Rosenberger

Space Division Multiplexing (SDM) Transmission System Using Optical Multicore Fibers

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Overview

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Space Division Multiplexing (SDM)

Channel Capacity Limits of Optical Fibers

Information Theory: Shannon-Hartley Theorem

Definition: Channel Capacity

$$Cn = 2B \cdot ld\ (L)$$

L:	Number of symbols (1Bit-Coding: 2; 2Bit-Coding: 4; ….)
B:	Bandwidth [Hz]
C_n:	Maximum Data Transmission Rate [Bit/s]

Shannon-Hartley Theorem/Shannon-Limit:

Channel capacity is limited by the *Signal-to-Noise Ratio* in the transmission system:

$$Cs = B \cdot ld\ (1 + \frac{S}{N})$$

B:	Bandwidth [Hz]
C_s:	Channel Capacity Limit [Bit/s]
S:	Signal Power
N:	Noise Power

Signal-to-Noise-Ratio reduced with increasing Bit/Symbol coding => fundamental capacity limit

Space Division Multiplexing (SDM)

Channel Capacity Limits of Optical Fibers

Non-Linear Effects in Optical Fibers

Optical fiber capacity limit influenced by material-dependent effects:

- Non-linear Kerr-effect:
  - Phase instabilities at higher electrical field amplitudes
- Brillouin scattering:
  - Signal reduction at higher power amplitudes
- Crosstalk between adjacent WDM channels => S/N reduced
- Fiber fuse effect: maximum power over all wavelengths limited to 1-2 W

Non-Linear Shannon-Limit in Optical Fibers: ≈ 100 TB/s (C-Band)
≈ 200 TB/s (S+C Band)

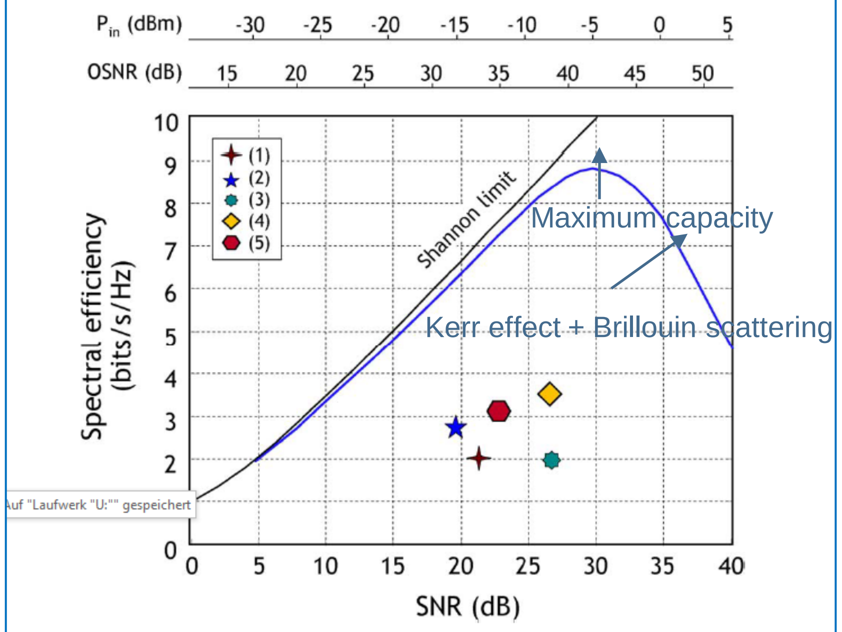

Fig. 38. Spectral efficiency results for recent record experiments. The capacity limit estimate curve for 500 km transmission of Fig. 35 is shown for comparison. There is about a factor three between the capacity limit estimate and the record capacities. The experimental data, labeled (1)–(5) in the legend, are from [200]–[204]. The upper axes apply only to the capacity limit estimation curve.

Source: Capacity Limits of Optical Fiber Networks
René-Jean Essiambre et. al., J. of Lightwave Technology, vol. 28, no. 4, Feb. 15, 2010

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Space Division Multiplexing (SDM)

Capacity Limit of Optical Fibers

Multiplexing Methods

Time **D**omain **M**ultiplexing (e.g. G-PON)

Wavelength **D**ivision **M**ultiplexing (CWDM, DWDM)

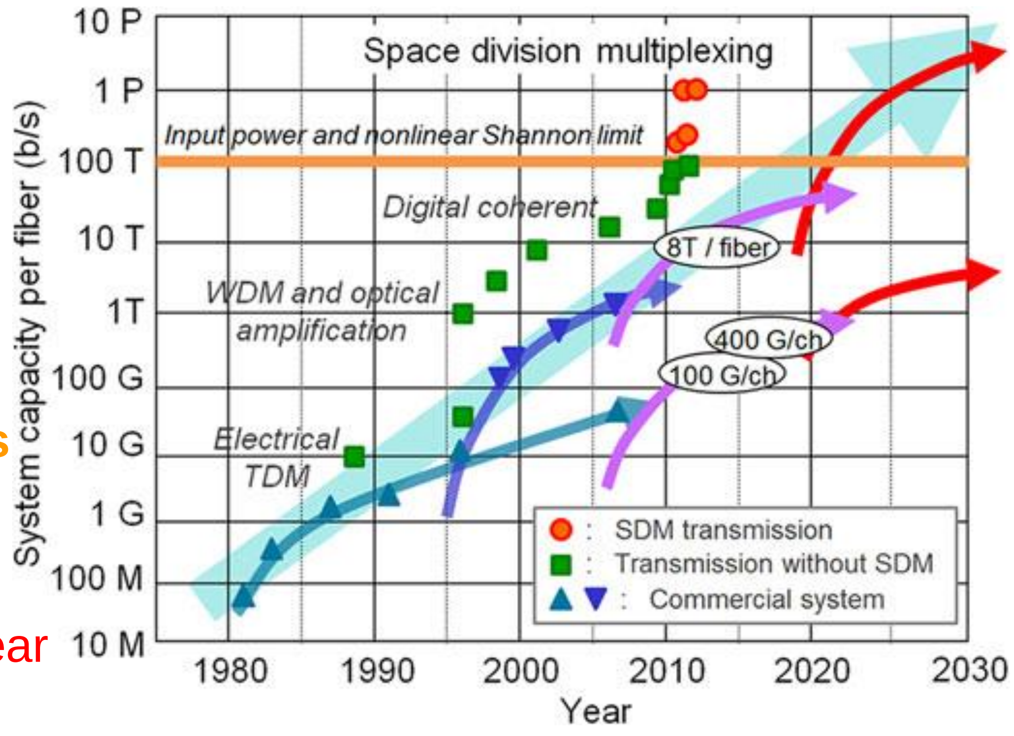
Digital Coherent: Phase- or/and amplitude modulation techniques (e.g. PAM-4, D-QPSK, 64-QAM, etc.)

Non-Linear Shannon-Limit in Optical Fibers: 100 - 200TB/s

⇓

Space-Division-Multiplexing (SDM):

- solution to increase fiber capacity beyond the Non-Linear Shannon limit of 100TB/s
- spatial concentration of **parallel optical structures**



Source: T. Mizuno *et al.* J. of Lightwave Technology, Vol. 34, No. 2, 2016

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Space Division Multiplexing (SDM)

Fibers for Space Division Multiplexing

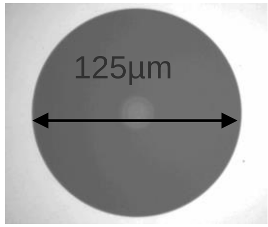
Data transmission capacity increase by fiber bundling/new fiber types

Fiber Ribbons:

- Maximum spatial compression of standard SM-/MM-fibers
- Ribbons with reduced pitch (180-200µm instead of 250µm) ready for deployment

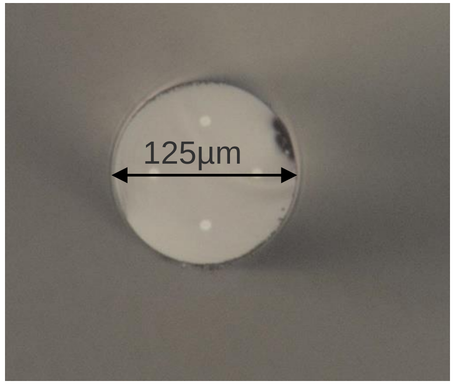
Few-Mode Fibers (FMF):

