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TP

Technical Paper

TP（技術資料）

空間分割多重伝送用光ファイバ増幅器

（Optical fibre amplifier for space division multiplexing transmission）

OITDA/TP 33/AM : 2021

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まえがき

シングルモードファイバ(SMF) を用いた従来の光ファイバ通信システムでは，時分割多重，波長多重，デジタルコヒーレント技術を用いることで伝送容量の拡大が図られてきた。しかし，通信トラフィックの増加に伴い，更なる光ファイバ通信システムの伝送容量の更なる増加が必要となっている。

近年、通信容量の飛躍的な増加を目的に，マルチコアファイバやマルチモードファイバを伝送路として用いる空間分割多重(SDM) の研究・開発が進められている。

この技術資料では，長距離の SDM 光ファイバ通信システムを構築する際に必要となる SDM アンプについて概要を紹介する。

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OITDA/TP（技術資料）

OITDA/TP 33/AM：2021

Optical fibre amplifier for space division multiplexing transmission

INTRODUCTION

Optical amplifiers (OAs) are essential components for developing a long-haul optical transmission system. IEC TC 86/SC 86C, therefore, has published many standards for OAs. Recently, a research project has been actively conducted to develop space division multiplexing (SDM) fibre transmission systems that use multi-core, multi-mode fibre, etc. A development effort is also made to fabricate optical fibre amplifiers (OFAs)that are necessary for extending the transmission distance, including a multi-core optical fibre amplifier, a few-mode optical fibre amplifier and a multi-core and few-mode optical fibre amplifier. This technical paper provides with a better understanding of OFAs for SDM fibre transmission systems.

1 Scope

This technical paper is written to provide general information on optical fibre amplifiers for space division multiplex transmission such as multi-core transmission, few-mode transmission, and multi-core & few-mode transmission. The paper describes the classification and outlines of amplifiers, state-of-the-art development technologies, and specific features and measurements.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61290-1, Optical amplifiers - Test methods - Part 1: Power and gain parameters

IEC 61290-1-1, Optical amplifiers – Test methods – Part 1-1: Power and gain parameters – Optical spectrum analyzer method

IEC 61290-1-2, Optical amplifiers – Test methods – Part 1-2: Power and gain parameters –Electrical spectrum analyzer method

IEC 61290-1-3, Optical amplifiers – Test methods – Part 1-3: Power and gain parameters –Optical power meter method

IEC 61290-3, Optical amplifiers - Test methods - Part 3: Noise figure parameters

IEC 61290-3-1, Optical amplifiers – Test methods – Part 3-1: Noise figure parameters – Optical spectrum analyzer method

IEC 61290-3-2, Optical amplifiers – Test methods – Part 3-2: Noise figure parameters –Electrical spectrum analyzer method

IEC 61290-3-3, Optical amplifiers - Test methods - Part 3-3: Noise figure parameters - Signal power to total ASE power ratio

IEC 61290-5-1, Optical amplifiers - Test methods - Part 5-1: Reflectance parameters - Optical spectrum analyzer method

IEC 61290-5-2, Optical amplifiers - Test methods - Part 5-2: Reflectance parameters - Electrical spectrum analyser method

IEC 61290-5-3, Basic specification for optical amplifier test methods - Part 5-3: Test methods for reflectance parameters - Reflectance tolerance test method using electrical spectrum analyzer

IEC 61290-10-1, Optical amplifiers - Test methods - Part 10-1: Multichannel parameters - Pulse method using an optical switch and optical spectrum analyzer

IEC 61290-10-2, Optical amplifiers - Test methods - Part 10-2: Multichannel parameters - Pulse method using a gated optical spectrum analyzer

IEC 61291-2, Optical amplifiers - Part 2: Single channel applications - Performance specification template

IEC 61291-4, Optical amplifiers - Part 4: Multichannel applications - Performance specification template

IEC TR 61292-1, Optical amplifiers - Part 1: Parameters of amplifier components

IEC TR 61292-3, Optical amplifiers - Part 3: Classification, characteristics and applications

IEC TR 61292-8, Optical amplifiers - Part 8: High-power amplifiers

IEC 60050-731, International Electrotechnical Vocabulary (IEV) - Part 731: Optical fibre communication

IEC 61291-1, Optical amplifiers – Part 1: Generic specification

IEC TR 61931, Fibre optic – Terminology

3 Terms, definitions and abbreviated terms

3.1 Terms and definitions

For the purposes of this paper, the terms and definitions given in IEC 60050-731, IEC 61291-1, IEC TR 61931, and the following apply.

3.1.1
erbium doped fibre amplifier
EDFA
amplifier with rare earth-doped fibre of which core is doped with erbium ions

3.1.2
space division multiplexing optical fibre amplifier
SDM OFA
optical fibre amplifier that is used for SDM (space division multiplexing) fibre transmission systems

3.1.3
multi-core optical fibre amplifier
multi-core OFA
optical fibre amplifier for multi-core fibre transmission

3.1.4
multi-core erbium doped fibre amplifier
multi-core EDFA
erbium-doped fibre amplifier for multi-core fibre transmission

3.1.5

multi-core fibre Raman amplifier
multi-core FRA
fibre Raman amplifier for multi-core fibre transmission

3.1.6
few-mode optical fibre amplifier
few-mode OFA
optical fibre amplifier for few-mode fibre transmission

3.1.7
few-mode erbium doped optical fibre amplifier
few-mode EDFA
erbium-doped fibre amplifier for few-mode fibre transmission

3.1.8
few-mode fibre Raman amplifier
few-mode FRA
fibre Raman amplifier for few-mode fibre transmission

3.1.9
multi-core and few-mode optical fibre amplifier
multi-core and few-mode OFA
optical fibre amplifier for multi-core and few-mode fibre transmission

3.1.10
multi-core and few-mode erbium doped optical fibre amplifier
multi-core and few-mode EDFA
erbium-doped fibre amplifier for multi-core and few-mode fibre transmission

3.1.11
multi-core and few-mode fibre Raman amplifier
multi-core and few-mode FRA
fibre Raman amplifier for multi-core and few-mode fibre transmission

3.2 Abbreviated terms

EDF	erbium-doped fibre
EDFA	erbium-doped fibre amplifier
FM	few-mode
FMF	few-mode fibre
FRA	fibre Raman amplifier
GFF	gain flattening filter
LD	laser diode
LP	linearly polarized
MC	multi-core
MCF	multi-core fibre
MDL	mode-dependent loss
MIMO	multi-input multi-output
MDG	mode-dependent gain
MDM	mode-division multiplexing
NF	noise figure

OA optical amplifier
OAM orbital-angular-momentum
OFA optical fibre amplifier
OSNR optical signal-to-noise ratio
ROPA remote optically pumped amplifier
SDM space division multiplexing
SNR signal-to-noise ratio
VOA variable optical attenuator
WDM wavelength division multiplexing
XT crosstalk

4 Classification of SDM OFA

Space division multiplexing (SDM) fibre transmission includes multi-core fibre (MCF) transmission, few-mode fibre (FMF) transmission, and multi-core (MC) & few-mode fibre (FMF) transmission, and has the potential to overcome capacity crunch and achieve an ultra-high exabit/s class capacity. A long-haul transmission system needs to have an optical fibre amplifier (OFA) to maintain high-level optical signal power for SDM transmission that uses multi-core EDFAs (MC-EDFAs), few-mode EDFAs (FM-EDFAs) and MC- & FM-EDFAs. When comparing with conventional EDFAs, input and output fibres used for MC-EDFAs, FM-EDFAs and MC-/ FM-EDFAs are MCF, FMF and MC& FMF, respectively. Amplification media used for the above are multi-core erbium-doped fibres (MC EDF), few-mode EDF (FM EDF) and multi-core & few-mode EDFs (MC and FM EDF). [1-4][1] Furthermore, MCFs, FMFs and MC & FMFs are used as Raman amplification media for multi-core fibre Raman amplifiers (MC FRAs), few-mode fibre Raman amplifiers (FM FRAs), and multi-core & few-mode fibre Raman amplifiers (MC & FM FRAs).

Figure 1 shows the classification of SDM OFAs that consist of MC OFAs and FM OFAs, as described in IEC TR 61292-3. The former has two types : MC-EDFA and MC-FRA, and the latter also has two types : FM-EDFA and FM-FRA. Furthermore, as various mode multiplexing is under consideration for FMF transmission, FM OFAs have mutiple mode types for amplification: linearly polarized (LP) mode, orbital-angular-momentum (OAM) mode, and coupled-core mode. MC & FM OFAs can be achieved by combination of MC & FM OFA techniques.

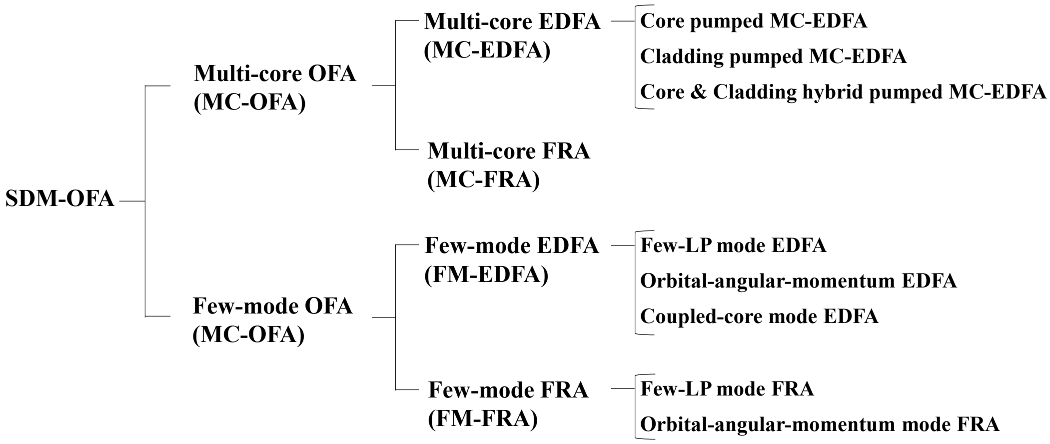


Figure 1 – Classification of SDM OFA

[1] The number in the square bracket shows the number of bibliographies

5 Multi-core OFA technology

5.1 Outline of multi-core EDFA

Figure 2 shows the concept of MC-EDFA. Although an EDFA for an MCF transmission system only needs an arrayed EDFA (arrayed several conventional gain blokes) with fans in/out device, MC-EDFAs are now under development with concept to achieve superior performance through the integration of optical components (which are described in IEC TR 61292-1) and cores of EDFs, without any degradation in amplification properties such as the crosstalk (XT) between optical signals (which propagates in each core), and the amplification efficiency. The XT characteristic is particularly important, as several cores of EDFs need to be incorporated with high density. Furthermore, it is also important to achieve the same amplification characteristics for each core. Use of MC-EDFA aims at making a system that is smaller with lower costs and lower power consumption than the arrayed EDFA.

