High-Throughput Optical Transmission Experiments with Space-Division Multiplexing

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• Introduction to SDM and SDM fibers

• Homogeneous multi-core fibers
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The final frontier

- **On-Off keying (OOK)**

- **16-Quadrature amplitude modulation (QAM)**

- **Binary phase-shift keying (BPSK)**

- **Space**

- **Power**

- **Wave length**
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
  - Signal mixing

- **Coupled-core multi-core fibers**
  - No skew
  - Signal mixing

**Simultaneous reception**
- **NOT required**
  - MIMO optional

- **Required**
  - MIMO required
Transmission experiments with SDM fibers

**Apparatus key**
- MCF = Multicore fiber
- SMF = Single mode fiber
- NT = Interleaver
- OP = Optical proc.
- C/L EDFA = C/L EDFA
- Opt. filter = Optical filter
- VOA = Variable optical attenuator
- WDM coupler = WDM coupler
- Power coupler = Power coupler
- Pol. cont. = Polarization controller
- Pol. beam combiner = Polarization beam combiner
- Decorrelation fiber = Decorrelation fiber

**Test-channel band**
- Comb Tx.
- 25 GHz comb

**SDM Transmission**
- 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 coupled core MCF
- 60 km 3-core coupled core MCF
- 28 km 15-mode fiber

**Comb Tx.**
- U.bhm OBPF
- Odd Ch.
- Even Ch.
- SP-IQ
- SP
- KWG
- Non-measurement band

**SDM Receiver**
- CoRx 80Gs/s 32GHz

**Results**
- 2020: 10.66 Pb/s
- 2015: 2.15 Pb/s
- 2018: 1.2 Pb/s
- 2022: 1.02 Pb/s

**Fiber Types**
- 305 μm
- 260 μm
- 220 μm
- 160 μm

**Fiber Specifications**
- 3.5 km 4-core few-mode MCF: 160 μm
- 28 km 15-mode fiber: 125 μm
- 2020: 1.01 Pb/s
- 2022: 1.02 Pb/s
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 resource sharing. Recent SDM research in the United States has focused on multi-mode SDM fiber with shared guidance.
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• 1 Pb/s transmission in a 15-mode fiber

• 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)

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

- Excellent gain performance
- Each core can be switched ON/OFF
- No independent pump control
- Performance optimization difficult
- Pump laser power consumption
- Only one pump combiner
- High pump powers

Cladding-pumped EDFA

- Number of pump combiners = number of cores

S. Takasaka et al., ECOC 2013, We.4.A.5
19 core EDFA Transmission

Apparatus key

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Comb

Tx.

Test-channel band

Even Ch.

Odd Ch.

Op-IQ

AWG

Non-measurement band

25 GHz comb

SDM Mux.

SDM Demux.

SDM Mux.

SDM Demux.

Load AOM

Loop AOM

Pol. Scr.

Pol.

DP

IQ

4 Ch. AWG

DP

IQ

SP

IQ

19-core C/L band EDFA

31.4 km MCF

CoRx 80Gs/s 32GHz

Rx. Path

>40dB to reduce intra-band crosstalk

Notch for Test Band

Relative power (dB)

Wavelength (nm)

Res: 0.1nm

Res: 0.02nm

1530 1540 1550 1560 1570 1580 1590 1600 1610
-60
-50
-40
-30
-20
-10
0
Rel. pwr (dB)
Wavelength (nm)

1546 1547 1548
-60
-40
-20
0
Rel. power (dB)
Wavelength (nm)
19 core EDFA Transmission

Test Band

Test channel

Rel. pwr (dB)
Wavelength (nm)

Res: 0.02nm

255 MHz
19 core EDFA Transmission

Apparatus key

- MCF = Mode-Comb Fiber
- SMF = Single-Mode Fiber
- INT = Interleaver
- OP = Optical Pump
- C/L EDFA = C-band/L-band EDFA
- Opt. filter = Optical Filter
- VOA = Variable Optical Attenuator
- WDM coupler = Wavelength Division Multiplexing Coupler
- Power coupler = Power Coupler
- Pol. cont. = Polarization controller
- Pol. beam combiner = Polarization beam combiner
- Decorrelation fiber = Decorrelation Fiber

