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Low Power Consumption Optical Amplification Using Multicore Erbium Doped Fiber Amplifiers

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2018/06/11

IEEE Photonics society, French Chapter

Outline

- Introduction
- Design of high capacity SDM systems
- Low power consumption MC-EDFA
- Characteristics of amplified SDM systems
- Perspective of SDM systems
- Summary

Introduction

The author wishes to thanks his colleagues
K. Matsumoto, H. Takeshita, S. Yanagimachi and M. Arikawa
who greatly contributed to most of the presented results.

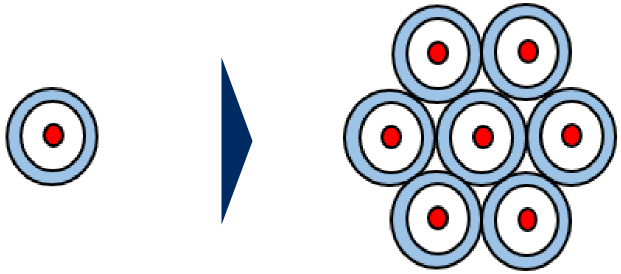
Space-Division Multiplexing

D.J. Richardson et al., *Nature Photonics, 7, 354-362 (2013)*

- Uninterrupted traffic growth of internet traffic
- Optical transmission system capacity
  - Digital coherent technology with standard fiber
  - Around 100Tb/s demonstrated
    [D. Qian et al., OFC2011, PDPB5]
- A promising approach to overcome the current limit:
  Space-division Multiplexing

Space-Division multiplexing and its benefits

Increase the number of fibers?



SMF x 1 SMF x N

• Fabrication with conventional technique

• Large foot print
  (1) High transport cost
  (2) High laying cost

Need more motivation…

Use new fiber?

- Using several cores of a **multicore fiber**
- Using several modes of a multimode fiber

Potential benefits of SDM

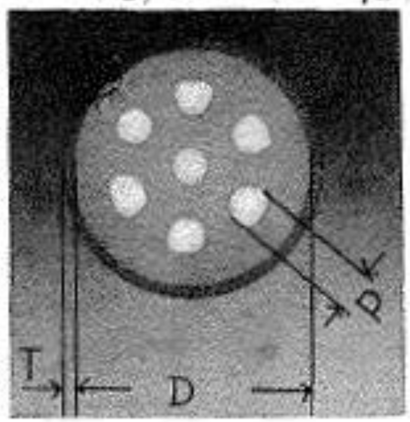
- Ultra-high capacity fiber link
- long-haul fiber link possible
- Integration
- Scalability
- **High efficiency amplification**
- Other

Future fibers?

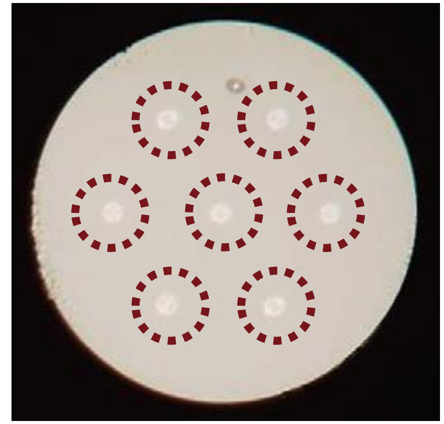
Space-Division Multiplexing with new fibers

S. Inao et al., OFC'79, WB1

Lotus ([illegible]) fiber



WB1 Fig. 3. Cross-sectional photograph of 7-core fiber: $d = 23\ \mu m$, $D = 150\ \mu m$, $t = 5\ \mu m$, $\Delta = 1\%$.

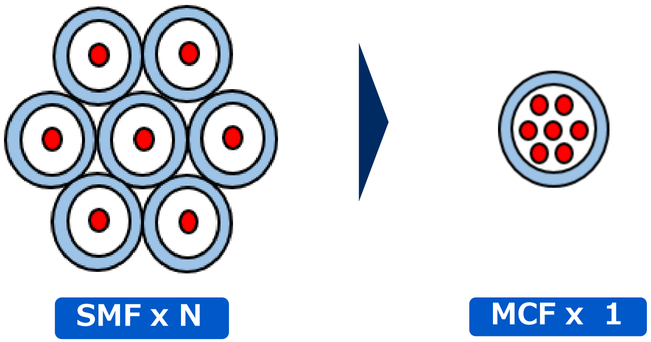


T. Takahashi et al., ECOC 2012 Th3C3

Year	**1979**	**2012**
Maker	Furukawa	Furukawa
N Cores	7	7
Clad Diameter [mm]	150	200
Core pitch [mm]	around 30?	56
Loss [dB/km]	3 (@0.850mm)	<0.2 (@1.550mm)
XT	-41dB/480m (-38dB/km)	-50dB/55km (-67dB/km)

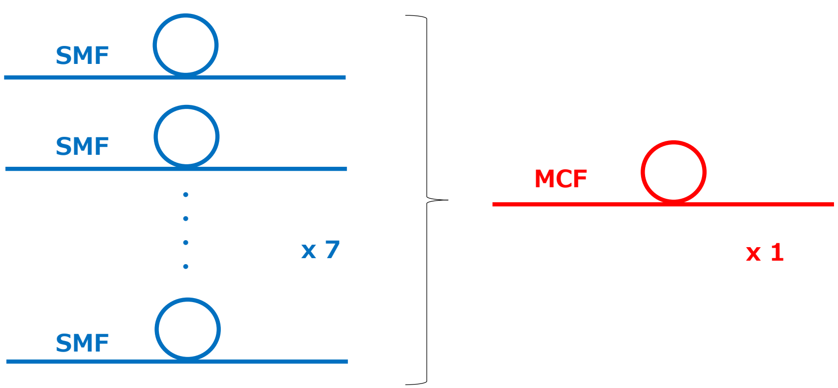
SDM transmission

Fiber



P. M. Krummrich, OFC2012, **OW1D.1** (2012)

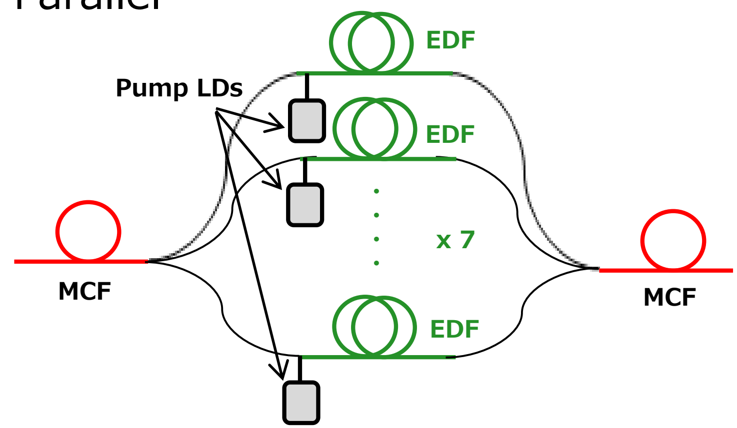
- Namely with Multi-core fiber (MCF)



