A Furukawa Company

SDM Fibers for Data Center Applications

OFC2019 M1F.4

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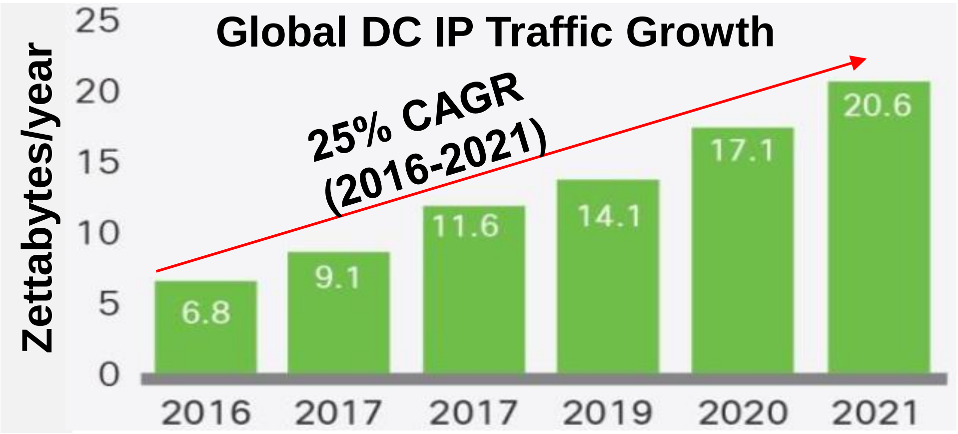
Acknowledgements
David J. DiGiovanni, Daryl Inniss, Alan McCurdy, Robert Lingle (OFS),
and R. Sugizaki (Furukawa Electric Co.) for their supports

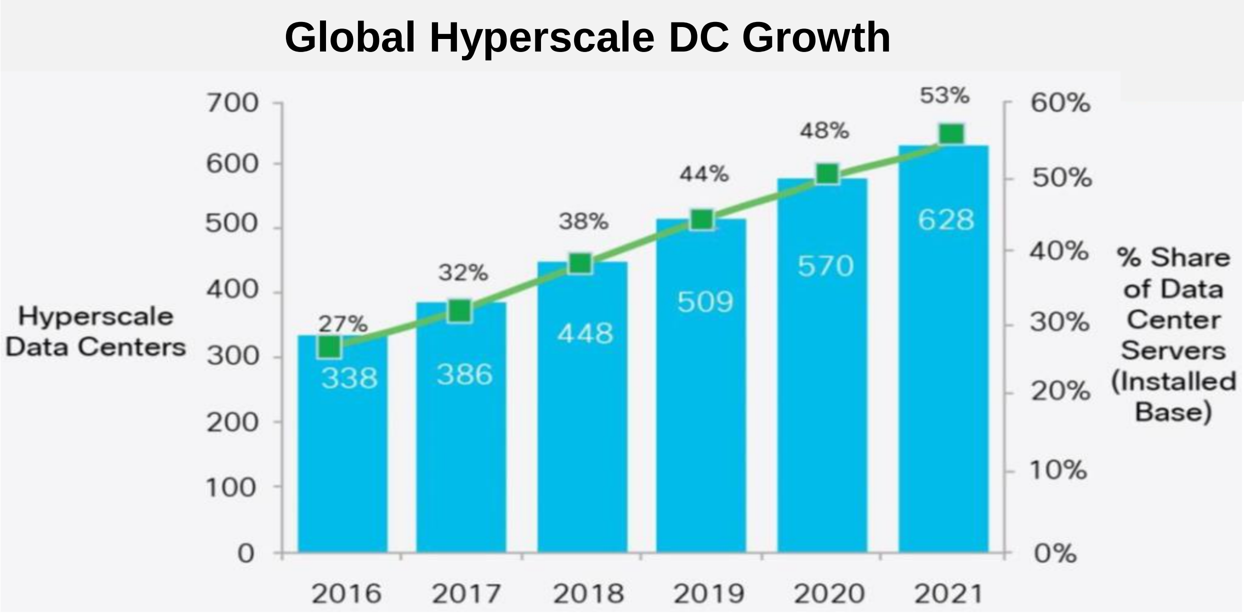
Outlines

- Introduction
- Multicore fibers for short-reach interconnects
- Connectivity techniques of multicore fibers
- Future opportunities & challenges

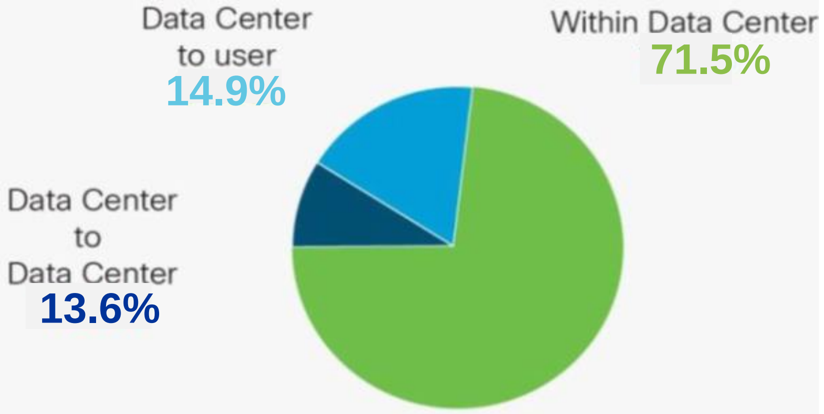
Traffic Growth in Data Center

Demands for High Bandwidth Interconnect





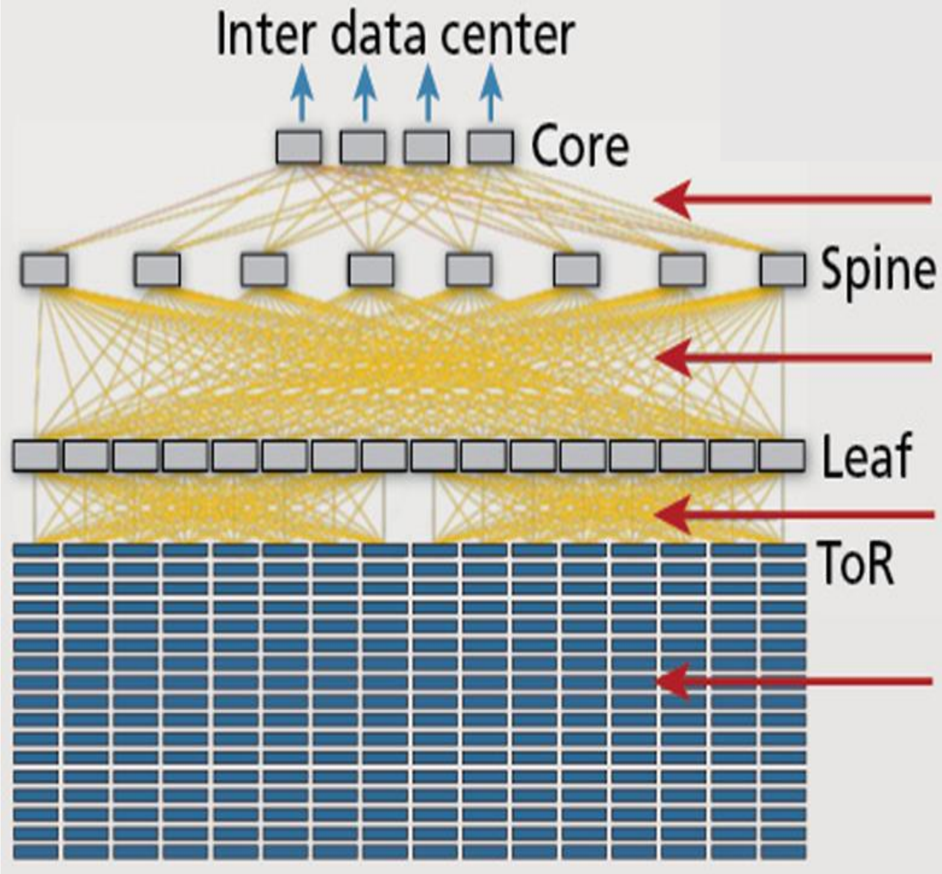
Cisco Global Cloud Index, 2016-2021



Total East-West traffic 85%

Massive volumes of data move over optical fiber interconnects inside cloud datacenter

Intra-Datacenter Networks



Typical Deployments in the Intra-Datacenter

Core Switch/ Router to Spine Switch
Deployed mostly 40GE LR4 & 100GE LR4/CWDM4
Start to deploy 400G-LR8 or 400G-CWDM8, roadmap is 800G

Spline Switch to Leaf Switch Links
Deployed mostly 40GE SR4/LR4 & 100GE CWDM4/PSM4
start to deploy 400G-DR4 or 400G-FR4, 800G next

