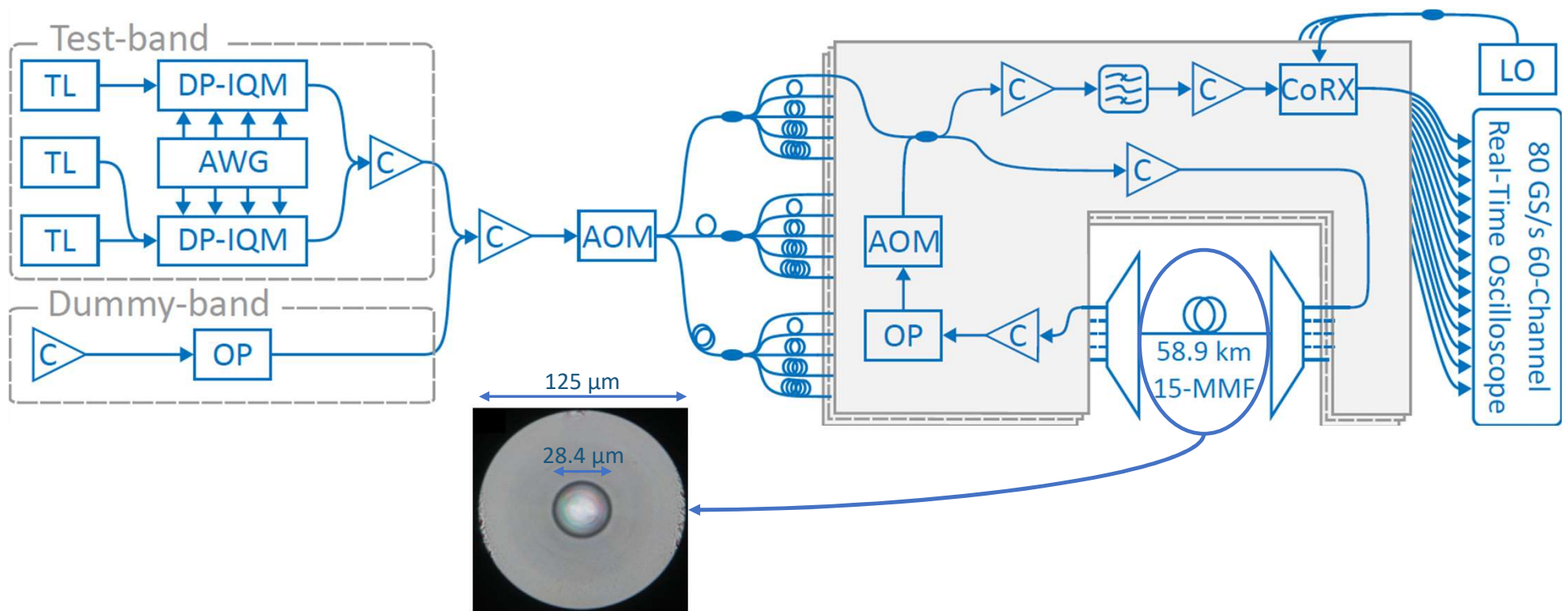


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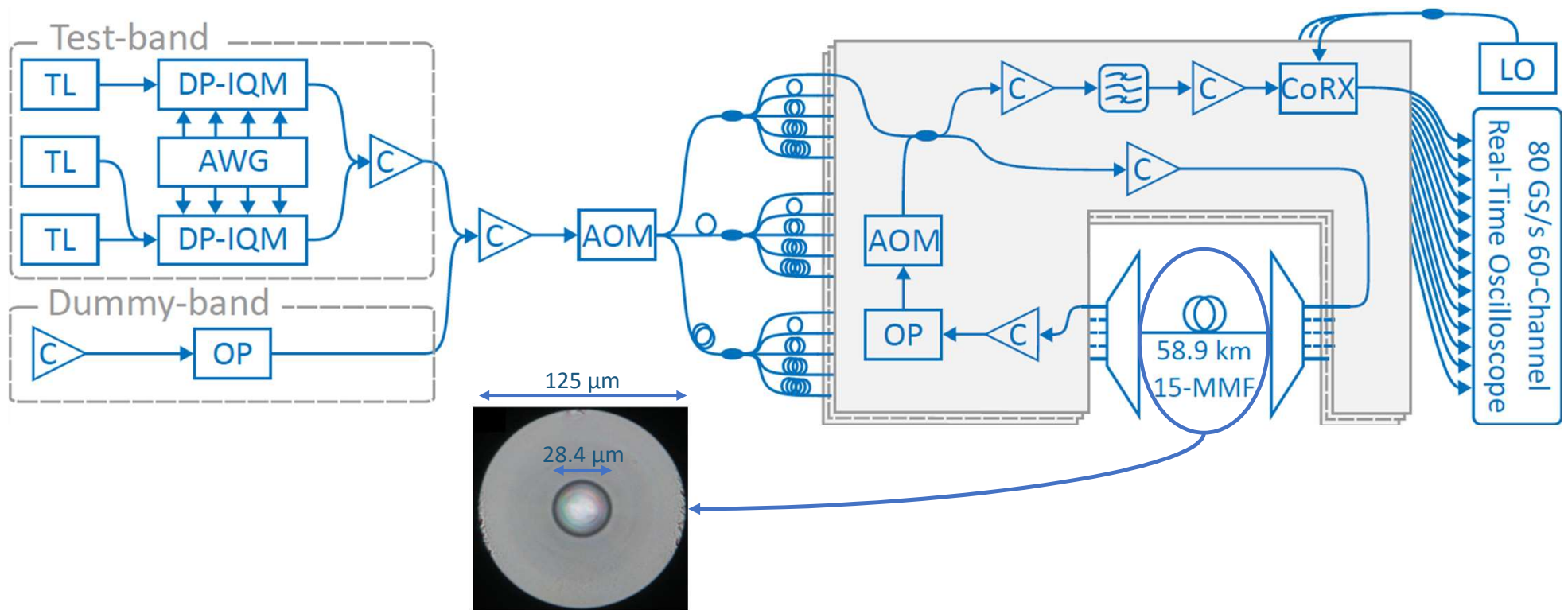