Rx. Path

- Q-factor/BER
- GMI
- Decoded throughput
19-core cladding pumped EDFA

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

S. Takasaka et al., ECOC’17 pp TH.2.D

inner glass cladding
Marker
Low index Polymer outer cladding
38 μm

Hexagonal double cladding structure EDF
• Total throughput after decoding 715 Tb/s after 2009.6 km
  – (64 recirculations, 345 wavelength channels)
• Decoded data throughput approximately 90% of GMI estimate
• 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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• Conclusions – SDM and Beyond
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., 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

  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


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
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

Increasing resources
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.
Spatial dimension in networking

Masahiko Jinno, JOCN, 11(3), 2019
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.
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• Conclusions – SDM and Beyond
Impact of enlarged cladding diameter fibers

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

D. Soma et al., ECOC 2015.

B. J Puttnam et al., CLEO 2012.

T. Kobayashi et al., OFC 2017.

H. Takahara et al., ECOC 2012.

D. Qian et al., FIO 2012.

D. Kong et al., CLEO 2020.

G. Rademacher et al., ECOC 2020.

R. Luis ECOC 2018

G. Rademacher et al., ECOC 2020.

B. J Puttnam et al., CLEO 2022.

G. Rademacher et al., ECOC 2022.
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 >519Gbd/s/A PDM-128QAM Signals’, ECOC’18 Mo4G.1

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

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

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

CLEO’22 JTh6B
Transmission set-up

- 31 channel test - band with highest quality PDM-256-QAM modulation
- Dummy wavelength channels modulated in single polar modulators with PDM emulation
- S-band dummy channels wavelength converted from L-band in flat dispersion HNLF
- 80 Gs/s, 36 GHz scope for offline processing after coherent reception
- 5 x 40 mW Raman pumps (1424.3 to 1452 nm) and 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 80 Gs/s, 36 GHz scope for offline processing after coherent reception
Wideband spectra and Raman gain

Fiber Transmission

Amp + SDM split

4-core 51.7 km MCF

4-core Raman pump MUX

SDM Demux

Core/band select switches

Receiver

CoRx 80Gs/s 36 GHz

Fiber input spectrum

Output spectrum without Raman

Wavelength (nm)

Relative power (dB)

Span loss (dB)

0
-10
-20
-30
1460 1480 1500 1520 1540 1560 1580 1600 1620

10 11 12 13

Fiber Transmission

Raman pumps

4-core SDM Mux

4-core SDM Demux

AWG

HNLF

WC

2W EDFA

Test band

OP

C

L

OP

L

C

OP

4 Ch. AWG

OP-IQ

test Ch.

OP

C

L

OP

L

C

OP

OP

OP

OP

OP

OP

OP

SP-IQ

AWG

2W EDFA

HNLF

WC

OP

C

L

OP

L

C

OP

2W EDFA

HNLF

WC

OP

C

L

OP

L

C

OP

Dummy λ-band

1543.1 nm

TL Ph-mod

OP

C

L

OP

L

C

OP

OP

OP

OP

OP

OP

OP

OP

OP

OP

OP

2W EDFA

HNLF

WC

OP

C

L

OP

L

C

OP

2W EDFA

HNLF

WC

OP

C

L

OP

L

C

OP

C-band pump ± L-band

OP

C

L

OP

L

C

OP

C-band pump ± L-band

Apparatus key

= Power coupler

= C/L WDM coupler.

= S/C+L WDM coupler

= VOA

= C/L EDFA

= Pol. cont.

= Tunable band-pass filter (TBPF)

= C/L EDFA

= Pol. cont.