Spatially integrated and scalable
High capacity

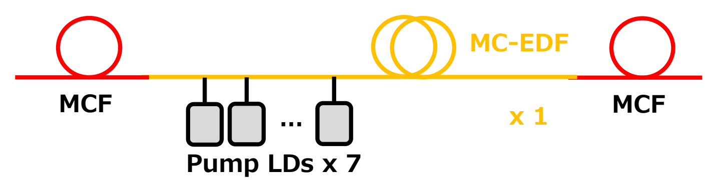
Amplifier

- Parallel



- Number of cores =Number of amplifiers
  → Large foot print

- With integration



H. Takahashi *et al*., ECOC 2012, **Th.3.C.3** (2012)

EDFA is also integrated
No integration of active devices

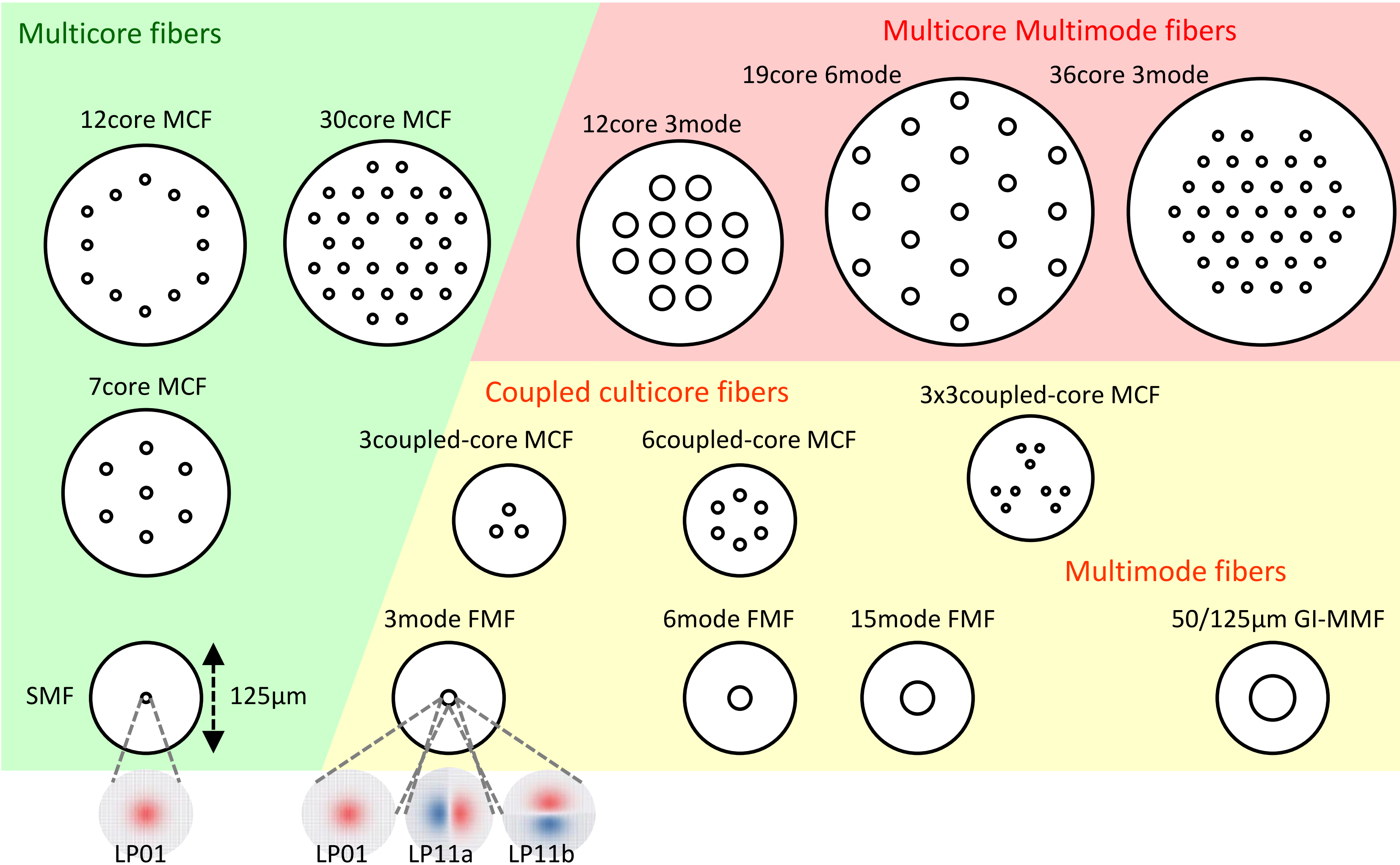
Efficient amplification

Design of high capacity SDM systems

- Different flavors
- XT compensation

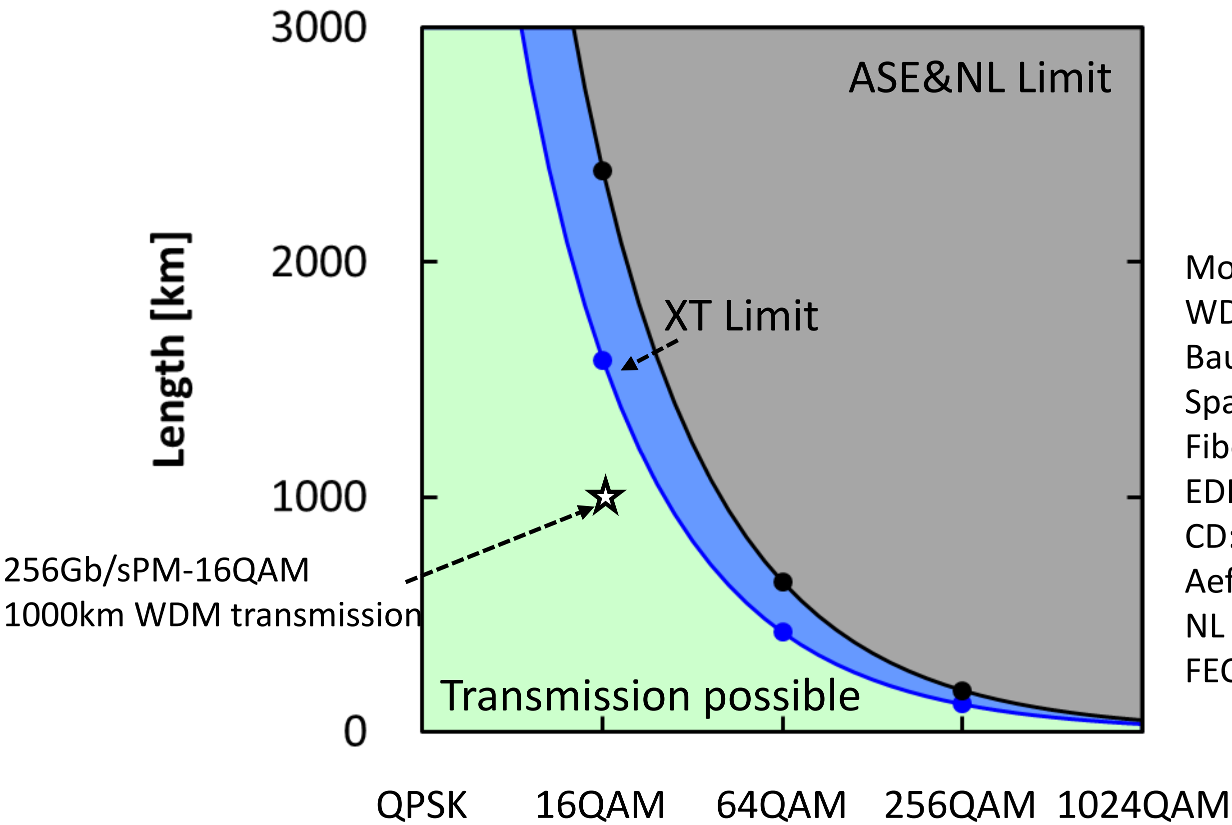
Fibers for high capacity SDM systems

Use of SDM to overpass the capacity limit of SMF



High capacity SDM system design: low XT design

Crosstalk of -30dB/100km

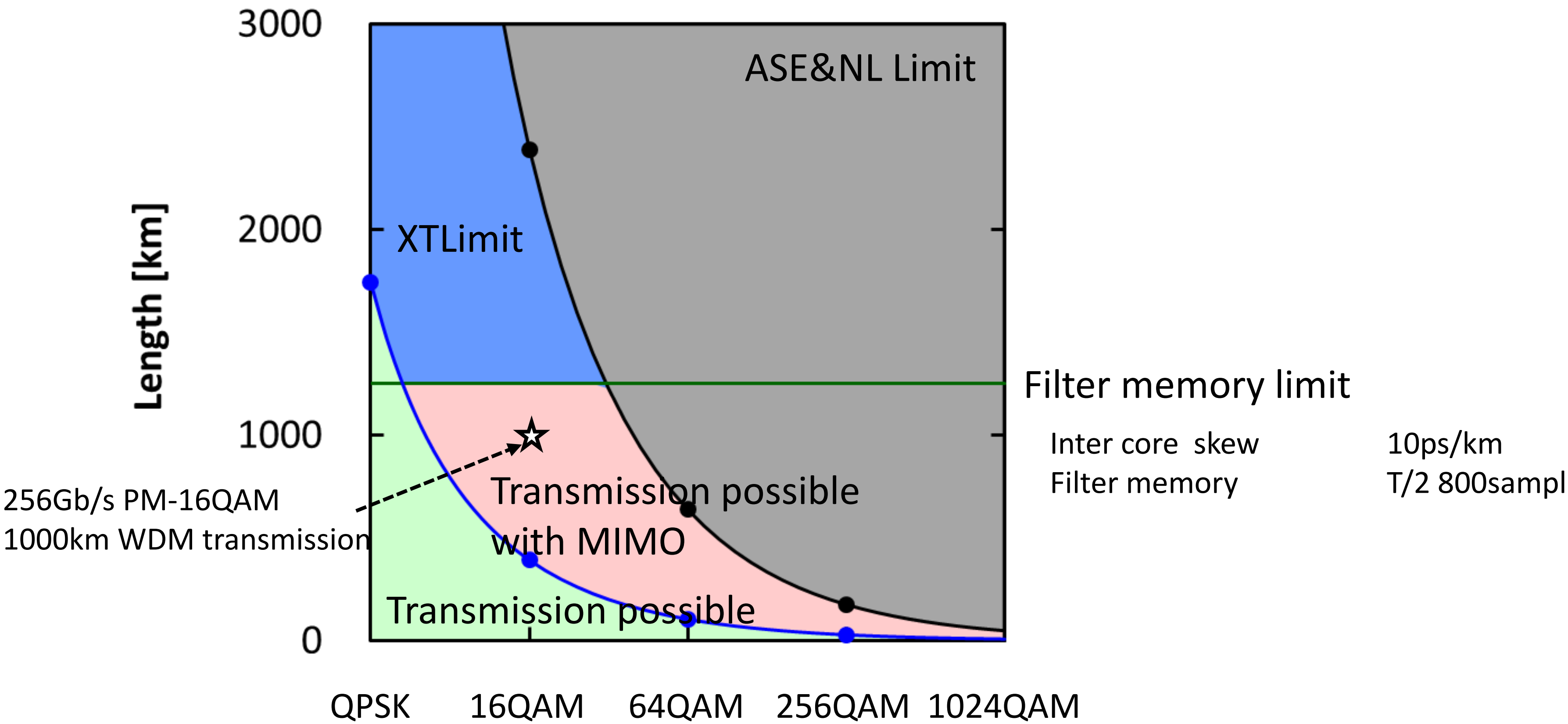


Modulation:	PM-M-QAM
WDM spacing:	50GHz
Baudrate:	32Gbaud
Span length:	100km
Fiber loss:	0.2dB/km
EDFA NF:	5.5dB
CD:	17ps/nm/km
Aeff:	80µm^2
NL Coefficient:	2.6x10^{-8}µm^2/W
FEC Limit on BER:	1.8x10^{-2}

- The proportion of proportion of distance limit due to XT limit is almost independent of modulation format

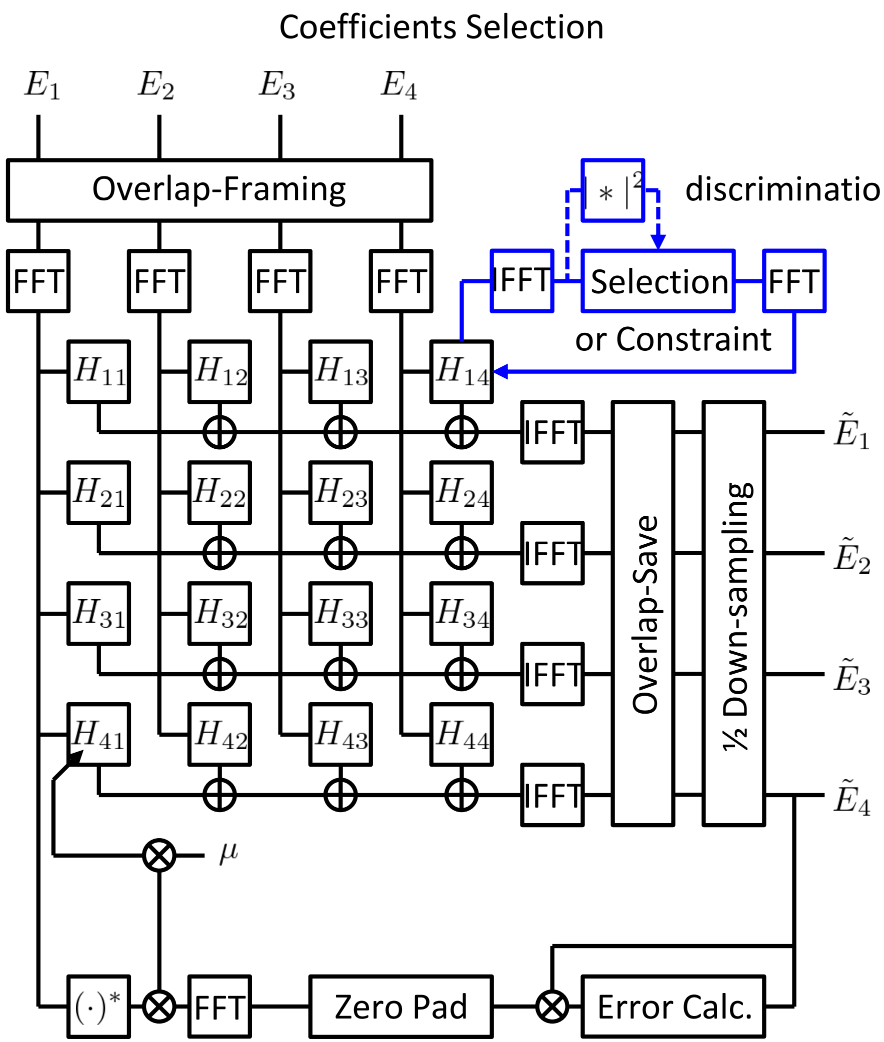
High capacity SDM system design: moderate XT design

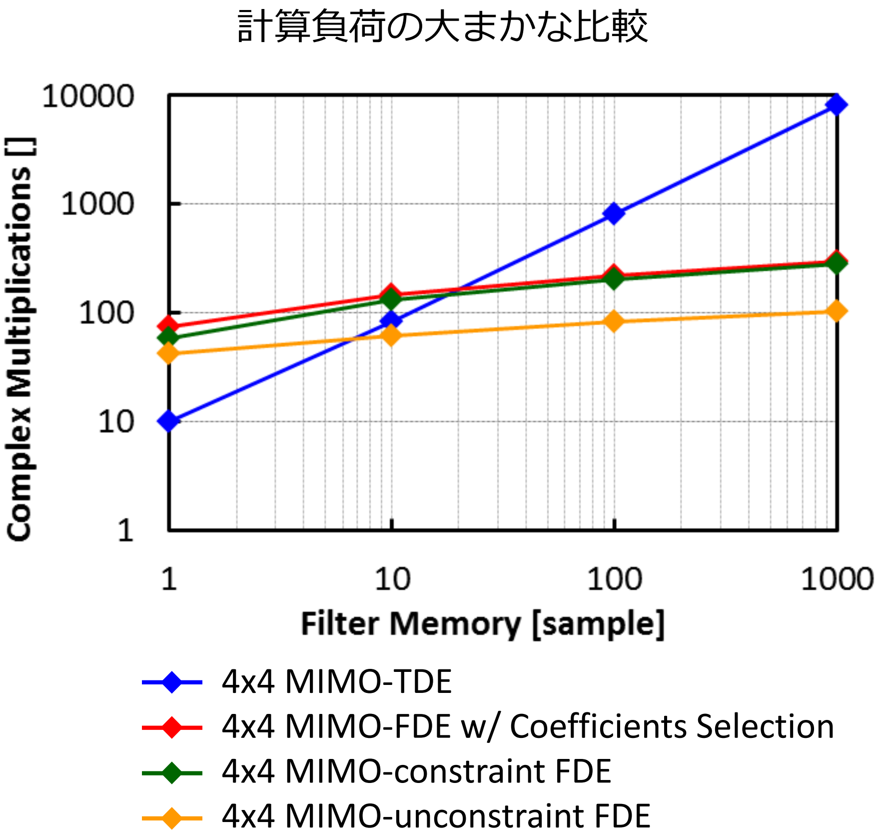
Crosstalk of -20dB/100km



- MIMO is efficient on short distance transmission.
- At long distance transmission, filter memory is the limiting factor.