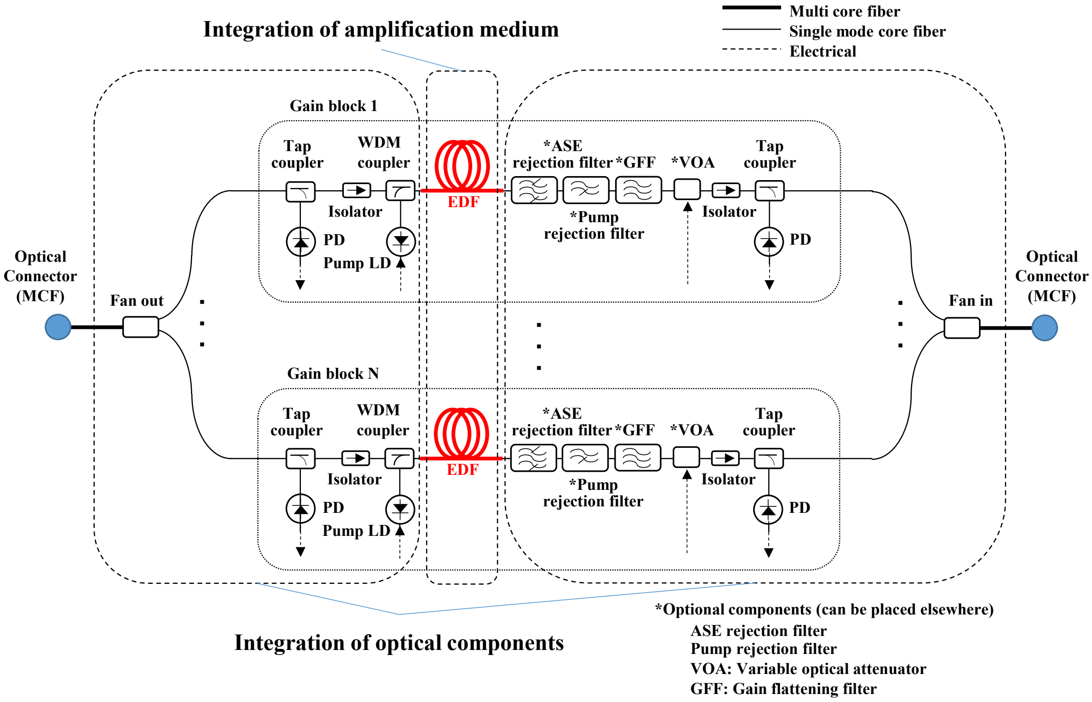


Figure 2 – Concept of MC EDFA

Figure 3 shows several amplification mediums and pump methods of the MC-EDFA. MC-EDF is now actively under development. [3, 4] Some of the advantageous points held by MC-EDFA are that multicore fibre fabrication technique would be applicable, and costs and size can be reduced through manufacturing. One of the challenging points is to make uniformed amplification characteristics in each core. There are two types of MC EDF: One is for a discrete pump only, and the other (that has a double cladding structure) is for a cladding pump. In the former type, a pump method and optical components used for the conventional EDFAs can be adapted. Additionally, it has a highly efficient pumping capacity and high-speed controlling ability. In the latter one, it is a lower power consumption type and can be downsized by decreasing the number of pump laser diodes (LDs) used. We have also heard that a bundled EDF and a multi-element EDF can be used as amplification media for MC-EDFAs.

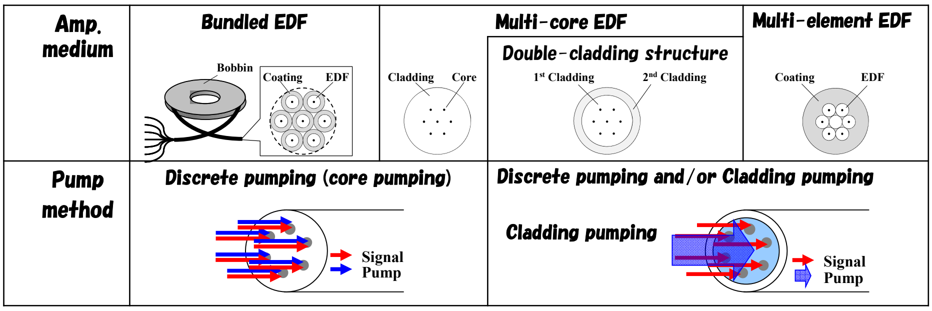


Figure 3 – Several amplification mediums and pump methods of MC-EDFA [3, 4]

5.2 State-of-the-art multi-core EDFA development technology

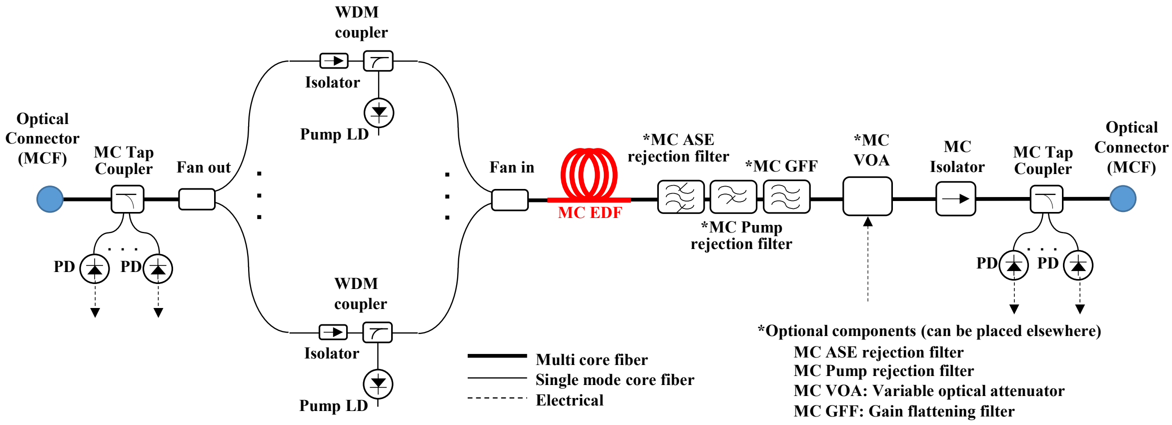
5.2.1 Core pumped multi-core EDFA

Figure 4 a) shows the configurations of core-pumped MC-EDFA with MC-EDF, and conventional WDM couplers, and Figure 4 b) shows one with MC-EDF and MC-WDM coupler. Other optical components used for the construction include a MC tap coupler that monitors the signal intensity of each core, a MC isolator, and optional components (can be placed elsewhere) such as MC ASE rejection filters, MC pump rejection filters, MC variable optical attenuators (MC VOA), and MC Gain flattening filters (MC GFF).

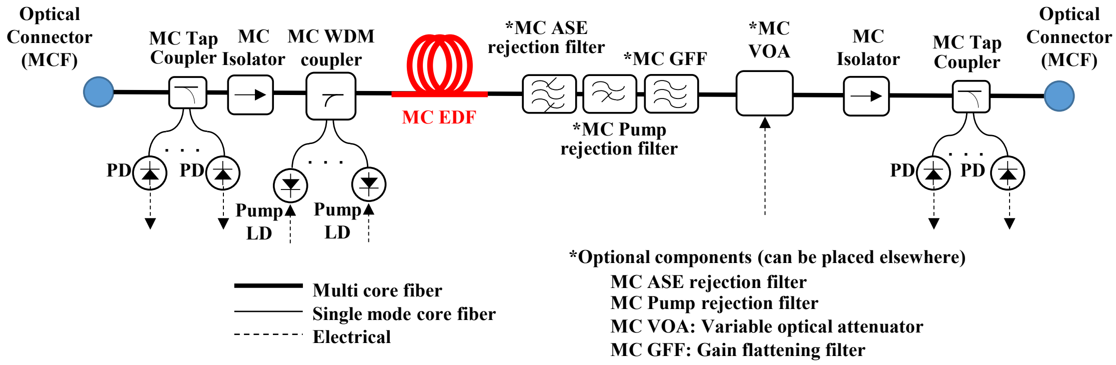
The most important component is a MC EDF that can be equipped with up to 19 cores with practical amplification characteristics by modifying of MCF fabrication technique, according to a previous report. [3-7] One of the important characteristics of MC EDFs is crosstalk between each core.Crosstalk is caused by mode coupling between cores. In general, most of crosstalk occurs depending on a distance between each core and an EDF length. As a length of MC EDF used as a transmission line is relatively shorter in the MC-EDFA than that in MCF, crosstalk of MC EDFs can be set to a larger value compared with other MCFs. A minimum core pitch of MC EDF is 30 μm according to a previous report, for the purpose of keeping the adequate crosstalk value.