- 2-mode-/4-mode fibers
- Fiber diameters: 125µm



Multicore fibers (MCF):

- Improved mode guidance compared to FMFs
- Crosstalk can be modified by variation of core pitch (strong vs. weak coupling)
- Singlemode and multimode cores available
- System compatibility issues favor a fiber diameter of 125µm:
  - 4-,7- and 8-core designs are common



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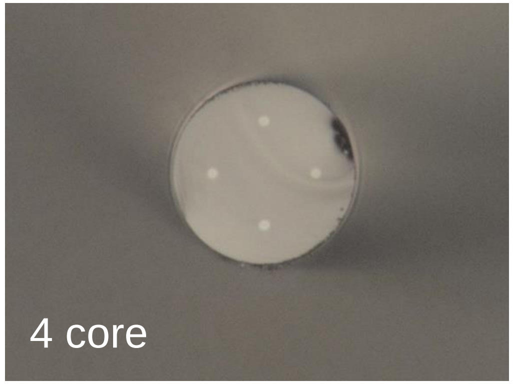
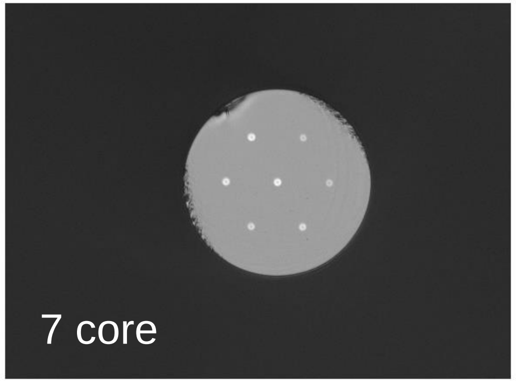
Space Division Multiplexing (SDM)
Multicore Fibers (MCF)

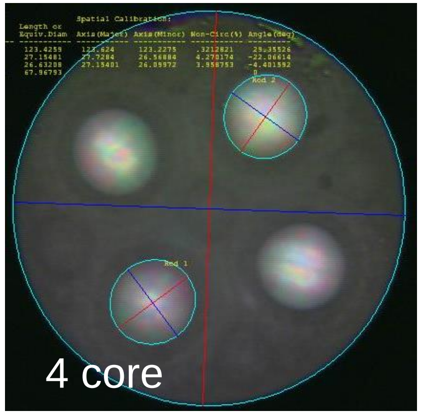
Multicore fibers, diameter: 125µm

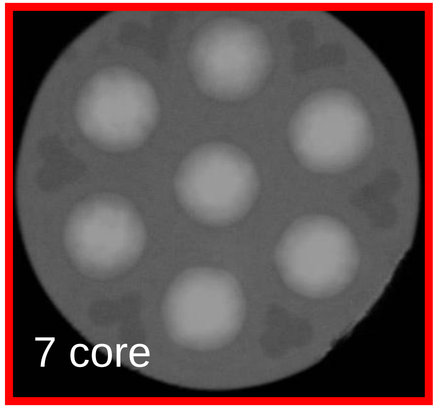
Singlemode:





Multimode:





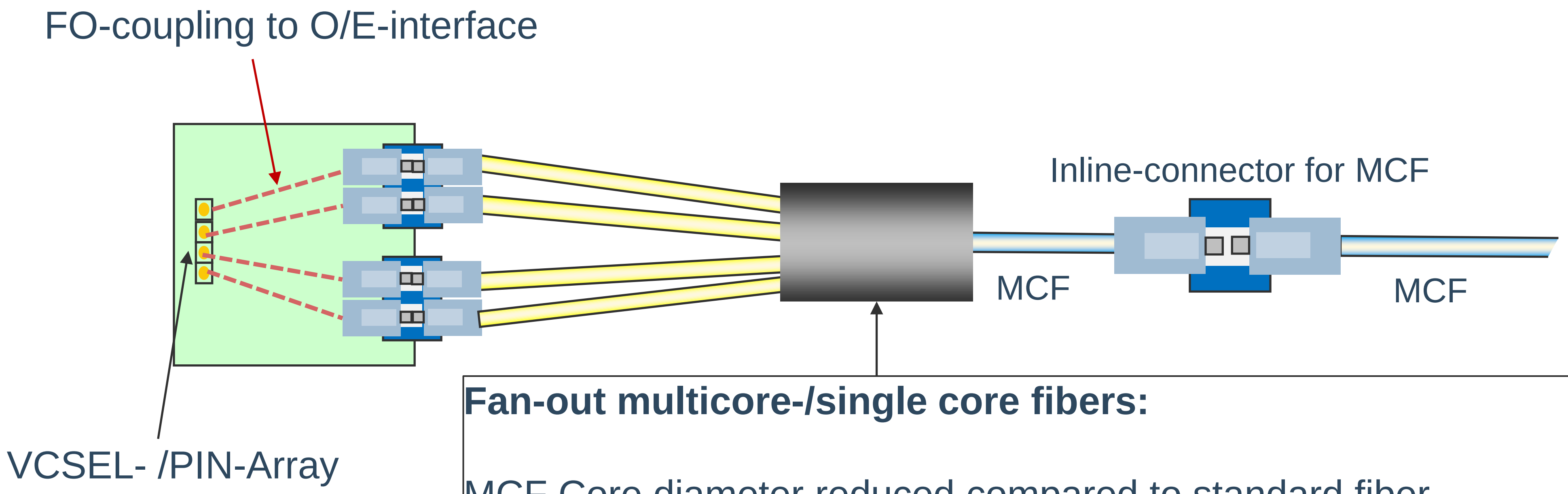
Source: Data Sheet OFS

- Publicly funded research project PRIMA was carried out using a 7-core-multimode fiber TFT080428 from OFS
- Why Multimode?
  Coupling between active components and MCF cores was considered easier using multimode cores
- ∅ core: 26µm
- core pitch: 39µm

Overview

SDM Data Transmission Systems
MCF Transmission Systems

Typical Setup of a state-of-the-art MCF data transmission system



Fan-out multicore-/single core fibers:

MCF Core diameter reduced compared to standard fiber

⇒ Low loss adiabatic tapers (with quite large length) additionally required within the fan-out