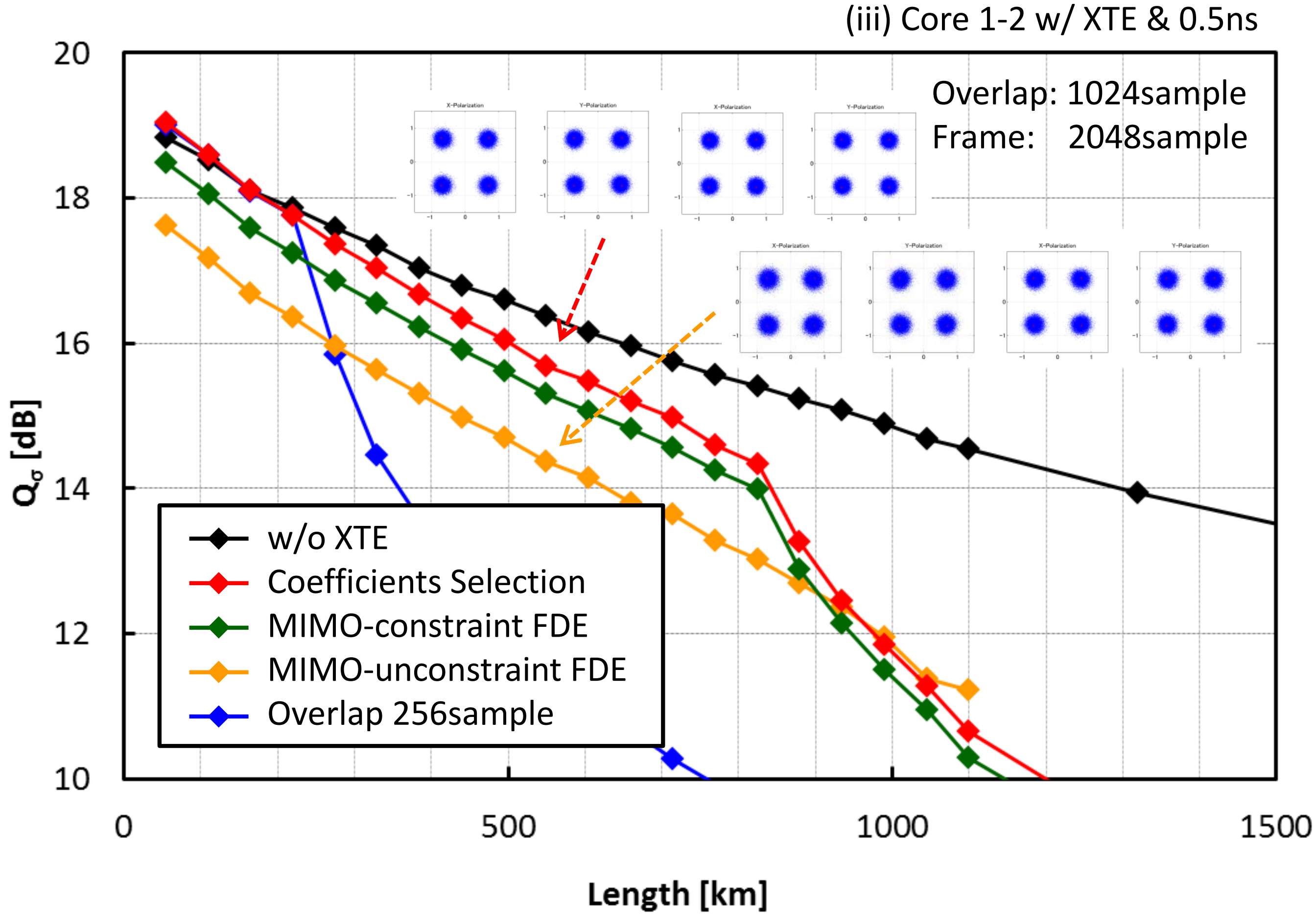
Coefficient selection with MIMO FDE



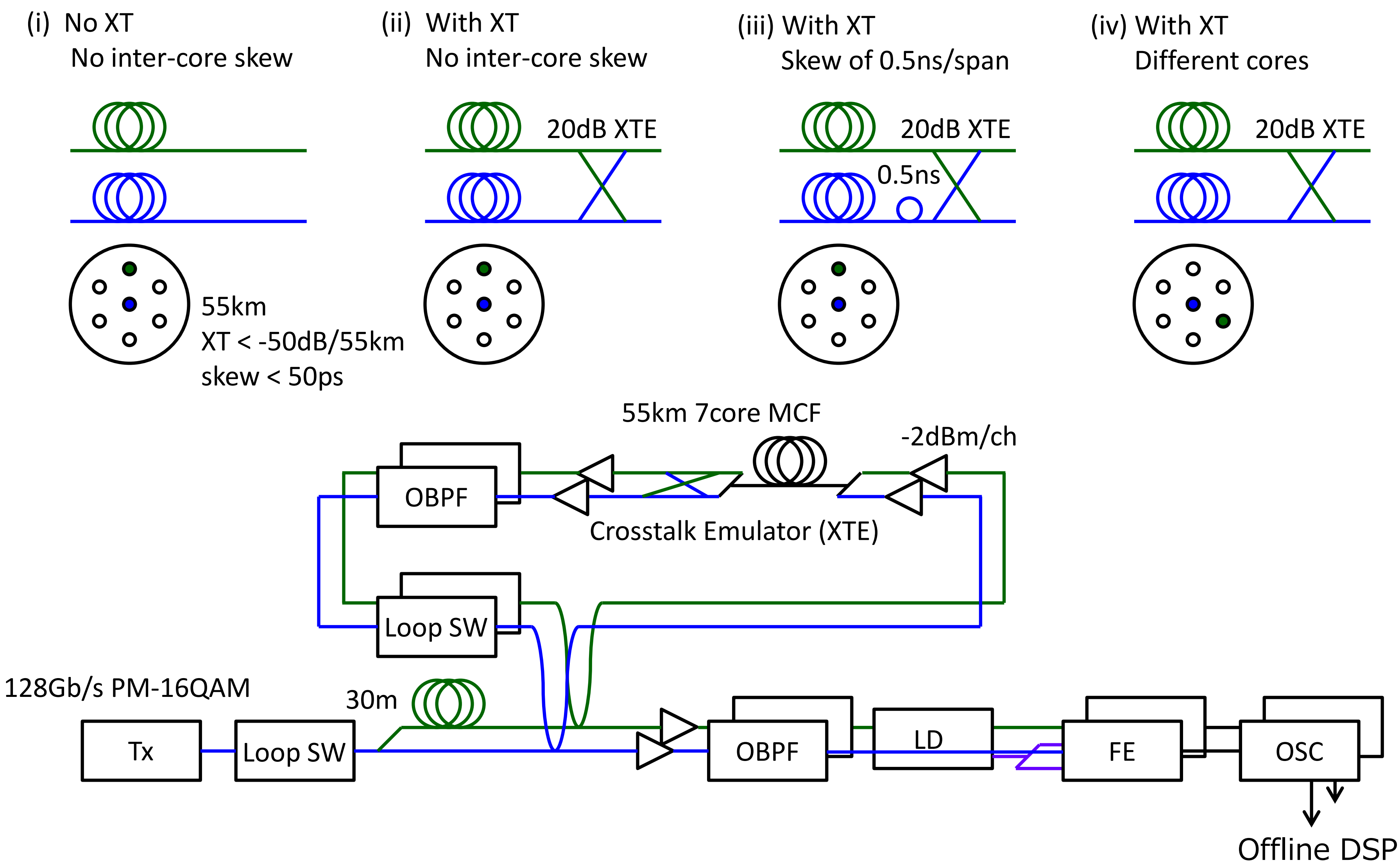


XT Compensation with MIMO-FDE

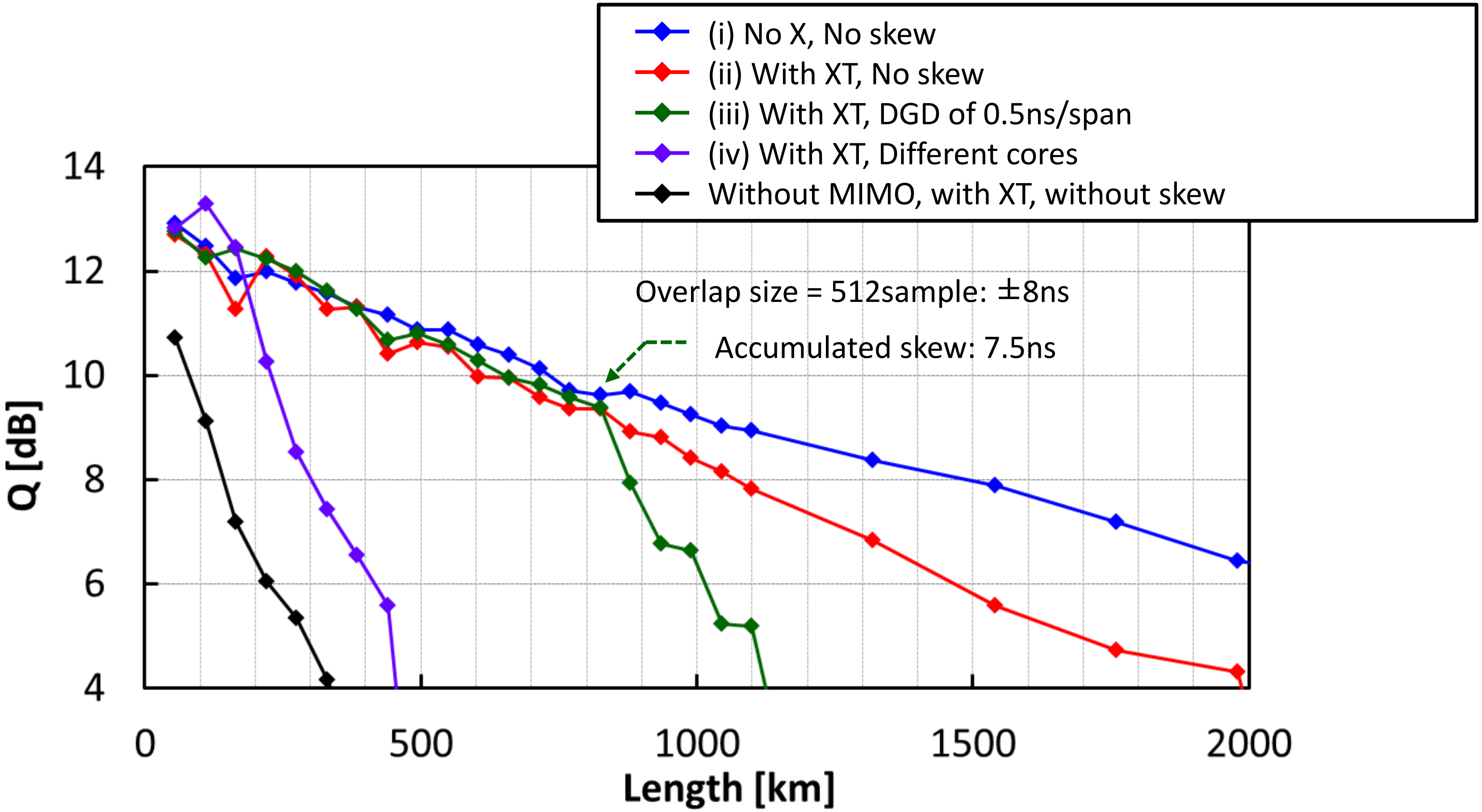
- MIMO coefficient selection and constraint FDE are efficient to compensate XT
- Unconstraint MIMO has difficulties for coefficient convergence



Evaluation of XT compensation with double loop configuration



Compensation of XT with MIMO-FDE



Signal management is a requirement for XT compensation.

Future SDM systems from a fiber perspective

MIMO-less approach

- Short distance
- Long distance with ultralow XT or XT management
- Early introduction

MIMO approach

- Fiber design becomes key
  - Relation between DSP and fiber
  - MGD / skew limit
- Coupled core may be an interesting approach

Low power consumption MC-EDFA

- Power consumption of amplification
- Pumping schemes for MC-EDFA
- Control of hybrid pumping scheme MC-EDFA

Part of these research results was obtained within "Research and Development of Space-Division Multiplexing Photonic Node", commissioned research of the National Institute of Information and Communications Technology (NICT), Japan

SDM-PN
Research and Development of Space-Division Multiplexing Photonic Node

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Power consumption of optical amplifiers

R. S. Tucker, *J. Sel. Top. Quantum Electron.*, **Vol.17**, No.2, Mar 2011

- Power consumption networks increase with exponential growth of capacity
- Limitation of electrical power consumption

- **Power consumption is key in power limited environment**
  - **Submarine cables, remote location**

As a traffic continues to increase..

- Electronic devices: further reduction of power consumption by CMOS process

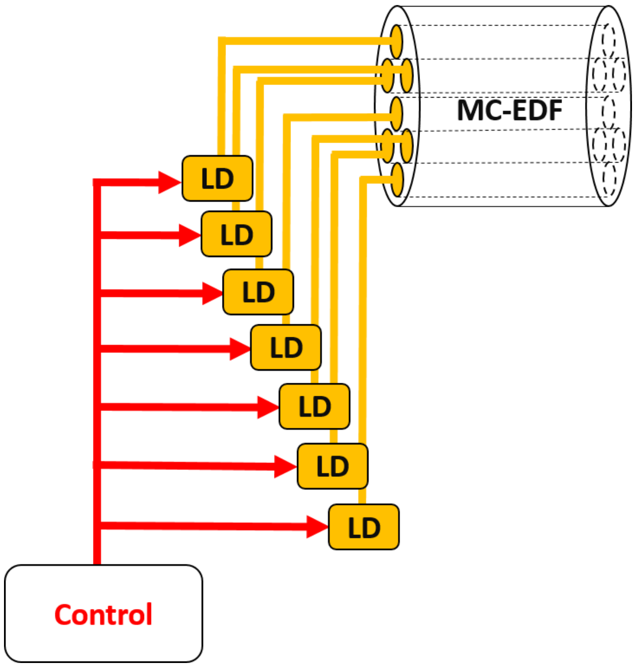
- Optical devices: power consumption continue to increase

- **and heat accumulating environment**
  - **Poor environment control, high integration**

For amplification, pump LDs are dominant

Pumping methods for MC-EDFA

Core pumping



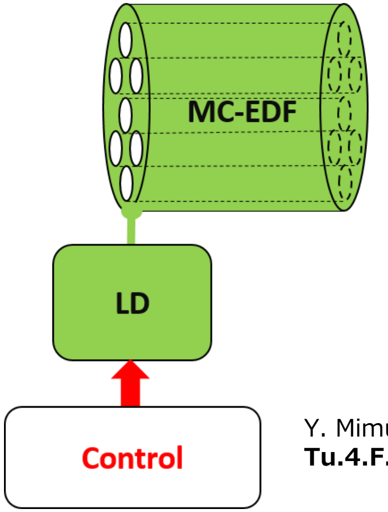
Number of LDs = Number of cores

Increment of cores mean increase of ..

(1)Power consumption
(2) Foot print
(3) Cost

Cladding pumping

LDs are also integrated !



Y. Mimura *et al.*, ECOC 2012, **Tu.4.F.1** (2012)

Number of LDs = Only 1
Reduction of power consumption

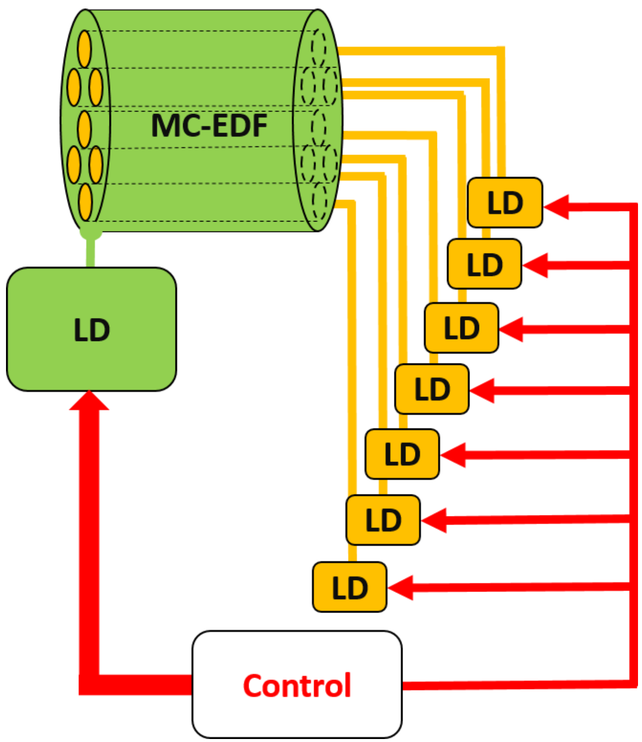
(1) No individual gain control
(2) Limited gain at C-band

Interest in hybrid of both

Hybrid pumping for power reduction

Hybrid pumping structure

Individual core pumping compensate gain variability and power of clad pumping



E. Le Taillandier de Gabory *et al.*, OFC 2017 **Th.1.C.1** (2017)

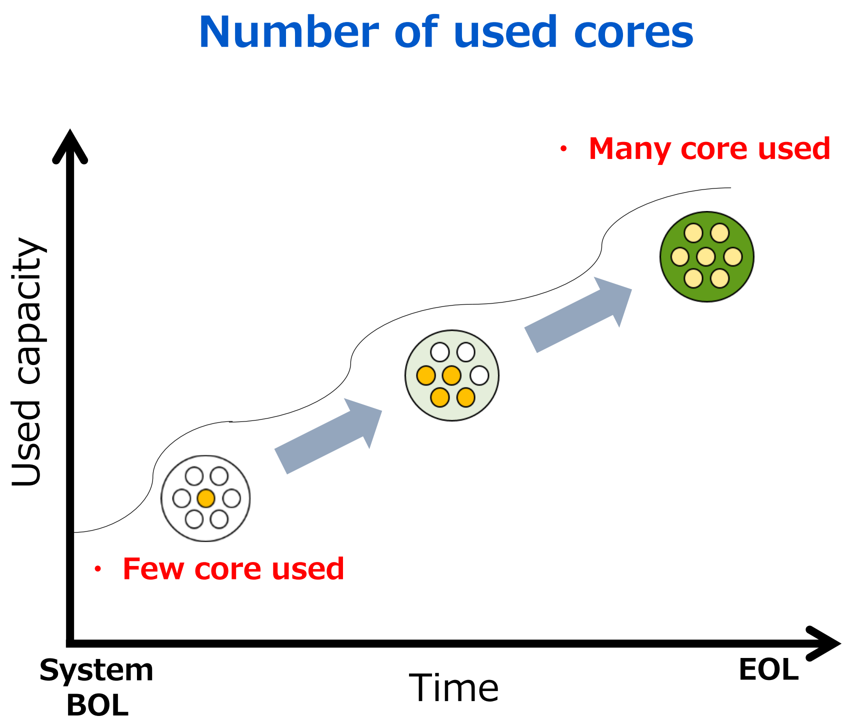
Characteristics of pump LDs

	Clad pump	Core pump
Mode	Multi-mode	Single-mode
Pump power	High (-30W)	Low (-5W)
λ	980 nm	1480 nm
Direction	Forward	Backward
# of LD	1	# of cores
Cooler	Without	With
Efficient at	・High power ・Many core used ・High temp.	・Low power ・Few core used ・Low temp.

