ECOC2021 Tutorial

Multicore Erbium Doped Fibre Amplification Techniques

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Collaborators

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Outline

- Background
- Configuration and component
- Amplification characteristics
- Reduction of power consumption
- Summary

What is multicore EDFA

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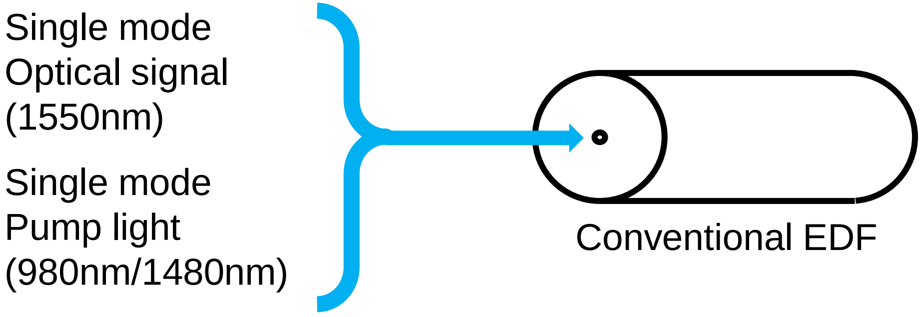
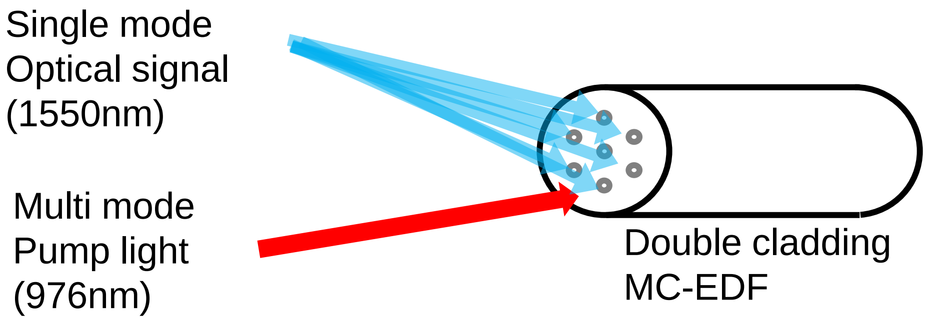
- Conventional EDFAs
  - Single core
  - Core pumping using a single mode LD
- Cladding pumped multicore (MC-) EDFAs
  - Multicore
  - Cladding pumping using a multimode LD



Configuration of conventional EDFAs



Configuration of cladding pumped MC-EDFAs

Expected point for MC-EDFA, part 1

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Lower power consumption

- In case that whole cladding pump is absorbed by Er ions at cores, power consumption is determined by those of pump LDs
- MM-LDs have ~1.5 times higher conversion efficiency of electric to optical power than that of single mode pump-LD

Conversion efficiency

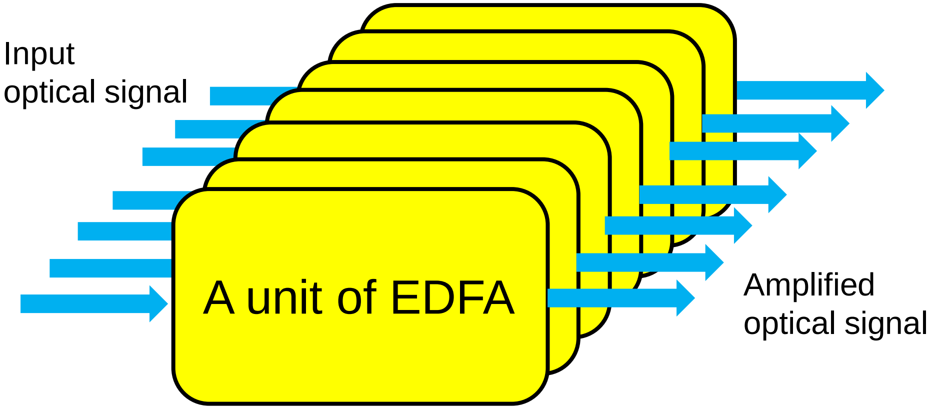
Multimode LD > ~1.5 x Single mode LD

Pump source **Single mode LD** → Conventional EDF (Core pumped)

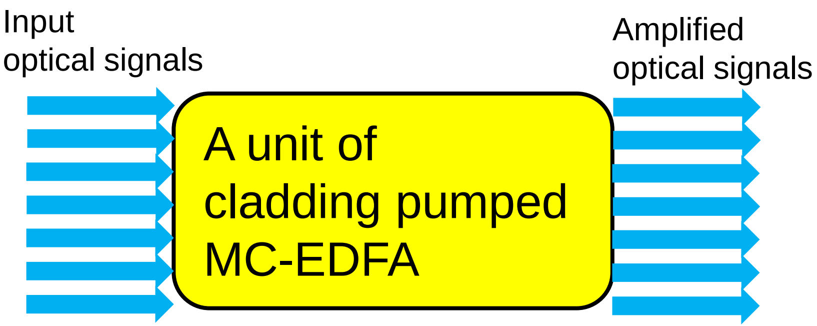
Pump source **Multimode LD** → Multi-core EDF (Cladding pumped)

Expected point for MC-EDFA, part 2

- Downsizing
  - Use only one unit of optical devices regardless of number of multicores
  - Conventional EDFA requires the same number of optical devices as the number of cores



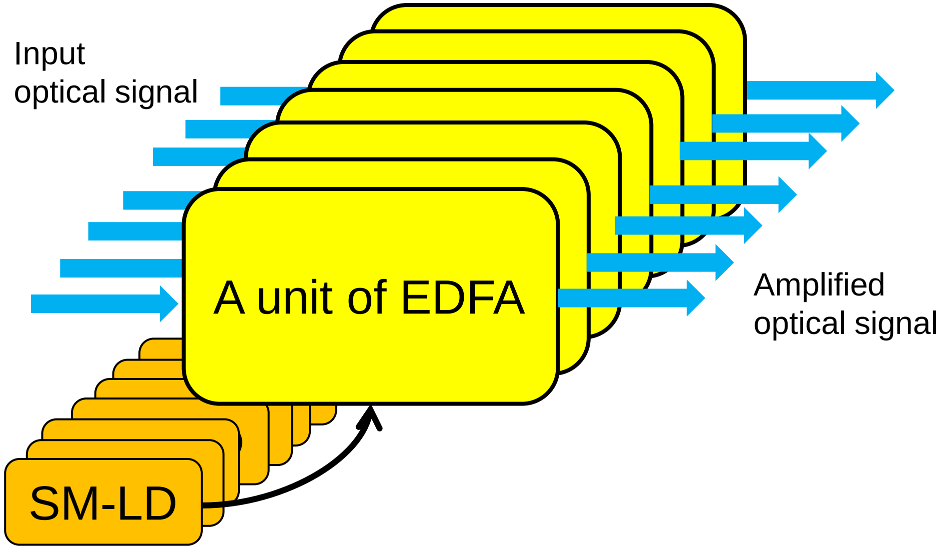
Number of units are
the same with number of signals

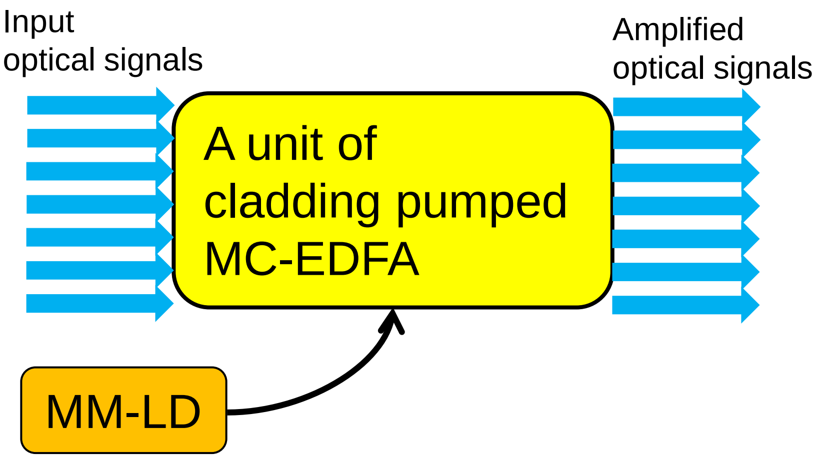


One unit is used
for multiple signal amplification

Drawback point

- Gain control of each core
  - One cladding pump for MC-EDF excitation

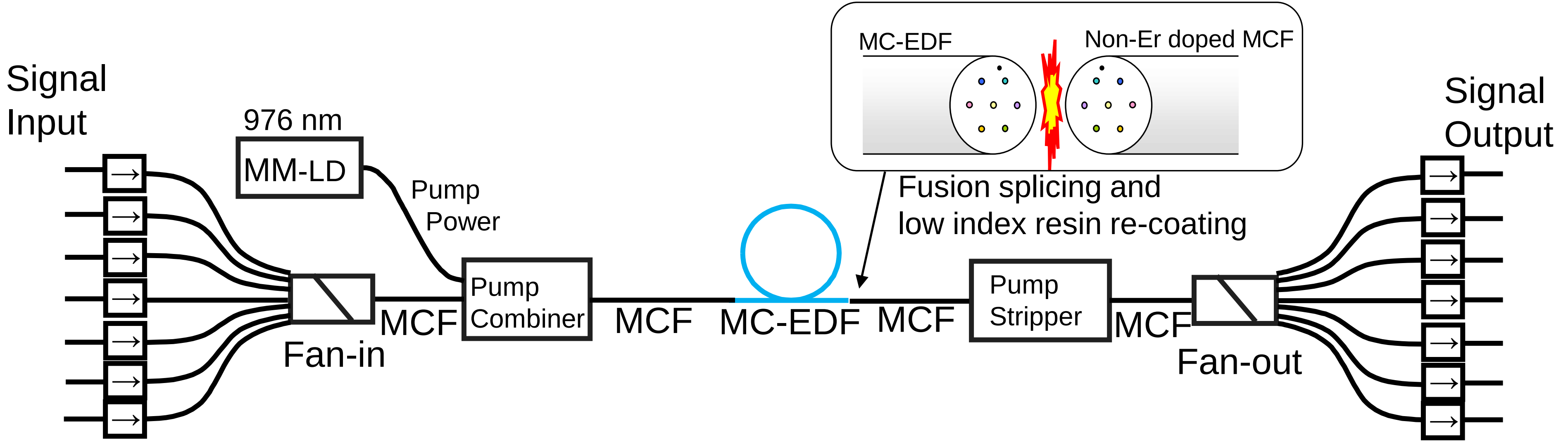




Configuration

Configuration

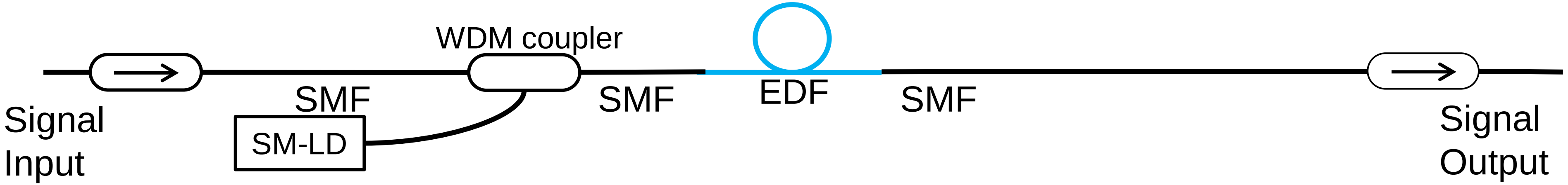
- Fan-in/out: SMF inputs are coupled with each core in a MCF
- Pump combiner : Multi-mode pump is injected in a cladding of the MCF
- MM-LD: Outputs wavelength stabilized high power multi-mode light
- Pump stripper: Pump in the cladding is removed