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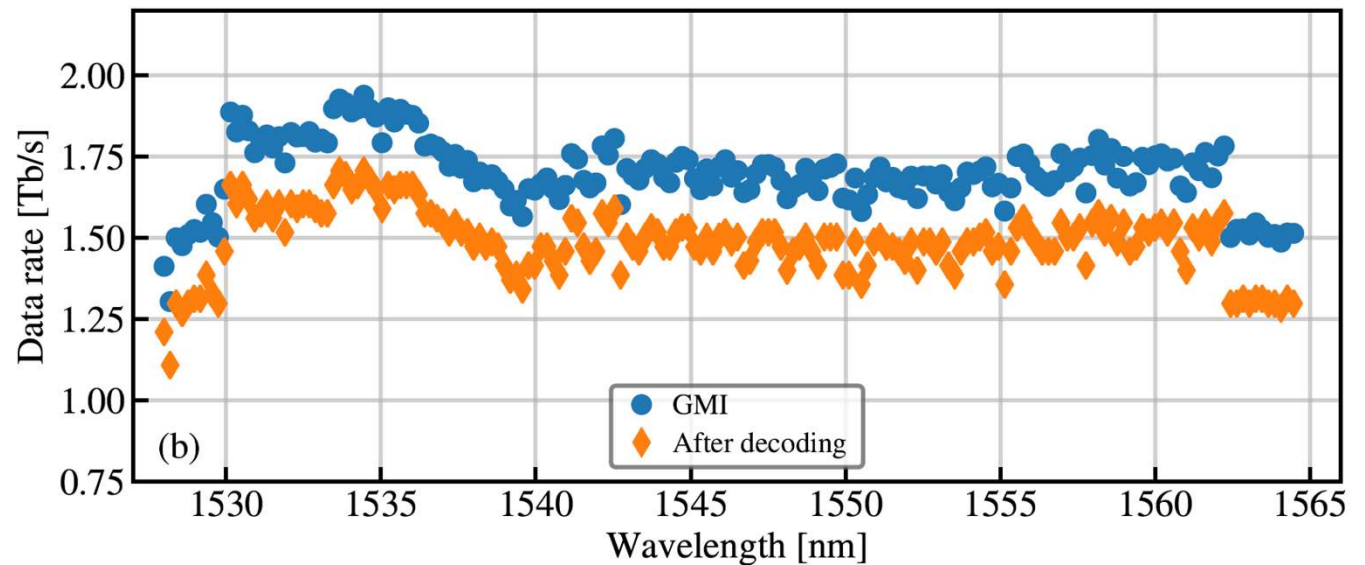
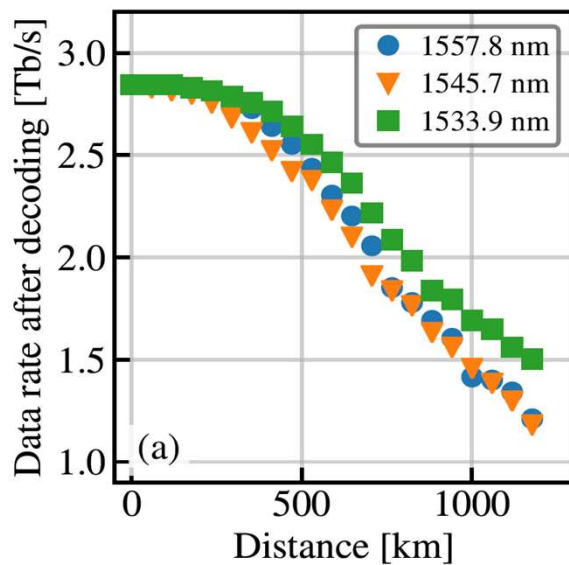


# 15-Mode looping experiments



# Long-distance MMF data transmission

- We transmitted 15x184x24.5 GBd PDM-16-QAM resulting in a decoded data rate of 273.6 Tb/s, the highest reported data rate in long-distance MMF transmission, and resulting in a record capacity-distance product for MMFs.



[M. van den Hout *et al.*, Optica, OFC 2023, Th4B.5 (2023)]



# Title

## Transmission of 138.9 Tb/s over 12 345 km of 125 $\mu\text{m}$ cladding diameter 4-core fiber using signals spanning S, C, and L-band

Menno van den Hout<sup>(1,2)</sup>, Benjamin J. Puttnam<sup>(1)</sup>, Giammarco Di Sciullo<sup>(1,3)</sup>, Ruben S. Luís<sup>(1)</sup>, Georg Rademacher<sup>(4)</sup>, Cristian Antonelli<sup>(3)</sup>, Chigo Okonkwo<sup>(2)</sup>, and Hideaki Furukawa<sup>(1)</sup>

- (1) Photonic Network System Lab, NICT, 4-2-1, Nukui-Kitamachi, Tokyo, Japan, [m.v.d.hout@tue.nl](mailto:m.v.d.hout@tue.nl)
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- (3) University of L'Aquila and CNIT, 67100, L'Aquila, Italy
- (4) INT, University of Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany

**M.A.5.5 – 14:45-15:00, Monday, 2 October 2023, Dochart**



# L'Aquila Field-Deployed Testbed



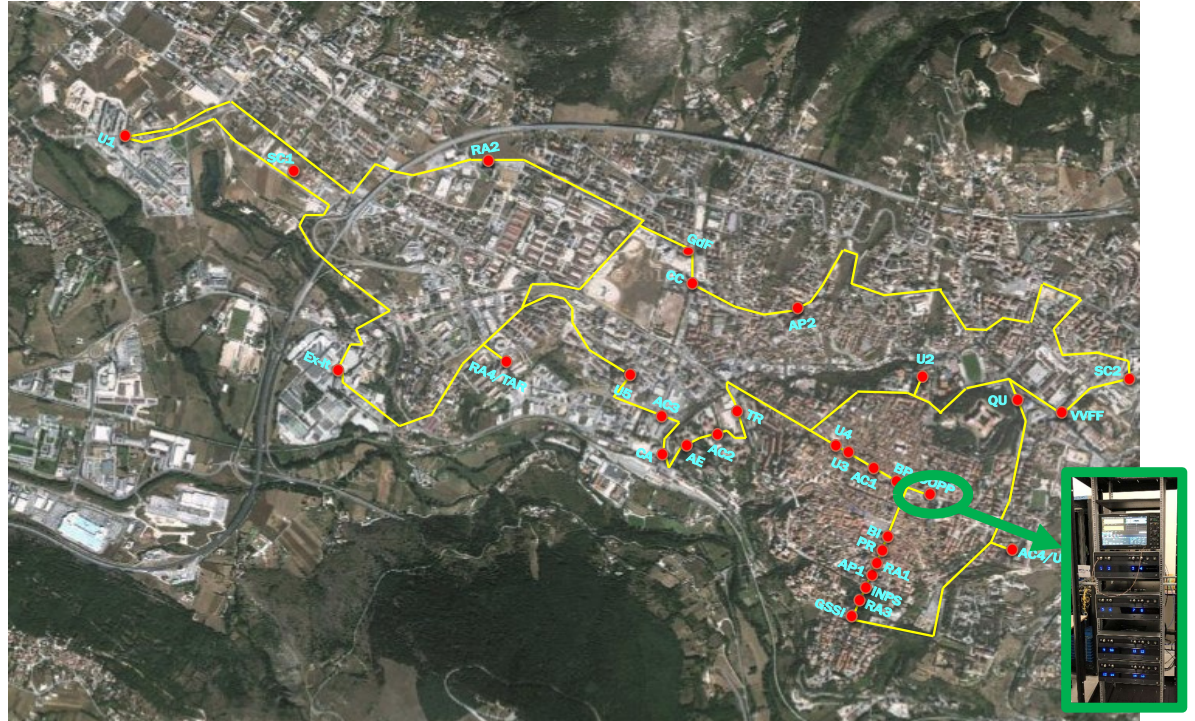


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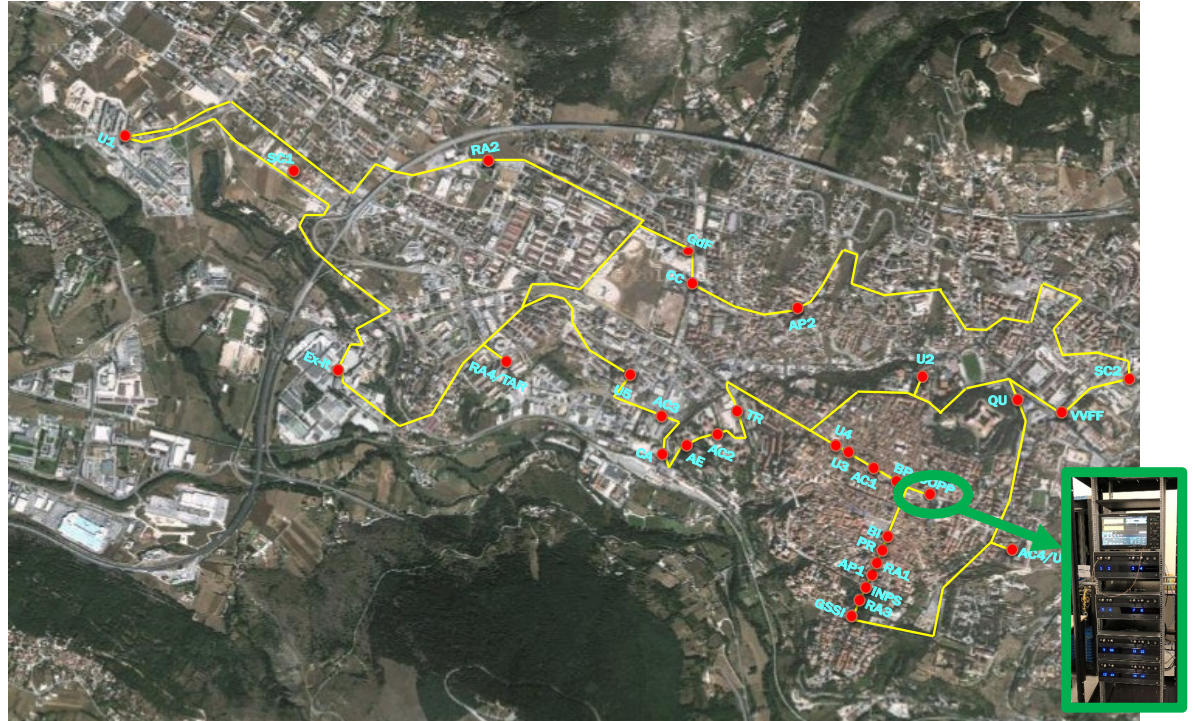
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- This infrastructure includes:





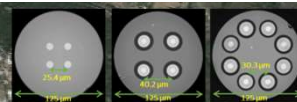
# L'Aquila Field-Deployed Testbed

- University of L'Aquila owns the first field-deployed SDM fiber infrastructure worldwide.
- This infrastructure includes:
  - Coupled-core 4-core fibers;
  - Uncoupled-core 4-core fibers;
  - Uncoupled-core 8-core fibers;



## Multi-core fibers

- Coupled-core 4C-MCFs.
- Uncoupled-core 4C/8C-MCFs.

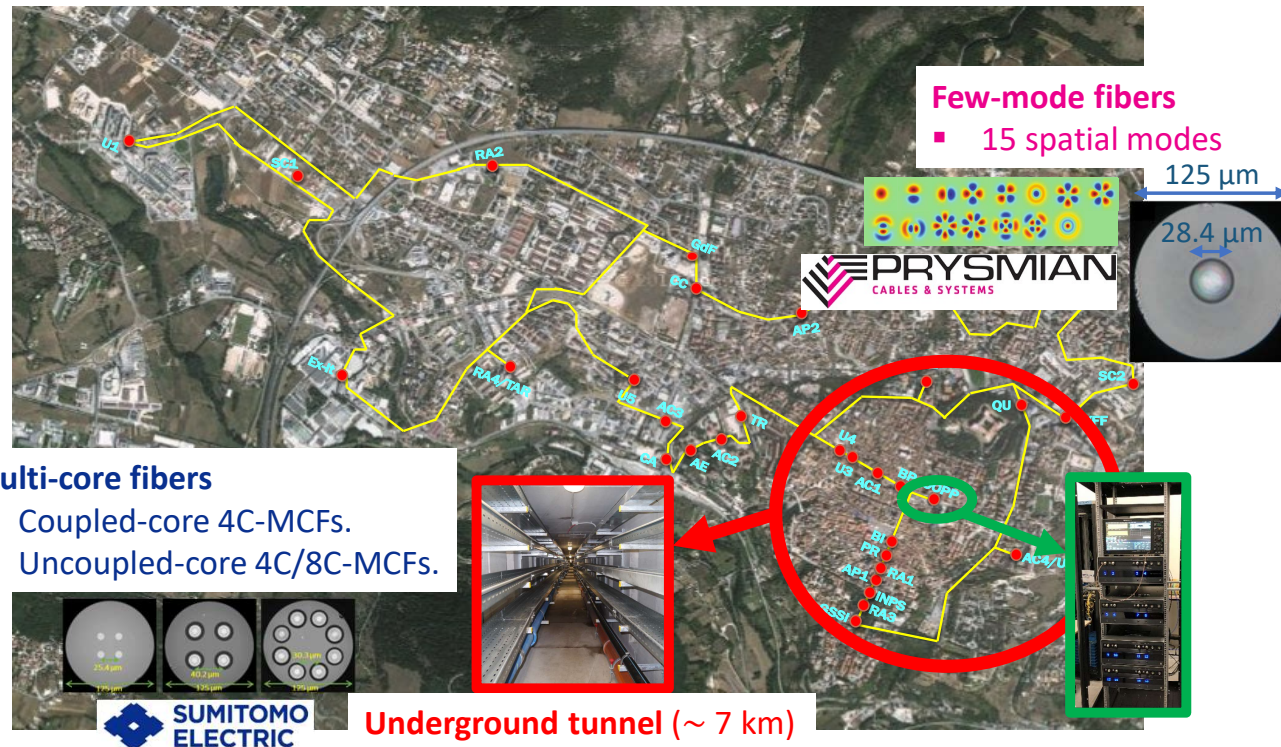


Underground tunnel (~ 7 km)