Several prototypes have already been launched, such as those equiped with a core-pumped MC-EDFA with MC-EDF and conventional WDM couplers, and those with MC-EDF and newly developed MC WDM coupler. Figure 5 a), b), and Figure 6 a), b) are examples to show configurations and amplification characteristics of a core-pumped MC-EDFA with 7-core MC-EDF and conventional WDM couplers, and of core-pumped MC-EDFA with 19-core MC-EDF and MC WDM coupler. [3, 5]

Other prototypes have also been demonstrated such as those of the core-pumped MC-EDFAs with a bundled EDF and a multi-element EDF. For the purpose of develoing a practical core-pumped MC-EDFA, uniformed amplification characteristics are required between the cores, and the components such as the MC tap coupler, MC GFF and etc. are indispensable, and each component should have a better performance and reliability and a lower price.

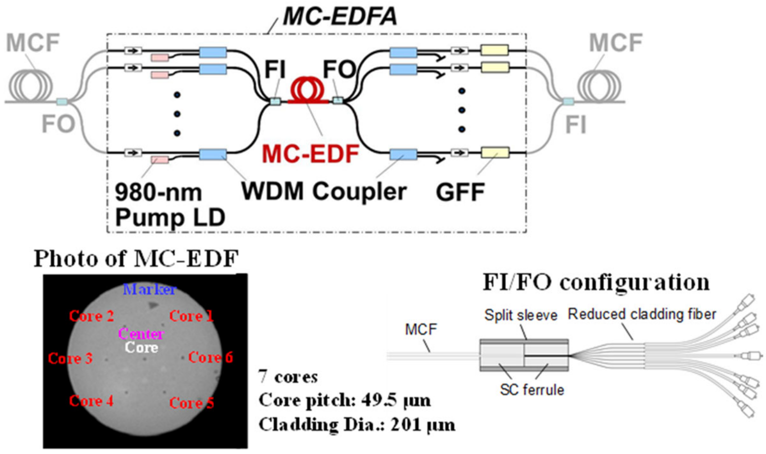


a) Using conventional WDM couplers

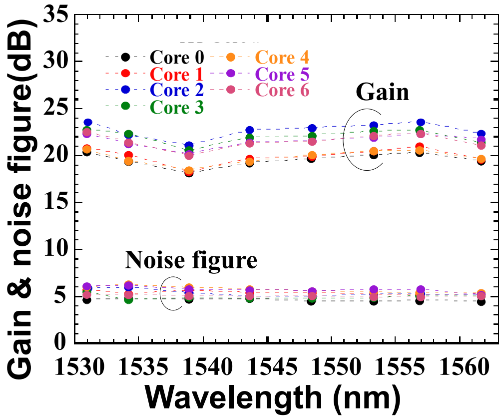


b) Using MC WDM couplers

Figure 4 – Configurations of Core pumped MC-EDFA

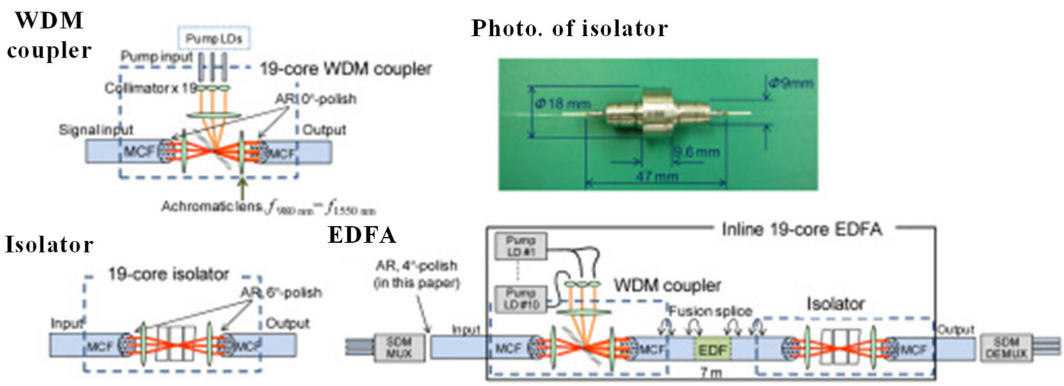


a) Configuration

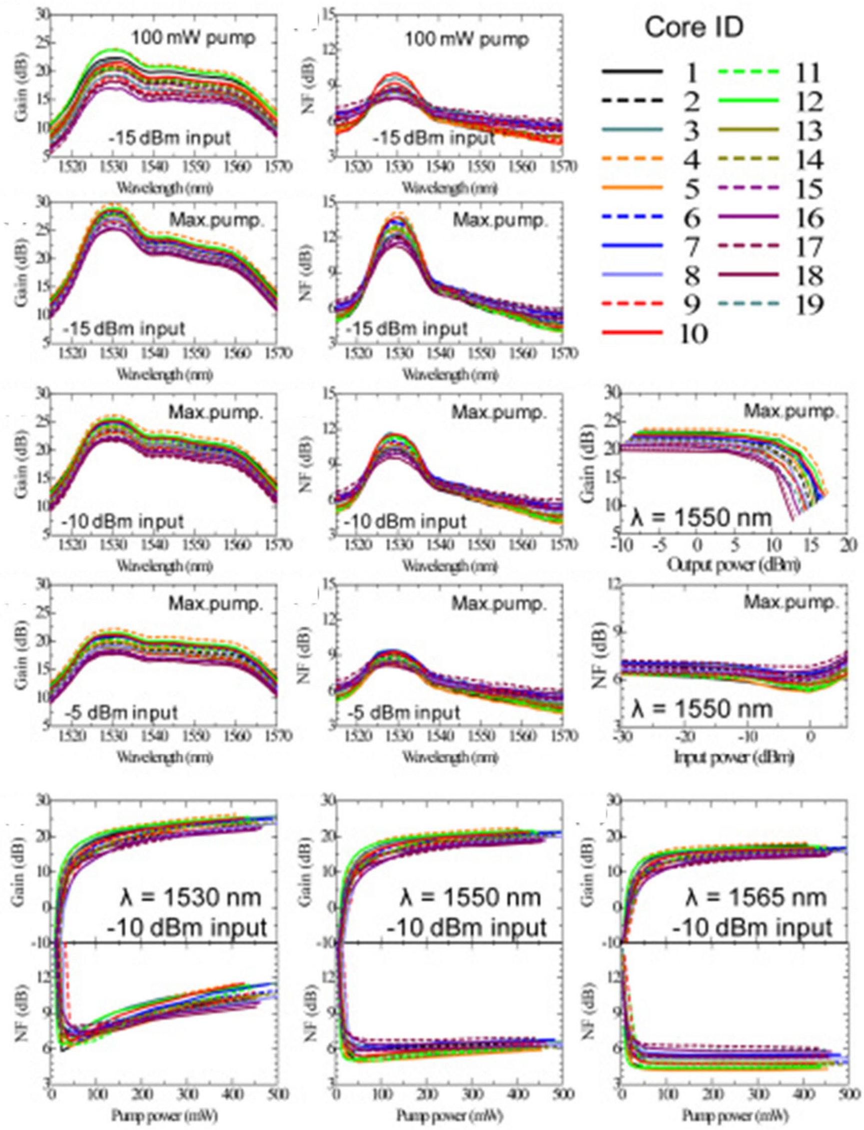


b) Amplification characteristics

Figure 5 – Configuration and amplification characteristics of core pumped MC-EDFA with 7-core MC-EDF and conventional WDM couplers [3]



a) Configuration



b) Amplification characteristics

Figure 6 – Configuration and amplification characteristics of core pumped MC-EDFA with 19-core MC-EDF and MC WDM coupler [5]

5.2.2 Cladding-pumped multi-core EDFA

Figure 7 shows configurations of a cladding-pumped MC-EDFA. To construct this amplifier, a MC-EDF for a cladding pump and a pump light combiner are required in addition to the optical components shown in the core-pumped MC-EDFA.

The cladding pump technique is used to increase the output of optical amplifiers as described in IEC TR 61292-8 Optical amplifiers – Part 8. It is thought that costs and power consumption can be reduced in a MC-EDFA, as the cores can be pumped collectively.

The MC EDF for a cladding pump has a double cladding structure that consists of cores, an inner cladding and outer claddings. It is reported that the MC EDF for a cladding pump can have up to 32-cores. [3, 4, 6-9]

A pumping light is coupled to an inner cladding of MC-EDF for a cladding pump through a pump light combiner. Since the inner cladding area is much larger than the core area, a high-power multi-mode LD is used to install a pumping light in an inner cladding. A pump light combiner uses the cladding pump techniques such as a fused bundled fibre pump combiner, a lens system combiner and a tapered fibre side-coupled combiner, as shown Figure 8 a), b) and c). [7] Currently, we can see several prototypes of the cladding-pumped MC-EDFAs. Figure 9 a) and b) are examples to show configurations and amplification characteristics of a EDFA with a 32-core cladding-pumped MC EDF. [9]

For developing a practical cladding-pumped MC-EDFA, the amplification characteristics of the cores should be uniformed, and the optical components should have better performance and reliability and a lower cost.