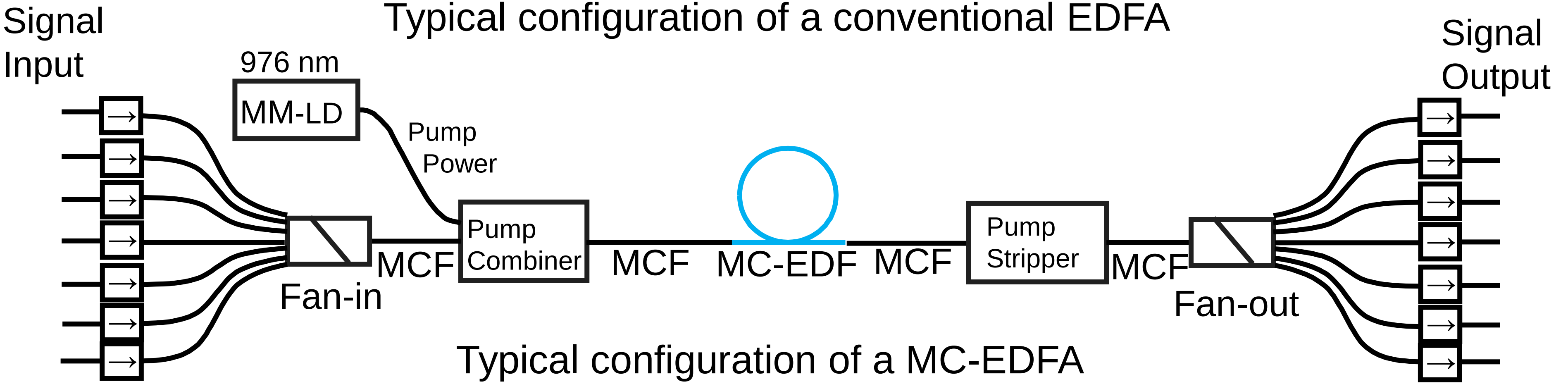
Typical configuration of a MC-EDFA

Comparison of configurations

- Similar configuration with that of an EDFA except Fan in/out devices and a pump stripper



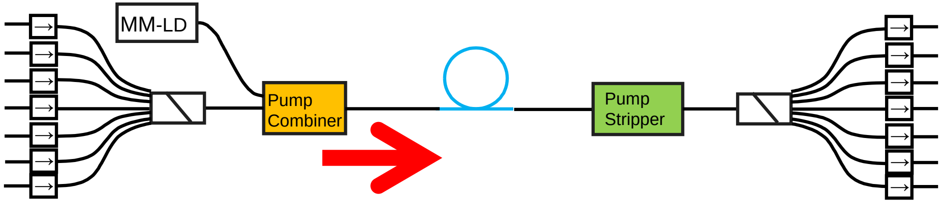
Typical configuration of a conventional EDFA



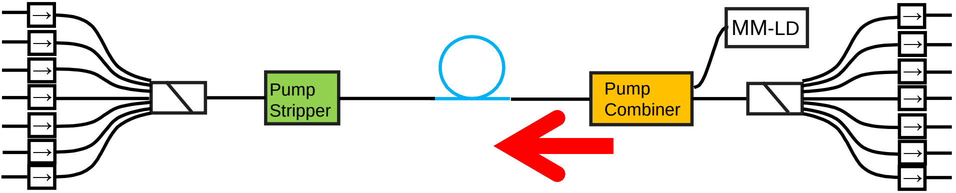
Typical configuration of a MC-EDFA

Available configuration

- Forward and Backward pumping is available
- No trial has been reported for bidirectional pumping
  - To avoid breaking MM-LDs since MM-LDs have no output isolators

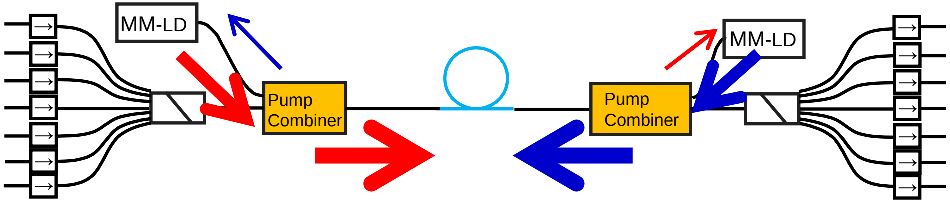


Forward pumping configuration



Backward pumping configuration

Risk of MM-LD breaking
by pump with reverse direction



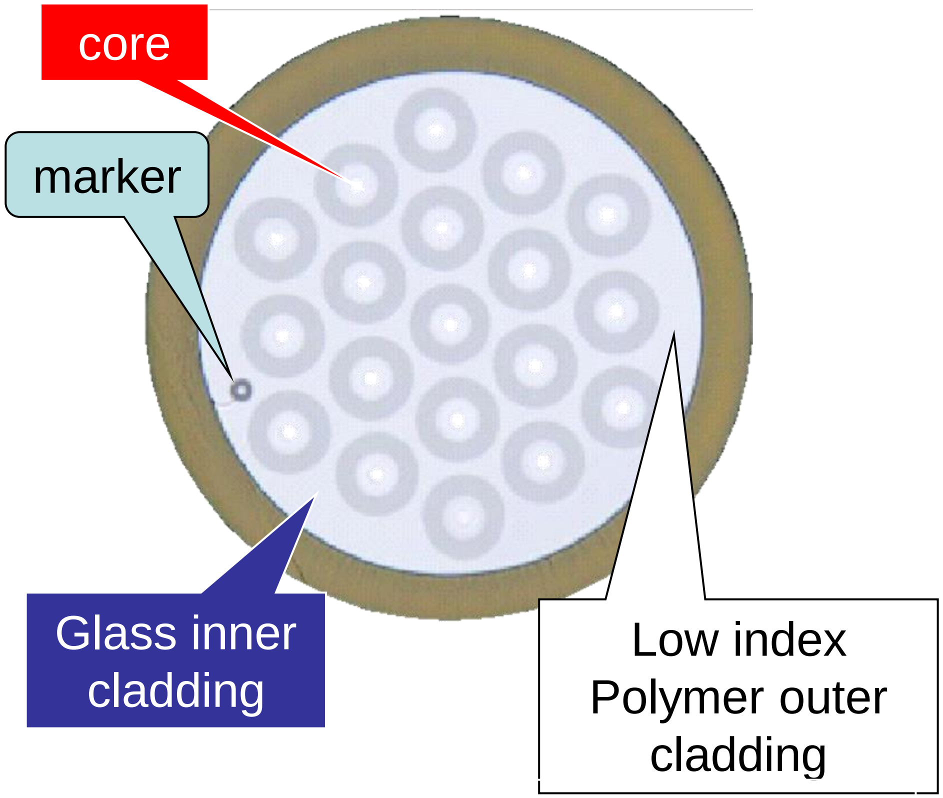
Bidirectional pumping configuration

Configuration and component

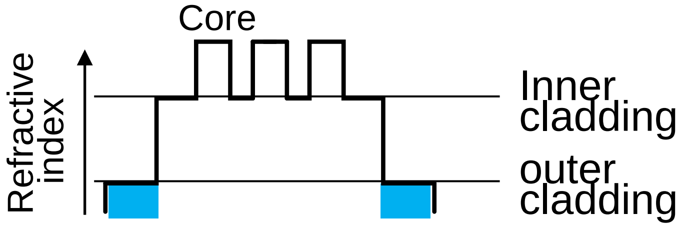
- MC-EDF
- MCF
- Pump combiner
- Pump stripper
- FIFO
- Integrated device

MC-EDF

Cross-section of typical MC-EDF



Double-cladding 19-core EDF



Low index polymer is used for guiding pump power in inner cladding

Inner cladding diameter:	200μm
Core pitch	: 38.5μm
MFD	: 7.3μm@1580nm
Absorption	: 11dB/m@1530nm
XT between core	: <-40dB@1640nm

Cladding diameter and core pitch is smaller than those of an MCF for signal propagation because of confinement of the XT

MCF

Cross-section of typical MCF

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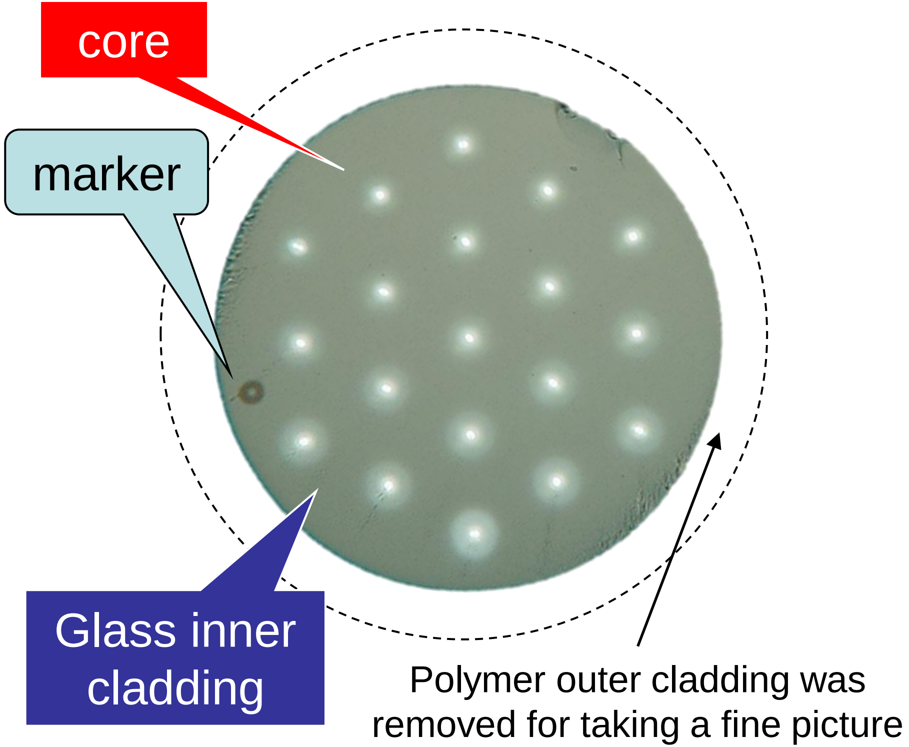


Double-cladding 19-core fibre

MCF is used for components, such as a pump combiner, a pump stripper, FIFO

Dimension and MFD of a MCF is the same with that of the MC-EDF so that fusion splicing is feasible

Two kind of fibres are necessary for assembling a MC-EDFA

Pump combiner

Fibre type pump combiner

Bundle type for 6 cores

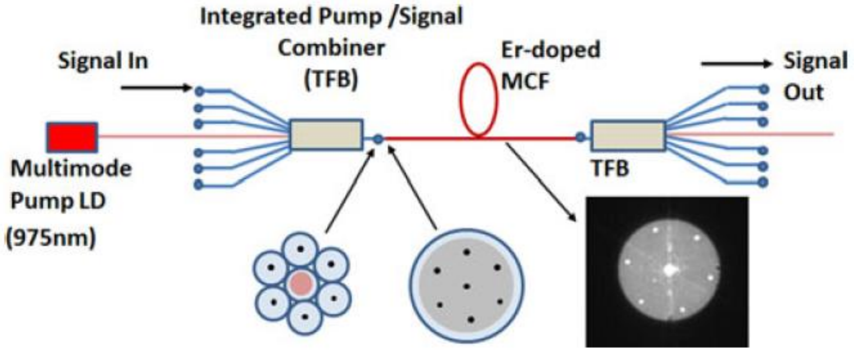


Fig. 5. Schematic diagram of a cladding pump multicore fiber amplifier. The length of MC-EDF was 50 m.