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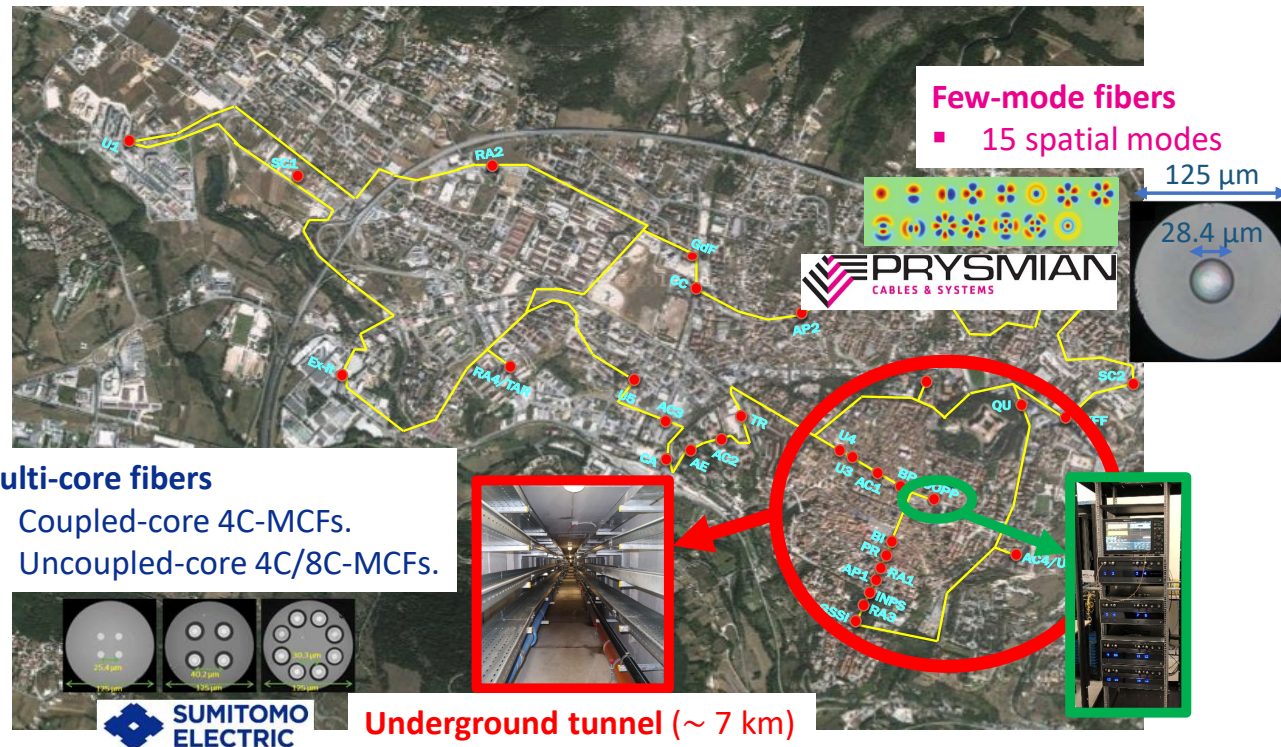
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  - 15-Mode fibers;





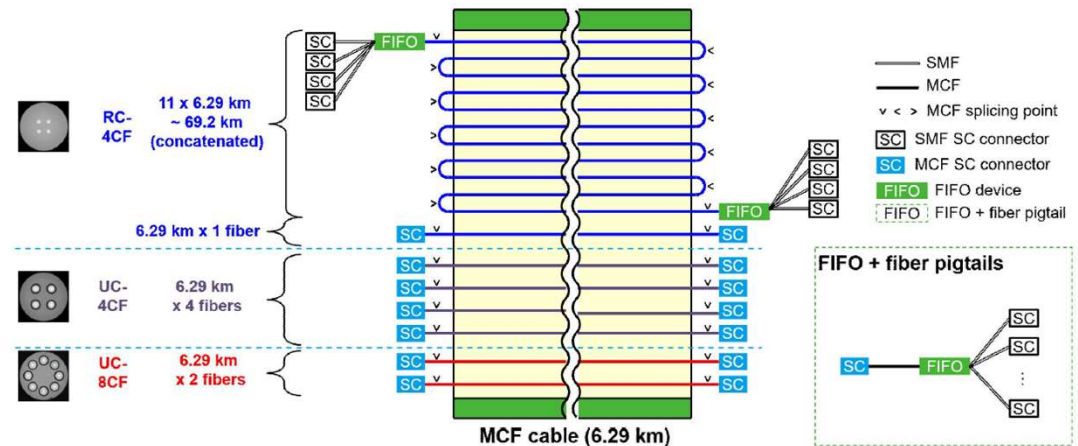
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  - Uncoupled-core 8-core fibers;
  - 15-Mode fibers;
  - Single-mode fibers.



# L'Aquila Field-Deployed Testbed - MCF

- Coupled-core 4-core fibers (12);
- Uncoupled-core 4-core fibers (4);
- Uncoupled-core 8-core fibers(2).