Reduction of power consumption by controlling pumping ratio

Control depending on used cores

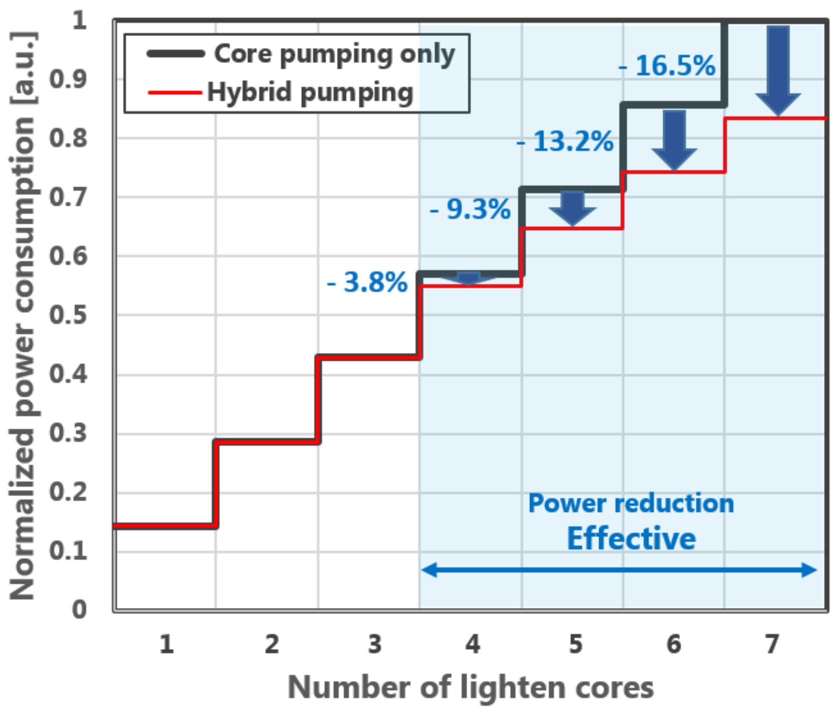
Control parameter



Time pass by and as the number of lighten cores increase ..

(1) Gradually increased clad pumping
(2) Correspondingly reduced core pumping

Reduction of power consumption



K. Matsumoto *et al.*, EXAT symposium 2017, **P-20** (2017)

(1) Compared with conventional core pumping
(2) Effect observed above 4 cores are used

Successfully reduced power consumption of up to 16.5 %

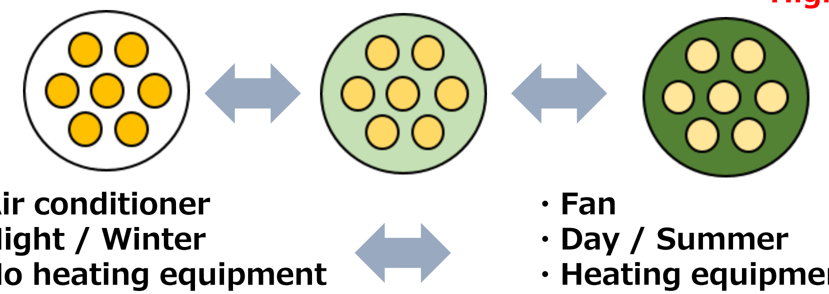
Control depending on temperature

Control parameter

Temperature

・ Low

・ High



- **Air conditioner**
- **Night / Winter**
- **No heating equipment (Low traffic)**

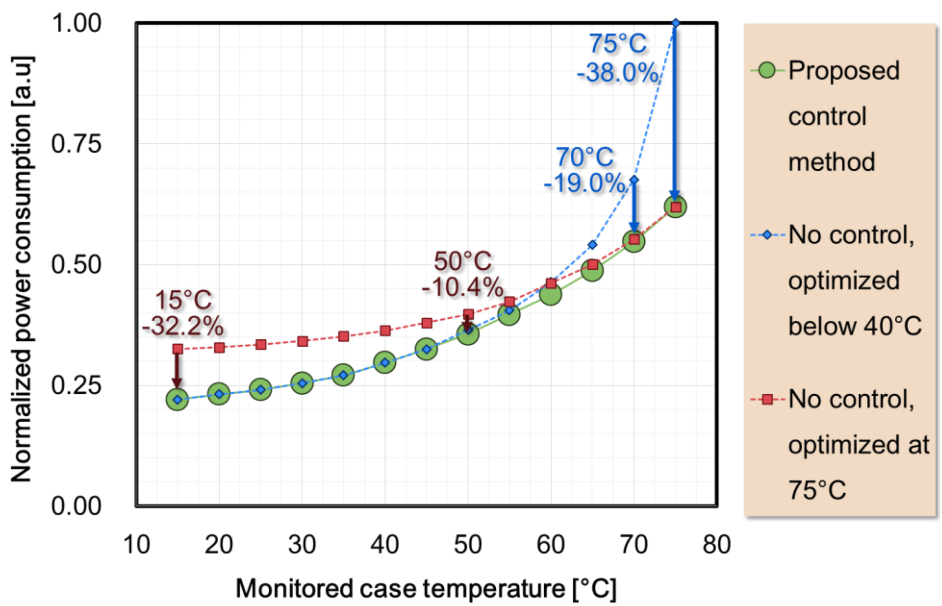
- **Fan**
- **Day / Summer**
- **Heating equipment (High traffic)**

As the case temperature varies ..

(1) High temp.; Increase clad pumping
Correspondingly decrease core pumping

(2) Low temp.; Increase core pumping
Correspondingly decrease clad pumping

Reduction of power consumption



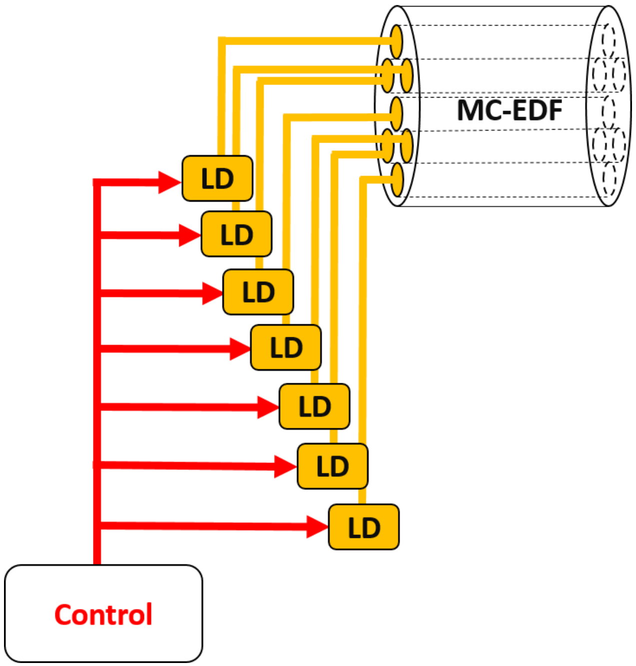
E. Le Taillandier de Gabory *et al.*, OFC 2017 **Th.1.C.1** (2017)

Compared with conventional core pump optimized at below 40 and 75 °C

Significant reduction of power consumption of >30%

Improvement of hybrid pumping scheme

Individually core pumped



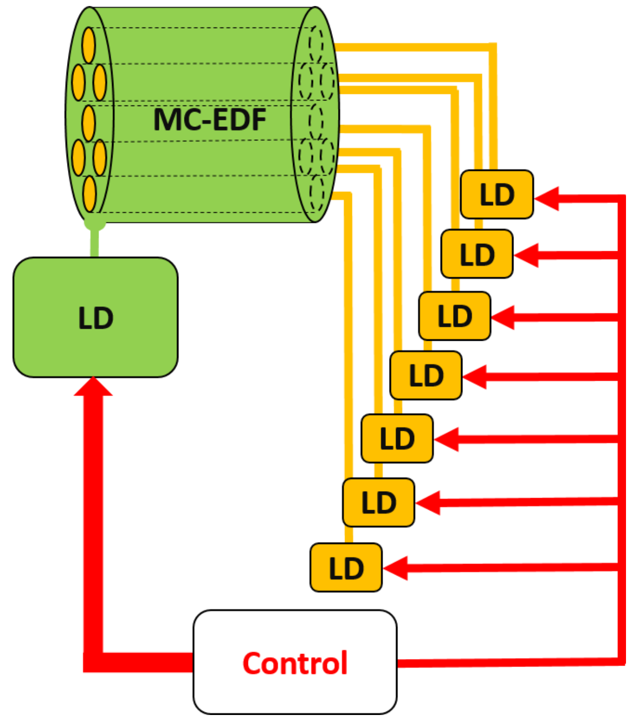
Number of LDs = Number of cores

Increment of cores mean increase of ..

~~(1) Power consumption~~
(2) **Foot print**
(3) **Cost**

≅

Hybrid pumping



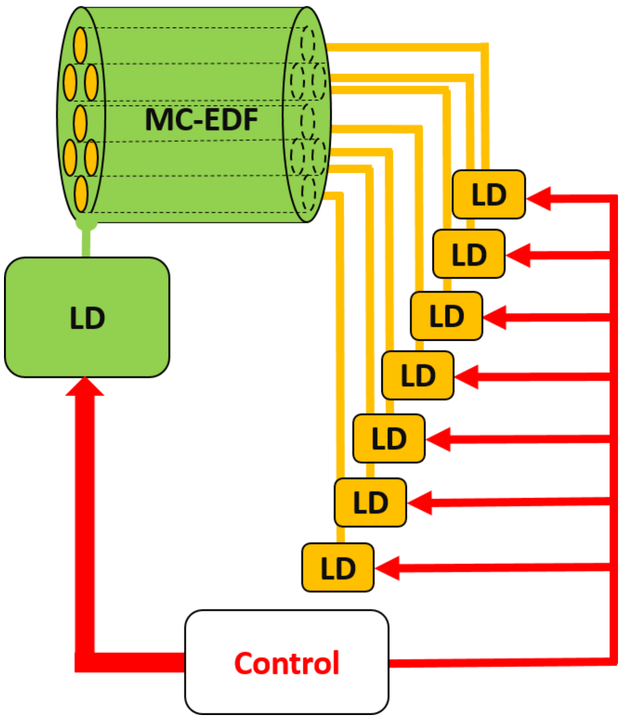
Power consumption has been successfully reduced ..

Number of LDs = Number of cores

Hybrid pumping is truly optimized scheme ?