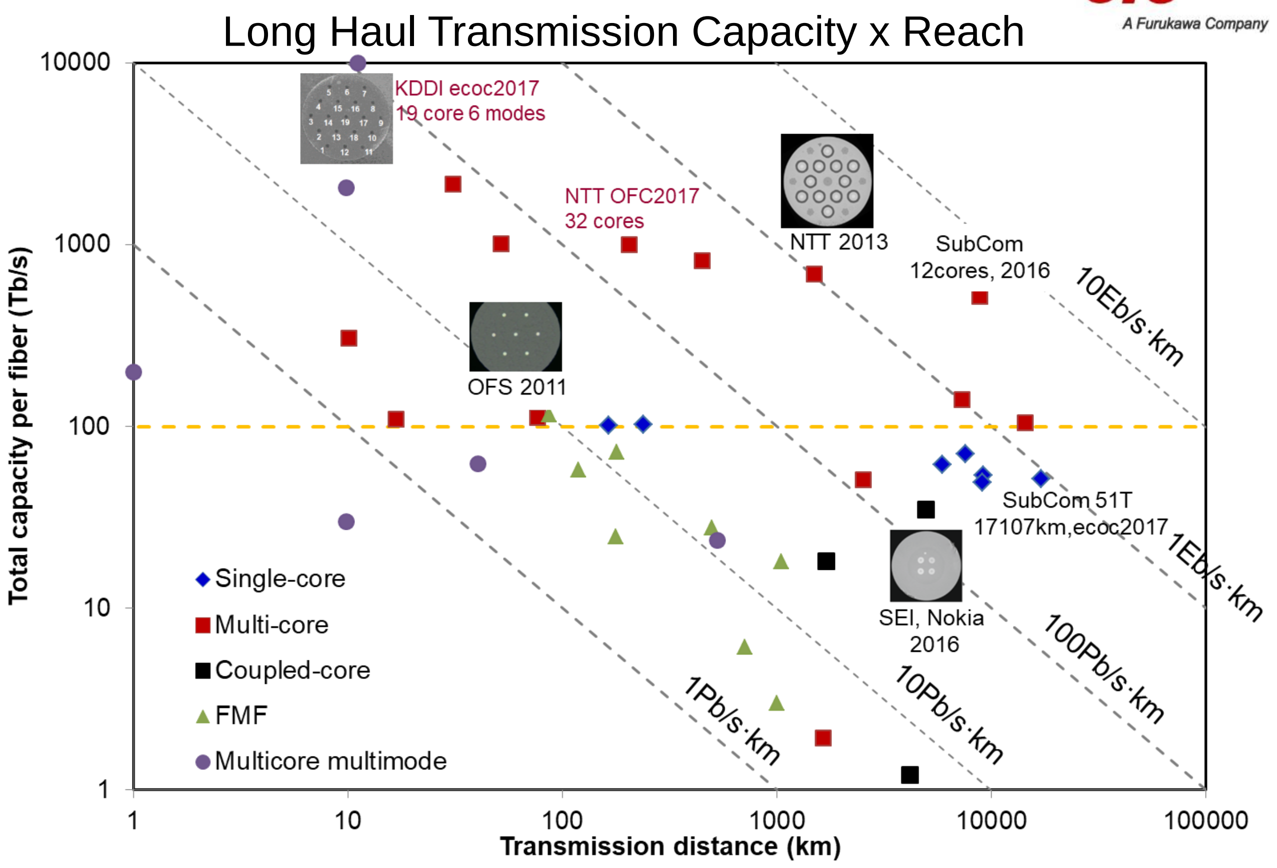
Leaf Switch to TOR Switch Links
Deployed mostly 40GE SR4 & 100GE SR4
start to deploy 400G-SR8 or 400G-AOC, 800G next

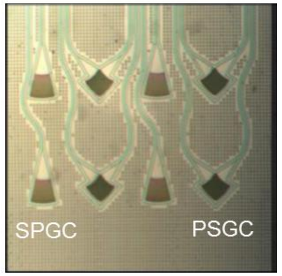
TOR Switch to Server Links
Deployed mostly 10GE SR /DAC, 25GE SR/DAC/AOC
400G CR8/ 400G-AOC next

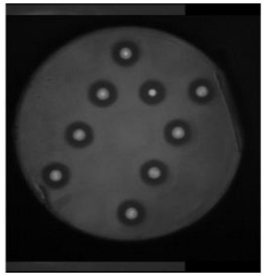
- For the link of 400G and beyond, most of optical paths for structured cabling (switch-to-switch) lead to 2 or parallel 8 fiber, MCF (w/ 8 core or 4 core) maybe improve the bandwidth density
- For ethernet switches, deployed mostly 3.2Tb/s based on 100G QSFP28 modules, 12.8Tb/s (Tomahawk III) in production, => 32 x 400GbE / 64x200GbE /128x100GbE ports

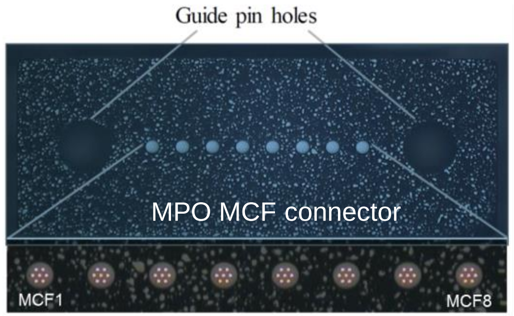
SDM Fibers for Data Center Applications

- SDM (MCF, FMF) developed to address the impending capacity crunch for LH network
  - Increase the carrying capacity of an optical fiber—”demonstrated”
  - Decrease system cost—have not demonstrated
- Multicore fiber for datacenter networks
  - Inter-core crosstalk not sever over short links
  - No need amplification
  - Direct connectivity to SiP or InP chips for high degree integration
  - Improve channel count and bandwidth density
  - When ‘space’ become highly valued, multicore fiber maybe provide critical role, e.g.
    - Multicore fiber for chip connectivity



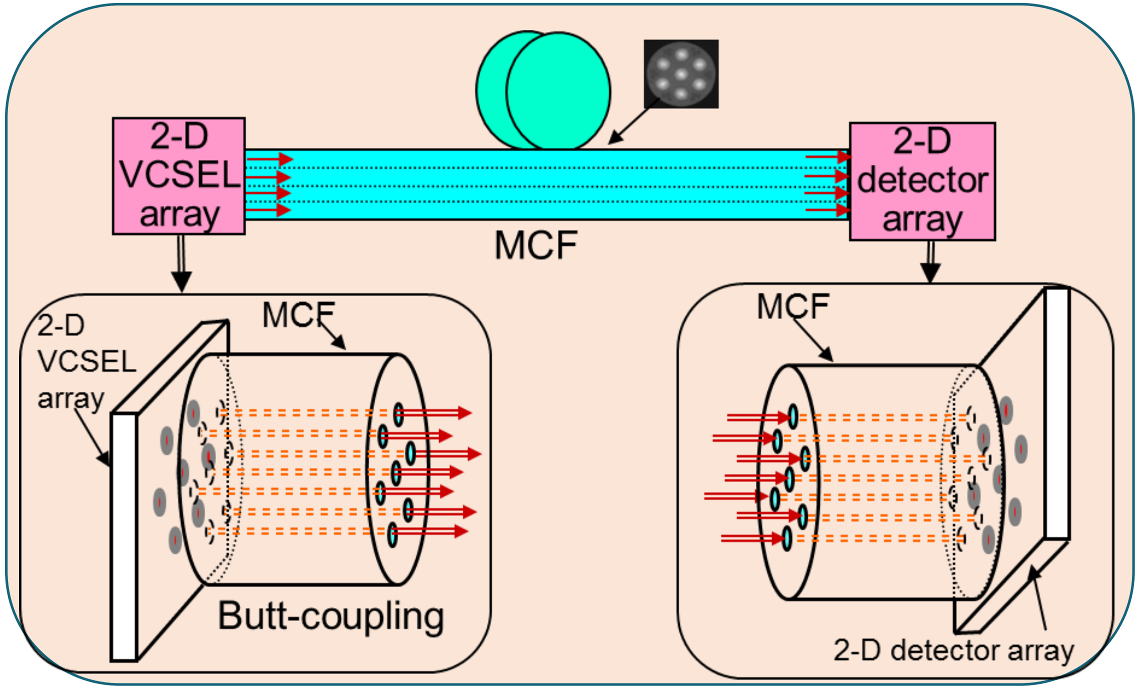




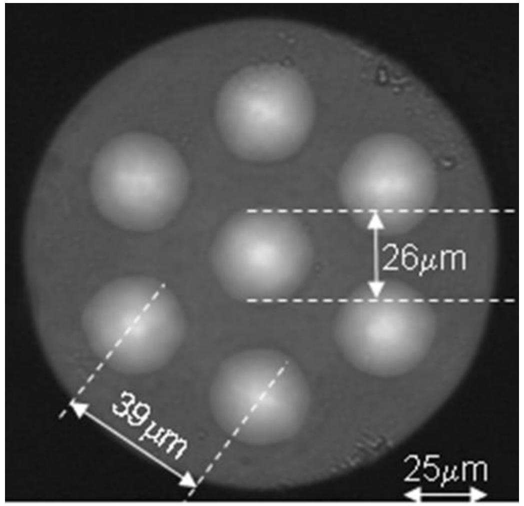


Multicore Multimode Fiber

- Increase bandwidth density of optical interconnects for HPC
- Specifically target to reduce the footprint of supercomputer
- Graded-index multimode cores for interfacing with 2-D VCSELs and PIN arrays via butt-coupling



B. Zhu, et al., ECOC2010, paper We.6.B.3.

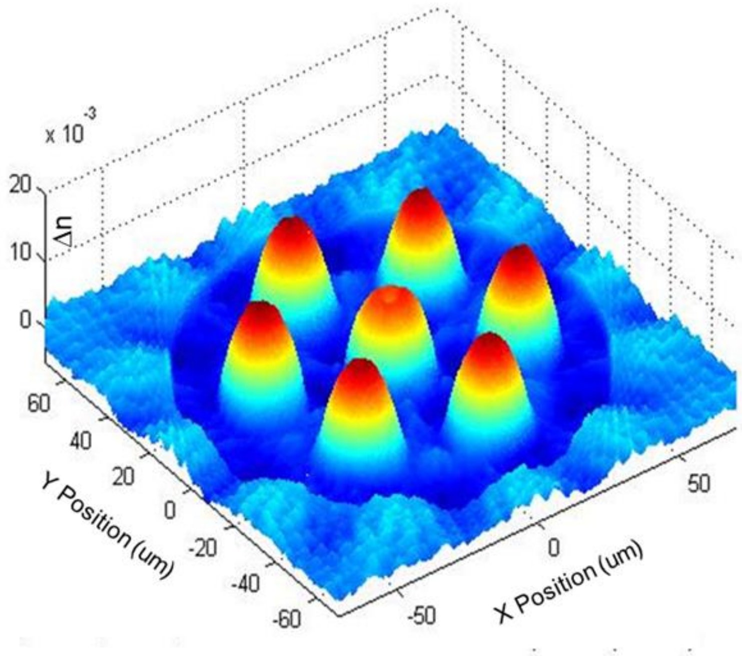


Optical fiber properties

- Core diameter of 26 μm,
- Core pitch of 39 μm and cladding diameter of 125 μm
- NA of cores: 0.21
- Attenuation: 2.2 dB/km @850nm and 0.5 dB/km @1310nm