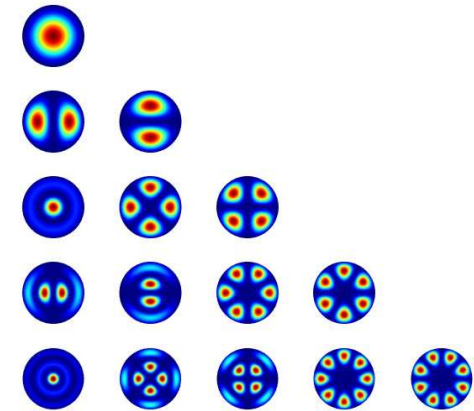
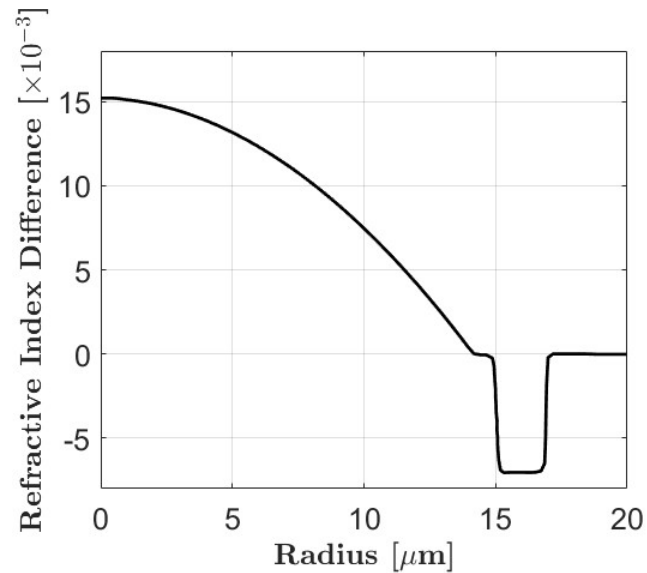
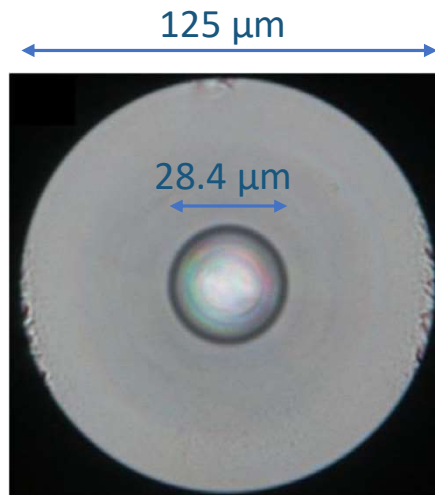


Fiber ID	RC-4CF	UC-4CF	UC-8CF
Coupling characteristics	Coupled	Uncoupled	Uncoupled
Core count	4	4	8
Core pitch	<sup>a)</sup> 25.4 ± 0.2 μm	<sup>a)</sup> 40.2 ± 0.2 μm	<sup>a)</sup> 30.3 ± 0.1 μm
Cladding diameter	125 μm	125 μm	125 μm
Mode field diameter	<sup>a,c,d)</sup> 10.1 ± 0.2 μm	<sup>b)</sup> 8.4–8.5 μm	<sup>b)</sup> 8.4–8.5 μm
Effective area of core mode	<sup>a,c,d)</sup> 80.9 ± 3.3 μm <sup>2</sup>	n/a	n/a
22-m cutoff wavelength λ <sub>cc</sub>	1.41–1.51 μm	1.21–1.24 μm	<sup>*</sup> 1.27–1.30 μm
Attenuation	<sup>c)</sup> 0.170–0.175 dB/km	<sup>c)</sup> 0.201–0.246 dB/km	<sup>b)</sup> 0.347–0.363 dB/km
Transmission suitable wavelength band	C to L bands	O to L bands	O band



# L'Aquila Field-Deployed Testbed – MM

- Large number of spatial modes within 125  $\mu\text{m}$  cladding diameter.

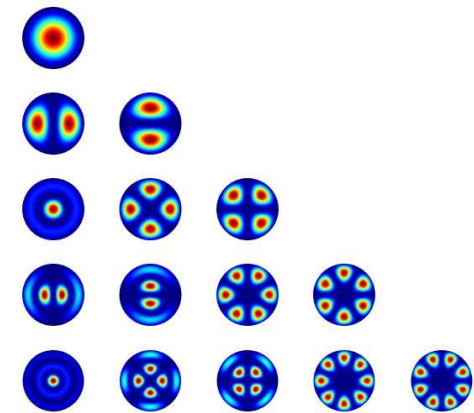
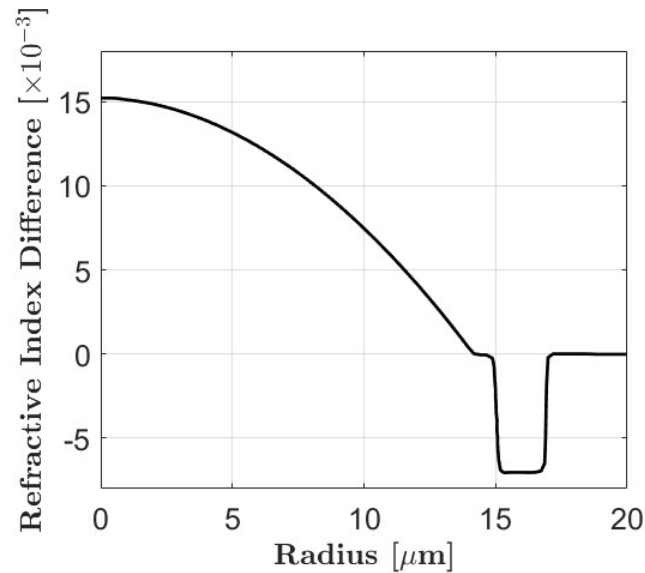
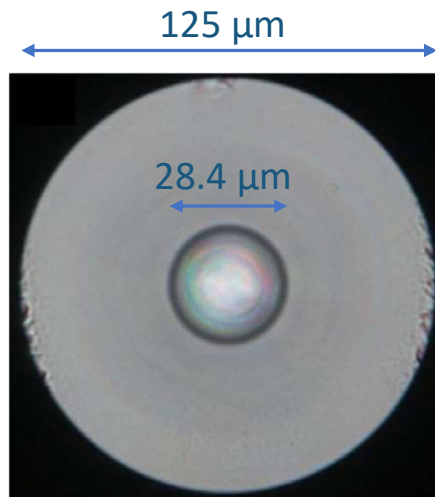


[P. Sillard *et al.*, JLT, vol. 34, pp. 425–430 (2016)]



# L'Aquila Field-Deployed Testbed – MM

- Large number of spatial modes within 125  $\mu\text{m}$  cladding diameter.
- Low attenuation ( $<0.24$  dB/km at 1550 nm) and low DMD ( $<100$  ps/km).