- Centre fibre was used for cladding pump input

K. S. Abedin et al., Optics Express, Vo. 20, No. 18, pp. 20191-20200 (2012).

Side Coupling type for 7cores

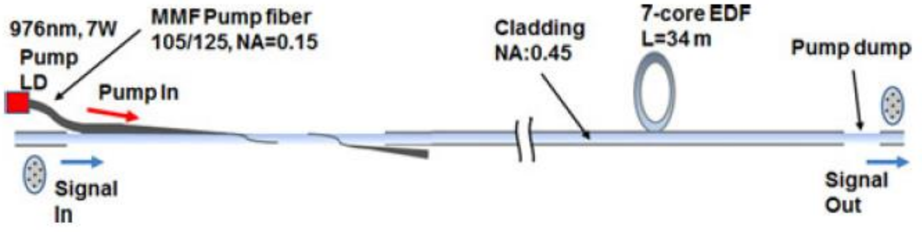
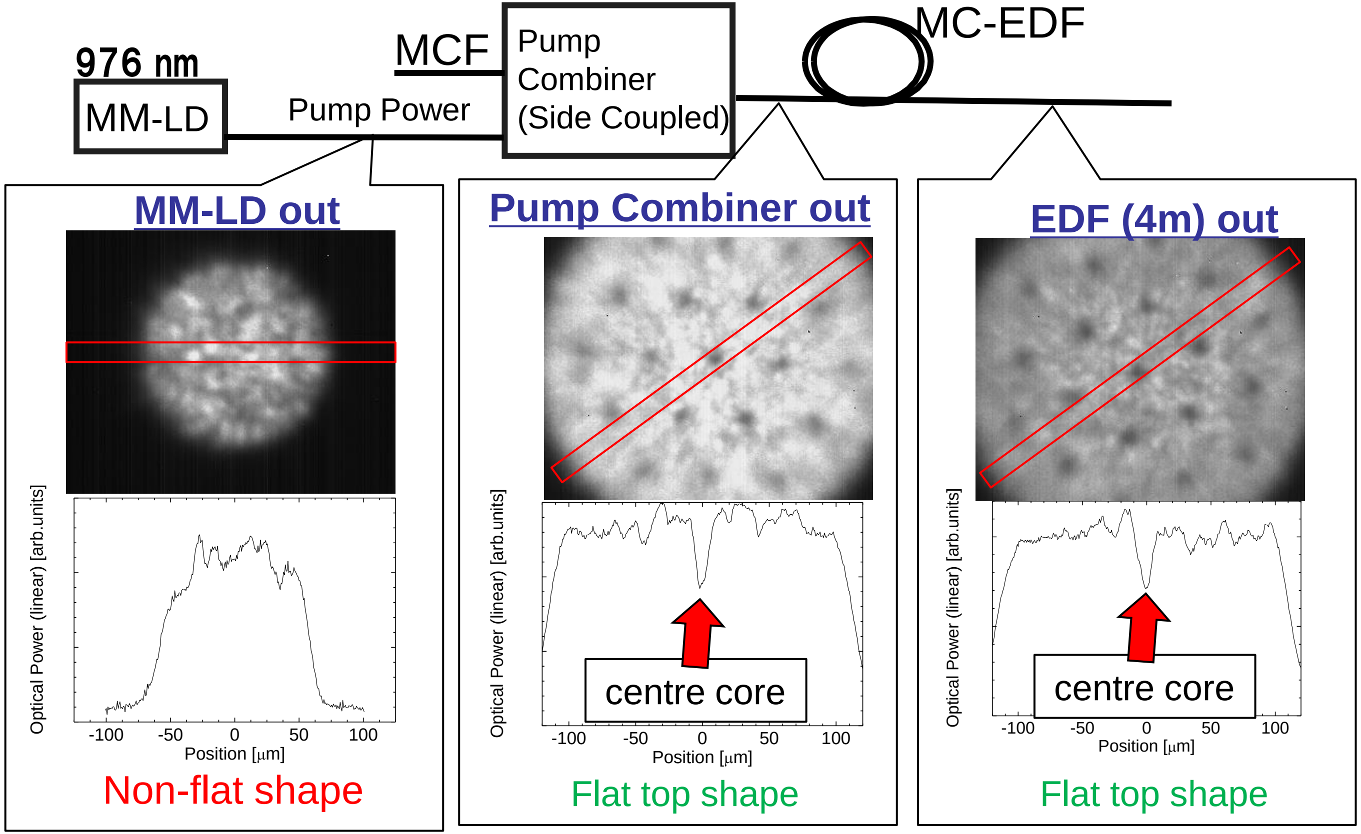


Fig. 8. Schematic diagram of a 7-core EDFA with side-coupled cladding pumping. The length of MC-EDFA was 34 m.

- Tapered multi-mode pump fibre on 7-core EDF was used
- Currently, Furukawa Electric uses pump combiner with the tapered pump fibres on a MCF because of better NF and handling

K. S. Abedin et al.,Optics Letters, Vol. 39, No. 4, pp. 993-996 (2014)

NFPs and power profiles of pump power

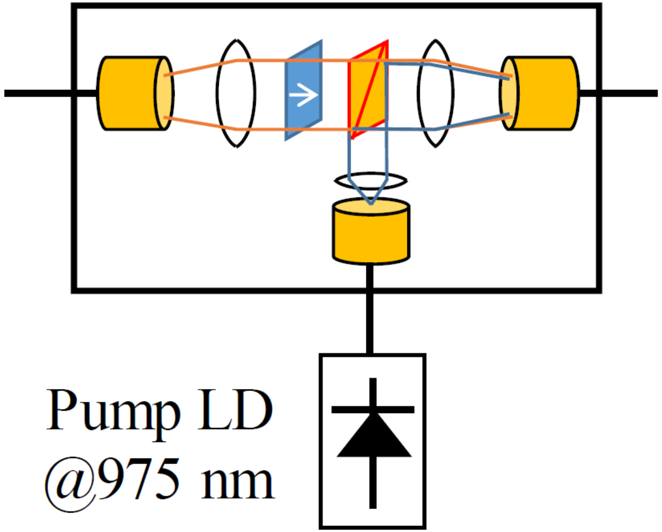


It is unknown how pomp power distribution is converted to flat top shape in the pump combiner.

Homogeneous pump power for each core

Free space optics type

- Pump combiner for 12-core EDF (cladding 90um, core pitch 16.4um)
- Coupling efficiency of pump power from MM-LD is 90%
- Integrated isolator



Configuration of pump combiner

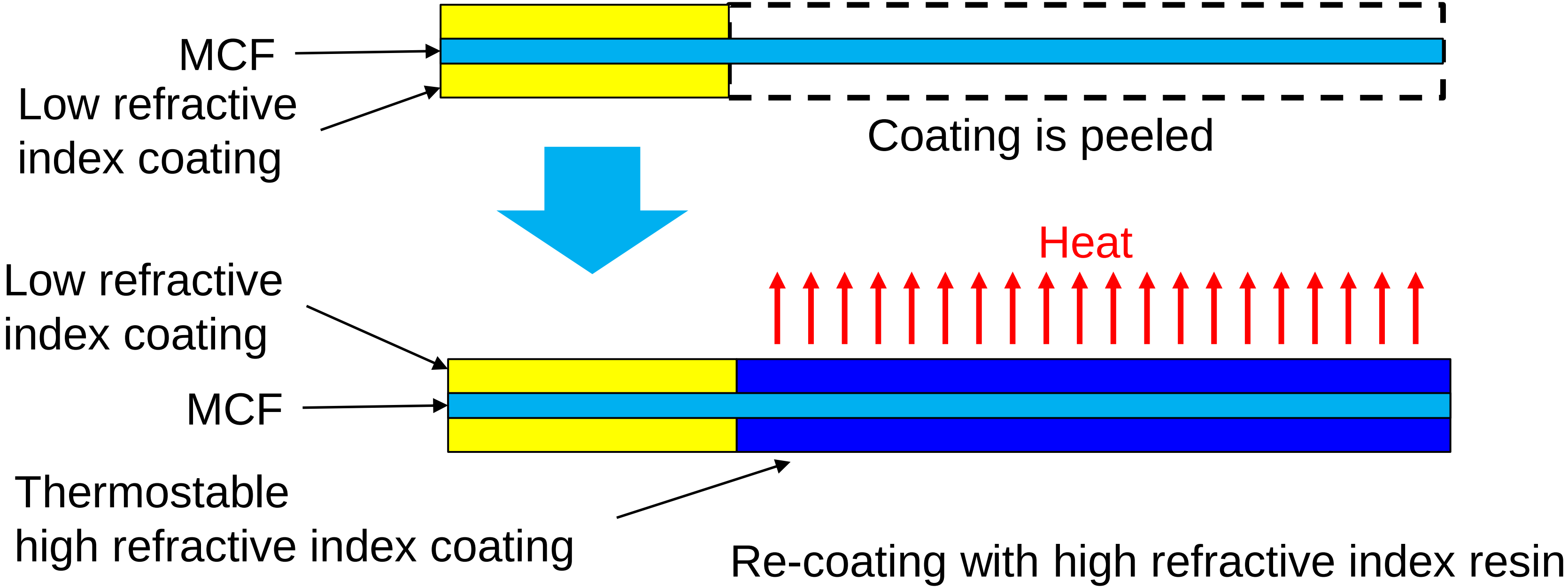
- Number of pump port is intrinsically one
- Pump power distribution of output 12-core fibre is not reported

M. Wada, et al., OFC2020, M4C3(2020)

Pump stripper

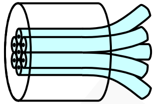
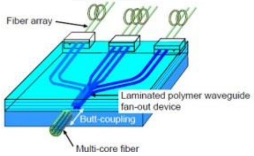
Configuration of pump stripper

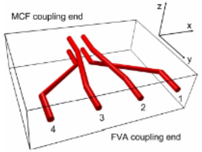
- Fibre device with high refractive index coating set on heat sink
- Cladding pump is removed in the high refractive index coating region
- Removed cladding pump is converted to heat in a package

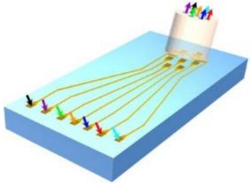
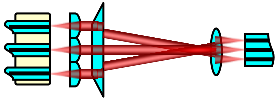


Input / Output devices

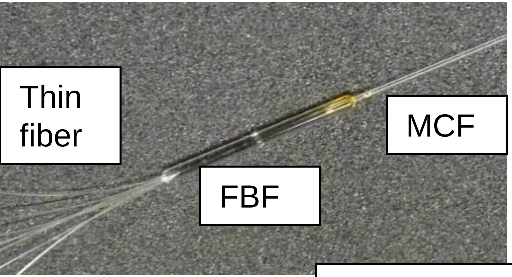
Types of Fan-in/out

- Fan-in/out
  - Fiber based
    - Fiber bundle type 
    - Fused taper type 
  - PLC based
    - Polymer type 