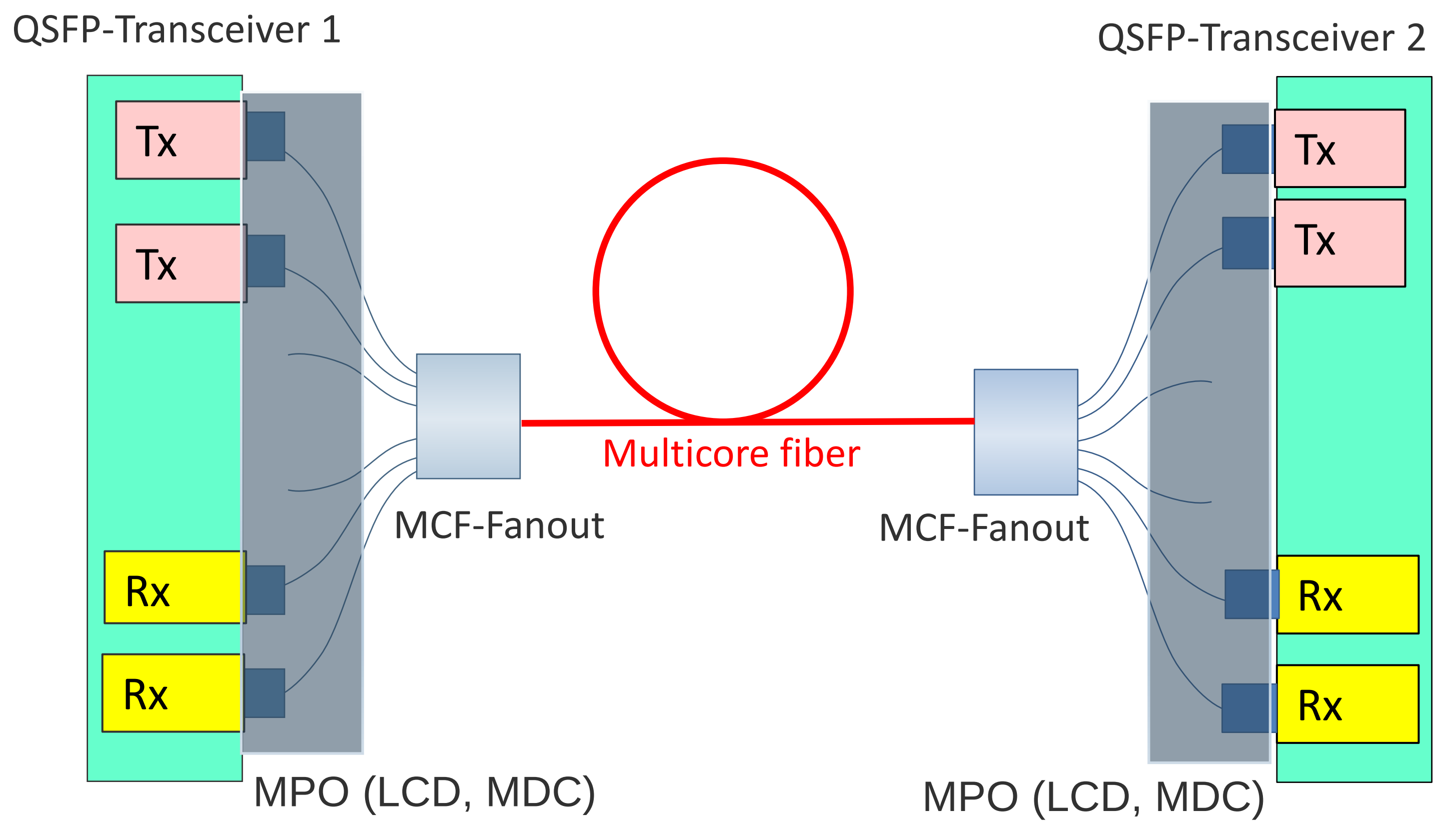
⇒ High Fan-out cost > 1000 €/pcs

SDM Data Transmission Systems

MCF Transmission Systems

MCF-Coupling to QSFP-Transceiver

Setup for 4- /7-Core-Fibers



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Overview

Research Project PRIMA

Data Transmission System for Multicore Fibers

Publicly Funded Reserach Project

The Research Project PRIMA was funded by the German ministry for education and research (BMBF)

Global Funding Measure:

Photonics made to measure - Functionalized materials and components for next-generation optical systems

Research Project:

Printed Freeform **M**icro-Optics for Tailored Photonic **A**ssemblies **(PRIMA)**

PRIMA Subproject with reference to multicore fibers:

Hybrid Transceiver Assemblies for multicore fibers

Project Partners:

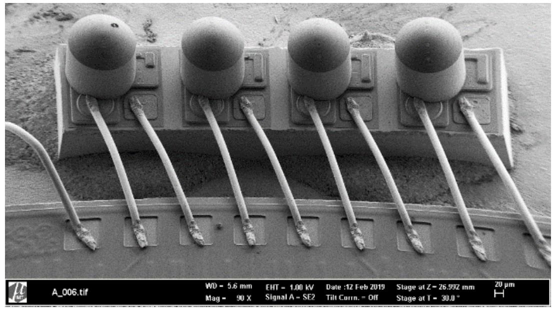
- FiconTEC Service GmbH, Achim
- Vanguard Photonics GmbH, Karlsruhe
- Karlsruhe Institut für Technologie
- Rosenberger Hochfrequenztechnik GmbH&Co, KG, Fridolfing

Bundesministerium für Bildung und Forschung

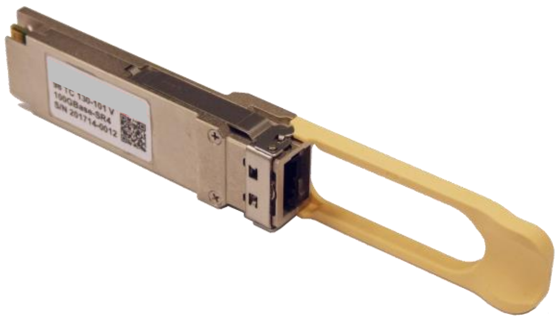
Research Project PRIMA
Data Transmission System for Multicore Fibers

Project Scope

- Setup of an optical transceiver concept for multicore fibers



- Application of 3D printed freeform elements for optical coupling
- Transceiver PCB shape/mechanical footprint: **QSFP module**



- Transmission system: Ethernet IEEE 802.3 bm: 100GBASE-SR4, 25 GBaud, multimode, wavelength: 850 nm

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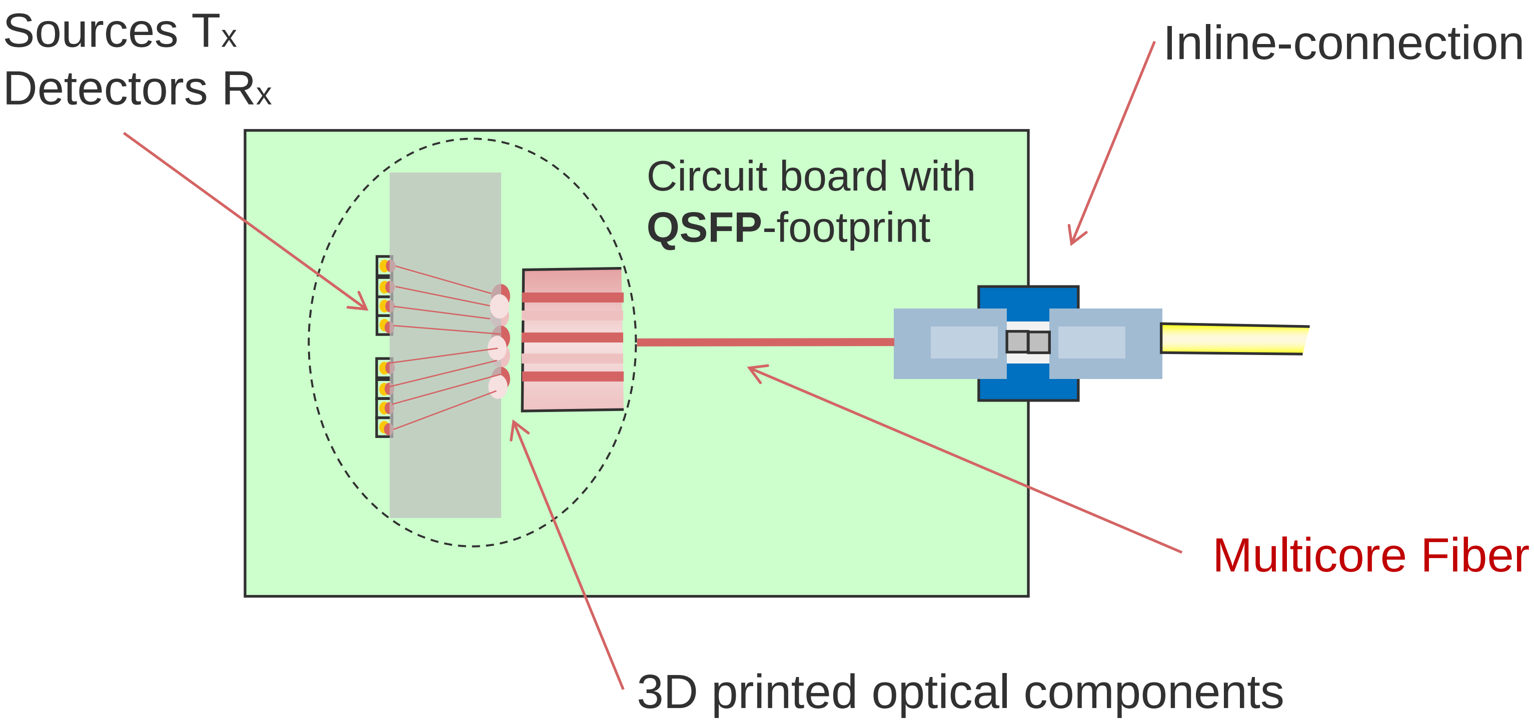
Research Project PRIMA
Data Transmission System for Multicore Fibers