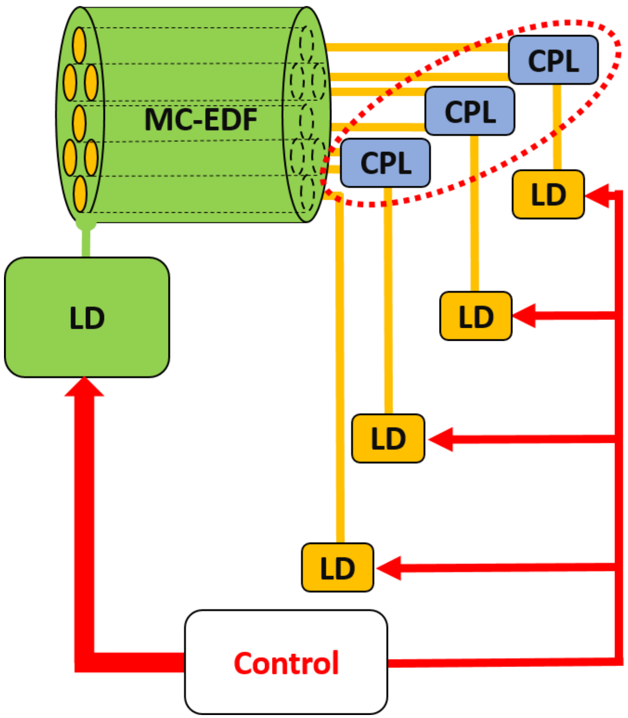
Approach to reduce the LD for core pumping

Hybrid pumping



~~(1) Power consumption~~
(2) Foot print
(3) Cost

Hybrid + †Core share pumping

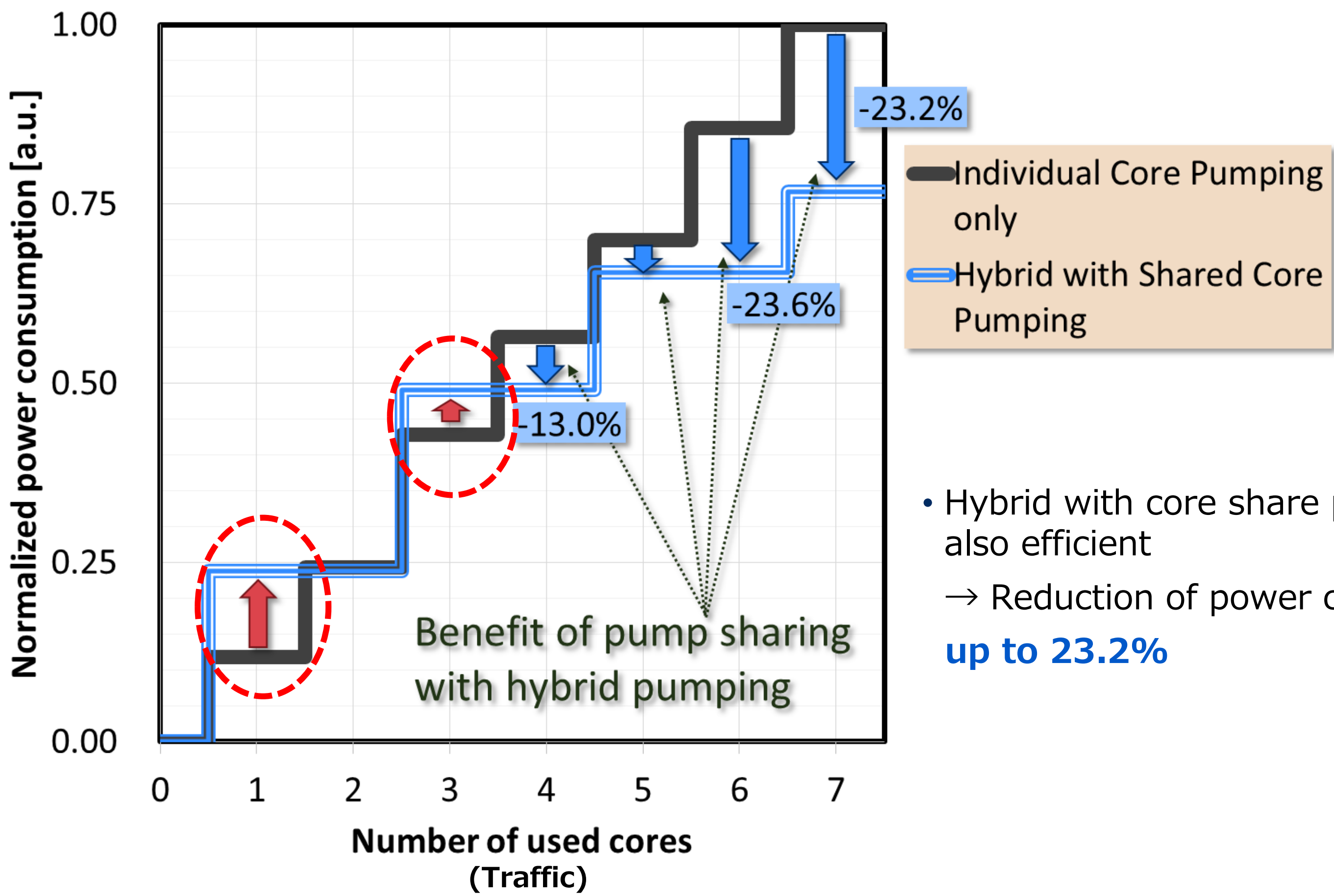


† A. Turukhin *et al.*, OFC 2016, **Th.4.C.1** (2016)

- Reduced the LD using **optical coupler**
- Continuing as-presented hybrid control

Low foot print and low cost expected with low power consumption

Evaluation of the reduction of power consumption



- Hybrid with core share pumping is also efficient

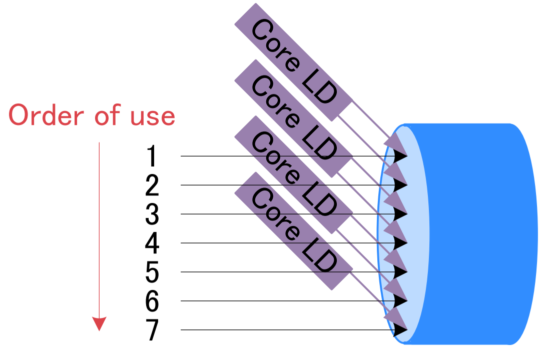
  → Reduction of power consumption **up to 23.2%**

- **Under the number of lighten core odd, unused pump power generated**

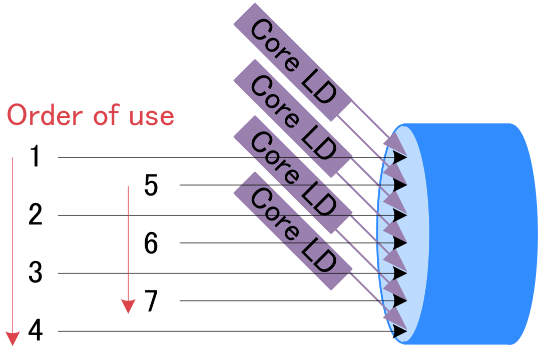
Not optimal over lifetime of the amplifier

Worst case

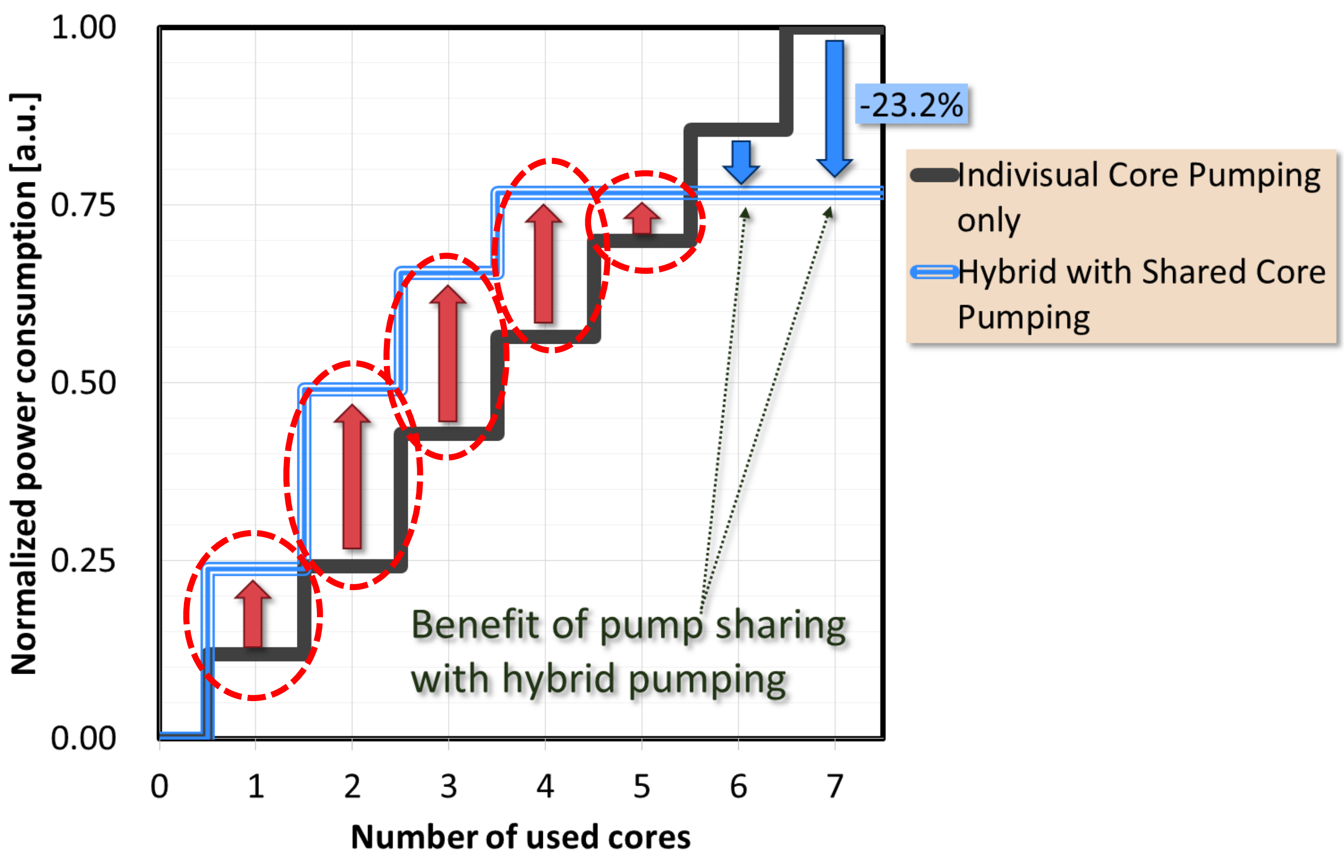
- **Previous results used a priori knowledge of the MC-EDFA structure.**
  - Cores sharing a lighten pump are used in priority.
  - **Best case:**



- **What would happen without a priori knowledge of the MC-EDFA structure?**
  - Plausible with no management of the SDM channels or with open line systems.
  - **Worst case:**



Power consumption under the worst case

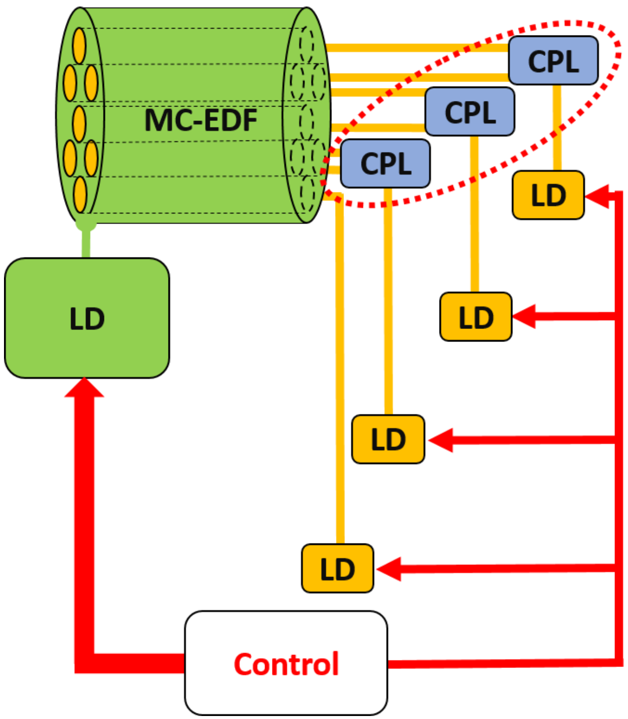


- **We achieved reduction of power consumption up to 23.2% ....**

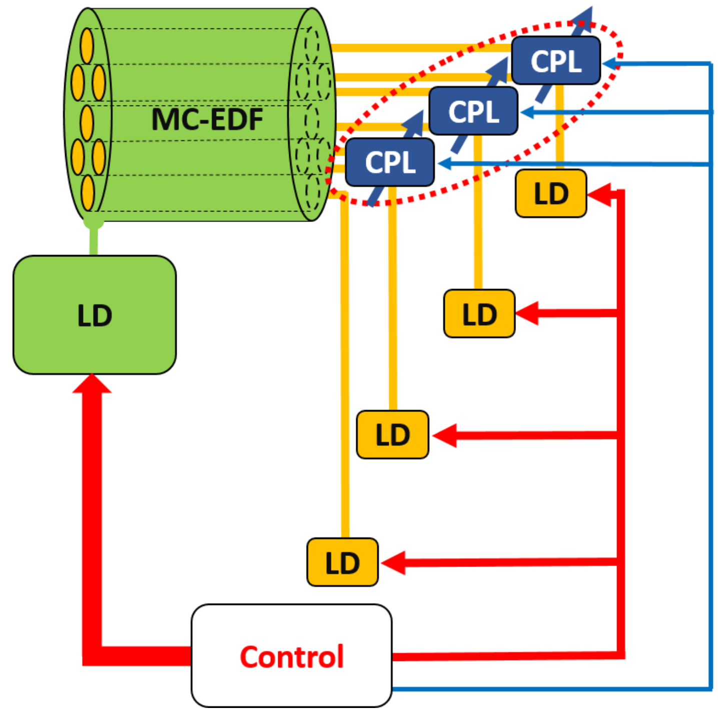
Without knowledge of core assignment, efficiency is low