[P. Sillard *et al.*, JLT, vol. 34, pp. 425–430 (2016)]





# Field-deployed 15-mode fiber characterization

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

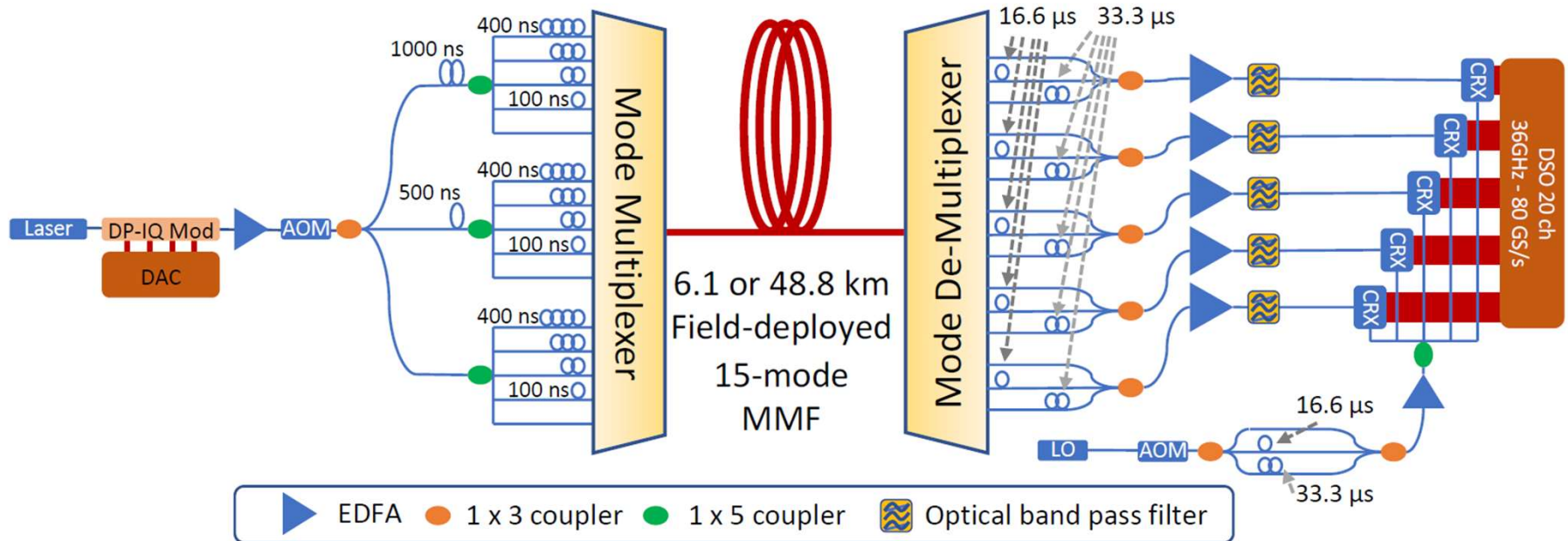
Georg Rademacher<sup>(1)</sup>, Ruben S. Luís<sup>(1)</sup>, Benjamin J. Puttnam<sup>(1)</sup>, Giammarco Di Sciullo<sup>(2)</sup>, Robert Emmerich<sup>(3)</sup>, Nicolas Braig-Christophersen<sup>(3)</sup>, Andrea Marotta<sup>(2)</sup>, Lauren Dallachiesa<sup>(4)</sup>, Roland Ryf<sup>(4)</sup>, Antonio Mecozzi<sup>(2)</sup>, Colja Schubert<sup>(3)</sup>, Pierre Sillard<sup>(5)</sup>, Frank Achten<sup>(5)</sup>, Giuseppe Ferri<sup>(5)</sup>, Jun Sakaguchi<sup>(1)</sup>, Cristian Antonelli<sup>(2)</sup>, Hideaki Furukawa<sup>(1)</sup>

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- (3) Fraunhofer Institute for Telecommunications HHI, Einsteinufer 37, 10587 Berlin, Germany
- (4) Nokia Bell Labs, 600 Mountain Ave, Murray Hill, NJ 07974, USA
- (5) Prysmian Group, Haisnes, France; Eindhoven, The Netherlands; Milano, Italy

[G. Rademacher *et al.*, ECOC 2022, Th3B.1 (2022)]



# Field-deployed 15-mode fiber characterization

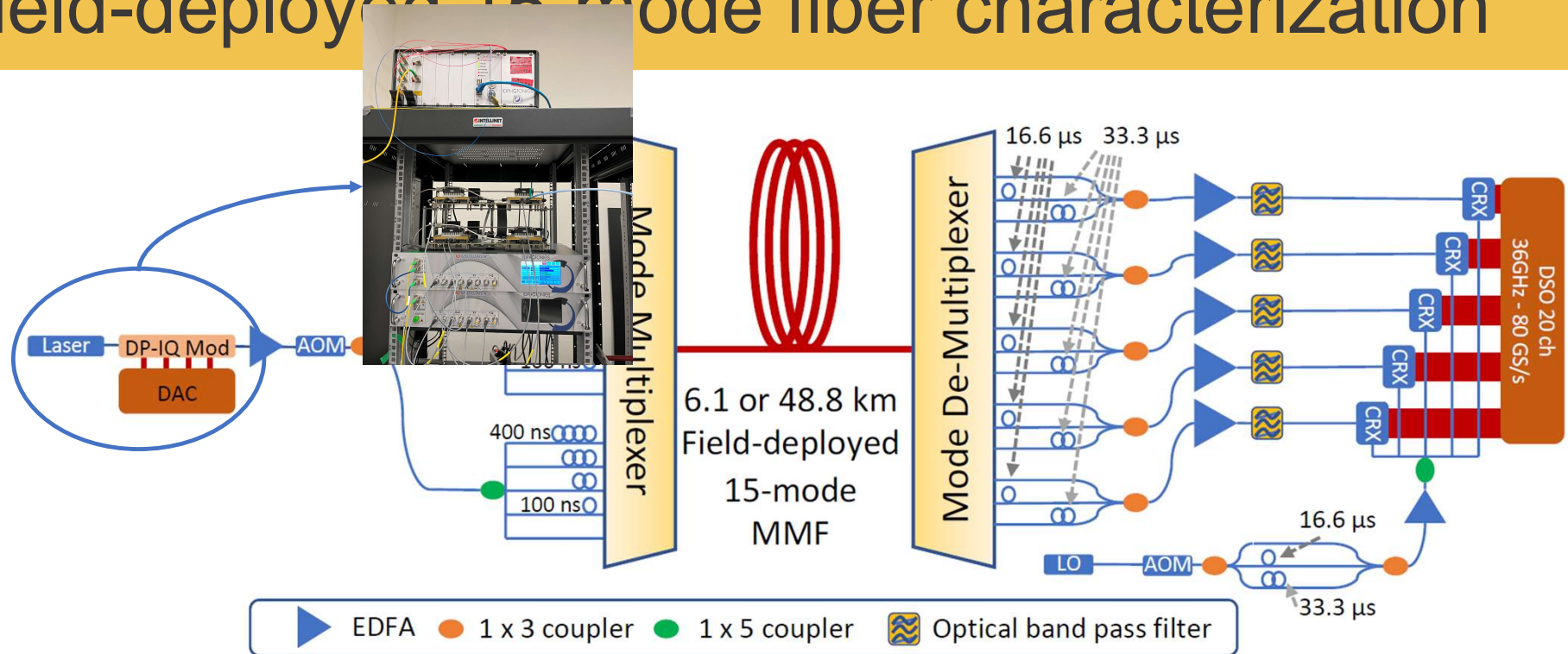


[G. Rademacher *et al.*, ECOC 2022, Th3B.1 (2022)]