Concept of the MCF data transmission system

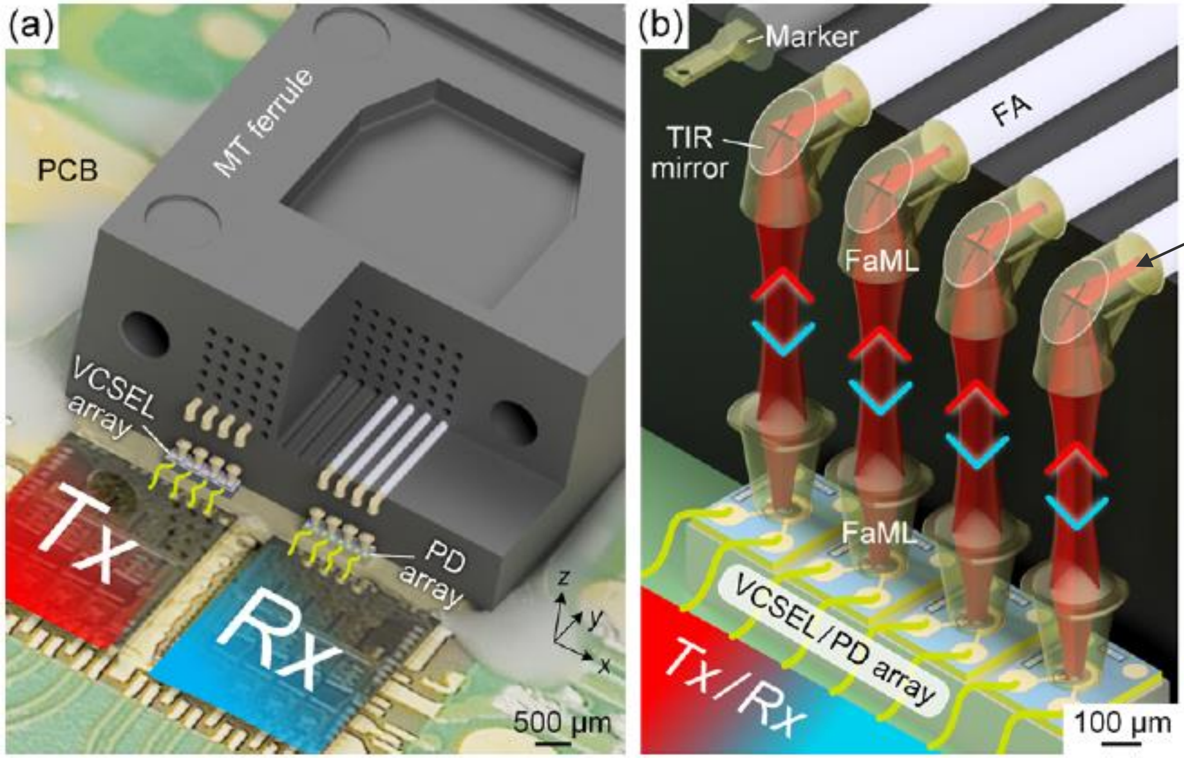
- Direct light coupling between MCF and O/E-conversion components **without implementation of MCF fanouts**

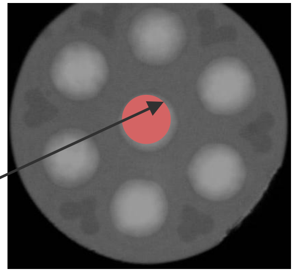


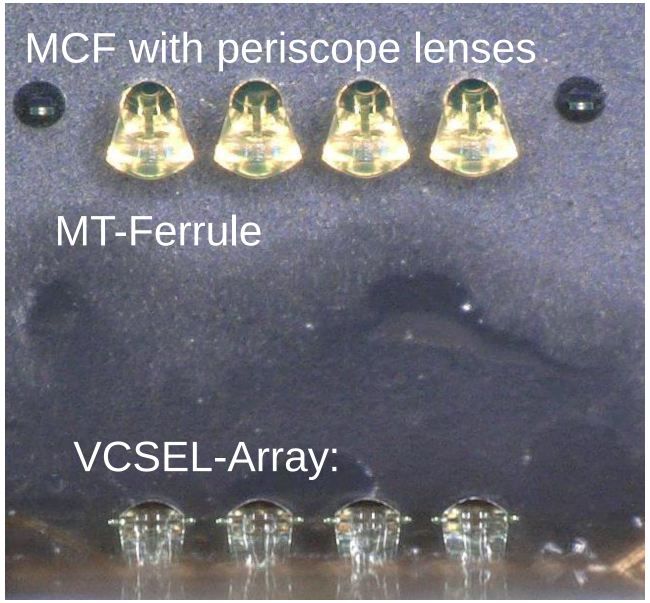
Research Project PRIMA
Preliminary Demonstration Unit

Evaluation of coupling efficiency of 3D printed lenses

Coupling of light into the central core of the 7-core-multimode fiber over 3D-printed lenses put on active components and fibers.







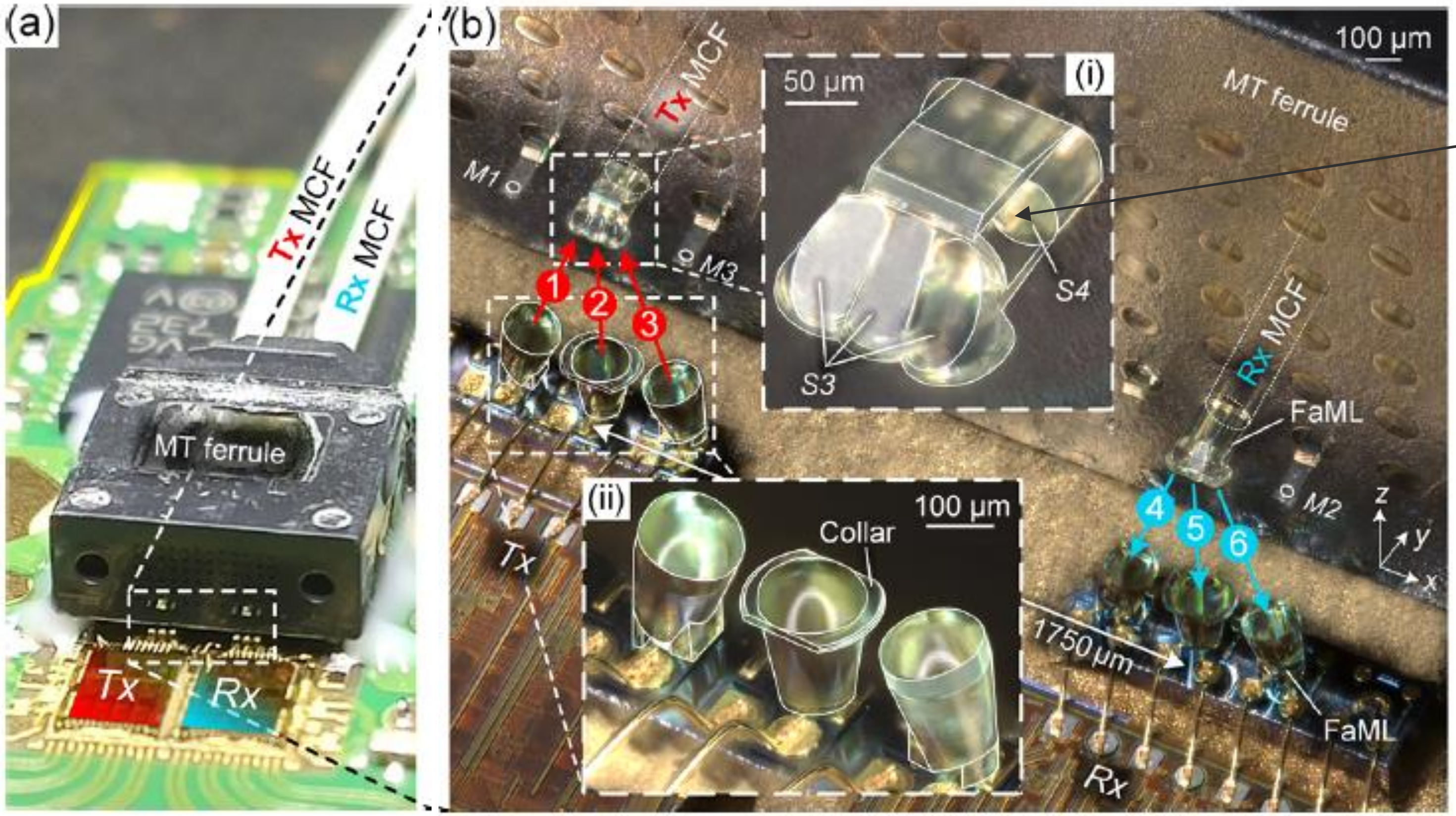
Ref: P. Maier, Y. Xu, M. Trappen, M. Lauermann, A. Henniger-Ludwig, H. Kapim, T. Kind, P.-I. Dietrich, A. Weber, M. Blaicher, C. Wurster, S. Randel, W. Freude, C. Koos
3D-printed facet-attached optical elements for connecting VCSEL and photodiodes to fiber arrays and multi-core fibers, in *Optics Express Fiber, Vol. 30, No. 26, 2022*