Approach to solve the problem

Hybrid + Core shared pumping



Hybrid + Variable shared pumping

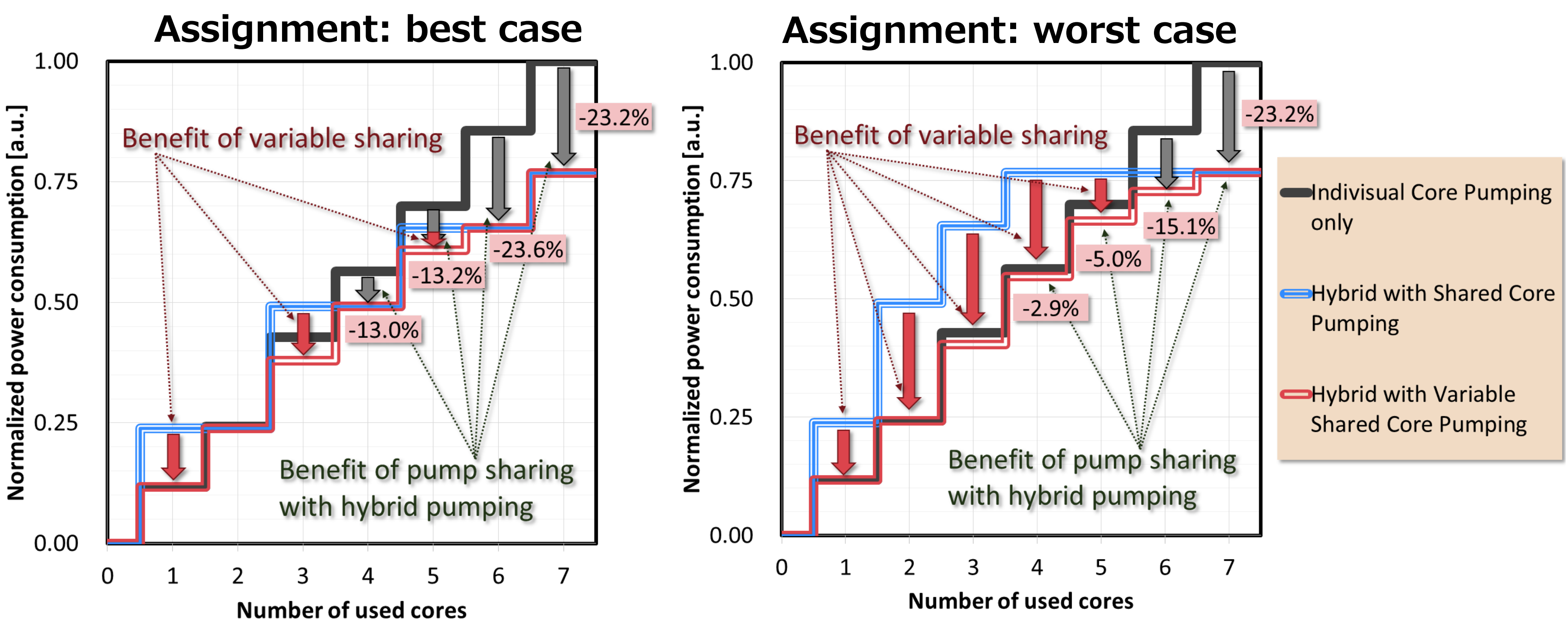


- Optical coupler has been changed to <u>**tunable optical coupler**</u>

Core pumping power become variable by tuning the optical coupler

Evaluation of the reduction of power consumption

“Hybrid + Core shared pumping” and “Hybrid + Variable shared pumping“



E. Le Taillandier de Gabory *et al.*, ECOC 2017 **M.1.E.2** (2017)

- Inconvenience of core share pumping is successfully overcome

Low foot print, low cost, and low power consumption achieved

Characteristics of amplified SDM systems

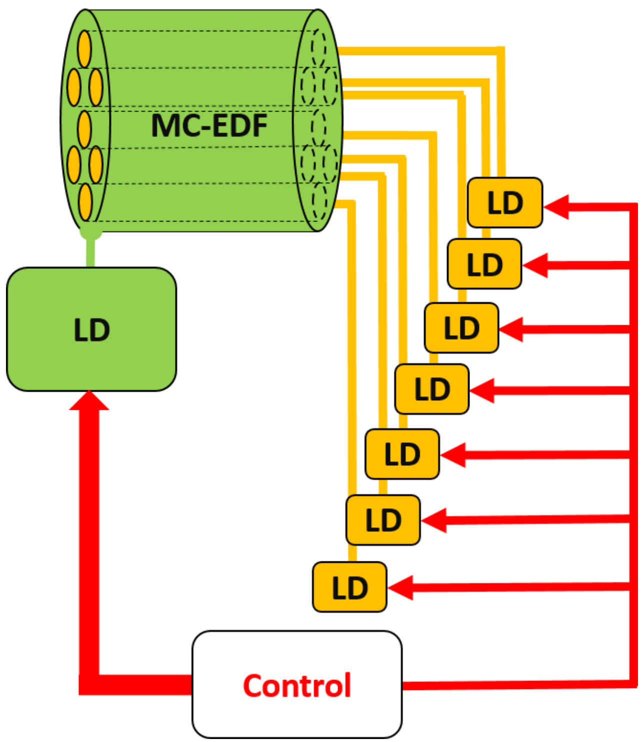
- Transmission experiments
- Signal assignment and path routing

Part of these research results was obtained within “Research and Development of Space-Division Multiplexing Photonic Node”, commissioned research of the National Institute of Information and Communications Technology (NICT), Japan

SDM-PN
Research and Development
of Space-Division Multiplexing Photonic Node

Purpose of transmission experiment

Hybrid pumping structure



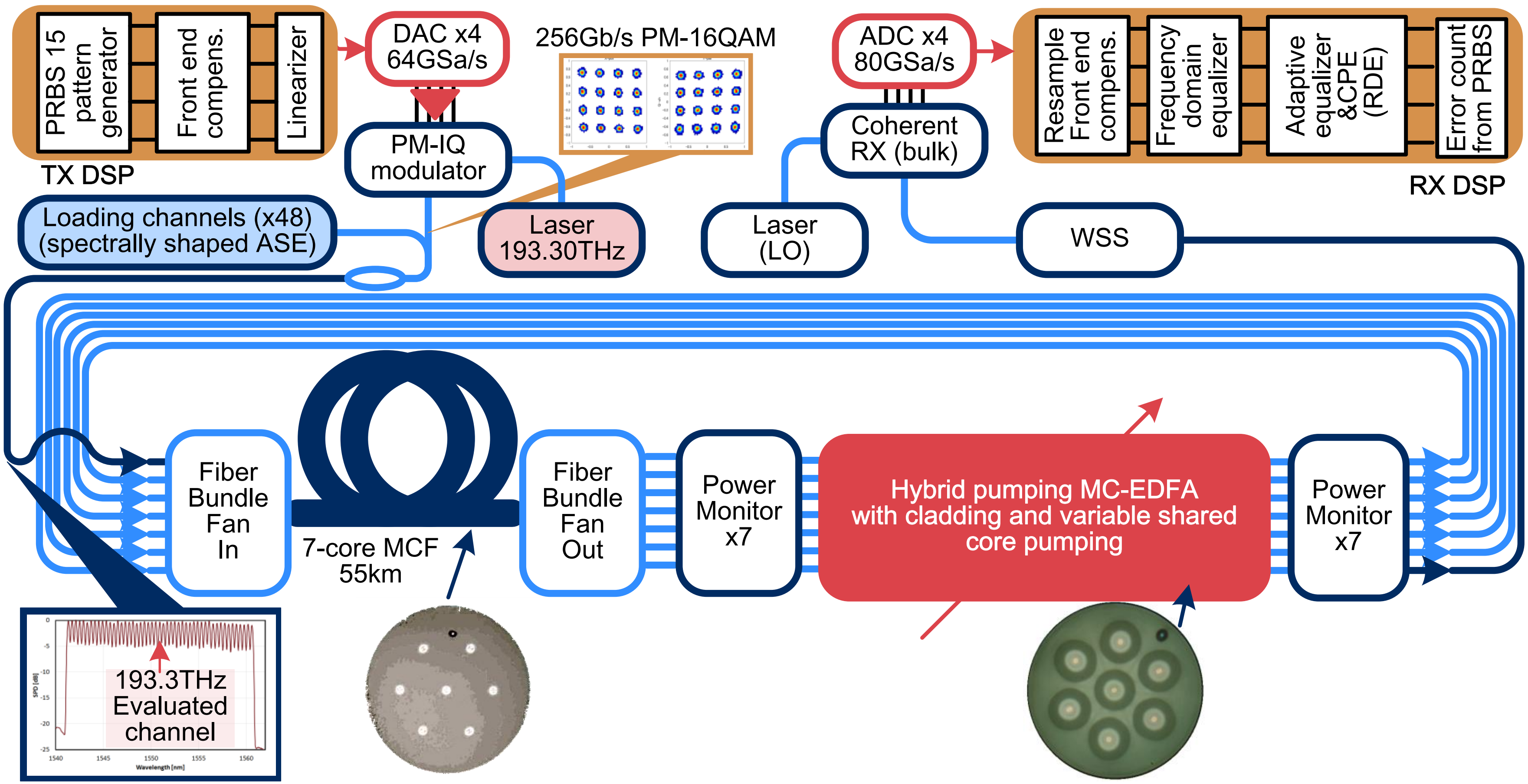
Characteristics of pump LDs

	Clad pump	Core pump
Mode	Multi-mode	Single-mode
Pump power	High (-30W)	Low (-5W)
λ	980 nm	1480 nm
Direction	Forward	Backward
# of LD	1	# of cores
Cooler	Without	With

- Hybrid pumping demonstrating pumping ratio control of LDs with different characteristics would change **noise figure** of amplifier

Influence on signal quality

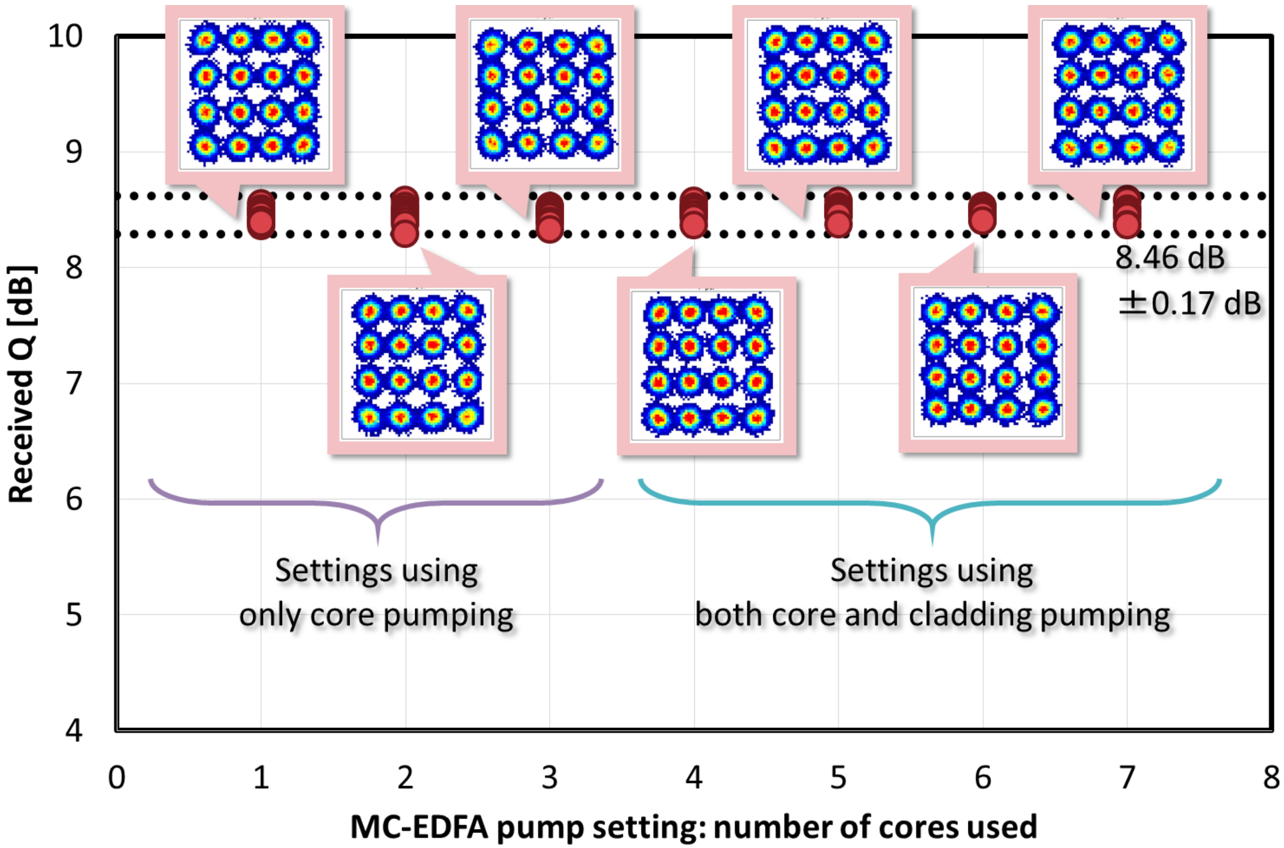
Validation with transmission experiment



- 256Gb/s PM-16QAM
- **7 times through the amplifier**

Pumping ratio has fixed to optimized values for the number of used cores of 1-7, respectively