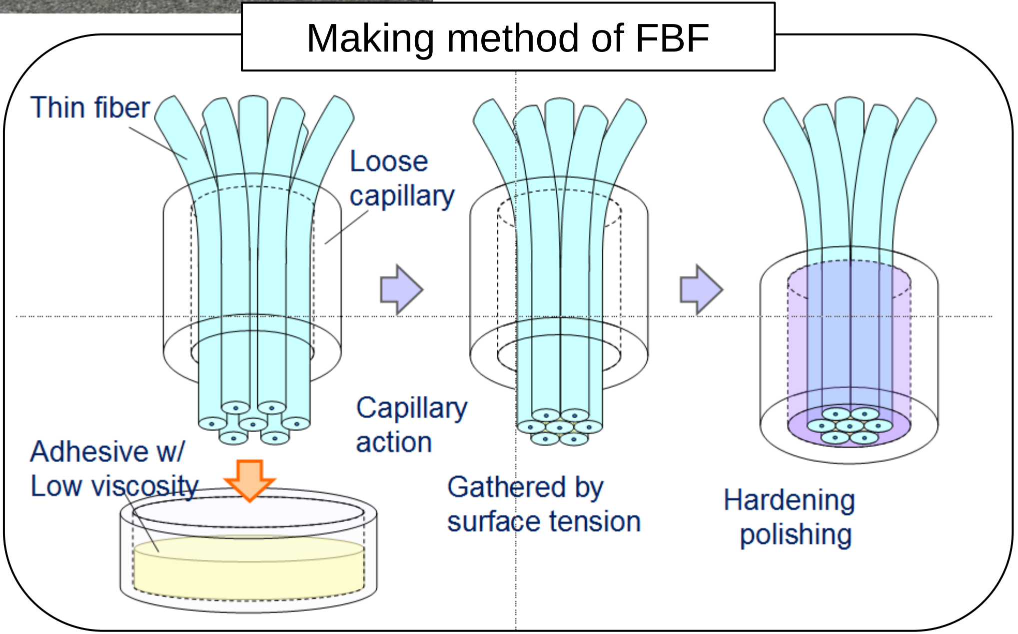
    - Laser drawing type 

    - SiP type 
  - Free optics based 

Fiber Bundle-type Fan-out



- Low insertion loss (<1dB per piece)
- Low reflection (<-65dB) thanks to angled polishing
- Low core-to-core XT (<-50dB)
- Good productivity for close-packing structure



- Cladding of the thin fibre is etched to match core pitch of the MCF
- MFD (7.3um) of the thin fibre matches that of a MCF
- Each thin fibre is fusion-spliced with a standard SMF using MFD matching technique

Device integration

Device integration

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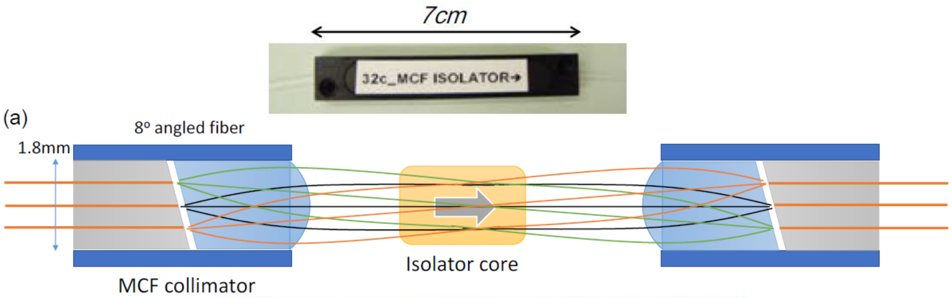
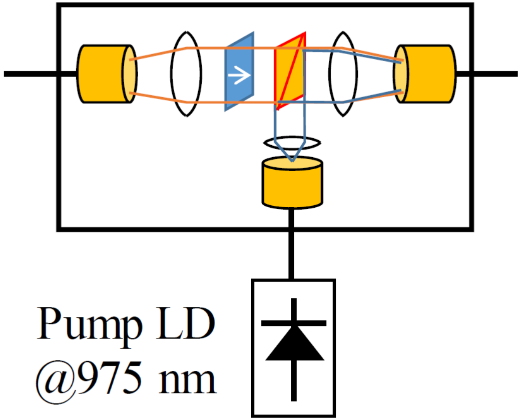
Contributes to significant downsizing



Optical Parameters	Typical
Number of cores	32 cores
Wavelength range	Full C-band
Average insertion loss	< 1.5dB
Core-to-core IL variation	< 1.5dB
Optical isolation	> 32dB
Back reflection	< -32dB

32-core integrated isolator

Y. Jung et al., ECOC2016, W2.B4(2016).



Pump coupling efficiency: 90%
Single stage isolator integrated

Isolator integrated 12-core pump combiner

M. Wada, et al., OFC2020, M4C3(2020)

Amplification characteristics

- EDF length dependence
- C-band 7core, 19core
- L-band 7core, 19core
- Core-to-core difference

Characteristics of amplification

Optimum EDF length for C-band amplification

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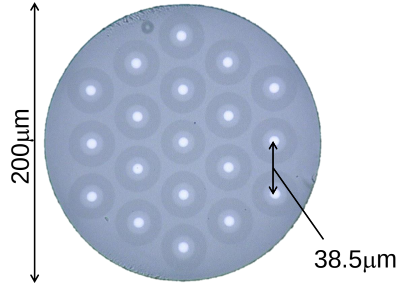
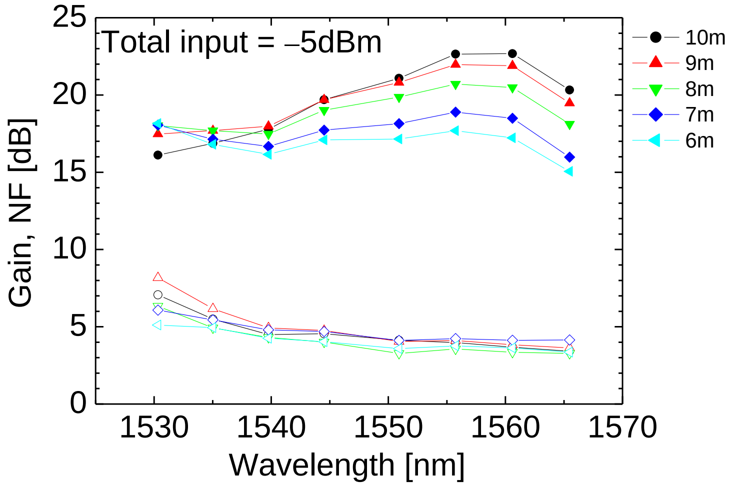
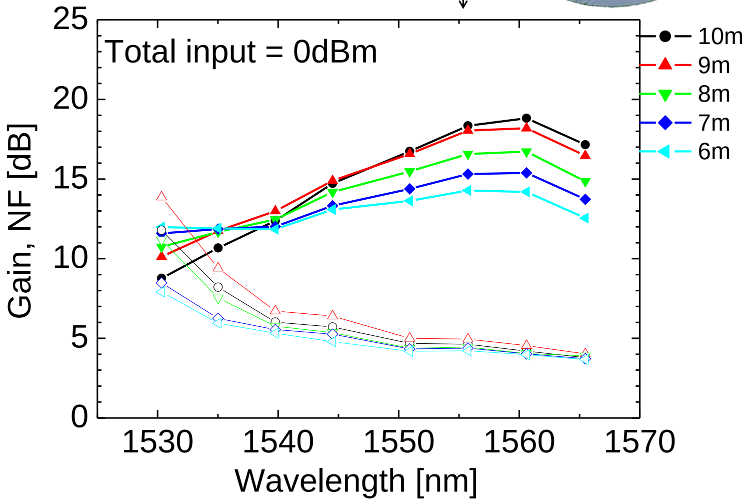
Amplification characteristics of 19-core EDFA

Pump power 35 W
Signals 8ch WDM
Measured with center core







Almost the same behavior as core pumped ones

S. Takasaka *et al*, OFC2018, Th.1.K.2 (2018)

EDF length dependence of 19-core EDF

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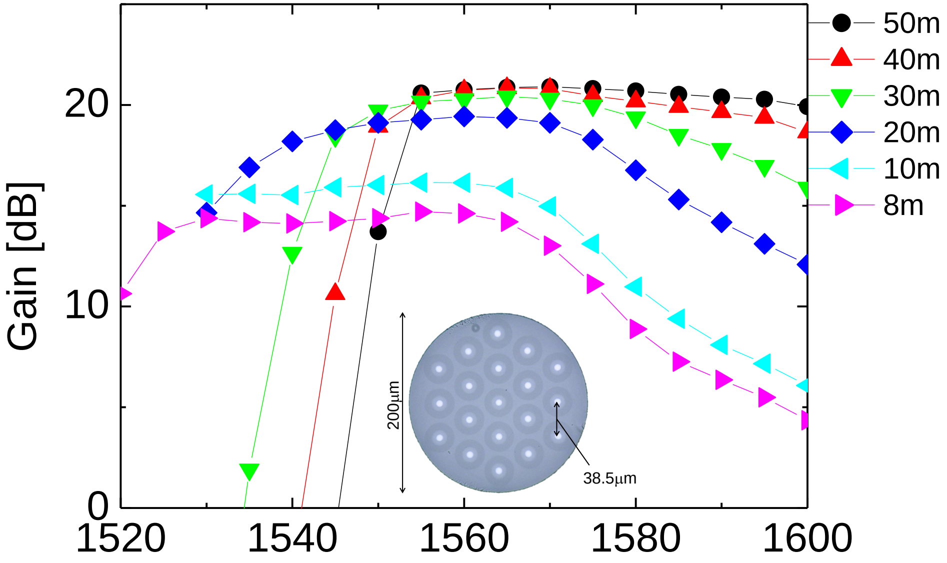
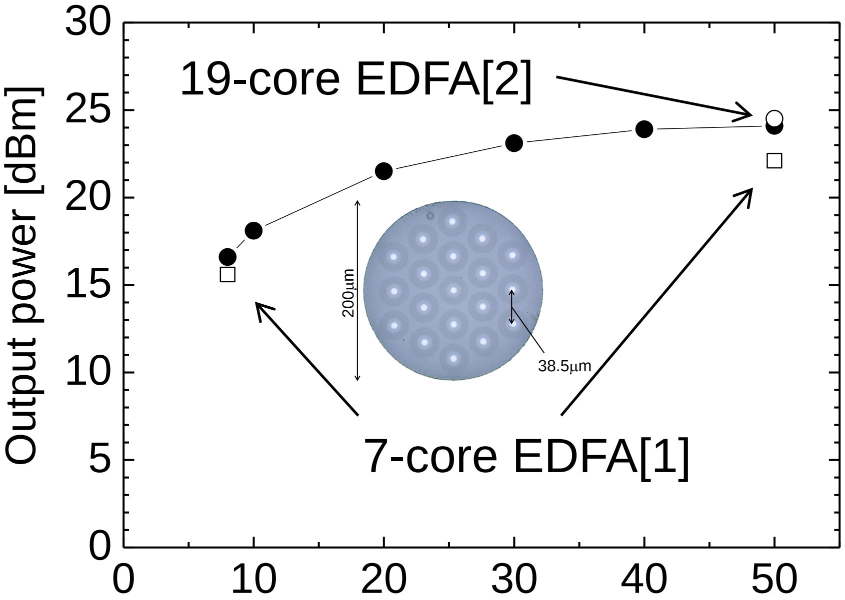
- Gain band shifts and increase with increase of EDF length

  Sweeping single channel signal with power of 0 dBm, pump power 35W



S. Takasaka *et al*, OFC2018, Th.1.K.2 (2018)

- Power saturates at around 50m
  - 0 dBm single channel signal located at maximum gain wavelength
  - Pump power 35W



Y. Tsuchida, ECOC2016 [1],
S. Takasaka, ECOC2017[2]

Comparison with cladding and core pumping

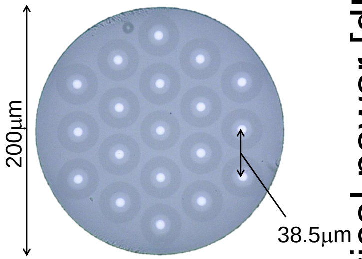
	Gain band	Output power
Core pumping (Conventional EDFA)	Depends on total core absorption [dB] (The absorption is a product of core absorption [dB/m] and EDF length)	Depends on input pump power (Total core absorption [dB] is high enough to absorb entire input pump power)
Cladding pumping (Cladding pumped MC-EDFA)	Depends on total core absorption [dB] (The absorption is a product of core absorption [dB/m] and EDF length)	Depends on absorbed cladding pump power (Estimated cladding absorption ratio is as small as <0.05 dB/m. Total cladding pump absorption [dB] is quit small.)