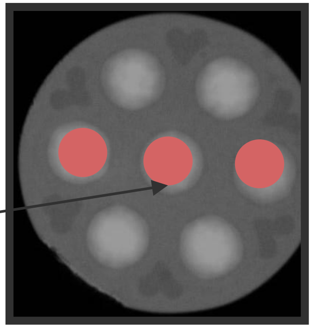
Research Project PRIMA

Final Demonstration Unit

Final setup for the MCF data transmision system without fanout

3-channel transceiver module





7-Core-MCF
Multimode

3 Cores in use

- 3 Periscope lenses on MCF endface
- 3 lenses (1,2,3 and 4,5,6) printed on VCSEL and PIN array

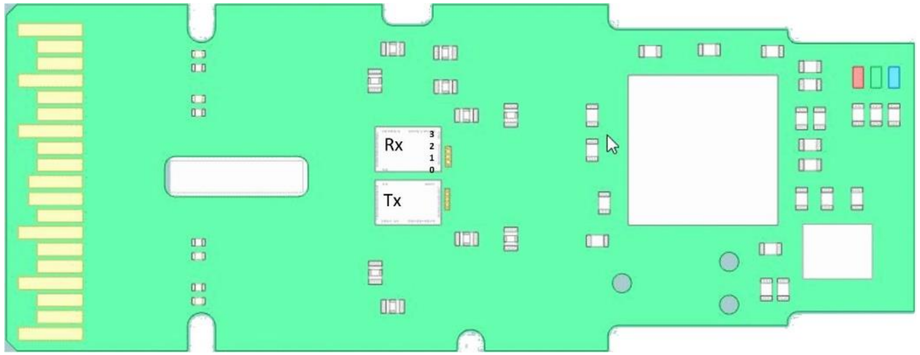
Ref: P. Maier, Y. Xu, M. Trappen, M. Lauermann, A. Henniger-Ludwig, H. Kapim, T. Kind, P.-I. Dietrich, A. Weber, M. Blaicher, C. Wurster, S. Randel, W. Freude, C. Koos
3D-printed facet-attached optical elements for connecting VCSEL and photodiodes to fiber arrays and multi-core fibers, in *Optics Express Fiber, Vol. 30, No. 26, 2022*

Overview

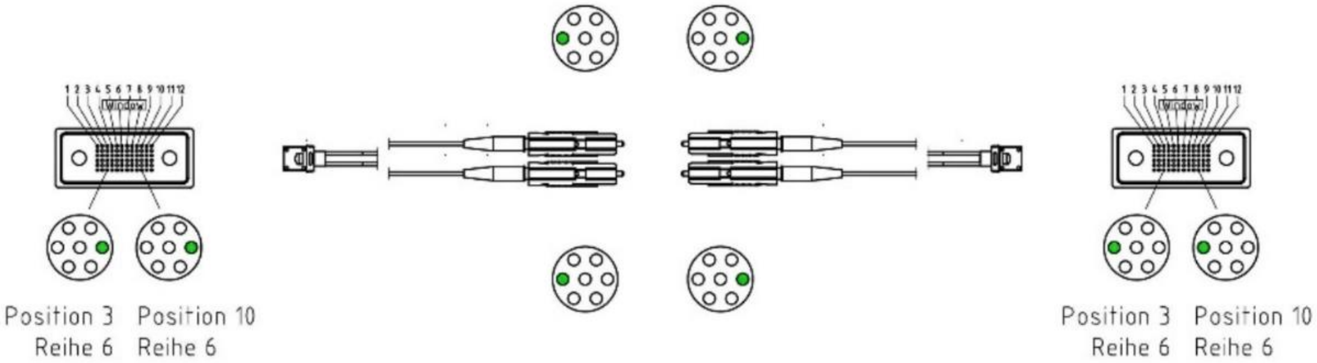
Passive Fiber-optic Components of Multicore Transmission Systems
Transceiver Assembly

Components

1. Assembled PCB for transceiver with QSFP-footprint, VCSEL- and PIN-Arrays (T_x and R_x) mounted



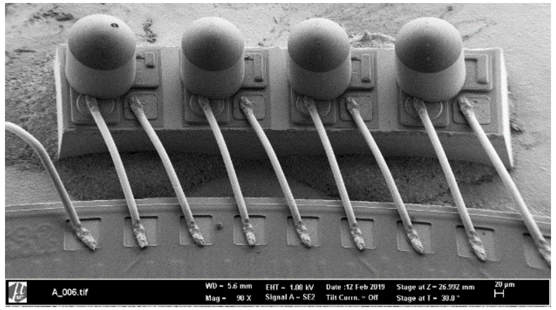
2. MCF-cable assembly/MT-ferrule MU-Duplex for FO-coupling with channel coding description



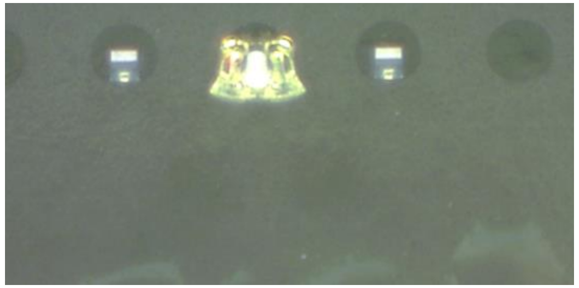
Passive Fiber-optic Components of Multicore Transmission Systems
Transceiver Assembly