Validation with transmission experiment

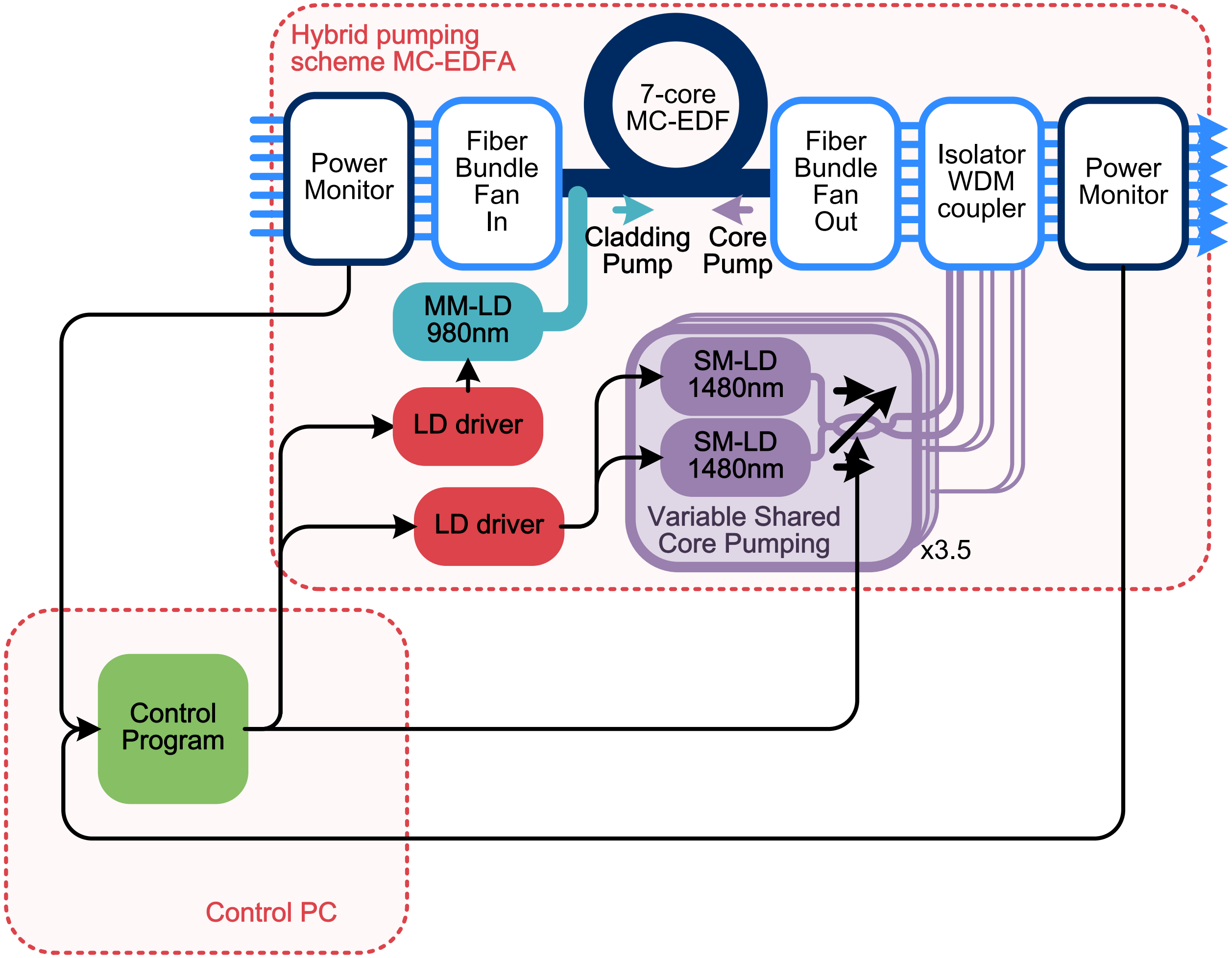


- No significant degradation of the received Q value depending on the hybrid control
  - Q variations of ±0.17dB are related to variations of transmitter

Hybrid pumping scheme can be used in transmission system

Influence of signal allocation on power consumption

Power consumption depends on signal allocation and selected pumping scheme

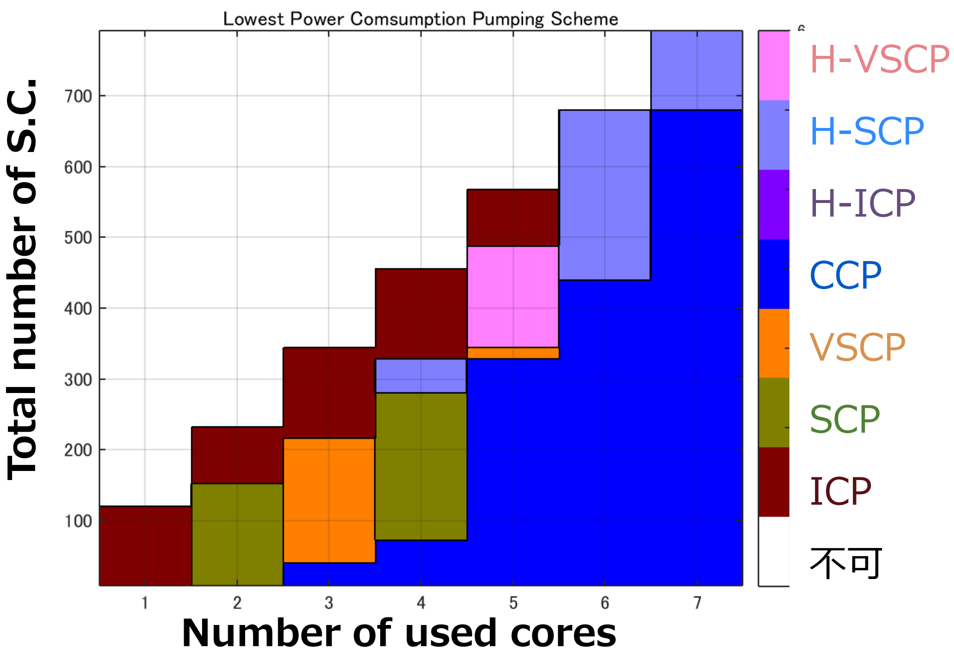


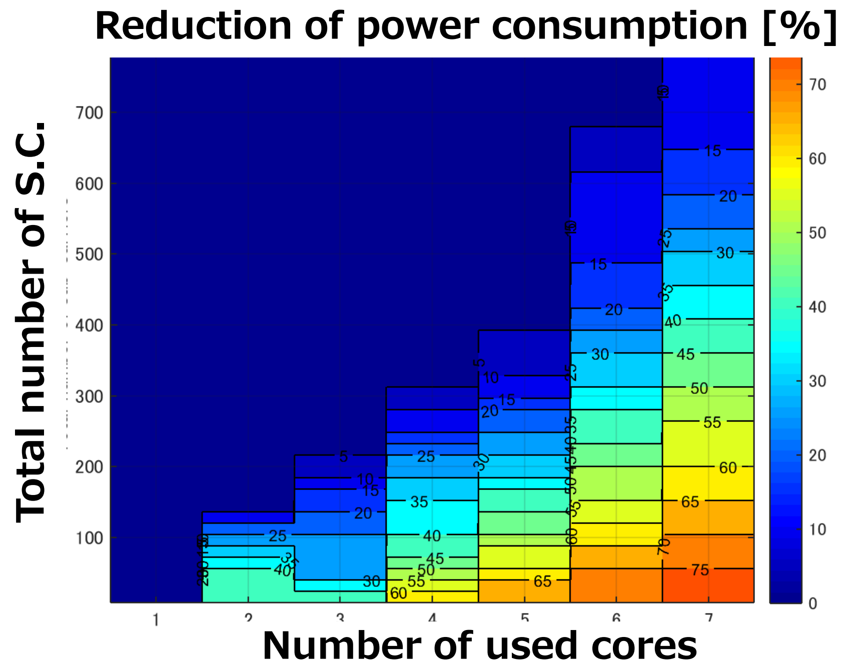
- The most power efficient pumping scheme will depend on the signal allocation

Menu card of available pumping schemes

Pumping scheme	Acronym	Use of core pumping	Use of clad pumping	Comments
Individual core pumping	ICP	**Yes**	No	Reference
Shared core pumping	SCP	**Yes**	No	With 3dB coupler
Variable shared core pumping	VSCP	**Yes**	No	With tunable coupler
Common cladding pumping	CCP	No	**Yes**	Need of core attenuation
Hybrid with individual core pumping	H-ICP	**Yes**	**Yes**	
Hybrid with shared core pumping	H-SCP	**Yes**	**Yes**	With 3dB coupler
Hybrid with variable shared core pumping	H-VSCP	**Yes**	**Yes**	With tunable coupler

Evaluation of optimal pumping scheme



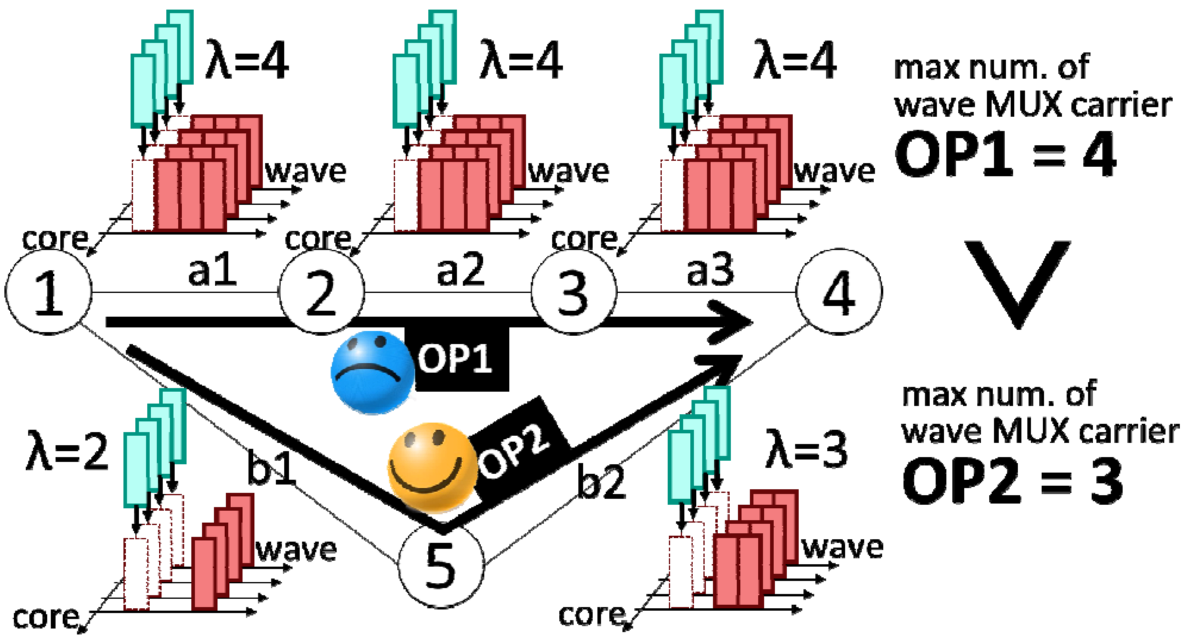


- Channel allocation on spatial superchannels of different sizes
- Simulation calibrated with MC-EDFA characteristics
- Assumptions
  - 112ch/core at maximum, 16 sub-carriers chunks
  - -3dBm/subcarrier
  - Spectrum equalized externally
- Reduction of power consumption relative to individual core pumping

Path selection algorithm for low power consumption with cladding pumping

- The selected optical path is **not always the shortest** optical path.
- The number of optical carrier per core is minimized.
- Minimum power consumption of MC-EDFA is achieved in each link.
- The total power consumption of MC-EDFA in the network is minimized.

different from conventional methods



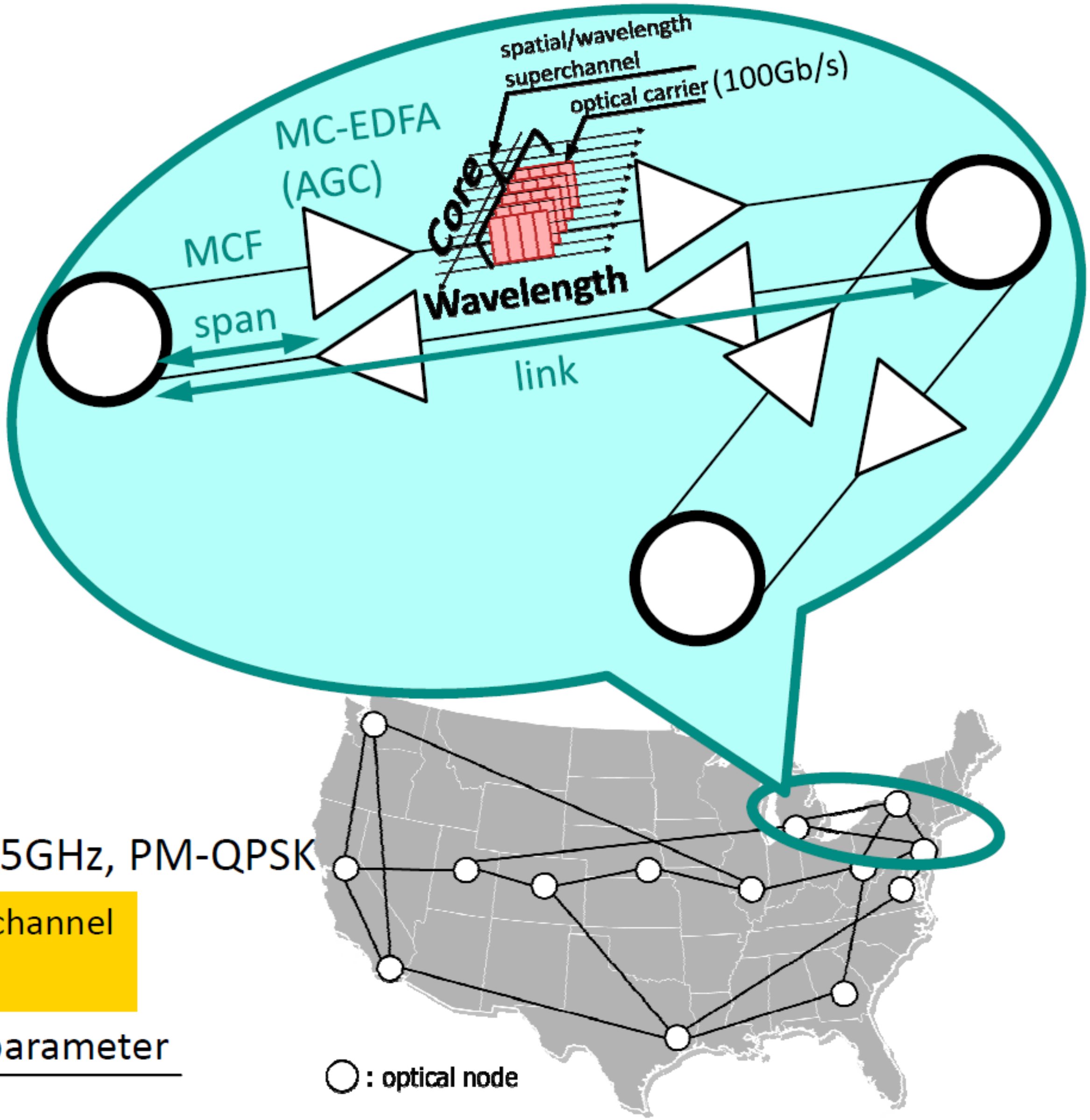
Simulation model for SDM network

- **Topology: NSFNET**
  - 16nodes, 21links
- **Node: CDC-ROADM**
- **Link: MCF**
  - 1, 2, 4, 8, 16 cores