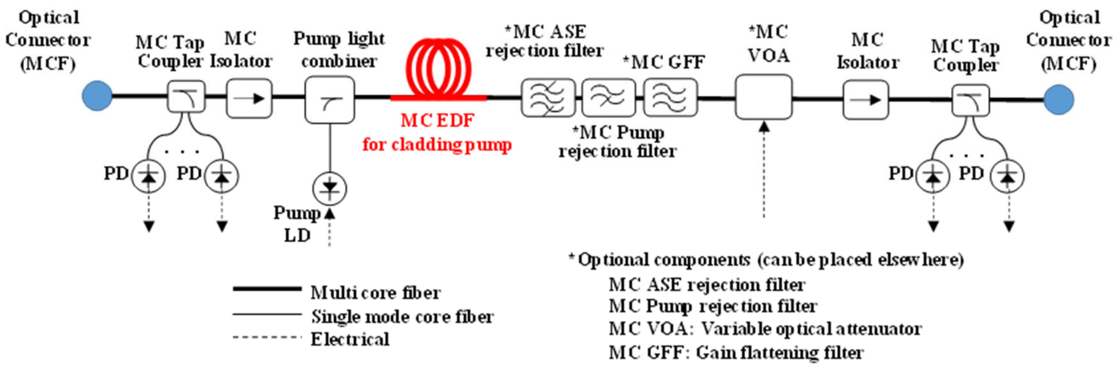
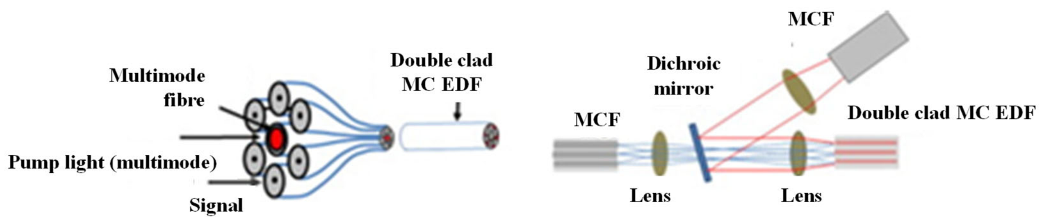
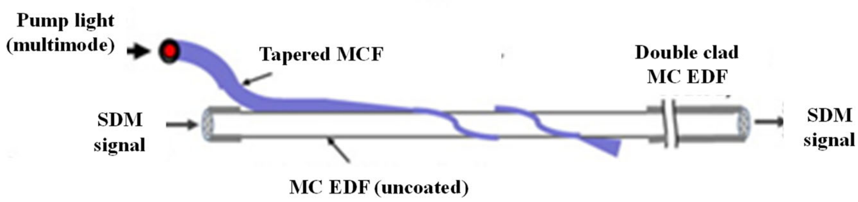


Figure 7 – Configuration of cladding-pumped MC-EDFA



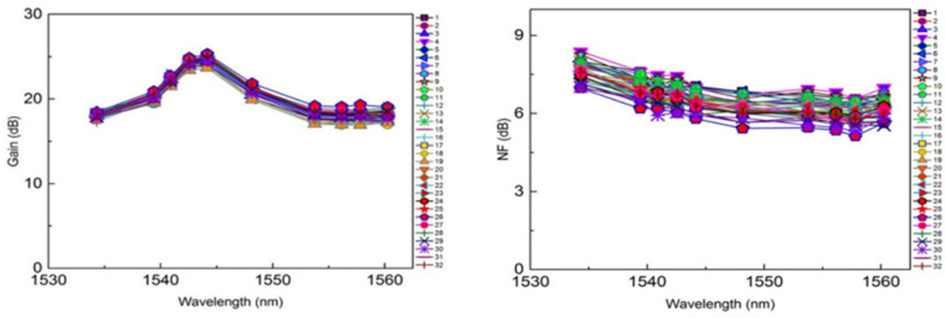
a) Fused bundled fibre pump combiner **b) Lens system combiner**



c) Tapered fiber side-coupled combiner

Figure 8 – Pump light combiner [7]

a) Configuration



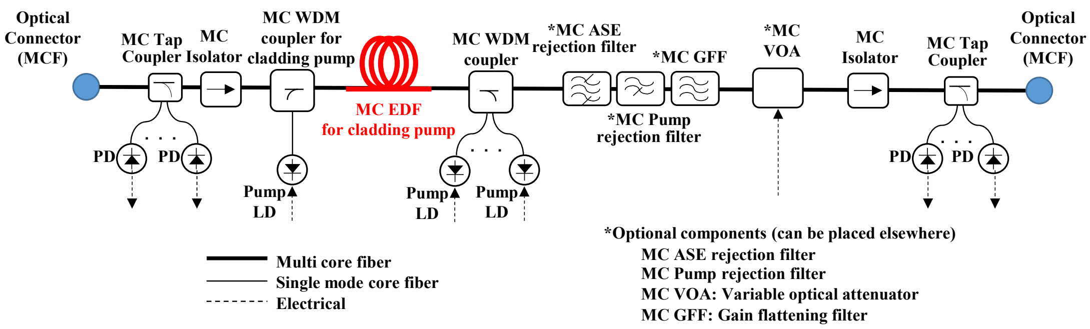
b) Amplification characteristics

Figure 9 – Configuration and amplification characteristics of EDFA with 32-core cladding pumped MC EDF [9]

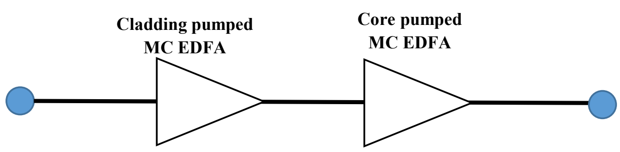
5.2.3 Core and cladding hybrid-pumped MC-EDFA

A cladding-pumped MC-EDFA pumps all the cores simultaneously, and has the potential to realize lower power consumption. However, it cannot adjust the pump power for each core, as the performance of each core changes depending on the number of input signal channels and incident power. If a core and a cladding hybrid-pumped MC-EDFA are combined, it enables lower power consumption of cladding pumping and core pumping that can adjust individual pump power to each core. [11]

Figure 10 a) and Figure 10 b) show two types of configurations of a core and a cladding hybrid-pumped multi-core EDFA. In Type 1, one MC EDF for a cladding pump is bidirectionally pumped to both a clad and a core. In Type 2, a cladding pumped MC-EDFA and a core pumped MC-EDFA are connected in cascade. Both types of prototypes have already been developed, and a MC-EDFA with lower power consumption and excellent controllability of each core has already been launched. Currently, efforts have been made to further reduce power consumption by optimizing the distribution ratio between the cladding pump power and the core pump power.



a) Type 1

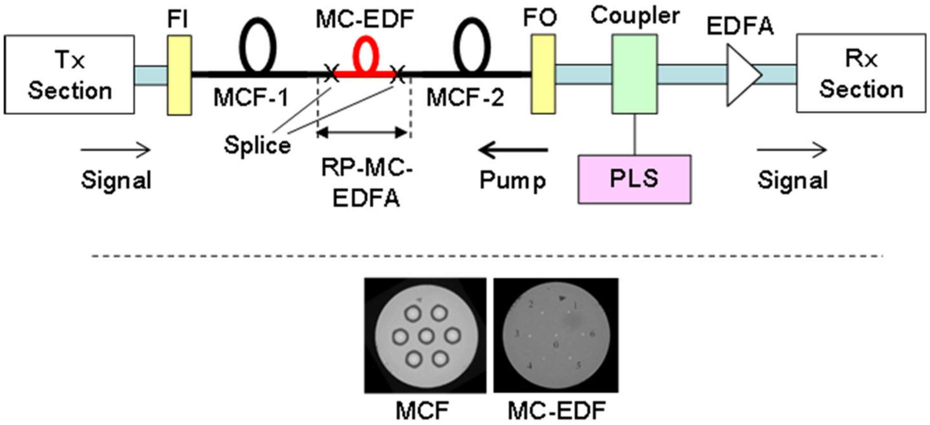


b) Type 2

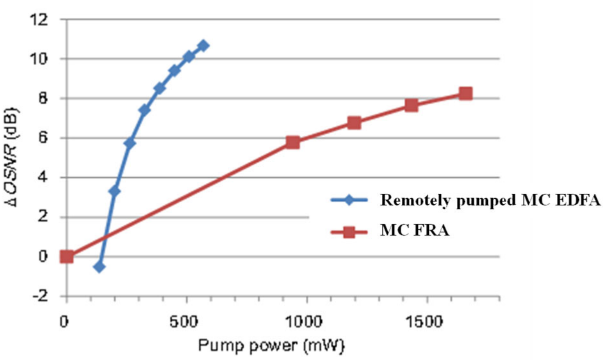
Figure 10 – Configuration of Core and Cladding hybrid pumped MC-EDFA

5.3 State-of-the-art remotely-pumped MC-EDFA and MC-FRA development technology

Remotely-pumped MC-EDFAs and MC-FRAs use optical fibre amplification technologies that have already been established. A remotely-pumped MC-EDFA can be worked by stimulating the MC EDF placed between the transmission MCFs from a distance. On the other hand, a MC-FRA can be worked by introducing Raman pumping into individual transmission MCF cores, and it is confirmed that effectiveness of the FRA can be achieved by improving the SNR (Signal-to-Noise Ratio) for transmission signal by the Raman amplification. Figure 11 a) and b) show configurations and SNR improvements by a remotely-pumped MC-EDFA and a MC FRA. [12]



a) Configurations



b) SNR improvement

Figure 11 – Configurations of Core and Cladding hybrid-pumped MC-EDFA [12]

5.4 Specific features and measurement

Basic optical characteristics of MC-EDFAs (minimum relevant parameters for transmission characteristics are described in IEC 61291-2 and IEC 61291-4) include a signal gain, noise characteristics, etc. that can be evaluated based on IEC 61290-1 series, IEC 61290-3 series, IEC 61290-5 series, by using optical fan-in and optical fan-out, as shown in Figure 12. In addition, characteristics of the core-pumped MC-EDFAs can be measured by individually pumping those of each core, but in the cladding-pumped MC-EDFAs and hybrid-pumped MC-EDFAs, the characteristics of the measured core are affected by the state of a signal inputting to the core that is different from the measured one. Therefore, it is necessary to pay attention to these points when making an evaluation.

As several cores in a MC-EDFA that are embedded in a common cladding suffer from XT from other cores, a XT evaluation method is required to measure a crosstalk component precisely. There are two methods of evaluating XT both of which can identify a signal incident occurred on each core by wavelength or a time unit. Figure 13 a) and 13 b) show the concept of these methods with different wavelengths and by a time separation of signals. In the former one, IEC 61290-1-1 can be used to compare the output signal intensity ratio for each wavelength [13], and in the latter one, IEC 61290-10-1 and IEC 61290-10-2 can be used to compare the output signal intensity ratio for each time to evaluate XT.