3D Printing and final termination

- **Step 1**: 3D-printing of beam forming elements on VCSEL-/PIN-Array and MCF

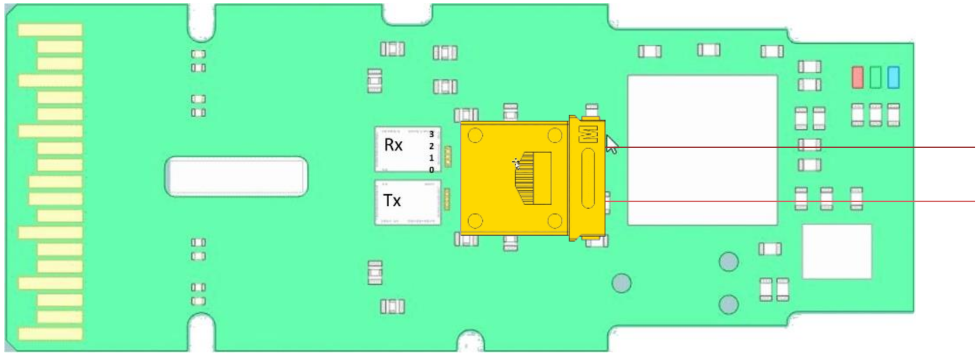


3D-printing of collimating lenses on VCSEL-/PIN-Array



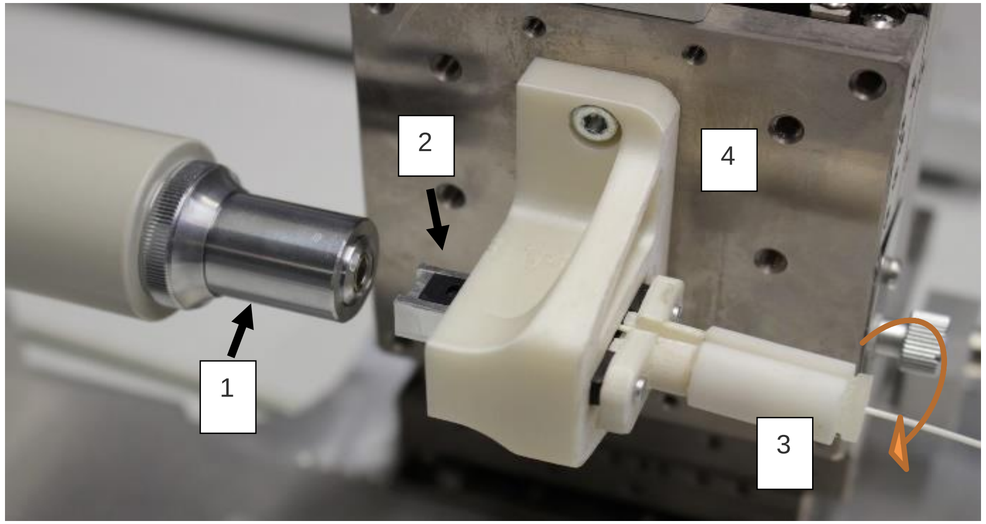
3D-printing of 3 periscope lenses on MCF terminated in a MT ferrule

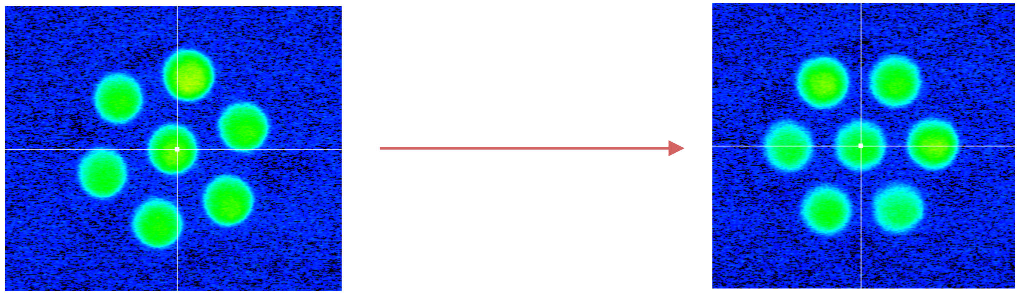
- **Step 2**: Positioning, (active) alignment and fixing of the MT-Ferrule on the PCB using a fully automatic positioning machine



Passive Fiber-optic Components of Multicore Transmission Systems
MT Ferrule

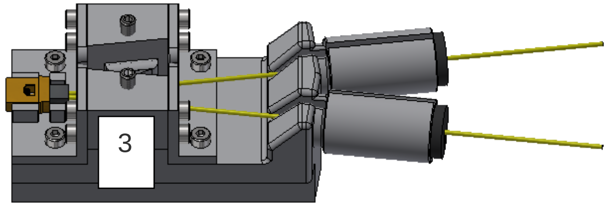
Manual MCF rotational alignment in a MT-ferrule



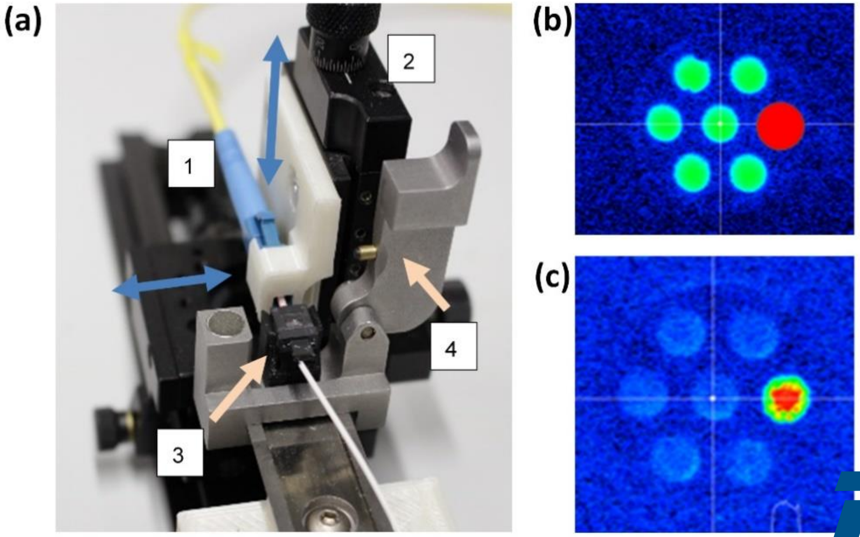


MCF core position monitoring using a near-field microscope

(1) Near-field microscope
(2) MT-ferrule holder
(3) MCF rotation device
(4) 3 axis linear stage



Fiber path control:



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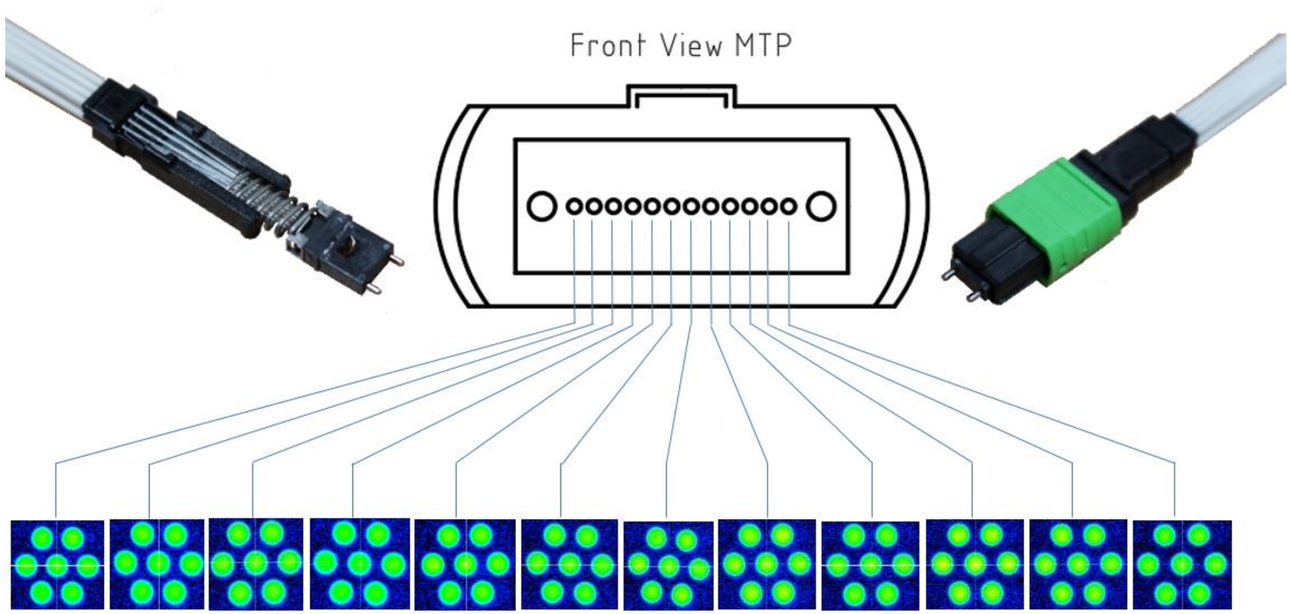
Passive Fiber-optic Components of Multicore Transmission Systems
MT Ferrule

Manual rotational MCF Alignment in a fully loaded MT ferrule



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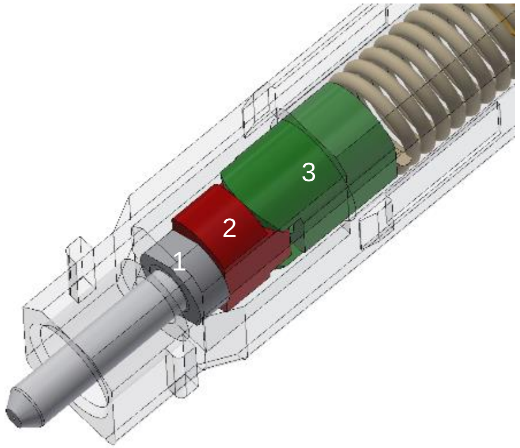
Passive Fiber-optic Components of Multicore Transmission Systems
Inline Connector