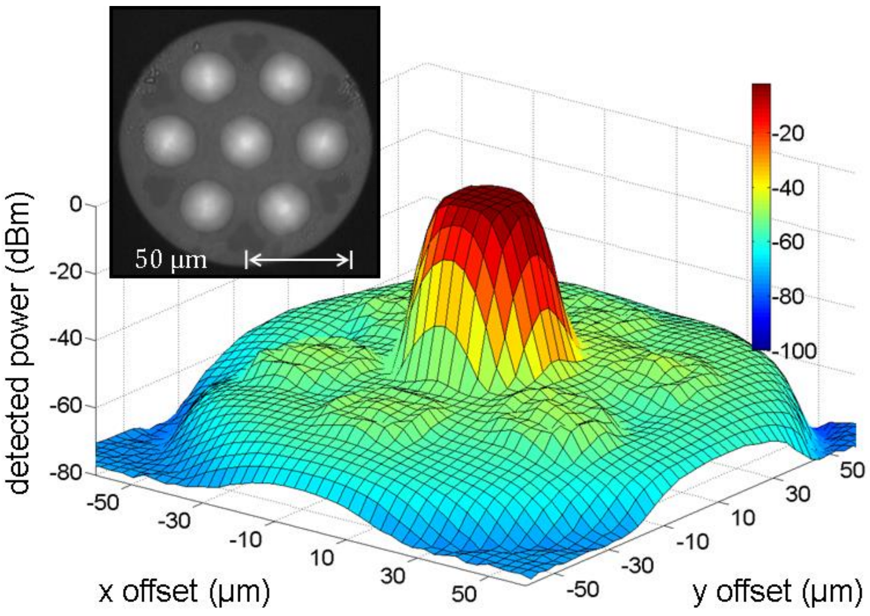
Crosstalk and DMD of Multicore Multimode Fiber

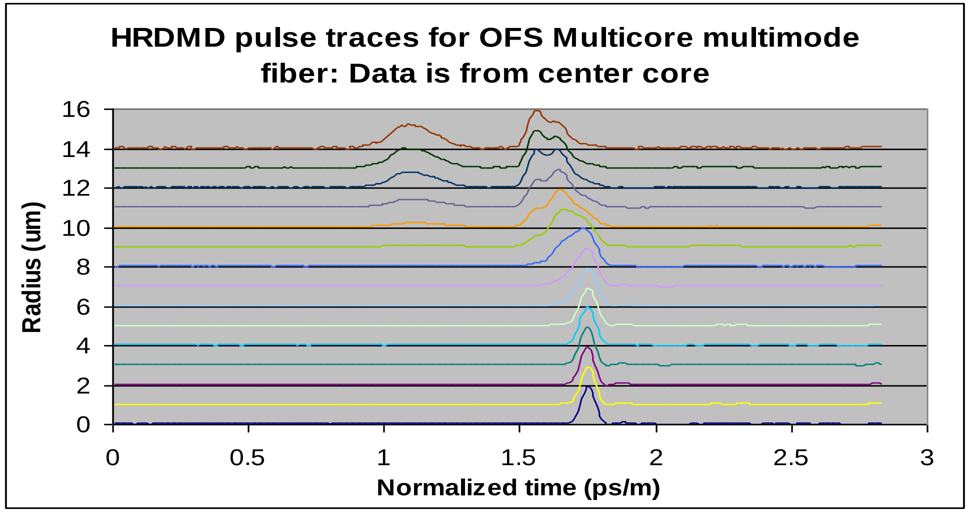
- Cross-talk below -40 dB for 100 m link
- DMD value: 0.12 ps/m within an 8-µm radial mask width



Graded-index profile

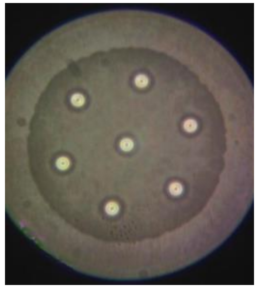
measured by interferometric optical phase tomographic technique



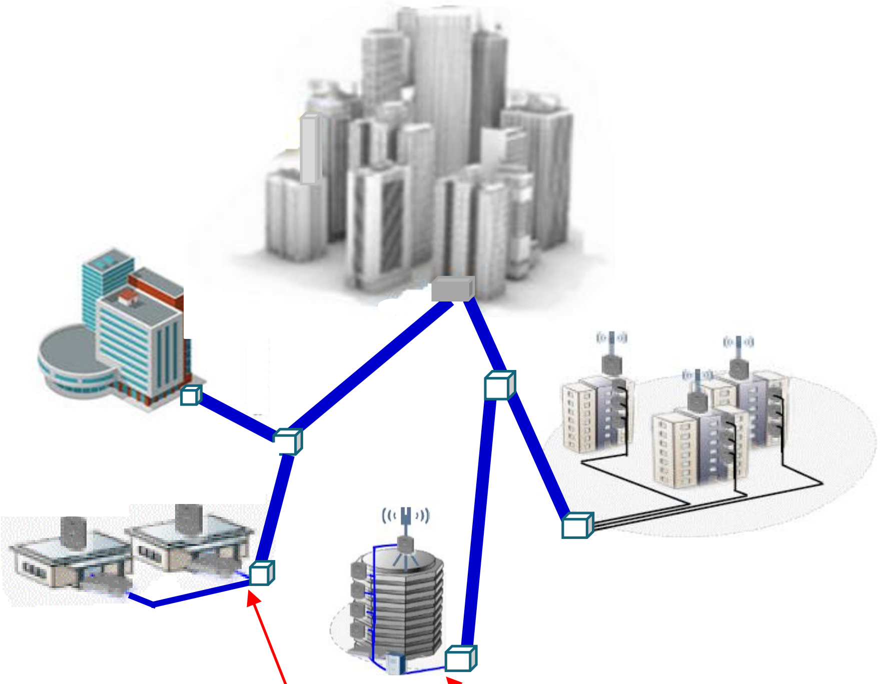


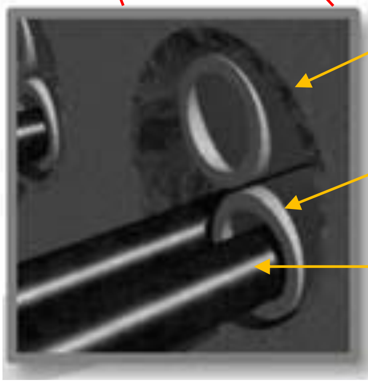
Multicore Single Mode Fiber for PON

- Concerns on shortage of optical fibers in underground sections (access networks/busy city)
  - Duct cabling congestion
  - How to maximum utilization of existing conduit line system?
  - Fiber density and small cable size become an important factor



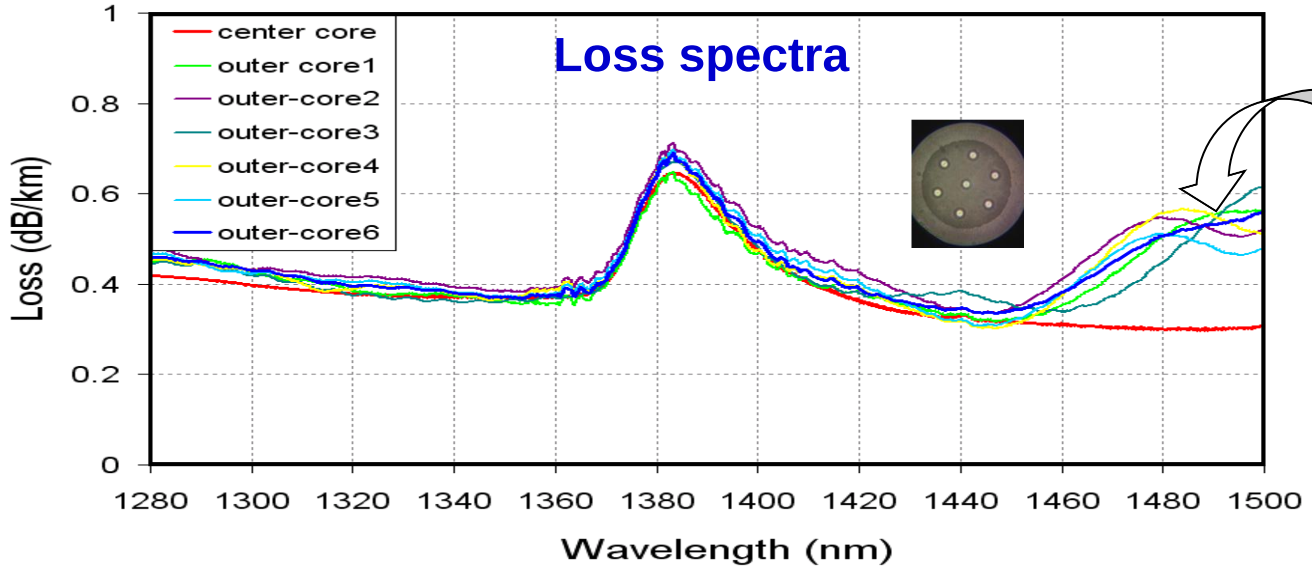
- Optical fiber properties
  - 7-core fiber arranged in a hexagonal array
  - Core diameter: 8 μm
  - Core pitch: 38 μm
  - Cladding diameter:130 μm
  - Coating diameter: 250 μm
  - Cutoff wavelength: 1.2 μm
  - MFD: 8.3 μm at 1.30 μm, 9.3 μm at 1.49 μm