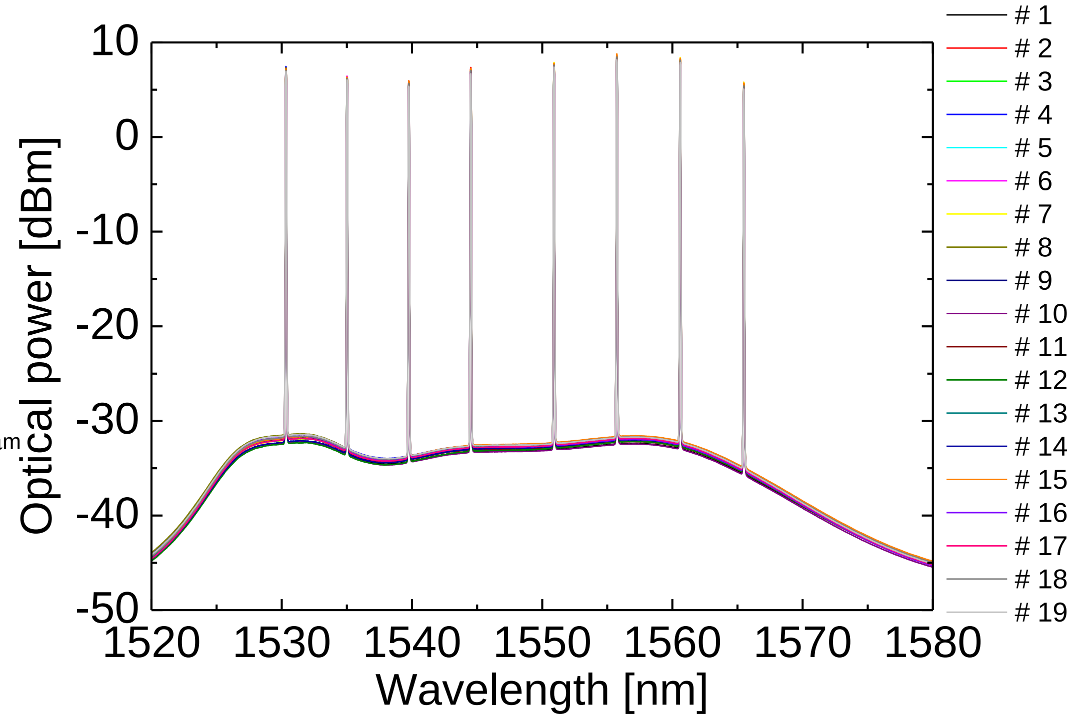
Characteristics in C-band

Output spectra of the 19-core EDFA

Similar spectra as C-band EDFAs with low core-to-core difference of <1dB

Input: 8WDM with total power of -5dBm, 35W pump power, EDF length 8m





Amplification characteristics in C-band

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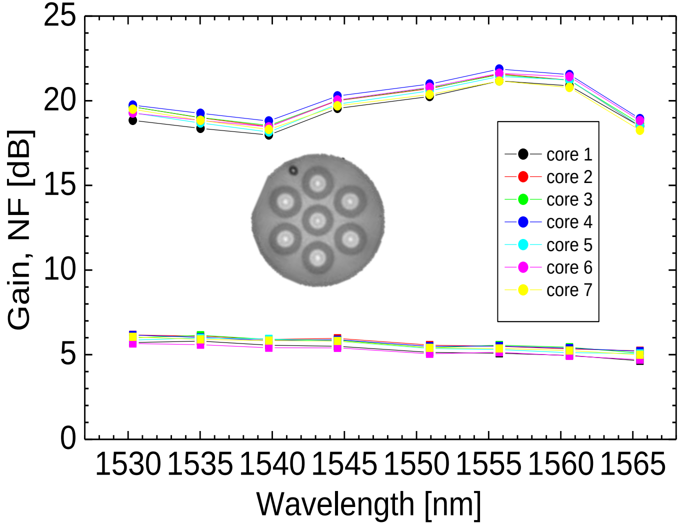
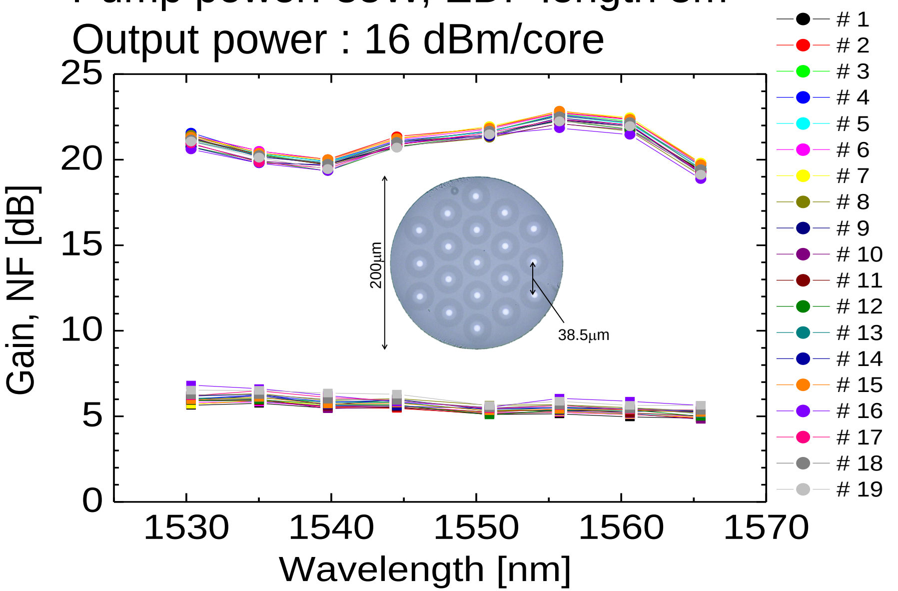
7-core EDFA

Input: 8WDM with total power of -5dBm
Pump power: 17W, EDF length 8m
Output power: 15 dBm/core



19-core EDFA

Input: 8WDM with total power of -5dBm
Pump power: 35W, EDF length 8m
Output power : 16 dBm/core



- The same cladding pump power density results in almost the same gain
- NF is worse by ~1dB because of additional loss on Fan in/out device

Characteristics in L-band

Amplification characteristics in L-band

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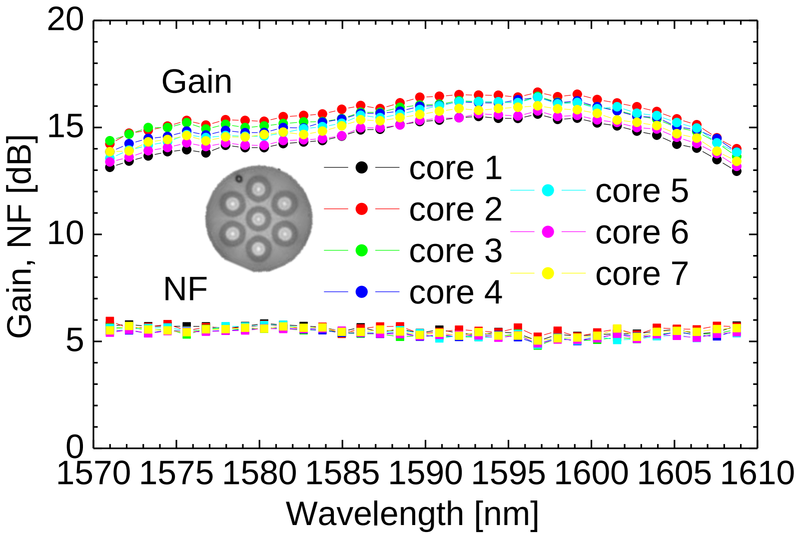
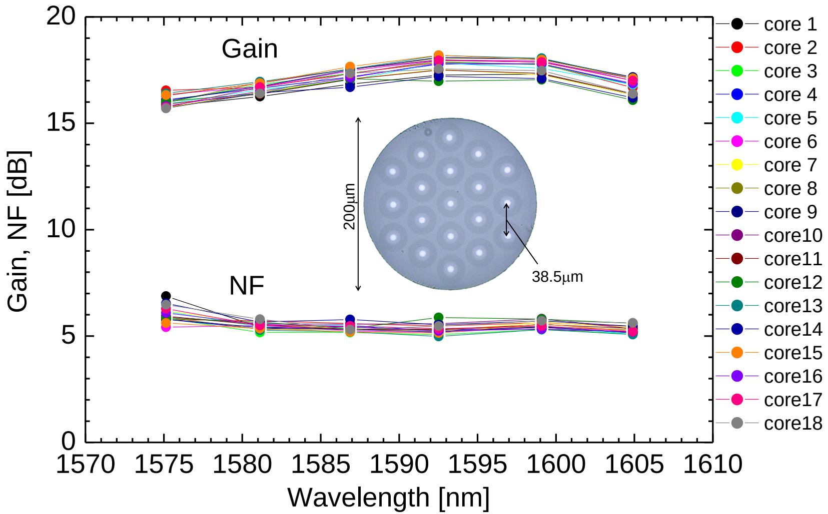
7-core EDFA

EDF length 50m
Input: 33WDM signals with total power of 7.5 dBm
Pump power 15.1 W, Output 22.7dBm/core



19-core EDFA

EDF length 50m
Input: 6WDM with total power of 7.5 dBm
Pump power 33.2 W, Output 24.5dBm/core