= Tunable band-pass filter (TBPF)

= T DFA

= Tunable laser

= Optical processor

= Optical circulator

= Decorrelation fiber

= power/OSA Monitor

32
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

CLEO’22 JTh6B
3000 km wideband transmission

- 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

OFC’21 F3B.3
Spectrum evolution over distance

**Apparatus key**
- **VOA** = VOA
- **Pol. cont.** = Pol. cont.
- **Tunable band-pass filter (TBPF)** = Tunable band-pass filter (TBPF)
- **Tunable laser** = Tunable laser
- **Interleaver** = Interleaver
- **Amp + coupler** = Optical processor
- **IWG** = IWG
- **Modulator (IQ or phase)** = Modulator (IQ or phase)
- **Optical circulator** = Optical circulator
- **Decorrelation fiber** = Decorrelation fiber
- **Monitor (OSA/Power meter)** = Monitor (OSA/Power meter)

**Amps + Couplers**
- **C/L EDFA**
- **T DFA**
- **S/C+L WDM**
- **C/L WDM**
- **Power coupler**

**Loop Transmission**

**Test-channel band**

**Band select switch**

**Rx**

**0.4nm filter**

**OP**

**C/L EDFA**

**AWG**

**DC**

**Loop AOM**

**Pol. Scr**

**SDM Mux**

**SDM Demux**

**SDM**

**Term.**

**Raman pumps**

**Mon.**

**Load AOM**

**Amp + SDM split**

**Loop**

**Transmission**

**Comb**

**AWG**

**OP**

**C/L EDFA**

**B2B**

**ONU**

**Spectrum evolution over distance**

**Band select switch**

**0.4nm filter**

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**Transmission**

**Comb**

**AWG**

**OP**

**C/L EDFA**

**B2B**

**ONU**
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

OFC'21 F3B.3
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• Conclusions – SDM and Beyond
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 Rx's

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

- SMF array
- 15-mode MMF
- Collimator
- Dielectric mirror
- Phase masks

- Mode Multiplexer
- 23 km 15-mode MMF

- Mode De-Multiplexer

- 16.6 μs
- 33.3 μs

- 15-mode transmission experimental set-up
Transmission link characteristics

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

![Graph showing transmission link characteristics](image)

- **C-Band**
  - GMI data rate: 1.14 Pb/s
  - Decoded data rate

- **L-Band**
  - Data rate estimated from GMI

![Graph showing data rate vs. wavelength](image)

- Decoded data rate
- Data rate estimated from GMI
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...
High-Capacity 5G Fronthaul Networks Based on Optical Space Division Multiplexing

Simon Rommel, Member, IEEE, Diego Perez-Galacho, Josep M. Fàbrega, 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, as well as for new immersive media applications. The expected 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

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

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
Astronomical Applications of Multi-Core Fiber Technology

Nemanja Jovanovic, Robert J. Harris, and Nick Cvetoejiev

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 pseudo-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].

Shaping the light amplified in a multimode fiber

Raphael Florentin1, Vincent Kermene1, Joel Benoist1, Agnès Desfarges-Berthelemot1, Dominique Pagnoux1, Alain Barthélémy1 and Jean-Pierre Huignard2

Exploiting multimode waveguides for pure fibre-based imaging

Tomáš Čízmárl1 & Kishan Dholakia2
High-resolution optical spectroscopy using multimode interference in a compact tapered fibre

Noel H. Wan¹,², Fan Meng¹,³, Tim Schröder¹, Ren-Jye Shiue¹, Edward H. Chen¹ & Dirk Englund¹

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

Ivo T. Leite⁰¹,²,³, Sergey Turlaev⁰¹,³,⁴, Xin Jiang⁰⁵, Martin Šiler⁶, Alfred Cuschieri⁰², Philip St. J. Russell⁰⁶ and Tomáš Čižmář⁰¹,³,⁶*
Quantum Communications

COMMUNICATIONS PHYSICS

ARTICLE

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

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Multidimensional Entanglement Generation with Multicore Optical Fibers

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

Quantum information processing with space-division multiplexing optical fibres

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SCIENTIFIC REPORTS

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.

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SDM and beyond

- Energy efficient data-centers
- High-data-rate communications
- New Photonic devices – Signal processing, imaging, sensing
- Secure Communications – Quantum + classical
- Beyond 5G/6G technologies
- New networking paradigms

SDM
Thanks for listening!