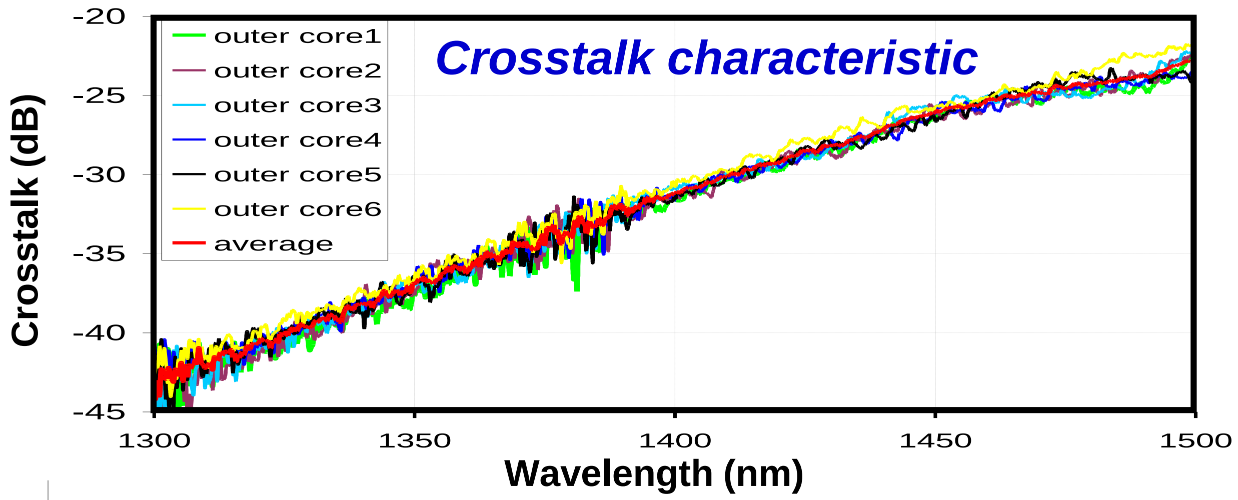
B. Zhu, et. al., Opt. Express, May 2010, 18, P. 11117

Loss and Crosstalk of 7-core Single Mode Fiber



B. Zhu, et. al., Opt. Express, May 2010, 18, P. 11117

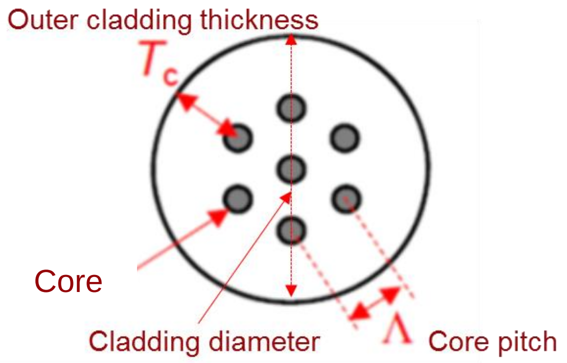
Increase loss for outer cores with wavelength; it can be reduced by increasing the outer clad diameter and appropriate clad and coating index



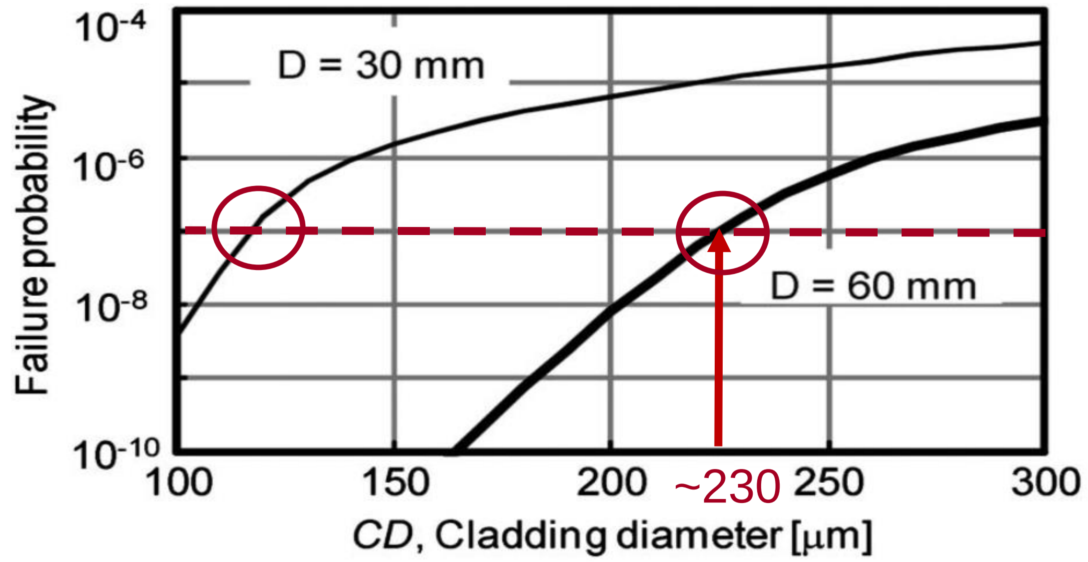
- Challenges in reducing loss as a trade-off with density, core-pitch, and crosstalk
- Wavelength dependent characteristic of crosstalk
  - 1310nm: Xtalk <40dB
  - 1490nm: Xtalk <24dB
  - Challenges in achieving low crosstalk in the entire transmission window

Optimization of MCF Designs for Datacenter

- MCF with 125-µm cladding diameter is preferable for short-reach interconnects
- 4 or 8 core MCF may be able to replace 4 or 8 parallel fibers in 400G DR4/SR8 or future 800G/1.6T links
- Linear array vs hexagonal structure



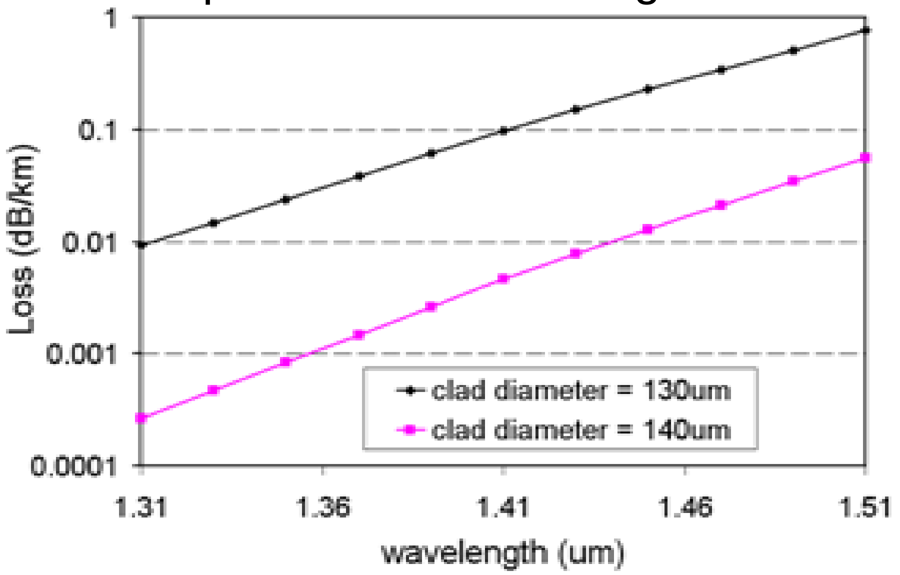
Failure probability vs CD



Proof level: 1%; Turn:100

S. Matsuo et al., Opt. Lett, Vol. 36, 4620, 2011

Impact of outer cladding thickness

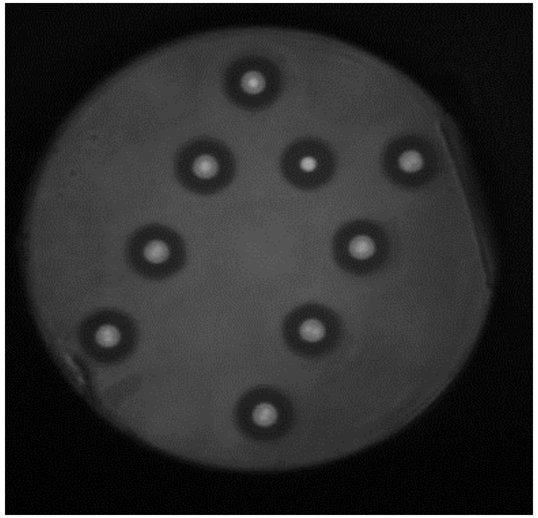


B. Zhu, et. al., Opt. Express, May 2010, 18, P. 11117

Linear Array Multicore Fiber

Linear array core structure of MCF is preferred for SiP to adapt linear transceiver arrays

- Optical fiber properties
  - 2x4 linear structure with round cladding
  - Core diameter: 8.6 μm
  - Core pitch: 54-μm
  - Cladding diameter:229 μm
  - Coating diameter:362 μm
  - Cutoff wavelength< 1520nm
  - Crosstalk < -40dB across C-band

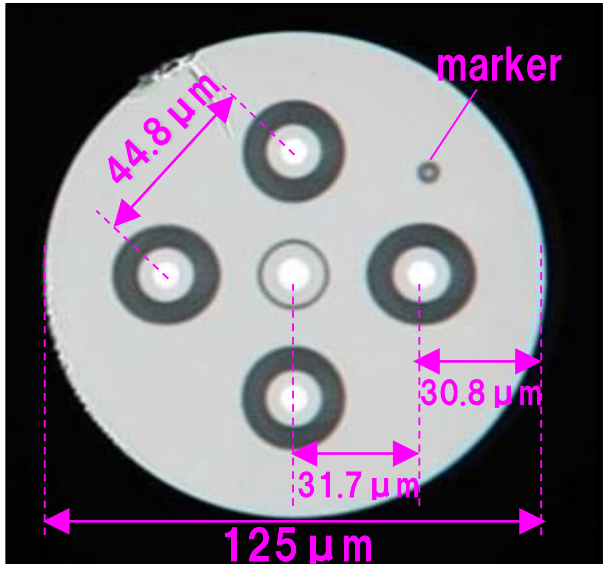


- Potentially for 400Gb/s or future 1.6Tb/s communication links using parallel PSM4 or PSM8
- Optical backplane interconnect