7-core, 19-coreEDFA show practical amplification characteristics

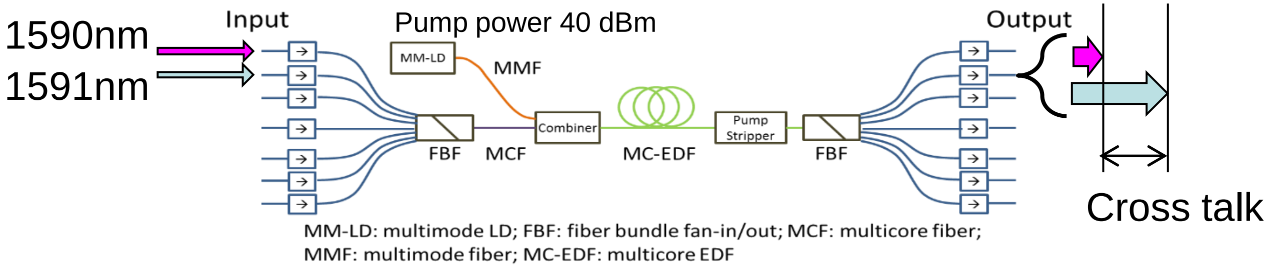
Y. Tsuchida et al., ECOC2016, M.2.A.2

S. Takasaka et al., ECOC2017, Th2.D.3

Crosstalk

Measurement method of XT for L-band amplification

Signal power 0dBm



Input Signal

Power 0 dBm

1591nm signal is input to core for measurement

1590nm signal is input to adjacent core

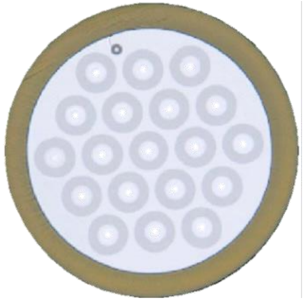
Measured XT

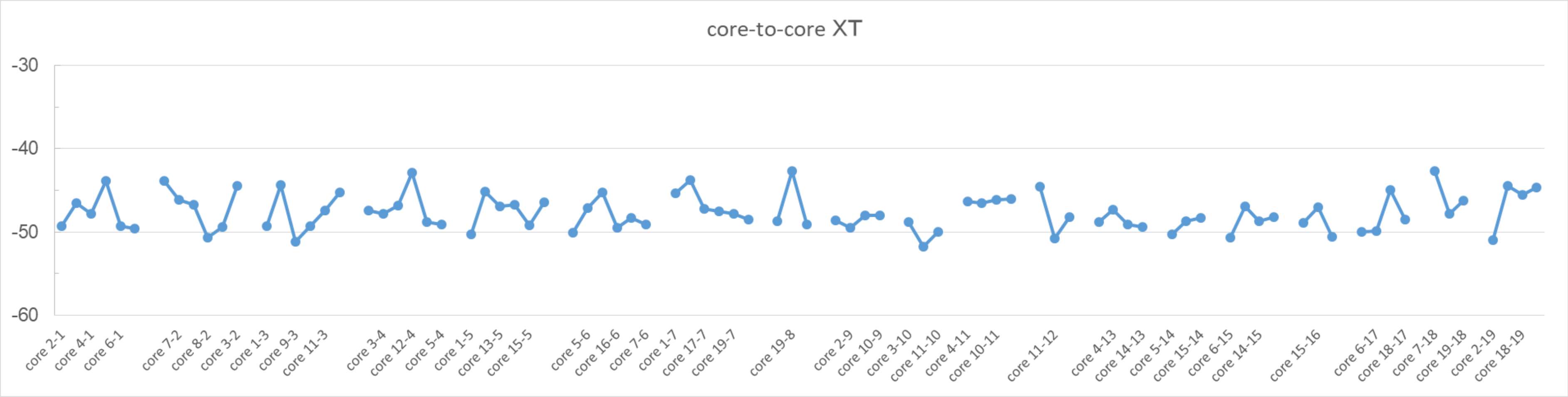
Power ratio of each power at core for measurement

Measured XT in L-band 19 core MC-EDFA

XTs <-42dB are confirmed

Enough XT for long distance transmission





Summary of amplification characteristics

Summary of amplification characteristics

Mostly the same characteristics with that of conventional EDFA

- Gain spectra Similar with those of conventional EDFAs
- NF spectra Similar with those of conventional EDFA

  NF is worse by ~1dB because of additional loss on Fan-in device
- Core-to-core difference of gain and NF

  Less than 1dB for both
- Core-to-core XT Adequately low <-42dB
- Output power C-band 15-16 dBm/core

  L-band >22 dBm/core

Insufficient power for practical application

Power consumption

Main issue of MC-EDFA

- Reduction of power consumption is significant issue

- Reference: conventional EDFAs
  - Output power — 20 dBm
  - Electric power consumption — ~1W (For pump SM-LD drive power, TEC power is not included)

Current power consumption

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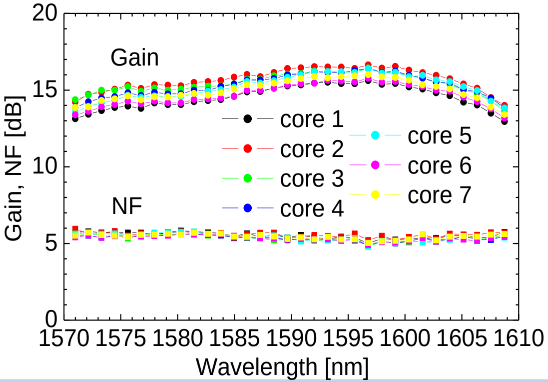
Under the same pump power density condition

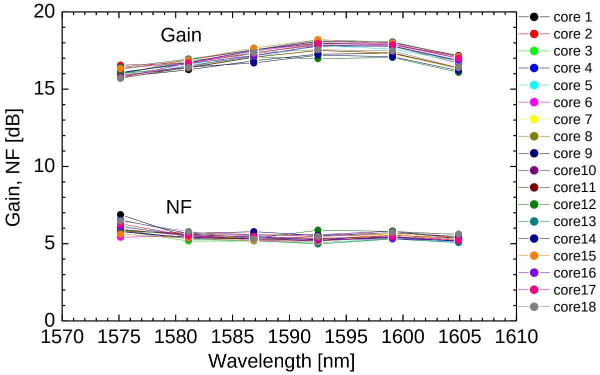
7-core EDFA

Input signal power (Total)
7.5 dBm/core (33WDM)
Cladding pump power
2.16 W/core (**15.1** W for 7 core)
Power consumption
~5.32 W/core
Averaged output power
22.7 dBm /core



19-core EDFA

Input signal power (Total)
7.5 dBm/core (6WDM)
Cladding pump power
1.75 W/core (**33.2**W for 19 core)
Power consumption
~3.5 W/core
Averaged output power
24.5 dBm /core



Candidates for pump power reduction

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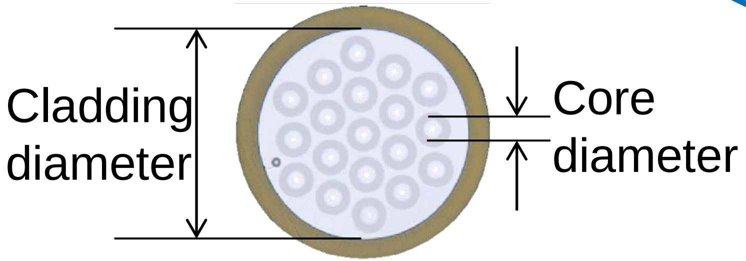
Improvement of EDF



- Cladding diameter decrease
- Core diameter increase
- Core number increase
- Er absorption ratio increase

Cladding pump recycling

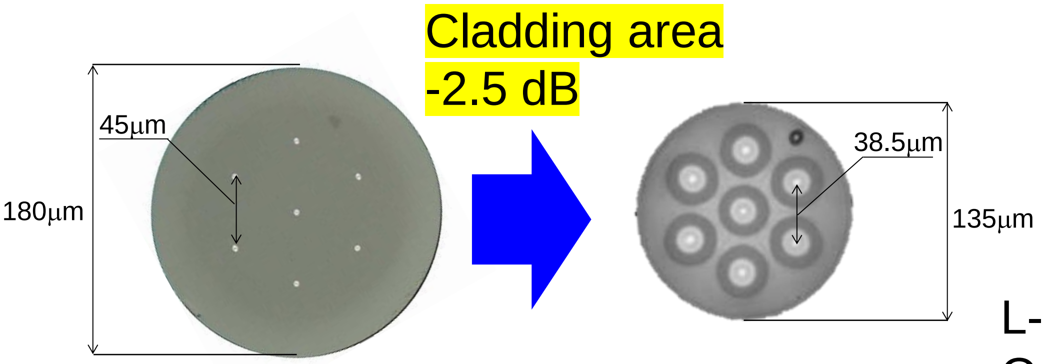
- Increase of collection ratio of cladding pump
  - Fibre device
  - Free space device

MM-LD

- Change wavelength from 976nm to 1480nm
- Increase Electric-Optical power conversion efficiency

Cladding diameter decrease

- Pump power is reversely proportional to the cladding area so that constant cladding pump power density is obtained



L-band
Output 19.1 dBm/core
Pump power 17.9W

L-band
Output 20.9 dBm/core
Pump power 15.3W

Output power 1.5 dB increase
Pump power 0.7 dB decrease
2.2 dB improvement in total

K. Takeshima *et al.*, JLT, vol.34, no. 2, pp. 761-767 (2016)., Y. Tsuchida et al., ECOC2016, M.2.A.2, (2016).

Core diameter increase

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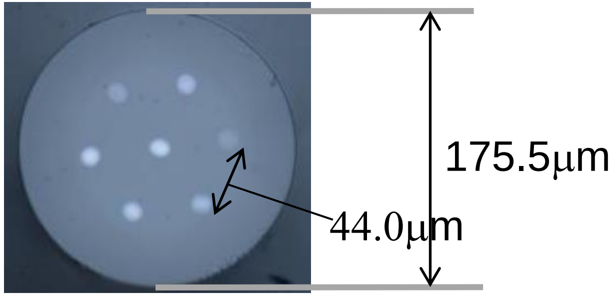
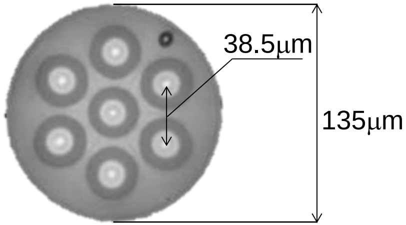
- Larger core diameter results in higher output power for a core (dBm/core) even though it is qualitative



6-mode 7-core EDF
Core dia. is 12.5 μm

- At L-band, total estimated output (summed over 6-mode) is 23.8 dBm/core
- Pump power 17.8 W



7-core EDF
MFD is 7.3 μm (No core dia. Information)

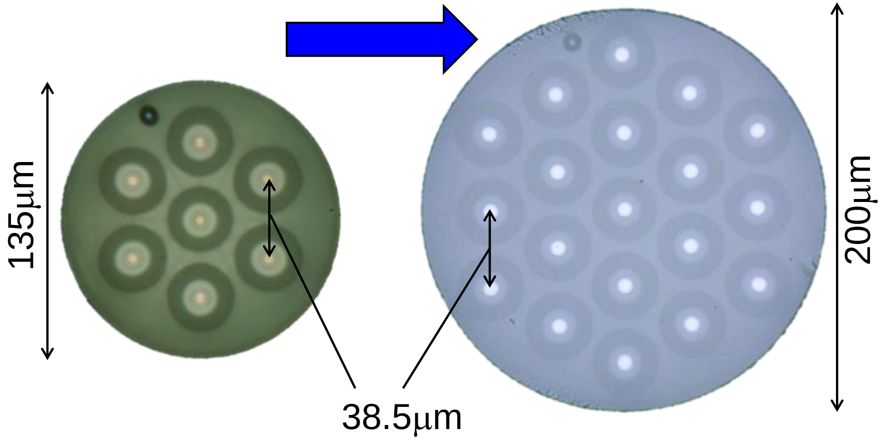
- At L-band, total *estimated* output is 20.6 dBm/core
- Assumed pump power 10.5 W for the same pump power density