parameter

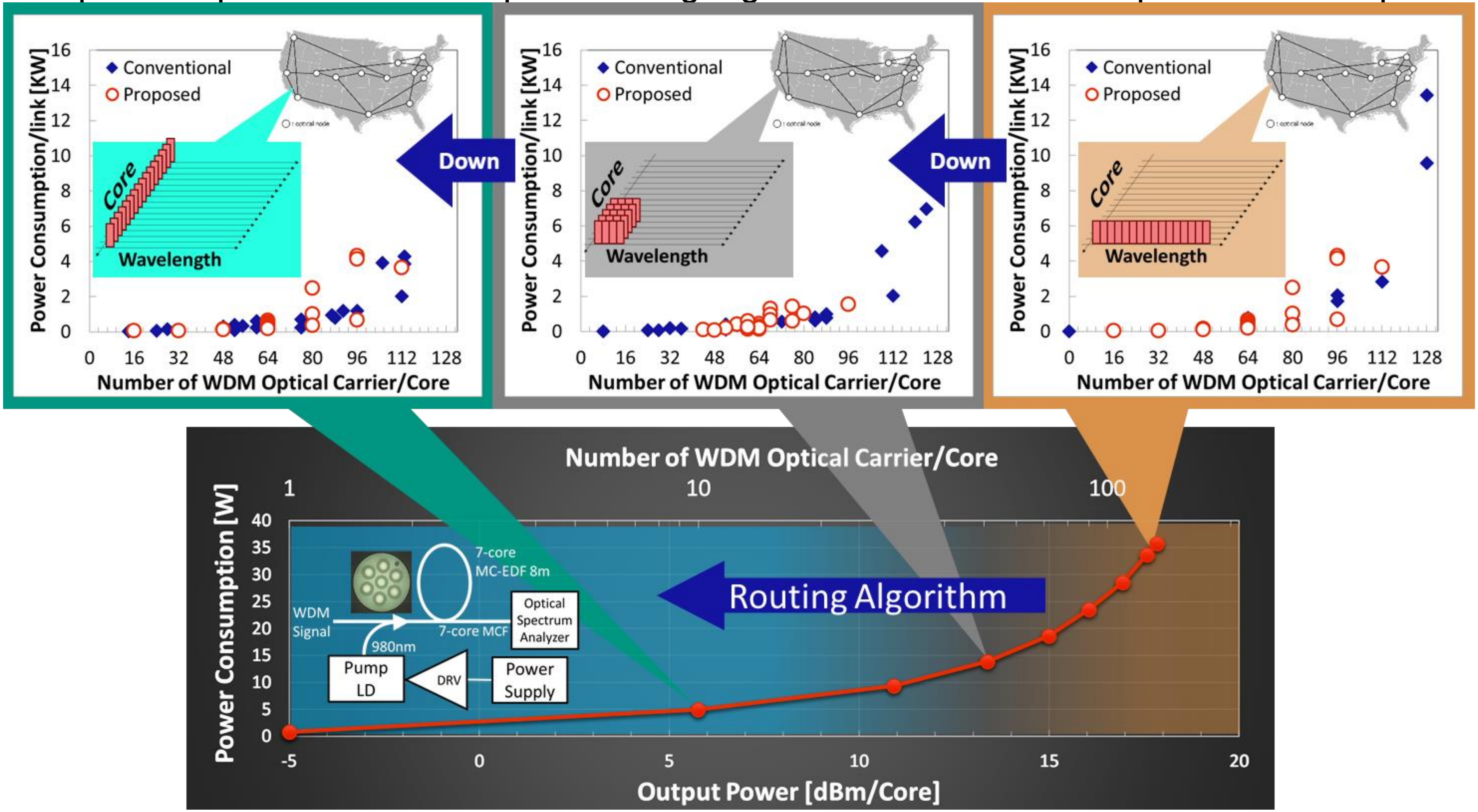
- **Traffic Demand**
  - 100 Gb/s
  - Random generation
  - Total capacity is constant
- **MC-EDFA Span: 80km**
- **MC-EDFA Gain: 20dB**
  - Cladding pump, AGC
- **Optical Carrier: 100Gb/s, 37.5GHz, PM-QPSK**
  - Spatial/Wavelength hybrid superchannel
    1s16w, 2s8w, 4s4w, 8s2w, 16s1w

parameter



Cladding Pumped MC-EDFA with Spatial Superchannels

- Cladding pumped MC-EDFA reduces power consumption of amplified optical link.
- Spatial superchannels and path routing algorithm reduces further power consumption.

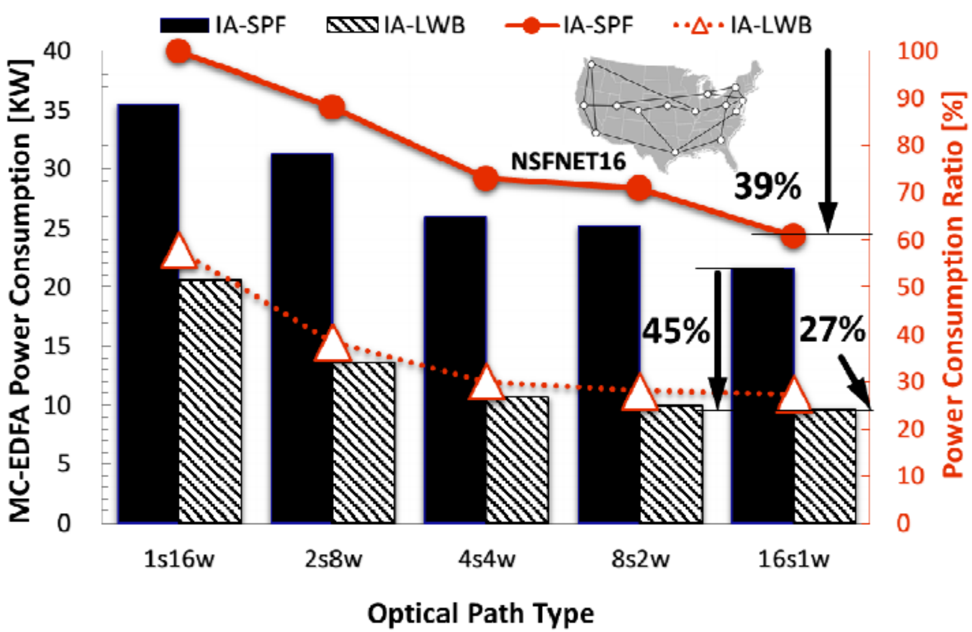


H. Takeshita et al., Proc. OFC 2018, M3J.5

Reduction of power consumption in SDM networks

39 % reduction by cladding pump
45 % reduction by proposed IA-LWB algorithm

- Total p.c. = Σ[{Σ(power consumption of MC-EDFA)}/link]
- Conventional algorithm (IA-SPF): reduction is NOT saturated.
  → **16 or more cores-MCF is the best**
- Proposed algorithm (IA-LWB): reduction is saturated at 4s4w.
  → **4 cores-MCF is sufficient**



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Perspective of SDM systems

- High core count
- Other perspectives

Higher core count

Clad pumping become more efficient

- Number of cores will continue to grow

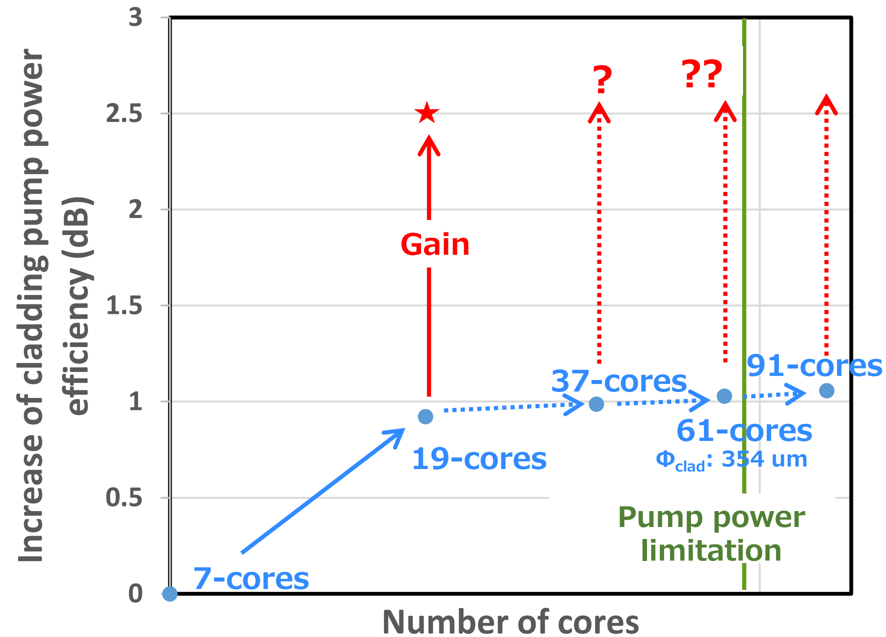
7-cores **19-cores**

S. Takasaka *et al.*, ECOC 2017 **Th.2.D.3** (2017)

$$\Sigma A_{core} / A_{clad}$$

- Increasing geometrical gain of clad pumping is expected
- Decoupling between number of cores of transmission fiber and amplifier fiber

- Geometrical performance increase



Hexagonal close-packed structure
Maximum pump power used in hybrid structure : 10W
Maximum pump power under current technology: 70W

5layers 61core

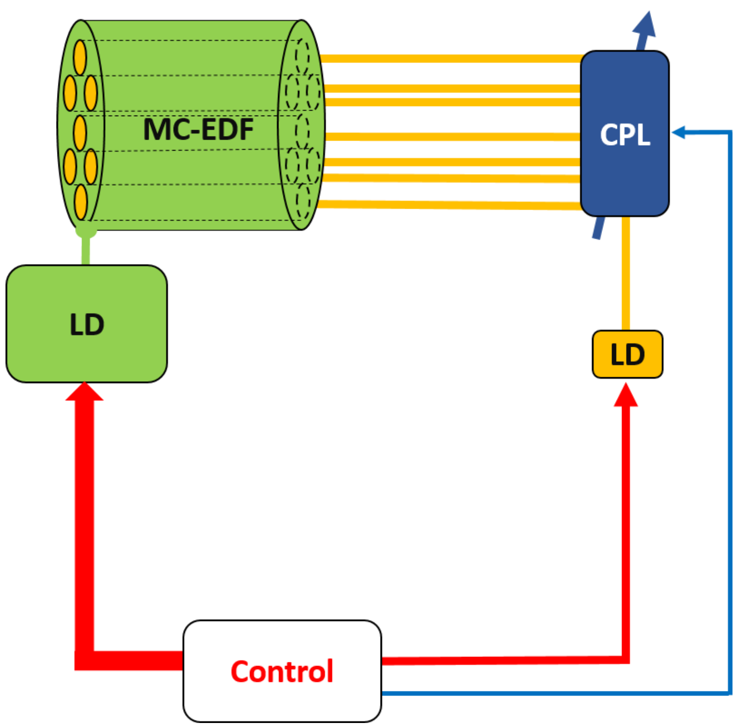
- Reported gain at higher number of cores is key

Core to core variation are a limiting factor

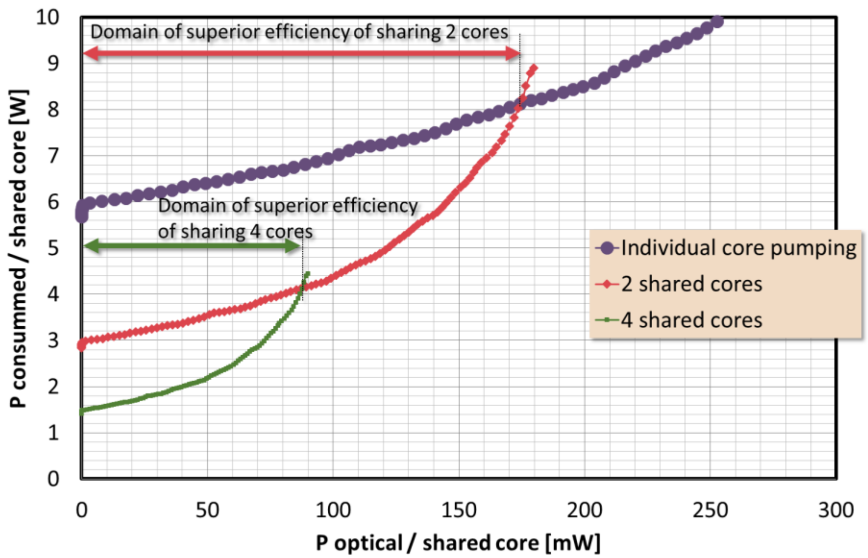
Core pumping for high core count

Promising hybrid pumping structure

- Number of LD for core pump is 1



- High linearity LD for core pump



Pump sharing techniques is beneficial at moderate pump power

- Improvement of linearity of pump LD will be the key

Further power reduction expected

Other perspectives

Improvement of cladding pumping

- Looking forward for future developments (ECOC 2018)

Summary

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Summary

- SDM technology enables **high capacity** system design
  - With correct XT or MIMO design
- SDM enables **lower power consumption** system design with MC-EDFA
  - Cladding pumping has high potential for power reduction of optical amplification
  - Hybrid of cladding and core pumping is the most viable solution at current point
    - The proposed amplifier enables more than **23% reduction of power consumption** compared to individual core pumping
    - **Less than ±0.2dB variation of received Q** after passing through the controlled amplifier
- Channel allocation and routing algorithm may contribute to power reduction in SDM systems
  - **Reduction of power consumption by 39%** in simulated SDM network using cladding pumped MC-EDFA
  - Additional reduction of power consumption by 45% with dedicated path routing algorithm

Part of these research results was obtained within "Research and Development of Space-Division Multiplexing Photonic Node", commissioned research of the National Institute of Information and Communications Technology (NICT), Japan

SDM-PN
Research and Development of Space-Division Multiplexing Photonic Node

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