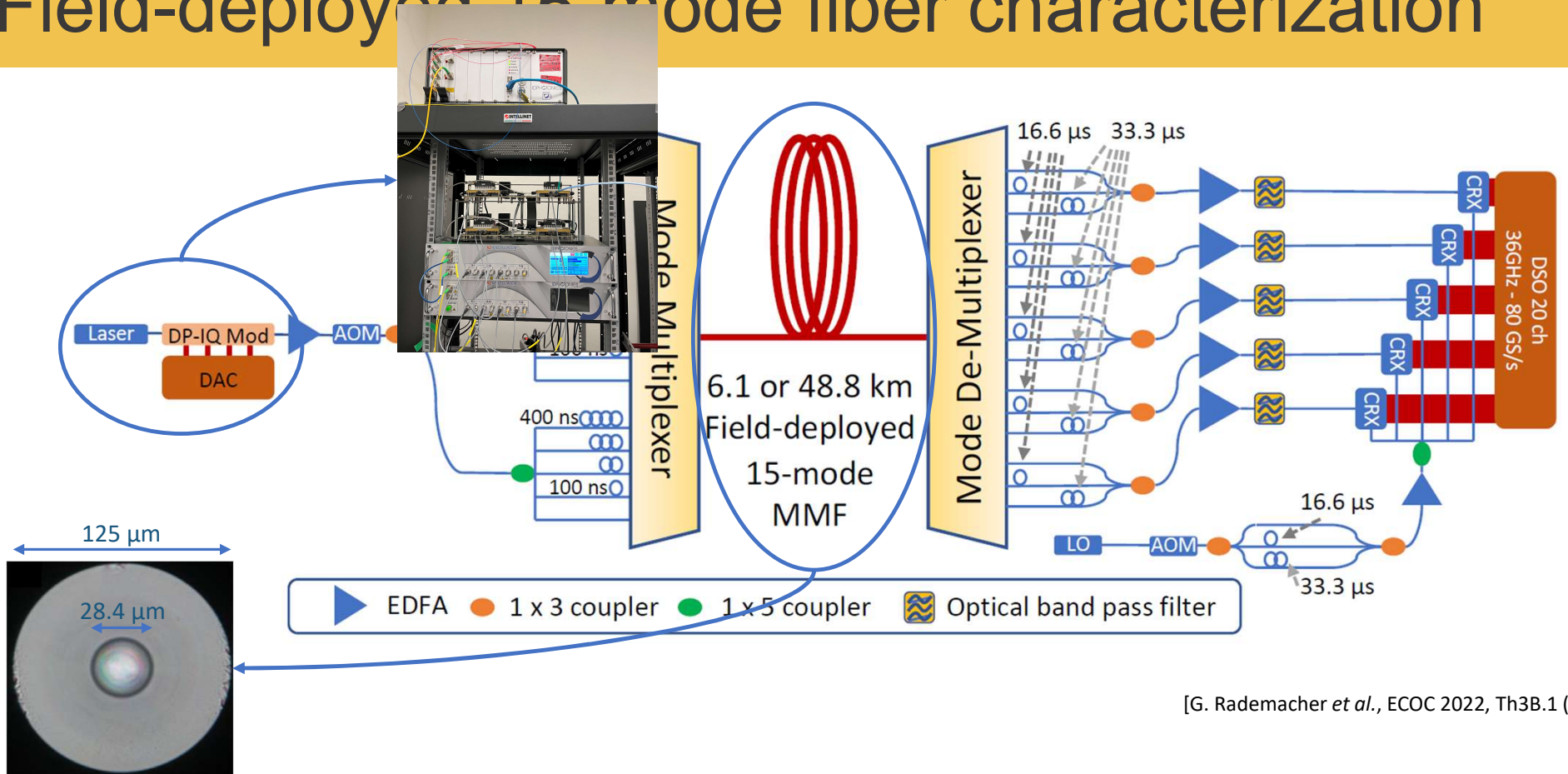
# Field-deployed 15 mode fiber characterization



[G. Rademacher *et al.*, ECOC 2022, Th3B.1 (2022)]



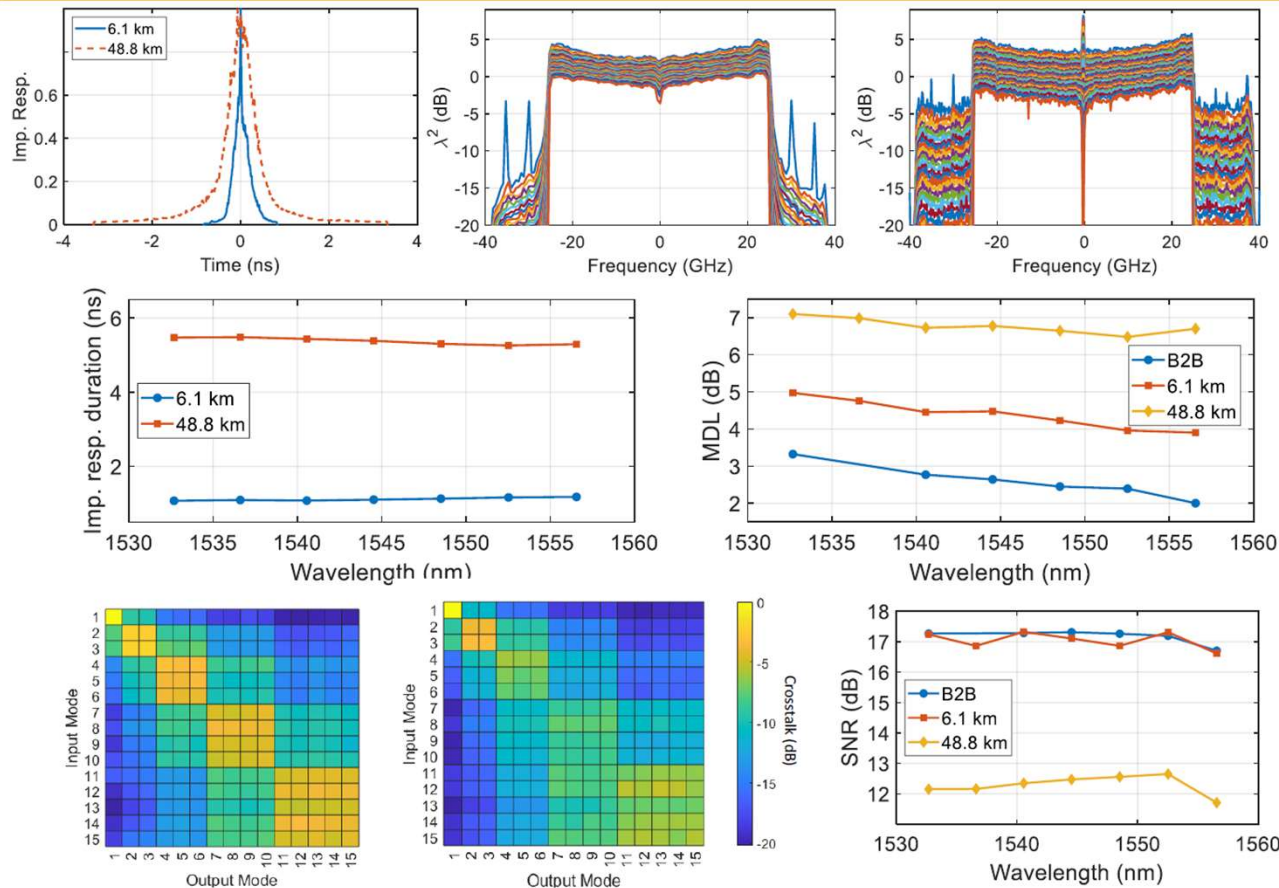
# Field-deployed 15 mode fiber characterization