MCF-optimized MU connector

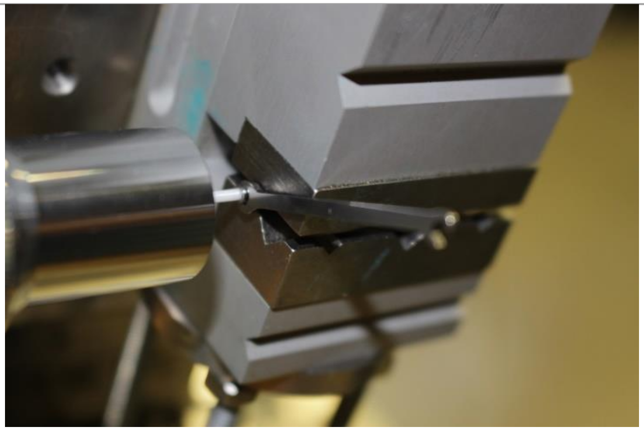
MCF-optimized MU-connector acc. to IEC 61754-6



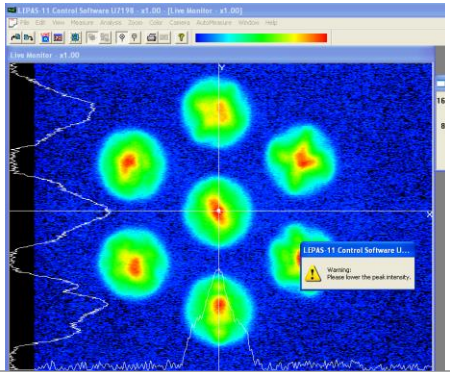
<u>Modification of the ferrule holder:</u>

- Ferrule holder flange, continuously rotatable (1)
- Plastic components to enable lateral movement in x an y direction (2), (3)
- Ferrule holder tilting is blocked

<u>Ref.</u> R. Nagase, K. Sakamaie, K. Watanabe, T. Saito, MU-Type Multicore Fiber Connector, IEICE Trans. Electron., Vol.E96–C, 1173,.No.9, September 2013



Ferrule rotational alignment device
Verification with near-field microscope



Overview

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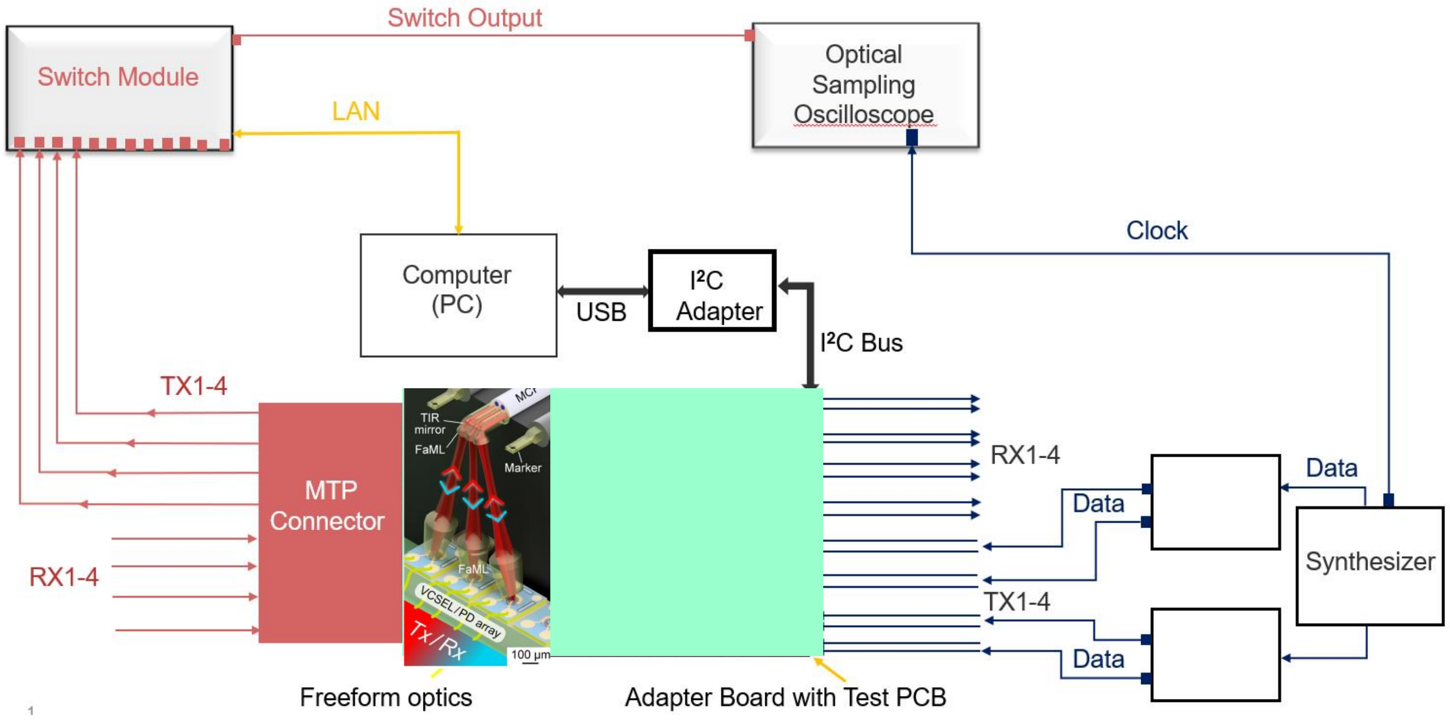
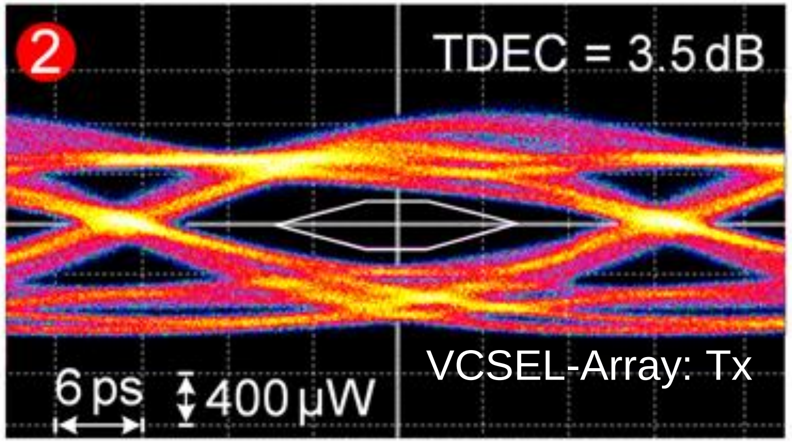
Test results

Tx-characterization

Test Setup acc. to IEEE 802.3 bm/ 100GBASE-SR4



25 GBaud@850 nm/channel
TDEC limit: 4,3 dB
MCF: central core

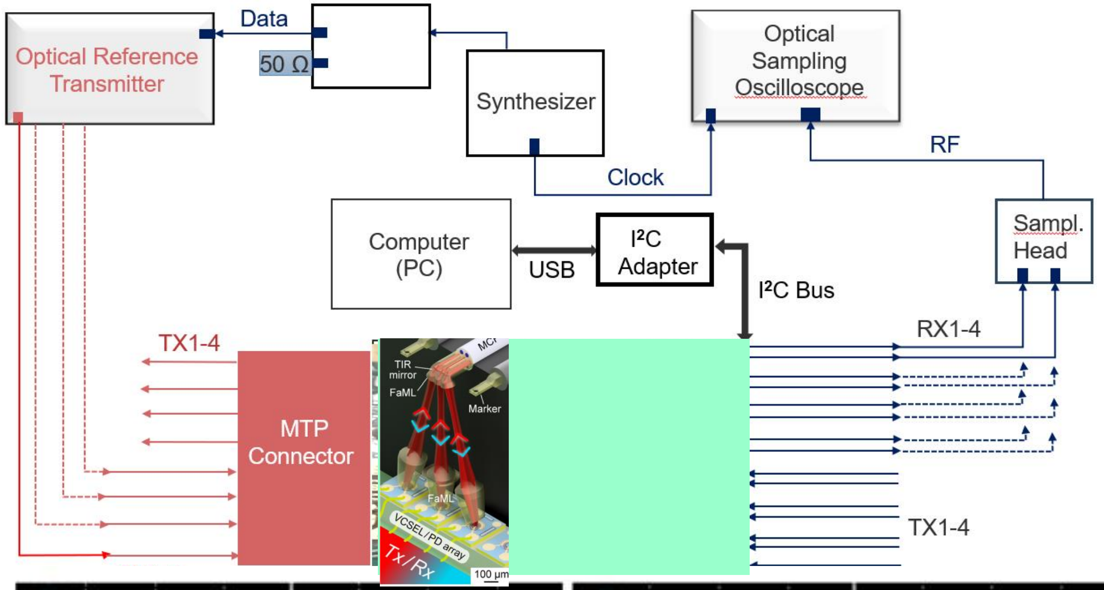


Ref.: P. Maier et al., 3D-Printed Optical Elements for Coupling of VCSEL and Photodiode Arrays to Multi-Core Fibers in an SFP Transceiver Assembly, in *Optical Fiber Communication Conference (OFC) 2022*, Technical Digest Series, paper W2A.1.