Y. Jung *et al.*, OFC2019, Th1B.7(2019), Y. Tsuchida et al., ECOC2016, M.2.A.2, (2016).

Core number increase

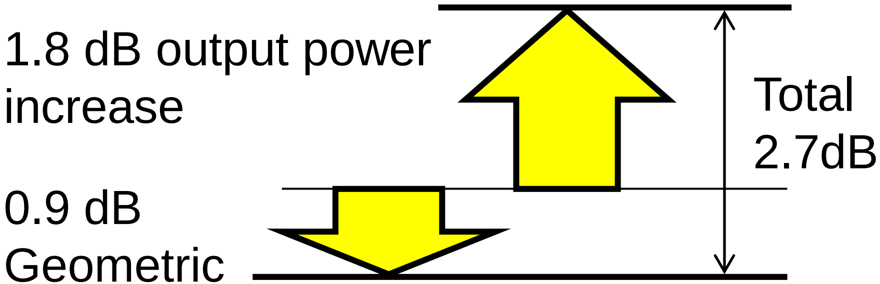
- Core number increase results in an output power increase that exceeds cladding area decreasing ratio under a constant cladding power density

Cladding area for a core: -0.9 dB



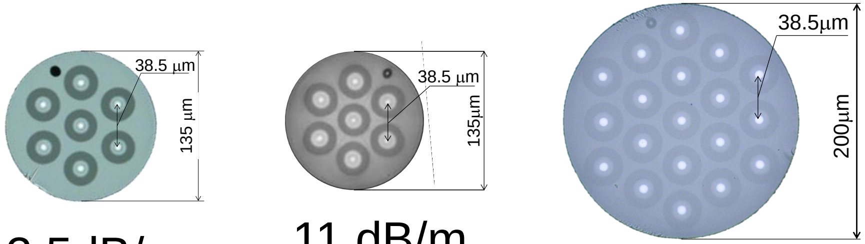
Cross-section of 19-core and 7-core EDF having the same core pitch, diameter, and absorption ratio

	Cladding pump power density	Output power
	mW/µm^2	dBm/core
7-core EDFA	1.05	22.7
19-core EDFA	1.05	24.5



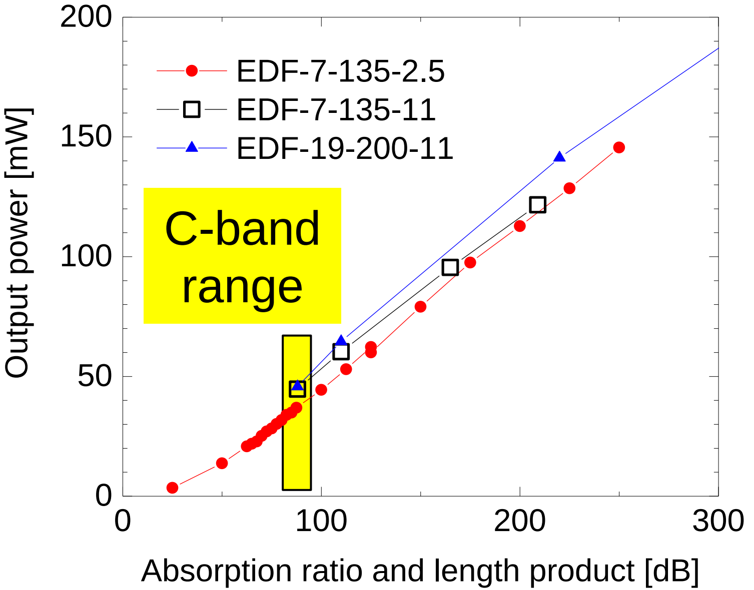
Er absorption ratio

- Absorption ratio itself does not affect output power since the a product of absorption ratio and EDF length (total absorption) determines the output power



2.5dB/m 11 dB/m 11 dB/m

Cross-section of 7-core and 19-core EDFs with the same core pitch, diameter

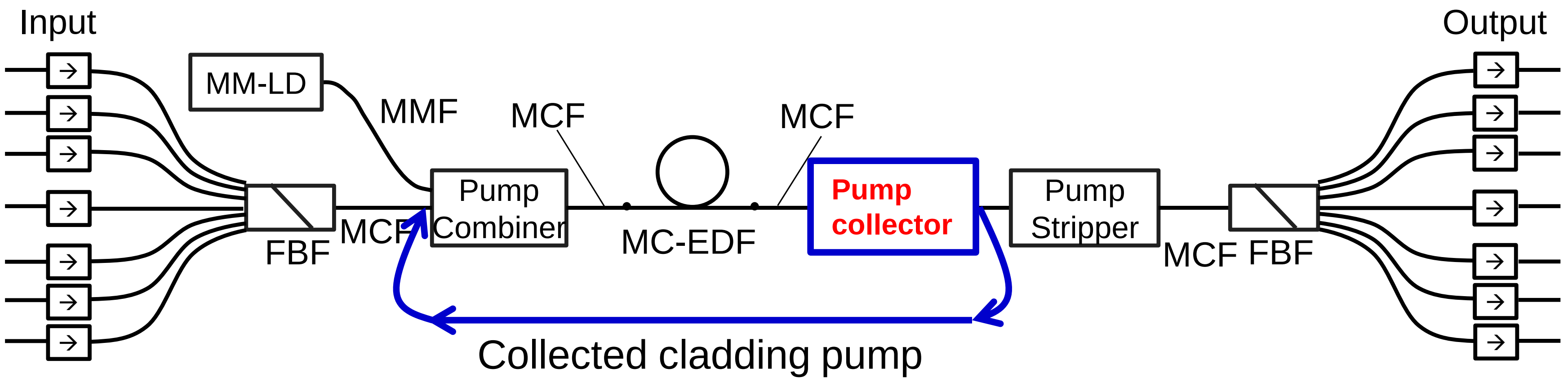


Total absorption dependence of output power

S. Takasaka et al., ECOC2019, P77, (2019).

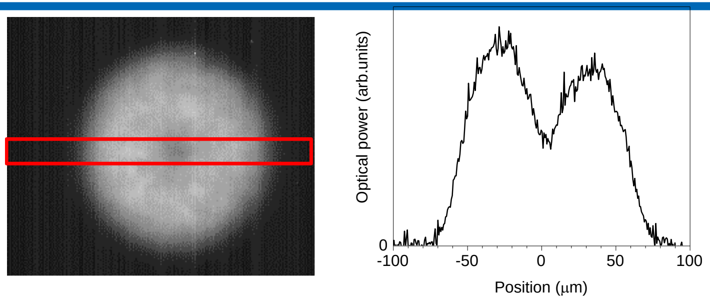
Cladding pump recycling configuration

- Residual cladding pump power is collected and returned to a pump combiner
- Pump collector
  - Fibre device: reversely used side-coupling pump combiner
  - Free space device

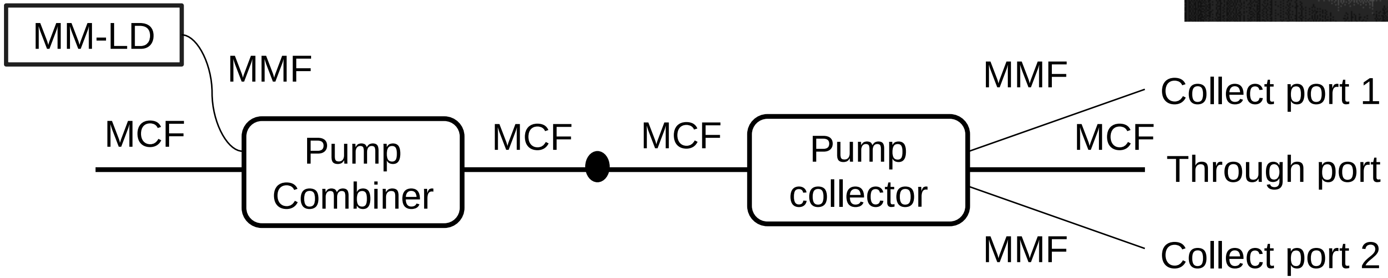


Fibre type pump collector

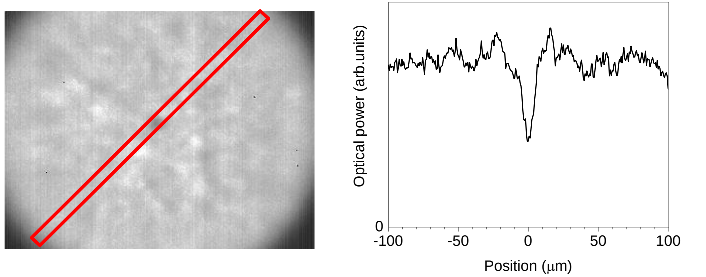
- Summed collection ratio is 30%
- Collect ports emits donut shape distribution



NFP of collection port (ϕ125μm)



	Collect port 1	Collect port 2	Through port
	%	%	%
Sample #1	15.2	14.8	63.5
Sample #2	15.7	14.9	61.9

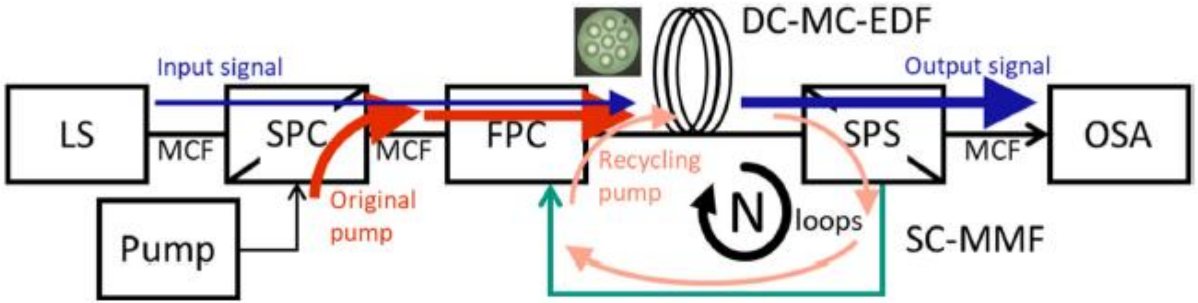


NFP of through port (ϕ200μm)

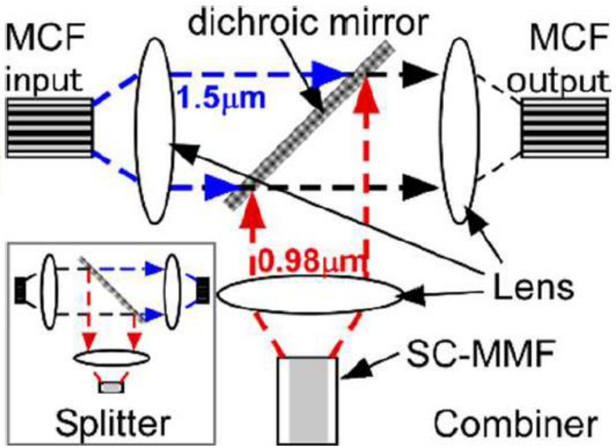
S. Takasaka et al., ECOC2019, P77, (2019).