- The round cladding design easy for handle and installation, however, the number of cores is limited by the cladding diameters

125µm cladding 5-core Fiber

Smooth upgradability from conventional single-core system to 5-core system



T. Gonda, et. al., ECOC2016, W.2.B1 (2016)

Optical properties

Item	Unit	Value	
		Outer cores	Centre core
MFD @1310nm	µm	8.3	8.8
λcc	nm	1192	1236
Bending loss @1550nm	dB/turn @R=10 mm	0.02	0.08
Attenuation loss @1550 nm	dB/km	0.22	0.20
XT @1550 nm*	dB	-74	-64

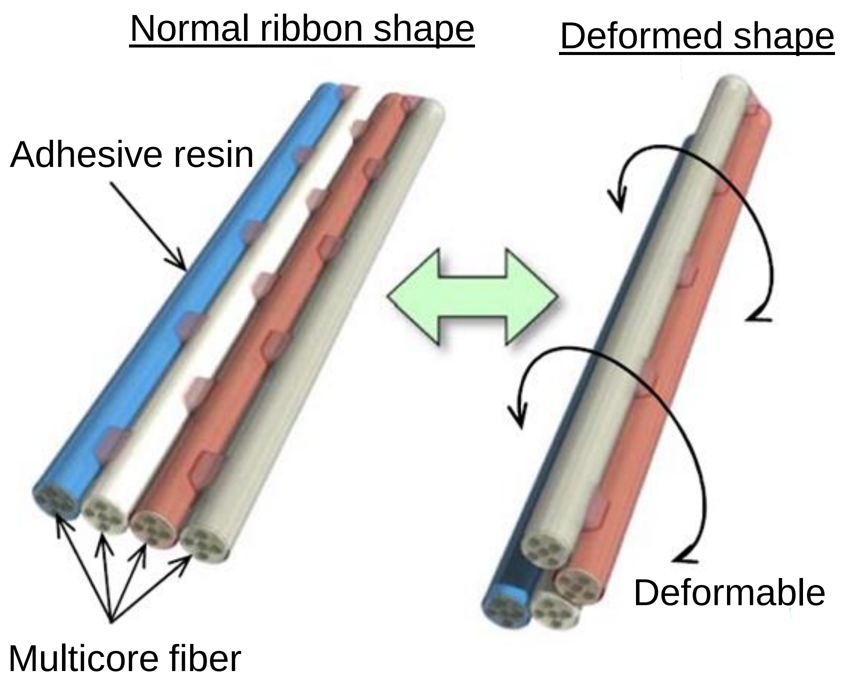
* after 1 km length fiber spool at R=80 mm

- Trench-assisted refractive index design for all cores & heterogeneous core structures
  - Reduce the crosstalk and lower bending loss
- Satisfy the requirement for ITU-T G.657.A1 recommendation (cable cut-off, MFD, bending loss)
- Sufficiently low crosstalk & good transmission performance

Ultra-high Density Multicore Fiber Cable (I)

Rollable multicore fiber ribbon

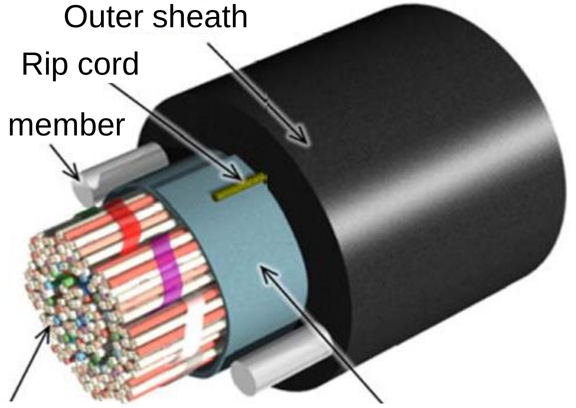
- 125-μm cladding 4-core fiber was adopted to ***rollable ribbon*** fiber to develop high density cable
  - Cable density= >8.4 cores/mm^2
- Rollable ribbon fiber
  - Partially bonded at intermittent points
  - The rollable ribbon can be rolled into a flexible, tight bundle =>the closest-packing cable structure
  - Enhance fiber routing and handling in small closure
  - Double the cable's fiber density compared to typical flat ribbon cable designs
  - Mass fusion splicing, similar to the conventional flat ribbon
  - Huge time and cost saving



M. Tsukamoto, et. al., IWCS2016, p594 (2016)

Ultra-high Density Multicore Fiber Cable (II)

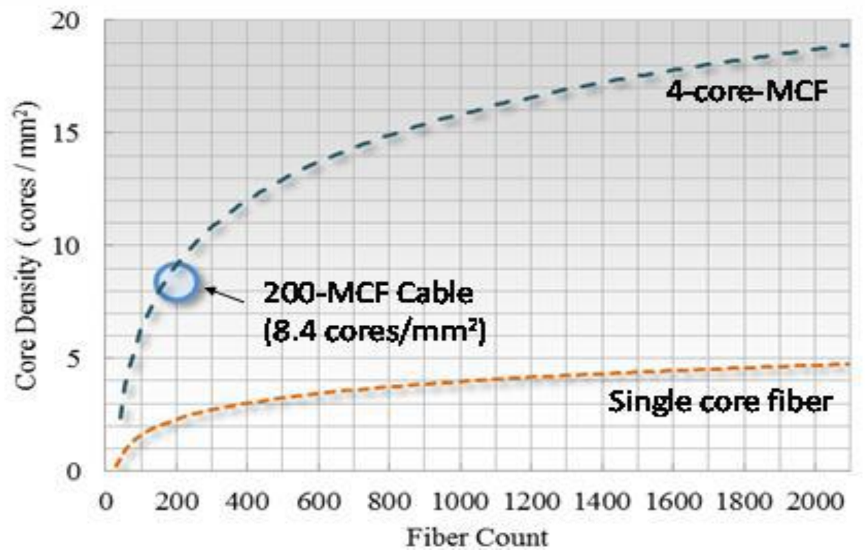
- 10 fiber bundles (each consists of 5 rollable multicore ribbon fibers spirally wrapped)
- 200 fibers (=800 cores) in an 11mm cable diameter using 125mm cladding 4-core fiber
  - Ultra-high cable density =>8.4 cores/mm²
  - Potential for core density > 15cores/mm²
- Equal performance of optical, mechanical and temperature as conventional single-core SMF



Temperature and mechanical characteristics

	Condition	Result	
		MCF	Single core fiber /reference
Temperature cycle	-30ºC to +70ºC,6 hours duration, 3 cycles	<0.1 dB/km	<0.1 dB/km
Repeated bending	R=160mm, 10 turns	<0.1dB	<0.1dB
Crush	1960N/100mm, t=1min	<0.1dB	<0.1dB
Twist	+/-90o /m 10 turns	<0.1dB	<0.1dB

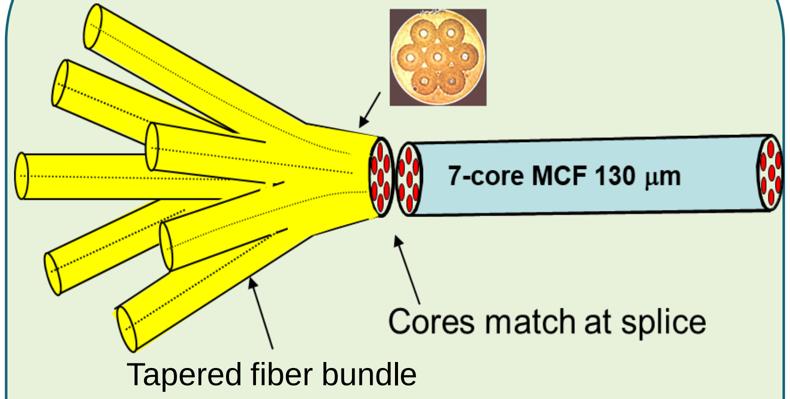
Core density of MCF cable



T. Gonda, et. al., OFC2018, Tu3B.1

Fan-in/out Devices

Fiber fused taper type

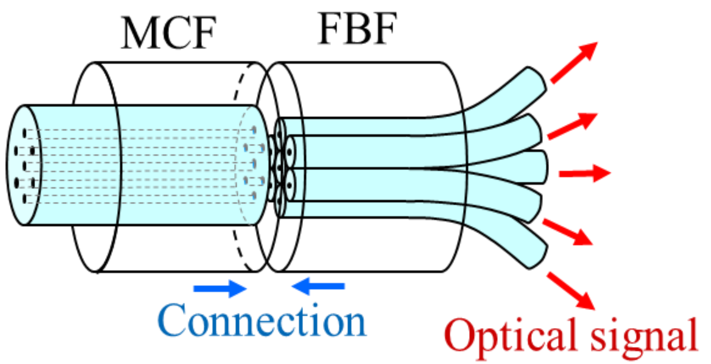


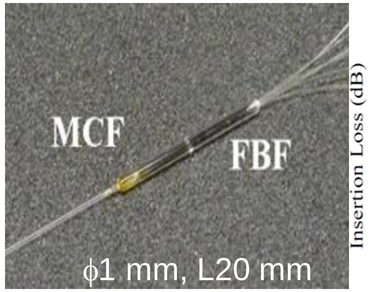
Measured Loss and Crosstalk

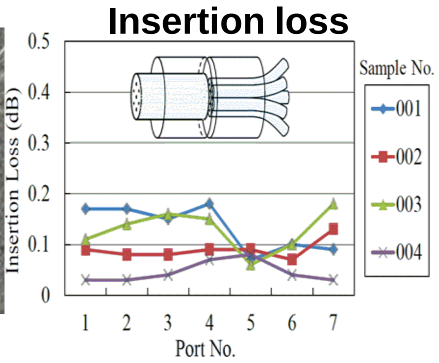
Core #	Loss (dB)	Crosstalk (dB)
center-core	0.38	
outer core1	1.6	-40.8
outer core2	0.9	-39.3
outer core3	1.2	-43.8
outer core4	1.0	-41.8
outer core5	1.3	-41.8
outer core6	0.9	-43.8
average	**1.17**	**-41.8**