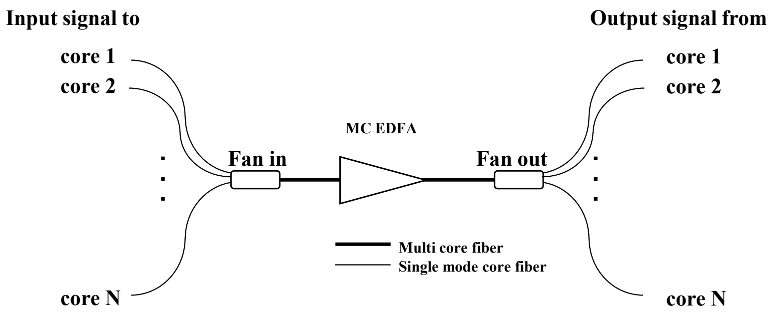


Figure 12 – Multi-core EDFA evaluation setup for basic optical characteristics

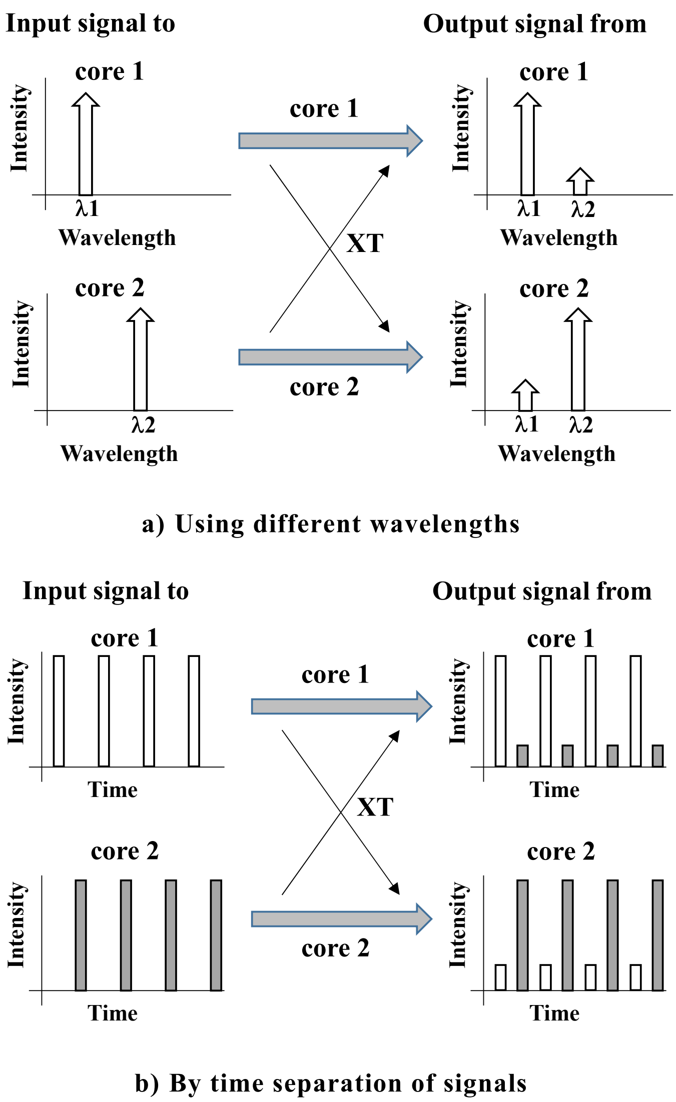


Figure 13 – XT evaluation method with different wavelengths

6 Few-mode OFA technology

6.1 Outline of few-mode EDFA

In the conventional single mode transmission, communications only used the LP_{01} mode, but for the purpose of increasing the transmission capacity, a mode-division multiplexing (MDM) system is used over FMFs to perform communications using multiple modes. The LP mode, the OAM mode, and the coupled-core mode are candidates of multiplexing modes [see Figure 14 a), b) and c)]. [2, 6, 14-16] Additionally, MDM generally uses MIMO (Multi-Input Multi-output) techniques to restore deteriorated signals caused by mode crosstalk to the original signals. It has been pointed out that the performance of MIMO system is affected by a mode-dependent loss (MDL) or a mode-dependent gain (MDG). Accordingly, optical amplifiers for the MDM system is indispensable to control a MDG in addition to satisfying the basic requirements for amplifiers such as a gain and noise figures.

Figure 15 shows configurations of FM-EDFAs. Optical components required for the construction include a FM EDF with equal amplification characteristics for each mode and a low MDG, a FM WDM coupler capable of amplification characteristics for each mode, a FM tap coupler that monitors the signal intensity of each mode, a MC isolator, and other optional components (can be placed elsewhere) such as a MC ASE rejection filter, a MC Pump rejection filter, a MC VOA and a MC GFF.

For achieving low MDG characteristics, it is necessary to use components that have low MDG characteristics. Particularly, it is essential to have a FM EDF with excellent performance. In addition, a FM VOA that can adjust a MDG may be required in many cases to change a loss for each mode.

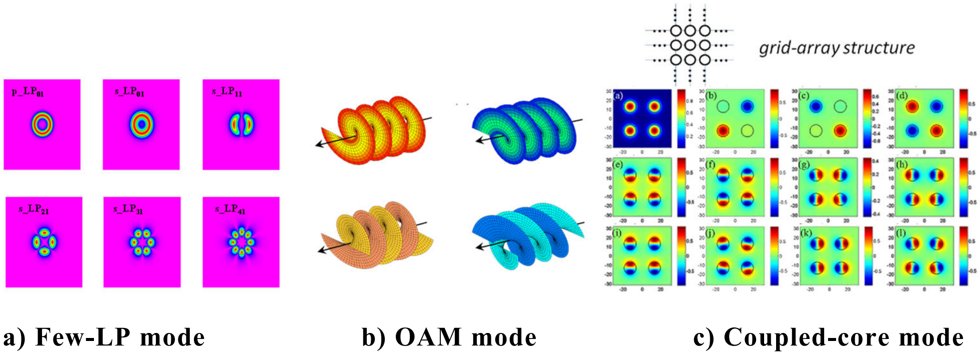


Figure 14 – Image of each mode propagating through the core [15, 16]

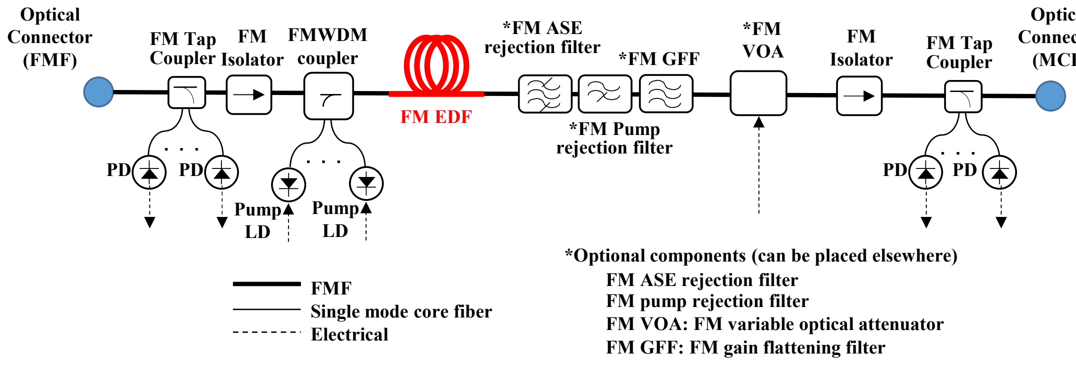


Figure 15 – Configuration of FM-EDFA

6.2 State-of-the-art few-mode EDFA development technology

6.2.1 Few-LP mode EDFA

FM EDFs with low MDG characteristics are now under development, and studies have been made to identify a proper pumping method. Mode amplification exceeding the LP_{01} mode can be provided by increasing a core diameter of the conventional EDFs (step core index and step erbium doping profile structure), although a size of MDG becomes larger (10 dB higher MDG in the LP_{01} signal mode compared to the LP_{11} signal mode) [see Figure 16]. Therefore, it is necessary to reduce the MDG size. This large MDG is due to difference in overlap integral of a signal power profile and an activated erbium-ion profile, as shown in

Figure 17. While conventional EDFs have the same erbium doping profile with optical index profiles, the power distribution of these two modes is quite different. If the EDF is pumped with the LP_{01} mode light, an activated erbium doping profile is expected to be close to the pumping light. The gain of an EDF depends on the overlap integral of a signal power profile and an activated erbium doping profile. It leads to a huge MDG found in few-mode EDFAs with conventional EDFs.