[G. Rademacher *et al.*, ECOC 2022, Th3B.1 (2022)]



# Field-deployed 15-mode fiber characterization



[G. Rademacher *et al.*, ECOC 2022, Th3B.1 (2022)]





# Spatial super channel switching SDM network node

## Demonstration of a Spatial Super Channel Switching SDM Network Node on a Field Deployed 15-Mode Fiber Network

R. S. Luis<sup>1</sup>, G. Rademacher<sup>1</sup>, B. J. Puttnam<sup>1</sup>, G. Di Sciullo<sup>2</sup>, A. Marotta<sup>2</sup>, R. Emmerich<sup>3</sup>, N. Braig-Christophersen,<sup>3</sup> R. Stolte<sup>4</sup>, F. Graziosi<sup>2</sup>, A. Mecozzi<sup>2</sup>, C. Schubert<sup>3</sup>, G. Ferri<sup>5</sup>, F. Achten<sup>5</sup>, P. Sillard<sup>5</sup>, R. Ryf<sup>6</sup>, L. Dallachiesa<sup>6</sup>, S. Shinada<sup>1</sup>, C. Antonelli<sup>2</sup>, H. Furukawa<sup>1</sup>

- (1) National Institute of Information and Comm. Technology, Koganei, Japan. E-mail : [rluis@nict.go.jp](mailto:rluis@nict.go.jp)
- (2) University of L'Aquila and CNIT, L'Aquila, Italy
- (3) Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institute, Berlin, Germany,
- (4) Finisar Australia, Rosebery, NSW, Australia,
- (5) Prysmian Group, Milano, Italy; Eindhoven, The Netherlands and Haisnes, France
- (6) Nokia Bell Labs, New Jersey, USA

[R. Luis *et al.*, ECOC 2022, Th3C.5 (2022)]





# Field-deployed UC-MCF characterization

## Characterization of Phase Stability and Core-to-Core Delays in a Field-Deployed Uncoupled-Core Multi-Core Fiber Cable

M. Mazur<sup>(1)</sup>, N. K. Fontaine<sup>(1)</sup>, R. Ryf<sup>(1)</sup>, L. Dallachiesa<sup>(1)</sup>, H. Chen<sup>(1)</sup>, D. T. Neilson<sup>(1)</sup>, A. Marotta<sup>(2)</sup>, T. Hayashi<sup>(3)</sup>, T. Nagashima<sup>(3)</sup>, T. Nakanishi<sup>(3)</sup>, F. Graziosi<sup>(2)</sup>, D. Blumenthal<sup>(4)</sup>, M. Harrington<sup>(4)</sup>, F. Quinlan<sup>(5,6)</sup>, A. Mecozzi<sup>(2)</sup>, and C. Antonelli<sup>(2)</sup>

- (1) Nokia Bell Labs, 600 Mountain Ave., Murray Hill, NJ 07974, USA [mikael.mazur@nokia-bell-labs.com](mailto:mikael.mazur@nokia-bell-labs.com)
- (2) University of L'Aquila and CNIT, 67100 L'Aquila, Italy
- (3) Sumitomo Electric Industries, Ltd., 1, Taya-cho, Sakae-ku, Yokohama, Kanagawa, 244-8588, Japan
- (4) University of California at Santa Barbara, Department of ECE, Santa Barbara, CA 9316 USA
- (5) Department of Physics, University of Colorado Boulder, Boulder, Colorado 80309, USA
- (6) National Institute of Standards and Technology, Boulder, Colorado 80305, USA

**Th.B.3.3 – 11:15-11:30, Thursday, 5 October 2023, Boisdale - Ground Floor**



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# Field-deployed 15-mode fiber characterization

## Broadband Characterization of Field-Deployed 15-mode Graded-Index Multi-Mode Fiber Cable

M. Mazur<sup>(1)</sup>, N. K. Fontaine<sup>(1)</sup>, L. Dallachiesa<sup>(1)</sup>, R. Ryf<sup>(1)</sup>, H. Chen<sup>(1)</sup>, D. T. Neilson<sup>(1)</sup>,  
A. Marotta<sup>(2)</sup>, P. Sillard<sup>(3)</sup>, G. Ferri<sup>(4)</sup>, F. Achten<sup>(5)</sup>, F. Graziosi<sup>(2)</sup>, A. Mecozzi<sup>(2)</sup>, and C. Antonelli<sup>(2)</sup>

(1) Nokia Bell Labs, 600 Mountain Ave., Murray Hill, NJ 07974, USA

(2) University of L'Aquila and CNIT, 67100 L'Aquila, Italy

(3) Prysmian Group, Parc des Industries Artois Flandres, Haisnes 62092, France

(4) Prysmian Group, Via Chiese, 6, 20126 Milano MI, Italy

(5) Prysmian Group, Eindhoven 5651 CA, The Netherlands

[mikael.mazur@nokia-bell-labs.com](mailto:mikael.mazur@nokia-bell-labs.com)

**Th.B.3.5 – 11:45-12:00, Thursday, 5 October 2023, Boisdale - Ground Floor**



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Thank you for your  
attention!

**Giammarco Di Sciullo**

*[giammarco.disciullo@graduate.univaq.it](mailto:giammarco.disciullo@graduate.univaq.it)*

Università degli Studi dell'Aquila