B. Zhu, et. al., OE, May 2010, 18, P. 11117

Fiber bundle type



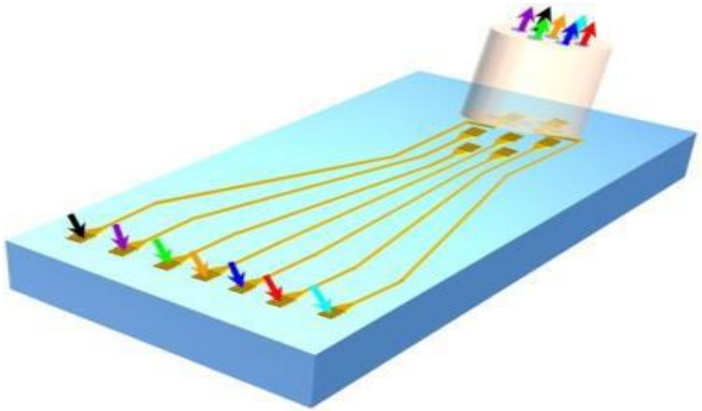


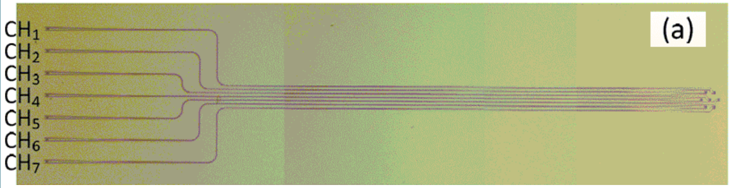


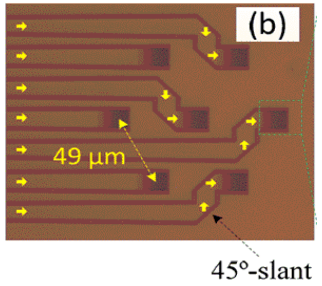
- Insertion loss (1.55μm) <0.2dB
- Crosstalk (1.55μm) <-65dB

T. Saito, et. al., OECC2016 ThC1-1

PLC based SiP type







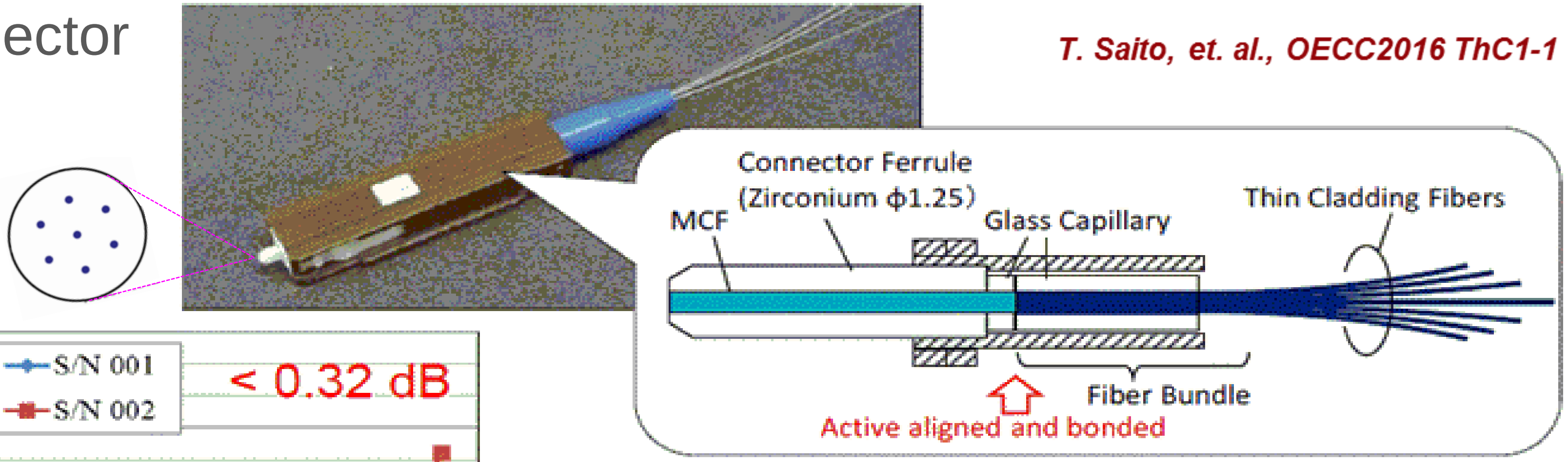
- Coupling loss: 6.8dB
- Crosstalk <-32dB

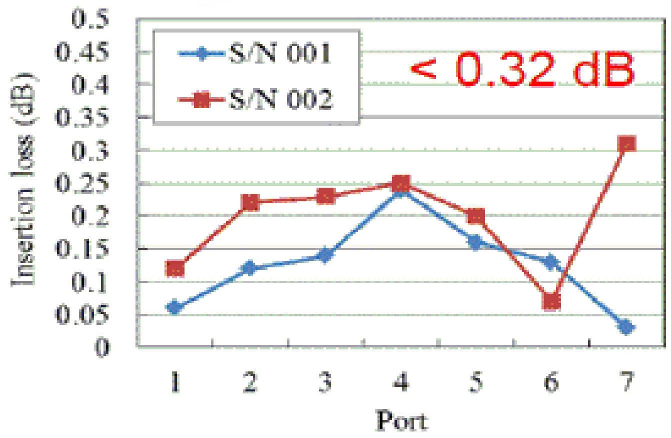
Y. Ding, et. al., ECOC2014 We1.1.3

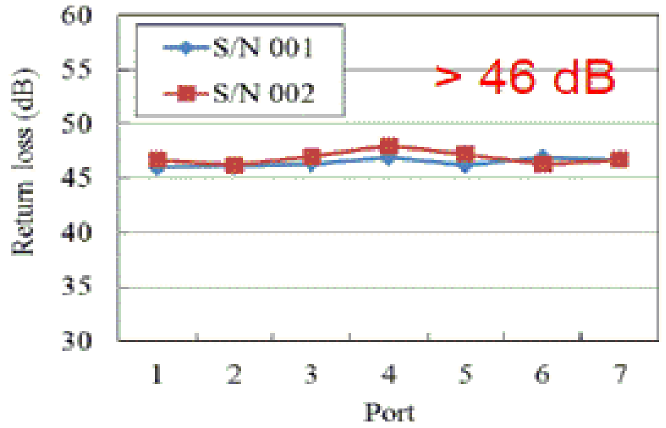
Connector type Fan-in/out

- MU-type connector
- 7-core MCF

T. Saito, et. al., OECC2016 ThC1-1







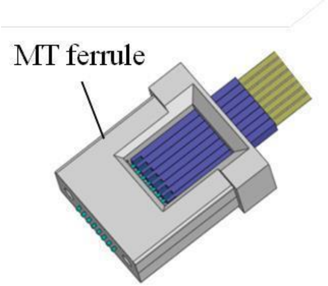
Conditions and Results of Environmental tests

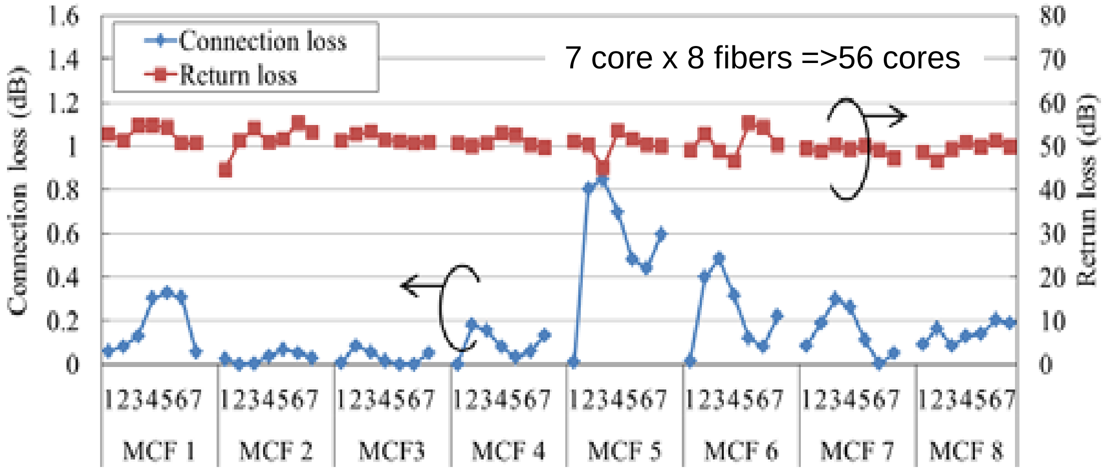
Test Items	Test conditions	Standards	Loss variation
Temperature cycling	-10 to 60°C, 5 Cycles	IEC61753-1 Category C	<0.1dB
Damp Heat	40°C , 95%, 96Hours	IEC61753-1 Category C	<0.1dB
Vibration	1.5mm P-P amplitude, 10 to 55Hz /min, 2 hours /X,Y, Z axis	IEC61753-1 Category O	<0.1dB
Impact	100G, 6ms, 5 Times /X, Y, Z axis 2 directions	JIS C5983	<0.1dB