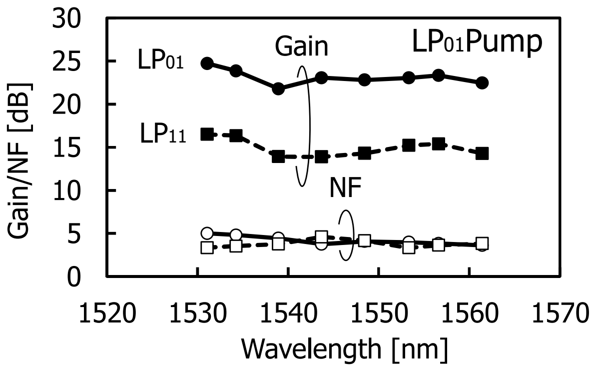
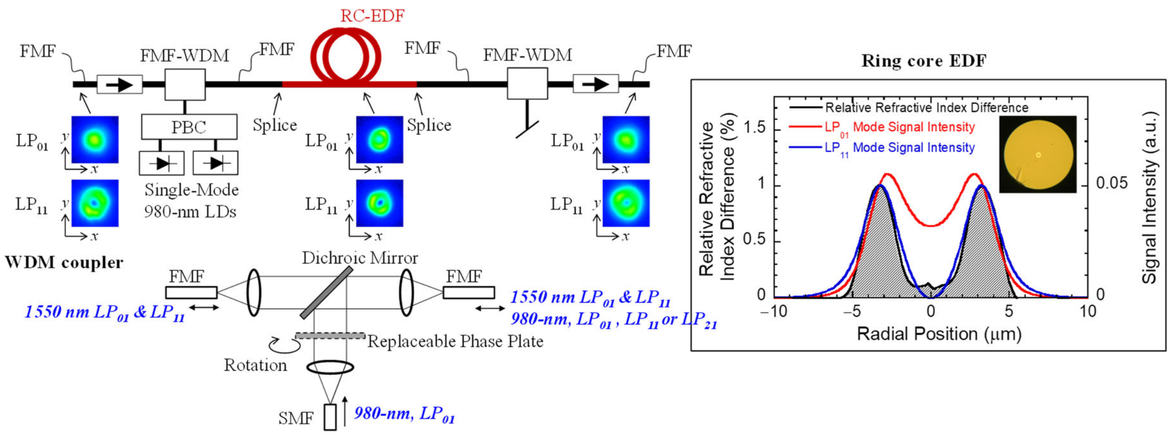


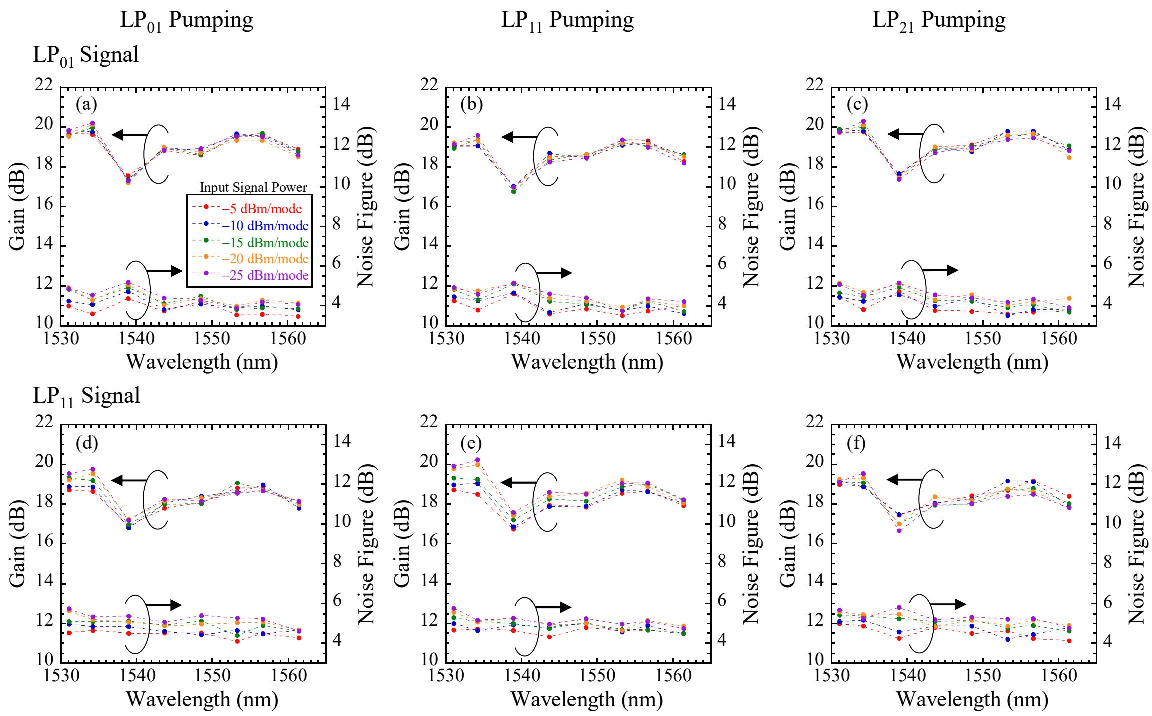
Figure 16 – An example of gain and NF of 2-LP FM-EDFA (large core, step core index and step erbium doping profile structured conventional EDF) [17]

Two approaches are proposed to reduce the MDG of FM EDF. One is to apply a higher-order pump light intensity mode. [18, 19] The activated erbium-ion profile varies in terms of pumping power distribution. For example, when using the LP_{21} mode for pumping, the gain of the LP_{11} signal mode could be larger than that of the LP_{01} mode. The MDGs of 2.5 dB to 1 dB were obtained for a step core index profile FM EDF by applying LP_{11} and LP_{21} mode pumping, respectively. The other approach is to change an erbium doping profile and a core index of FM-EDF. [17, 20-22] If the erbium doping profile is adjusted to the pump light intensity of higher-order modes such as a ring erbium doping profile, 4-LP signal mode amplification with 1 dB MDG is expected in theory. Furthermore, another proposal is made that uses a ring-core EDF having a ring-like profile for both the core index and the erbium doping profile. A theoretical study has shown that almost identical gains could be obtained for 6-LP modes by using a ring-core EDF. The ring-core FM EDF has been proven to reduce the MDG experimentally for a 2-LP mode EDF. Figure 17 a), b) and 18 a), b) show configuration and amplification characteristics of 2-LP mode. An EDFA prototype that consists of a ring-core FM EDF, a FM WDM coupler and two MC isolators has achieved a MDG of less than 1.0 dB between LP_{01} and LP_{11} signal mode, and some of three-mode EDFAs [20, 21]

In addition, a FM VOA is under development using a spatial light modulator and a long period fibre grating. The MDG can be controlled in a range between -7 dB to +5 dB by changing the ratio of the LP_{01} to LP_{11} pump modes with long period fibre grating. [23] Currently, research is underway to further increase the number of modes.

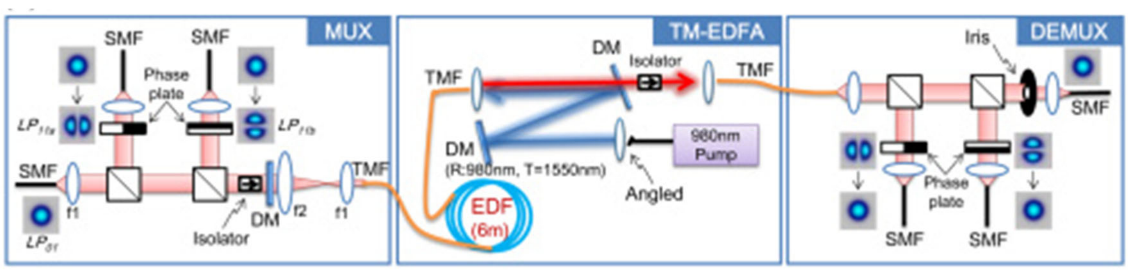


a) Configuration

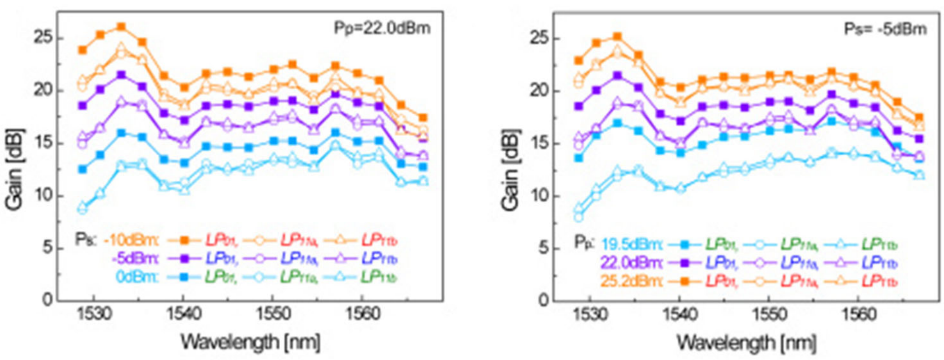


b) Amplification characteristics

Figure 17 – Configurations and amplification characteristics of 2-LP mode EDFA's prototype which consisted with ring-core FM EDF, FM WDM coupler and two MC isolators [20]



a) Configurations



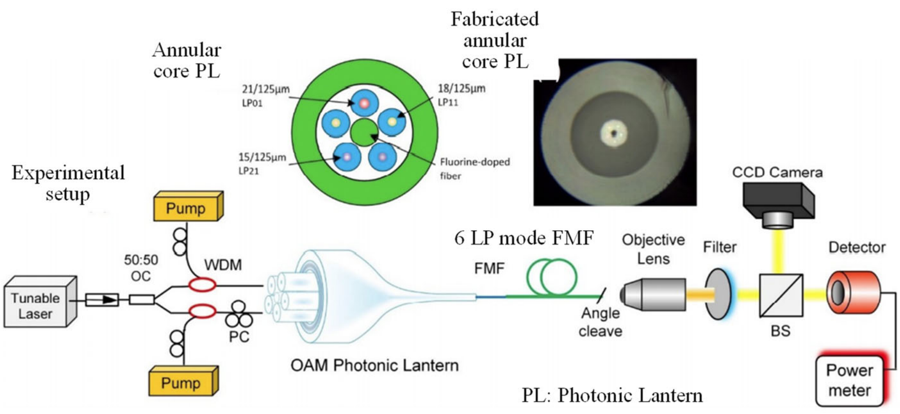
b) Amplification characteristics

Figure 18 – Configurations and amplification characteristics of 3-LP mode EDFA's prototype which consisted with ring-core FM EDF [21]