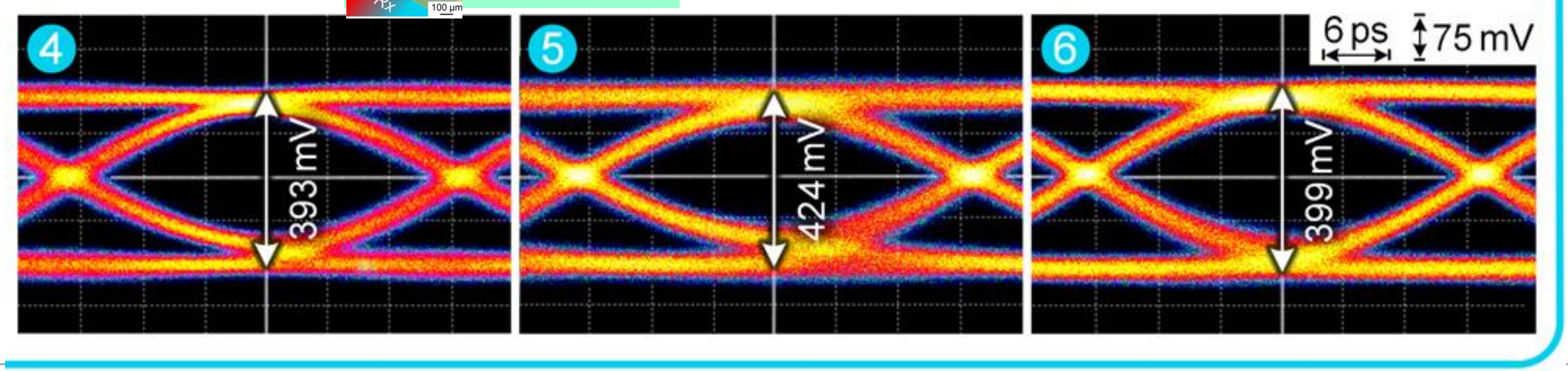
Test results

Rx-characterization

Test Setup acc. to IEEE 802.3 bm/ 100GBASE-SR4



- Ideal reference laser source 850 nm
- Clock recovery active



Ref.: P. Maier et al., 3D-Printed Optical Elements for Coupling of VCSEL and Photodiode Arrays to Multi-Core Fibers in an SFP Transceiver Assembly, in *Optical Fiber Communication Conference (OFC) 2022* Technical Digest Series, paper W2A.1.

Test Results

Evaluation

- 3D-printed optical elements (lenses, periscopes etc.) are suited to establish a effective FSO* coupling between individual MCF cores and active components like VCSEL/PIN diode arrays.
- The results of T_x- and R_x-characterization of the MCF transceiver demonstration unit showed us that the requirements of the IEEE 802.3 bm Ethernet standard can be met without using a state-of-the-art MCF-fanout.
- T_x characterization results leave a margin for the improvement of the optical coupling efficiency
- Signal-to-Noise ratio and thermal position and shape stability of the lenses of the demonstration unit leave a further margin for improvement

*FSO: Free Space Optics

Overview

Summary

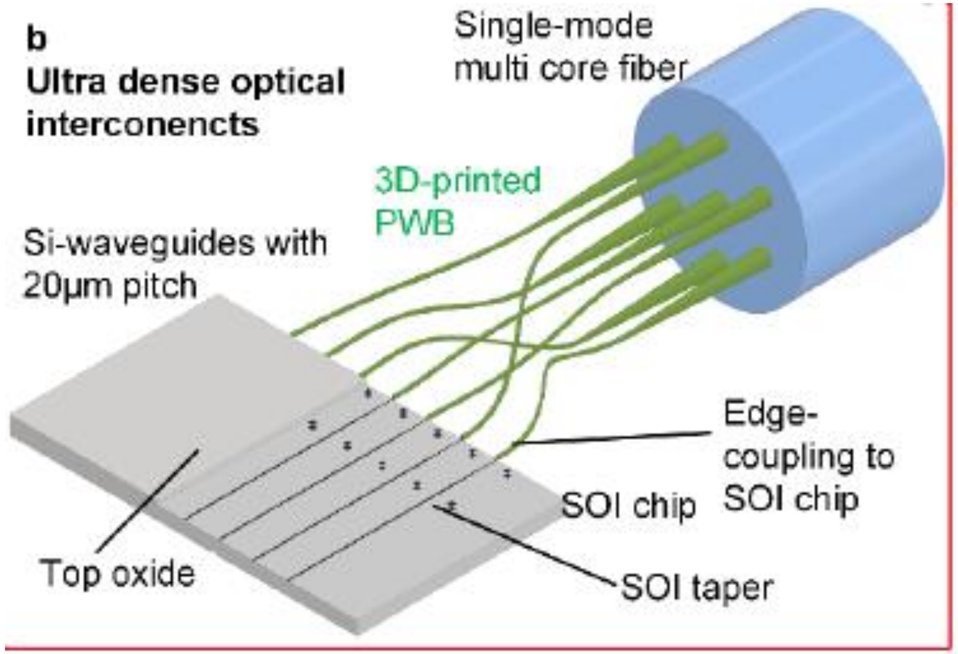
- SDM data transmission system with multicore fibers was designed without using fan-outs on single core fibers and conventional fiber-optic transceivers
- Instead of using fiber-optic fan-outs multicore fibers and active components are linked with a free-space-optics (FSO) connection.
- This FSO connection is created by lenses directly printed on fiber endfaces and VCSEL/PIN diode surfaces
- A QSFP style 100G-Ethernet multimode transceiver demonstration unit was built acc. to IEEE 802.3 bm (100GBASE-SR4)
- MT ferrules were used to attach MCFs to the QSFP-type board
- Several devices for a manual rotational alignenment of MCFs in MT ferrules were built
- A MU-type inline connector optimized for MCF was developed as transceiver interface
- A demonstration unit with 3 active cores was evaluated acc. to IEEE 802.3bm (25GBaud, WL: 850 nm) with following results:
  - Multichannel 25GBaud-Ethernet over multicore fiber without fan-outs is feasible
  - IEEE802.3bm requirements could be met
  - FSO between VCSELs (T_x) and MCF still needs some improvement

Outlook

Continuation in a new funded research project

Demonstration unit with Photonic Wirebonds

- MCF singlemode transceivers to be designed
- Attachment between MCFs and waveguide chips containing active components via photonic wirebonds
- Demonstration units with 4-Core or 7-Core singlemode fibers



Ref.: Photonik Wire Bonding as a Novel Technology for Photonic Chip Interfaces
Lindenmann, Nicole
2018 ; Karlsruhe Series in Photonics and Communications / Karlsruhe Institute of Technology, Institute of Photonics and Quantum Electronics (IPQ) ; 21

Special Thanks to

- Team Rosenberger OSI: M. Brechtel, C. Hahn, M. Komarow, W. Vogelsang
- Team Rosenberger Hochfrequenztechnik: A. Henniger-Ludwig, H. Kapim, S. Schmidt
- Team KIT: C. Koos, Y. Xu, M. Trappen
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