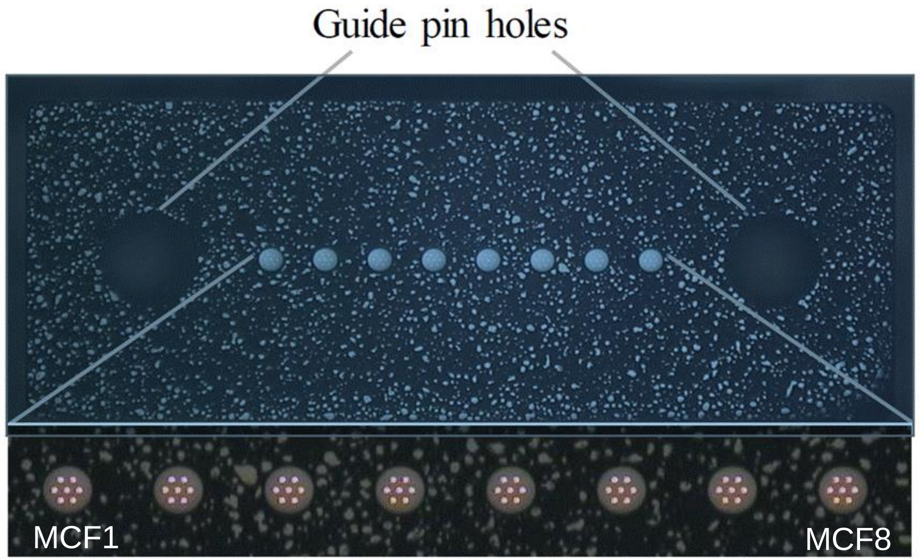
Multiple MCF Connector: 8 Fibers-7 core

K. Watanabe et al., JLT, 34, 2, p. 351 (2016)

- High density MPO type MCF connector with PC connection
  - Insertion loss < 0.9dB
  - Return loss >43dB
  - Loss variation <+/- 0.07dB (temperature cycle testing, -10 to 60 deg. C)

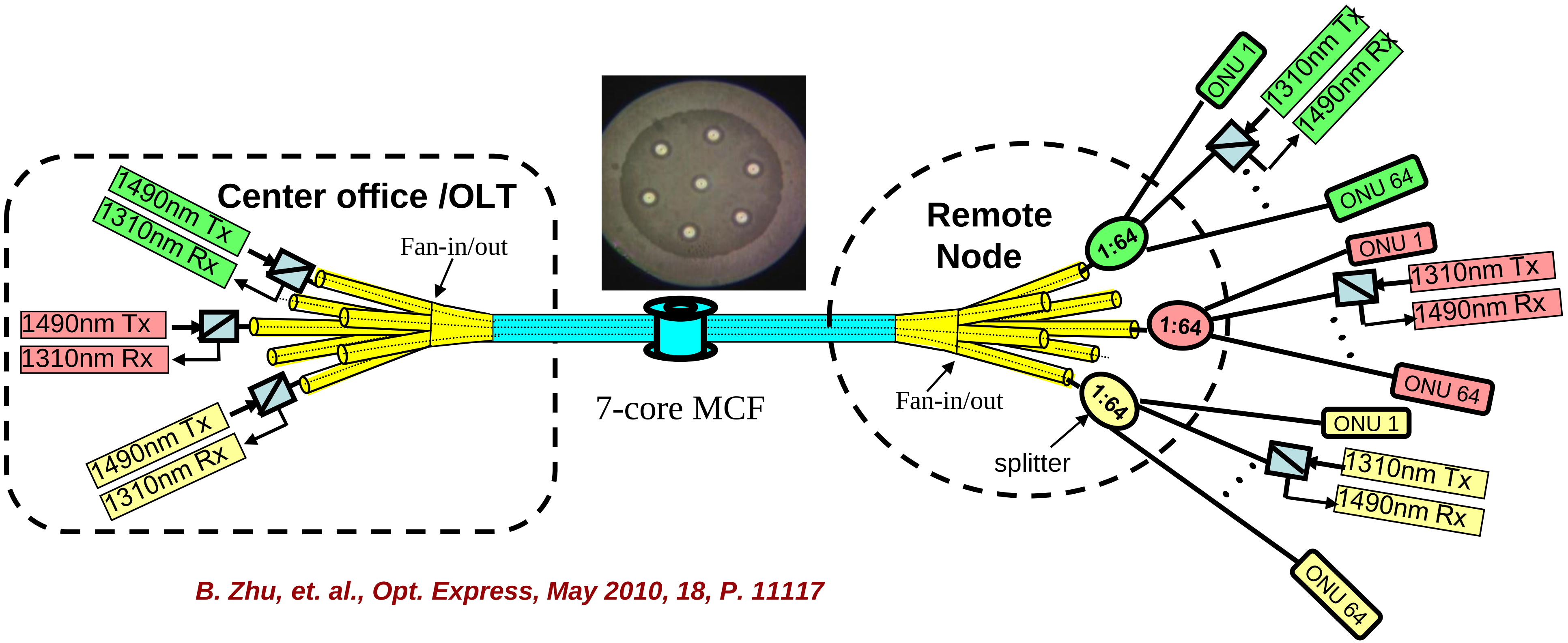






Bi-directional PON Link using 7-core Fiber

PON transmission: 7x64 end users over one "single fiber"



B. Zhu, et. al., Opt. Express, May 2010, 18, P. 11117

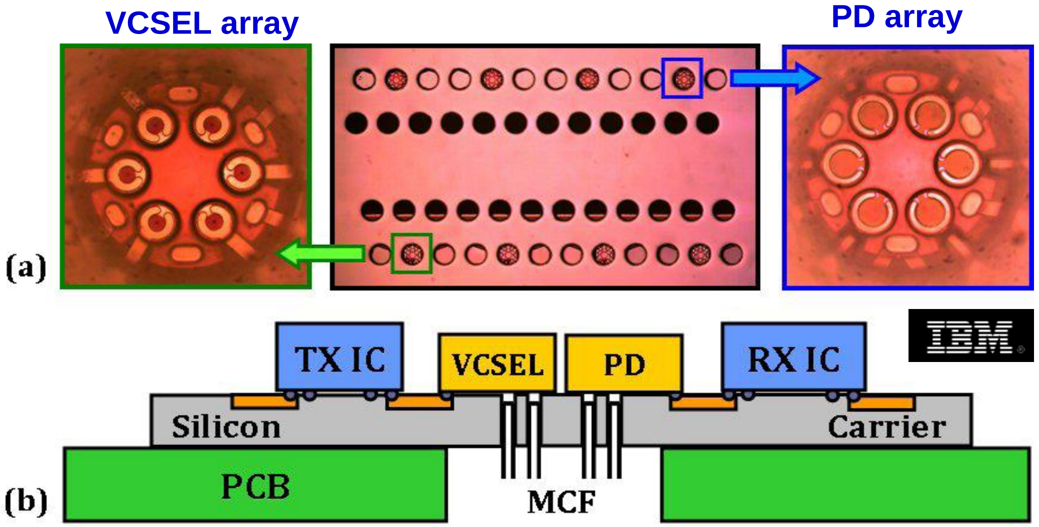
- Seven-core MCF bi-directional transmissions for PON
  - 11.3-km 7-core MCF
  - 1:64 way splitter (i.e. 7x64 ONU)
  - Bidirectional transmission for 1310-nm upstream and 1490-nm downstream

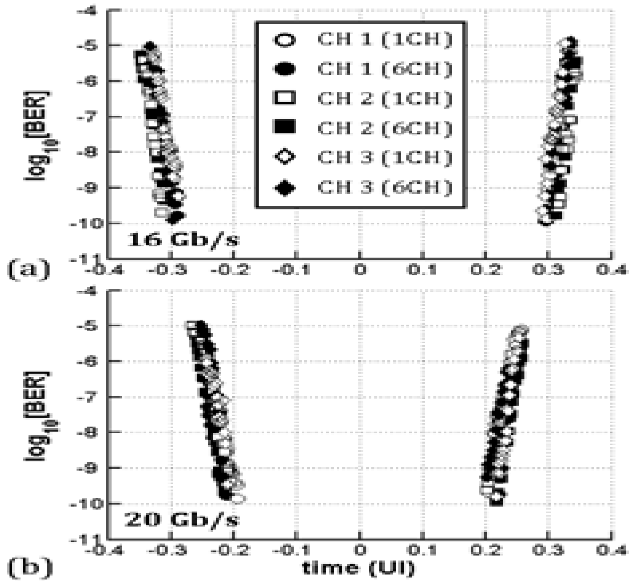
120Gb/s End-to-End Multicore Multimode Fiber Optic Link

For high performance computers and data centers

- 2-D VCSEL array and 2-D PD array interfaced with the six-core in a multicore graded-index fiber
- Transmissions of 16-Gb/s and 20-Gb/s/channel are both demonstrated
- 120-Gb/s end-to-end transmission link over 100-m multicore MMF without fan-in/out
- Negligible degradation of electrical and optical crosstalk on BER performance
- Compact, small size and high level integration

- Why not been commercialized so far?





B. G. Lee, et al., JLT. Vol. 30, pp886, (2012)

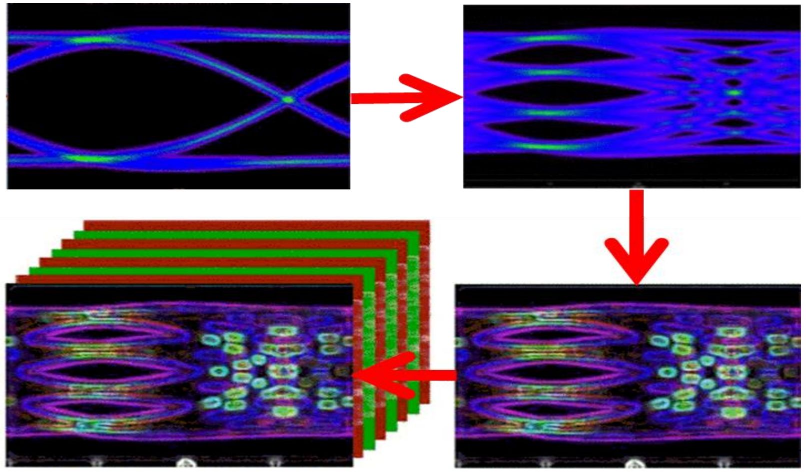
End-to-End Multicore Fiber Link by SiP Transceiver

- 8-core MCF 800Gb/s duplex w/o fan-in/out
  - Enabled by Silicon Photonics (SiP) transceiver with grating coupler array
  - 2λ x 100Gb/s PAM4 per core
  - 4 Tx w/ SPGCs
  - 4 Rx w/ PSGCs
    - SPGC: single-polarization grating coupler
    - PSGC: polarization-splitting grating coupler
  - High throughput density
  - Replacing pluggable modules with on-board optics