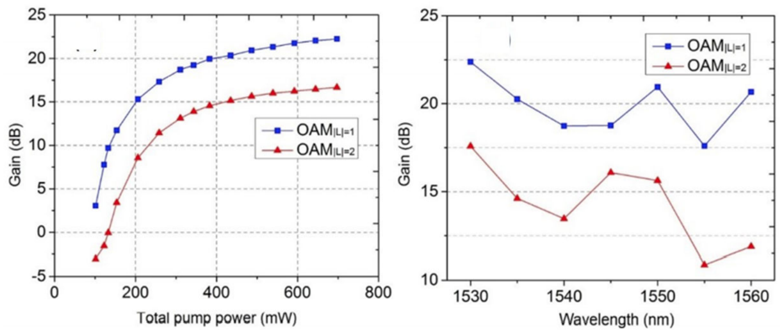
6.2.2 OAM mode EDFA and Coupled-core mode EDFA

It is reported that an EDFA with the OAM mode has been achieved that uses a ring-core EDF structure, or an annular-core photonic lantern structure and FMFs. [24-26] In the former, simulations have shown that 18-OAM mode amplification with a low MDG can be achieved. Some experiments have also been conducted for 2-OAM mode amplification. In the latter, although experiments of 2-OAM mode amplification have been conducted [see Figure 19 a) and b)], some issues still exist with MDG. In addition, An OAM-mode OFA for one OAM mode is reported that uses a PbS-doped ring-core fibre with approximately 3 dB of on/off signal gain at 1 550 nm. [27]

It is also reported that coupled-core mode EDFAs are achieved by using a coupled-core EDF. [28, 29] Some experiments have demonstrated that coupled-core amplification can be achieved either with a core or a cladding pump.



a) Experimental setup



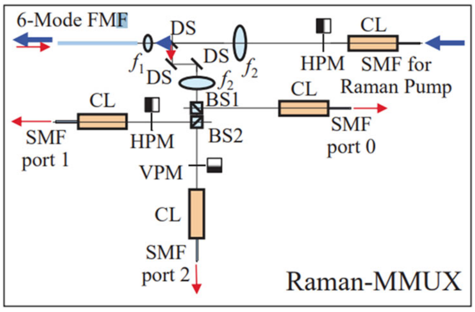
b) Amplification characteristics

Figure 19 – Configurations and amplification characteristics of 2-OAM mode EDFA [26]

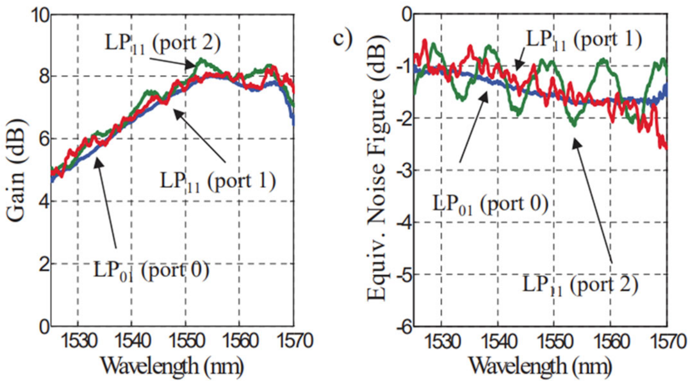
6.3 State-of-the-art FM FRA development technology

Distributed Raman amplification in an FMF requires a small MDG as well as a relatively flat gain over the signal band in the same way as an FM-EDFA.

A FRA for 2-LP modes has been proved in an FMF transmission experiment [see Figure 20 a) and b)]. [30] The experiment shows that the MDG could be minimized by optimizing the modal pump power distribution of LP_{01} and LP_{11} modes. Studies have also started to achieve Raman amplification for high-order mode transmission for over 2-LP modes. [31] Studies on OAM FRAs also have commenced, and some experiments resulted in several dB of on/off signal gains for 2-OAM modes. [32, 33]



a) Experimental arrangement of mode multiplexer with a backward Raman pump coupler



b) On-off Gain of the Raman amplification, and equivalent noise figure at the FMF end

Figure 20 – 2-LP modes FM FRA experiment [30]

6.4 Specific features and measurement

Basic optical characteristics of FM-EDFAs (minimum relevant parameters for Transmission characteristics are described in IEC 61291-2 and IEC 61291-4) include a signal gain, noise characteristics, etc. that can be evaluated based on IEC 61290-1 series, IEC 61290-3 series, IEC 61290-5 series, by using mode converters, a mode combiner and a mode splitter, as shown in Figure 21. However, if using the setup illustrated in Figure 15 for measurement, it cannot discriminate between different LP mode output signals with mixed intra-mode such as LP_{11a} and LP_{11b}. Thus, for characterising the MDG, the amplitude and phase transfer matrix of the amplifier should be measured between each input/output pair across all the wavelengths. [34].

In addition, the crosstalk characteristics between modes can be evaluated by separating the wavelength and a time unit, as is the case of MC-EDFA [see Figure 13]. The wavelength separating method may use IEC 61290-1-1. For comparing the output signal intensity ratios for each wavelength, IEC 61290-10-1 and IEC 61290-10-2 can be used in the time separating method to compare the output signal intensity ratios for each time unit for the purpose of evaluating XT.

Furthermore, when a propagation matrix evaluation in the amplifier is required in MIMO transmission, it is necessary to have a new evaluation method not available in the current IEC documents.

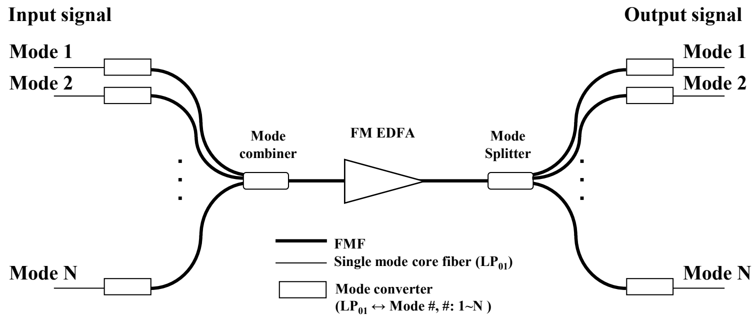
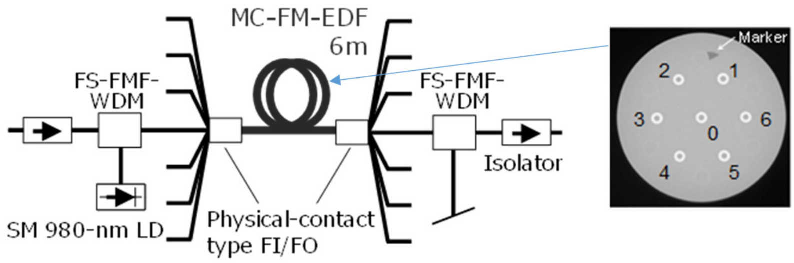


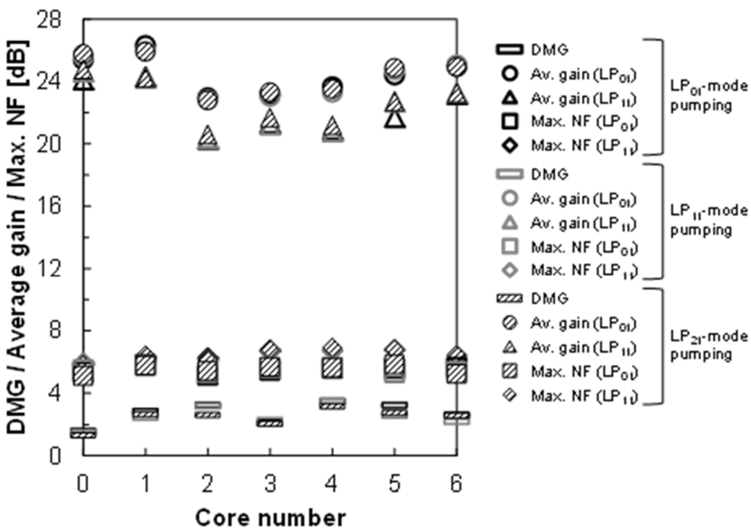
Figure 21 – FM-EDFA evaluation setup for basic optical characteristics

7 MC and FM OFA technology

MC & FM-EDFAs that incorporate the MC-EDF and FM-EDF technologies is also under development. [35-38] For example, we can see a newly created multi-core with a ring core, and it is confirmed that seven cores with a low MDG and 2-LP mode amplification is available, as shown in Figure 22 a) and b). Currently, the number of modes and cores has increased, and amplification using MC & FM EDFs with 7-core – 6-modes, etc. are also demonstrated. We believe that the number of EDF cores and modes would continue to increase in the future. It is also necessary to develop optical components for producing this amplifier.



a) Configurations



b) Amplification characteristics

Figure 22 –MC- and FM-EDFA [36]

Bibliography

[1] T. Morioka, Y. Awaji, and R. Ryf, "*Enhancing optical communications with brand new fibers*," IEEE Com. Mag., Vol. 50, p. 531-542, 2012.

[2] D. J. Richardson, J. M. Fini, and L. E. Nelson, "*Space division multiplexing in optical fibres*," Nature Photonics, Vol.7, p. 354-362, 2013.

[3] M. Yamada, H. Ono and S. Matsuo, "*Multicore EDFA for long distance transmission*," Photonics West 2014: Next-Generation Optical Communication: Components, Sub-Systems and Systems, TuS1-2, 2013.

[4] H. Ono, K. Takenaga, K. Ichii, and M. Yamada, "*Amplification Technology for Multi-Core Fiber Transmission*," SUM 2014 IEEE Photonics Society Summer Topical Meeting on Space Division Multiplexing for Optical Systems and Networks, ME2.1, 2014.

[5] J. Sakaguchi, W. Klaus, B.J. Puttnam, J.M.D Mendinueta, Y. Awaji, N. Wada, Y. Tsuchida, K. Maeda, M. Tadakuma, K. Imamura, R. Sugizaki, T. Kobayashi, Y. Tottori, M. Watanabe, R.V. Jensen, "*19-core MCF transmission system using EDFA with shared core pumping coupled via free-space optics*," Optics Express, Vol. 22, pp. 90-95 2014.