Free space type pump collector

- Insertion loss of multimode pump input : 0.1 dB
- Recycling ratio 55.2%



Configuration of cladding pump recycling



H. Takeshita et al., JLT. Vol.38, No.11, pp.2922-2929 (2020).

Wavelength change of MM-LD

- Pump-to-Output conversion efficiency of pump at 1480 nm is 23.7% higher than that of pump at 980 nm

2.6dB higher gain
@constant pump
23.7% lower power
@constant gain

8-WDM input signal
Total input power -5dBm

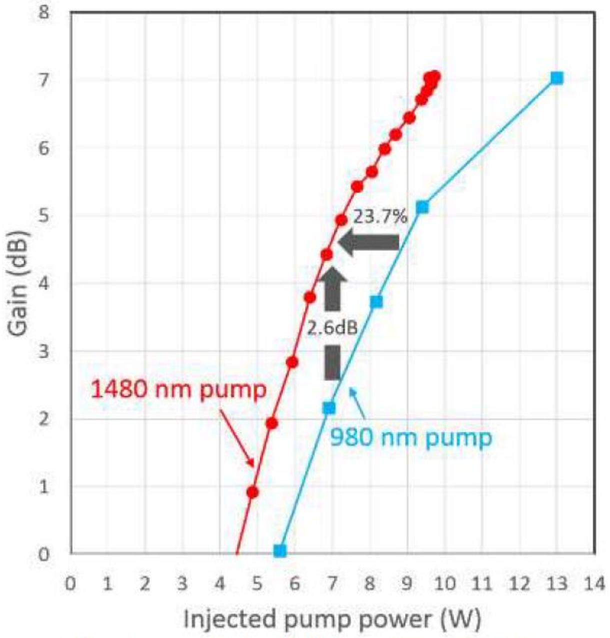
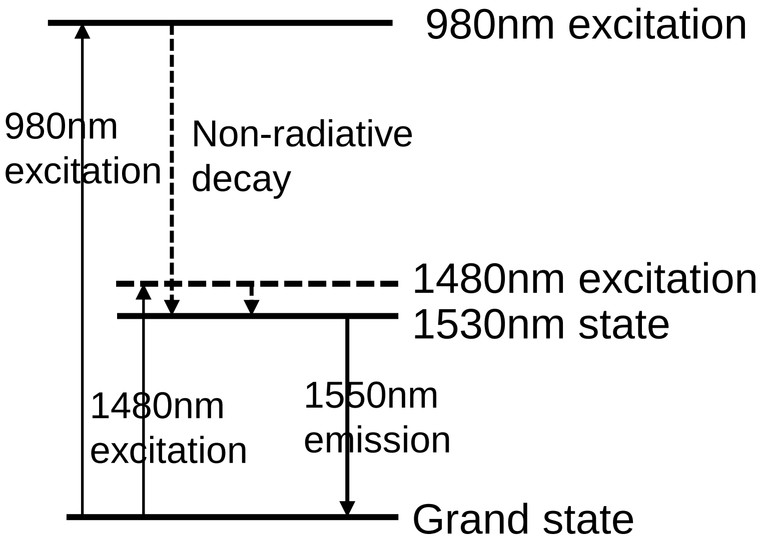


Fig. 4: The injected pump power vs. gain.



K. Matsumoto et al., ECOC2018 (2018).

Reduction of power consumption

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Improvement of EDF

- valid — Cladding diameter decrease
  - Inversely proportional to cladding area
- valid — Core diameter increase
- valid — Core number increase
- invalid — Er absorption ratio

Cladding pump recycling

- valid — Increase of collection ratio of cladding pump

MM-LD

- valid — Change wavelength from 976nm to 1480nm
- valid — Increase Electric-Optical power conversion efficiency

Estimation of future power consumption

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- Current L-band 19-core EDFA outputs 24.5 dBm/core
  - Pump power: 35 W, Input WDM signal 7.5 dBm
  - Cladding diameter 200 μm, core pitch 38.5 μm

- Target
  - L-band MC-EDFA with output power of 20 dBm/core
  - Power consumption is 1W/core

- Estimated condition to achieve the target
  - Cladding diameter of 19-core EDF should be decreased to <175 μm
  - Pump power should be <9.5W according to the cladding diameter for constant pump power density
  - If pump recycling technique is applied, further reduction would be added

Increase of C-band output

Another issue for MC-EDFA

- Low C-band output power is also a significant issue
  - Total cladding pump absorption [dB] for a C-band amplification is quite smaller than that for an L-band MC-EDFA since matching EDF length for C-band is ~1/6 shorter than that for L-band
  - Almost cladding pump that is not absorbed by Er-doped core just passes through the MC-EDF

- Reference: conventional EDFAs
  - Output power 20 dBm
  - Electric power consumption ~1W
(SM-LD drive power is considered, TEC power is not included)

Candidate to increase output power in C-band

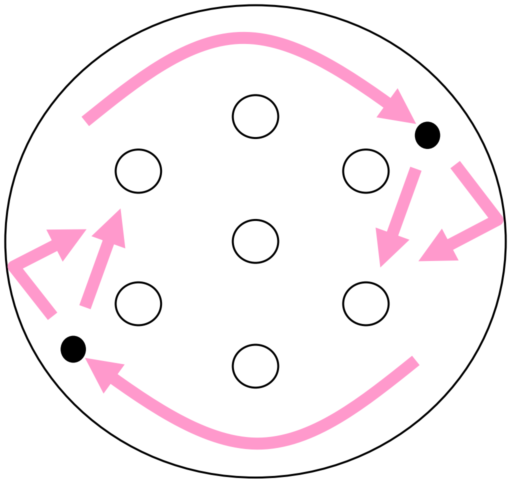
Cladding pump scattering

- Insert Mie scattering bodies

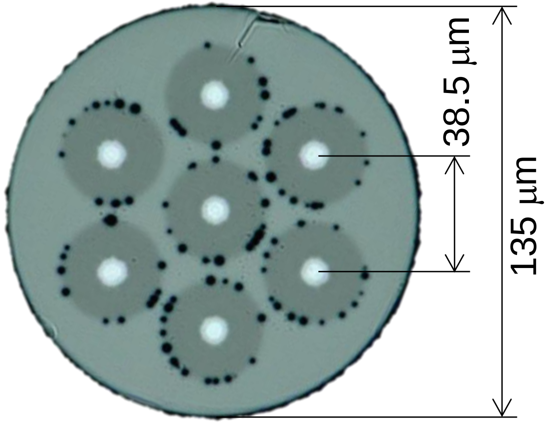
Expected effect by Mie scattering

- Insertion of Mie scattering bodies

Cladding pump light that does not contributes to core excitation would be scattered through Mie scattering and collide to the core



- Fabricated 7-core EDF

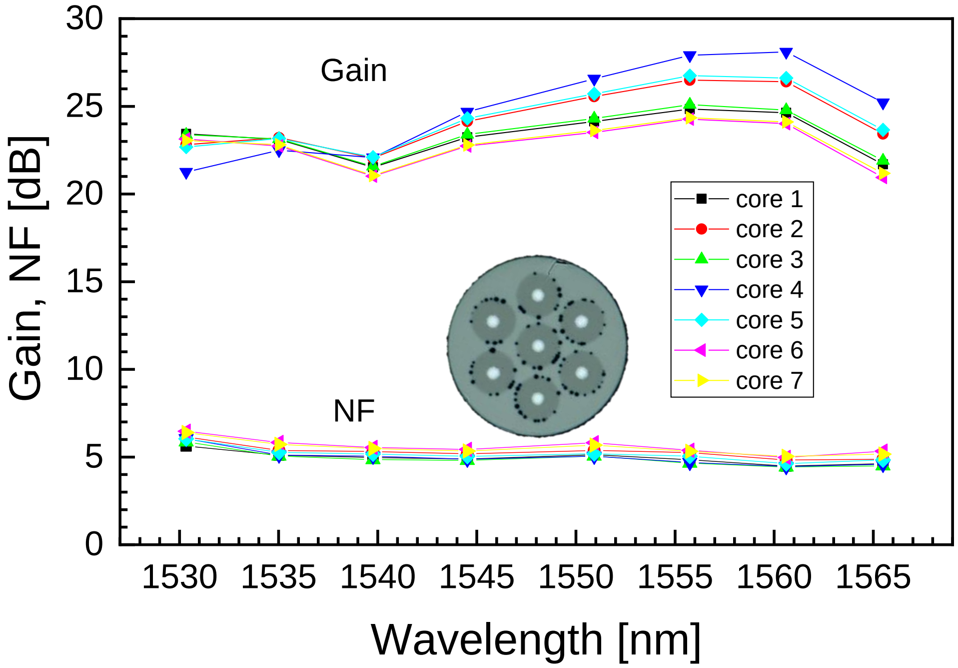


Cross-section of bubbles inserted 7-core EDF

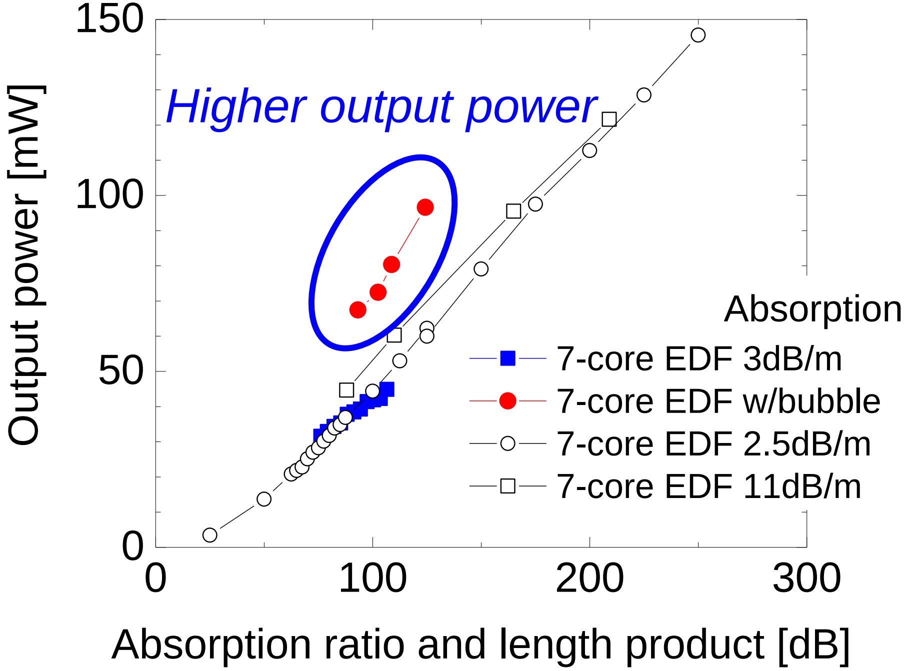
S. Takasaka et al., ECOC2020, Th2A (2020).

Mie scattering increases output power

- 7-core EDF including bubbles as Mie scattering bodies shows ~2dB increase, e.g., 18.4 dBm/core at least



Gain and NF spectra of the 7-core EDFA



Total core absorption dependence

Candidate to increase output power in C-band

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Cladding pump scattering — valid — Insert Mie scattering bodies

There are many ways to scatter the cladding pump including the bubble insertion

Summary

- We have reviewed configuration and components of MCZ-EDFA
- Amplification characteristics of MC-EDFA has achieved to those of conventional EDFA except power consumption and C-band output power

- Candidates for reduction of power consumption has been reviewed
  - Quantitative means is cladding diameter decrease and pump recycling technique
  - L-band MC-EDFA with output power of 20 dBm/core is possible under power consumption less than 1W/core by the cladding diameter decrease

- Possibility of C-band output power increase has been introduced

Bound to Innovate