Scaling SiP Transceiver

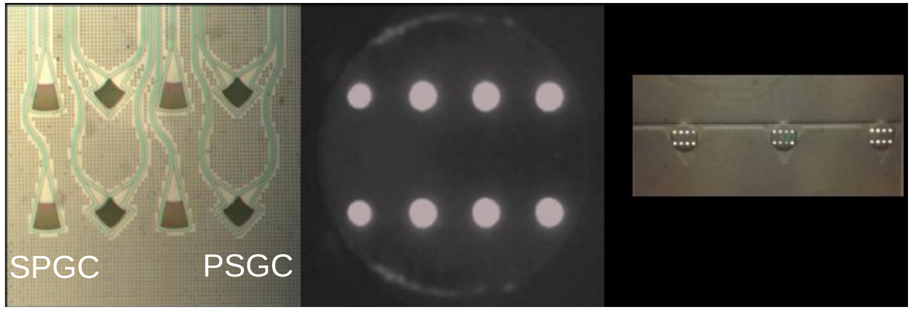
50Gb/s NRZ

100Gb/s PAM4



800Gb/s duplex 2λ x PAM4 8-core MCF

200Gb/s 2λ x PAM4



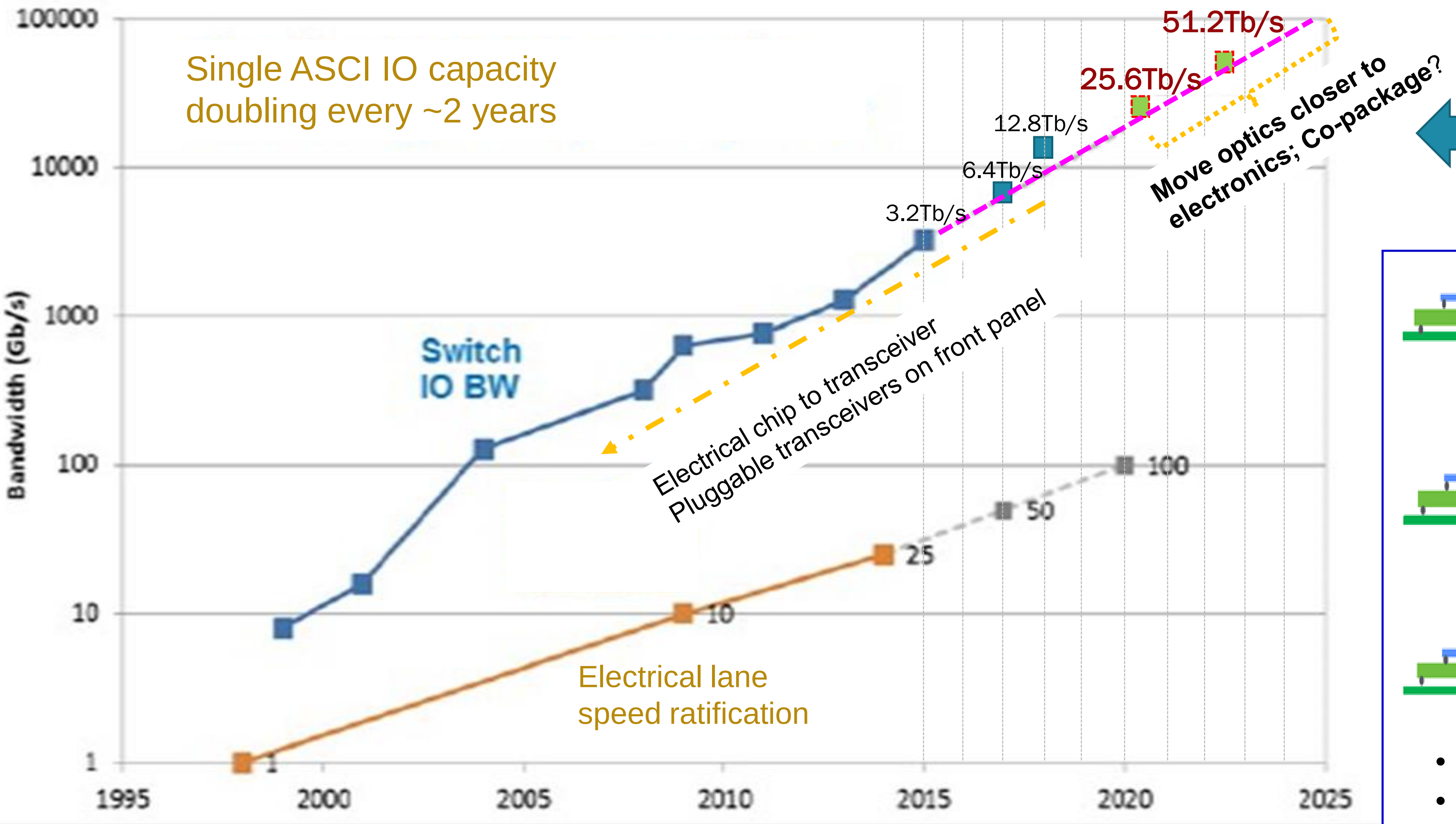
P. Dobbelaere, Luxtera OECC 2015

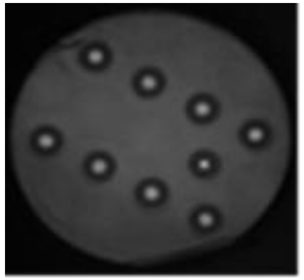
- End-to-end 200-Gb/s MCF transmission over 500m of 8-core fibers with SiP transceivers

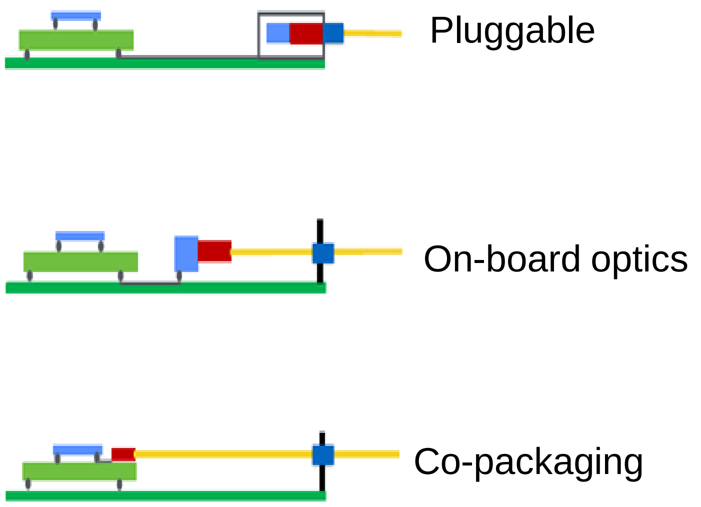
(by T. Hayashi, et al., ECOC2017 Th2.4.8)

Increasing Switches Capacity
Driving Optics to Move Closer to Electronics

Future ethernet switch demands for **high bandwidth density & high channel count**







- Reduce electrical trace penalty
- Increase bandwidth density

Chart by D'Ambrosia shown in https://www.nextplatform.com/2017/09/08/signposts-roadmap-10tbsec-ethernet/

High Density Co-packaging

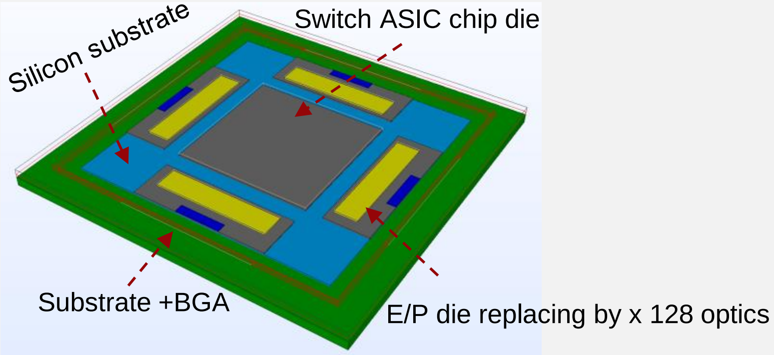
An opportunity for multicore fiber?

- Future data center switch ASICs have an optical I/O challenge
- 12.8Tb/s switches 32 x 400G modules challenging of the faceplate capacity
  - DR8 (PSM8) 8ch Tx, 8ch Rx X 32 modules =512 fibers for 12.8 Tb/s switch (bidirectional)
  - PSM4 4ch Tx, 4ch Rx X 32 modules=256 fibers for 12.8Tb/s switch
- 25.6Tb/s and beyond
  - Increase channel speed … 50Gbd PAM4 to achieve 100G per channel
  - More wavelengths?
  - Increase # of channels
  - **Move to on-board or co-package optics with switch ASIC with fiber connectors on front panel**

- Optical I/O density on a co-packaged interface
  - Take example of 512 optical channels, 4 separate transceiver ‘chiplets’ 128 channel each
  - With standard SMF or MMF fiber array 250μm pitch =32mm wide
  - **MCF arrays could help substantially** e.g. 8-cores w/ 300μm coating diameter

SMF/MMF array on 250μm pitch	4 ch/mm
8-core MCF array on 300μm pitch	26.7 ch/mm

- ASIC package limitation



Challenges

- High cost of MCF
  - Low-cost MCF manufacturers technologies
- Connectivity /integration with MCF
  - It is expensive, partly due to low volumes
  - Low-cost non-hermetic packaging for MCF to chips connectivity
    - The temperature during packaging of fibers to the board can be cycled as high as 260°C
    - The MCF needs to have high thermal stability at high temperature/harsh environments
    - OFS PYROCOAT® polyimide coating: operation temperature -65 to +300°C
  - Pluggable vs fully integration
    - Pluggable SDM transceivers (e.g MCF receptable with fan-in/out device, by K. Shikama et.al., OFC2018 W1A.7)
- Ecosystem and tooling not mature
- Industry standardization

Thank You!