[6] T. Mizuno, and Y. Miyamoto, "*High-capacity dense space division multiplexing transmission*," Optical Fiber Technology, Vol. 35, pp. 108-117, 2017.

[7] K. S. Abedin, M. F. Yan, Thierry F. Taunay, B. Zhu, E. M. Monberg, and D. J. DiGiovanni, "*State-of-the-art multicore fiber amplifiers for space division multiplexings*," Optical Fiber Technology, Vol. 35, pp. 64-71, 2017.

[8] Y. Tsuchida, K. Maeda, Y. Mimura, H. Matsuura, R. Miyabe, K. Aiso and R. Sugizaki, "*Amplification characteristics of a multi-core erbium-doped fiber amplifier*," 2012 Optical Fiber Communication Conference and Exposition (OFC 2012), OM3C.3, 2012.

[9] S. Jain, T. Mizuno, Y. Jung, Q. Kang, J. R. Hayes, M. N. Petrovich, G. Bai, H. Ono, K. Shibahara, A. Sano, A. Isoda, Y. Miyamoto, Y. Sasaki, Y. Amma, K. Takenaga, K. Aikawa, C. Castro, K. Pulver, Md Nooruzzaman, T. Morioka, S. U. Alam, and D. J. Richardson, "*32-core Inline Multicore Fiber Amplifier for Dense Space Division Multiplexed Transmission Systems*," Optics Express, Vol. 25, No. 26 , pp. 32887-32896 2017.

[10] K. Maeda, Y. Tsuchida, S. Takasaka, T. Saito K. Watanabe, T. Sasa, R. Sugizaki, K. Takeshima, and T. Tsuritani, "*Cladding pumped multicore EDFA with output power over 20 dBm using a fiber based pump combiner*," 20th OptoElectronics and Communications Conference (OECC 2015), PWe.30, 2015

[11] H. Ono, Y. Miyamoto, T. Mizuno, and M. Yamada, "*Gain Control in Multi-Core Erbium-Doped Fiber Amplifier with Cladding and Core Hybrid Pumping*," IEEE J. Lightwave Technology, Vol. 37, No. 13, pp. 3365-3372, 2019.

[12] H. Masuda, H. Ono, H. Takara, Y. Miyamoto, K. Ichii, K. Takenaga, S. Matsuo, K. Kitamura, Y. Abe, and M. Yamada, "*Remotely pumped multicore erbium-doped fiber amplifier system with high pumping efficiency*," SUM 2013 IEEE Photonics Society Summer Topical Meeting on SDM for Optical Comm., WC3.3, 2013.

[13] H. Ono, T. Mizuno, H. Takara, K. Ichii, K. Takenaga, S. Matsuo and M. Yamada, "*High power superfluorescent source with stable single-transverse-mode output using a multimode Er-doped fibre*," Electron. Lett., Vol. 50, No. 14, pp. 1009-1010, 2014.

[14] Y. Jung, SU. Alam, and D. J. Richardson, "*Optical Amplifiers for Mode Division Multiplexing*," Handbook of Optical Fibers. Springer, Singapore. https://doi.org/10.1007/978-981-10-1477-2_49-1, 2018.

[15] C. Xia, M. A. Eftekhar, R. A. Correa, J. E. Antonio-Lopez, A. Schülzgen, D. Christodoulides, and G. Li, "*Supermodes in Coupled Multi-Core Waveguide Structures*," IEEE J. of Selected Topics in Quantum Electronics, Vol. 22, No. 2, pp. 196 – 207, 2016.

[16] L. Marrucci, C. Manzo, and D. Paparo, "*Optical Spin-to-Orbital Angular Momentum Conversion in Inhomogeneous Anisotropic Media*," Phys. Rev. Lett. Vol. 96, pp. 163905-1 – 163905-4, 2006.

[17] H. Ono, T. Hosokawa, K. Ichii, S. Matsuo and M. Yamada, "*Improvement of differential modal gain in few-mode fibre amplifier by employing ring-core erbium-doped fibre*," Electron. Lett., Vol. 51, No. 2, pp. 172 - 173 (2014).

[18] N. Bai, E. Ip, T. Wang and G. Li, "*Multimode fiber amplifier with tunable modal gain using a reconfigurable multimode pump*," Optics Express, Vol. 19, No.17, pp. 16601-16611, 2011.

[19] R. N. Mahalati, D. Askarov and J. M. Kahn, "*Adaptive modal gain equalization techniques in multi-mode erbium-doped fiber amplifiers*," IEEE J. Lightwave Technol., Vol. 32, No. 11, pp. 2133–2143, 2014.

[20] H. Ono, T. Hosokawa, K. Ichii, S. Matsuo, H. Nasu, and M. Yamada, "*2-LP mode few-mode fiber amplifier employing ring-core erbium-doped fiber*," Optics Express, Vol. 23, No. 21, pp. 27450 – 27418, 2015.

[21] Y. Jung, Q. Kang, V. A. J. M. Sleiffer, B. Inan, M. Kuschnerov, V. Veljanovski, B. Corbett, R. Winfield, Z. Li, P. S. Teh, A. Dhar, J. Sahu, F. Poletti, S. U. Alam, and D. J. Richardson, "*Three mode Er ring-doped fiber amplifier for mode-division multiplexed transmission*," Optics Express, Vol. 21, No. 8, pp. 10383–10392, 2013.

[22] E. Ip, M.J. Li, K. Bennett, A. Korolev, K. Koreshkov, W. Wood, C. Montero, and J. Liñares, "*Experimental Characterization of a Ring-profile Few-mode Erbium-doped Fiber Amplifier Enabling Gain Equalization*," 2013 Optical Fiber Communication Conference (OFC 2013), JTh2A, 2013.

[23] M. Wada, T. Sakamoto T. Mori, N. Hanzawa, T. Yamamoto, and F. Yamamoto, '*Modal gain controllable all-fiber type multimode fiber amplifier*," 18th OptoElectronics and Communica-tions Conference (OECC 2013), TuS4-5, 2013.

[24] J. Ma, F. Xia, S. Chen, S. Li, and J. Wang, "*Amplification of 18 OAM modes in a ring-core erbium-doped fiber with low differential modal gain*," Optics Express, Vol. 27, No. 26, pp. 38087–38097, 2019.

[25] J. Liu, S. Chen, H. Wang, S. Zheng, L. Zhu, A.Wang, L. Wang, C. Du, and J. Wang, "*Amplifying Orbital Angular Momentum Modes in Ring-Core Erbium-Doped Fiber*," American Association for the Advancement of Science, Vol. 2020, Article ID 7623751, https://doi.org/10.34133/2020/7623751, 2020

[26] N. Wang, Z. S. Eznaveh, J. C. A. Zacarias, J. E. Antonio-Lopez, S. Leon-Saval, P. Sillard, C. Gonnet, A. Schülzgen, G. Li, and R. Amezcua-Correa, "*Erbium-Doped Fiber Amplifier for OAM Modes Using an Annular-Core Photonic Lantern*," 2017 Conference on Lasers and Electro-Optics (CLEO2017), STu4K.4, 2017.

[27] L. Xu, Y. Shang, J. Yang, Z. Chen, F. Pang, H. Liu, Y. Dong, N. Chen, J. Wen, and T. Wang, "*Orbital Angular Momentum Optical Amplifier Based on PbS-Doped Ring-Core Fiber*," Frontiers in Physics, https://doi.org/10.3389/fphy.2020.00198, 2020.

[28] J. C. Alvarado-Zacarias, N. K. Fontaine, H. Chen, J. E. Antonio-Lopez, S. Wittek, J. Li, S. Gausmann, R. Ryf, C. Gonnet, A. Amezcua-Correa, M. Bigot, A. Schülzgen, G. Li, P. Sillard, and R. Amezcua-Correa, "*Coupled-Core EDFA Compatible with FMF Transmission*," 2018 Optical Fiber Communication Conference (OFC 2018), Th4A.3, 2018.

[29] T. Ohtsuka, M. Tanaka, H. Sakuma, T. Hasegawa, T. Hayashi, and H. Tazawa, "*Coupled 7-Core Erbium Doped Fiber Amplifier and Its Characterization*," 2019 Optical Fiber Communication Conference (OFC 2019), W2A.19, 2018.

[30] R. Ryf, A. Sierra, R. Essiambre, S. Randel, A. Gnauck, C. A. Bolle, M. Esmaeelpour, P. J. Winzer, R. Delbue, P. Pupalaikis, A. Sureka, D. Peckham, A. McCurdy, and R. Lingle, "*Mode-equalized distributed Raman amplification in 137-km few-mode fiber*," 37th European Conference on Optical Communications (ECOC 2011), Th.13.K.5, 2011.

[31] M. Esmaeelpour, R. Ryf, N. K. Fontaine, H. Chen, A. H. Gnauck, R. Essiambre, J. Toulouse, Y. Sun, and R. Lingle, “*Transmission Over 1050-km Few-Mode Fiber Basedon Bidirectional Distributed Raman Amplification*,” IEEE J. Lightwave Technol., Vol. 34, No. 8, pp. 2133–2143, 2016.

[32] L. Zhu, J. Li, G. Zhu, L. Wang, C. Cai, A. Wang, S. Li, M, Tang; Z. He, S. Yu, C. Du, W. Luo, J. Liu, J. Du, and J. Wang, "First Demonstration of Orbital Angular Momentum (OAM) Distributed Raman Amplifier over 18-km OAM Fiber with Data-Carrying OAM Multiplexing and Wavelength-Division Multiplexing," 2018 Optical Fiber Communication Conference (OFC 2018), pp. 1-3, 2018.

[33] K. Rottwitt1, J. G. Koefoed, K. Ingerslev, and P. Kristensen, “*Inter-modal Raman amplification of OAM fiber modes*,” APL Photonics No. 4, No. 3, 030802, 2019.

[34] N. K. Fontaine1, B Huang1, Z. S. Eznaveh, H. Chen1, J Cang1, B. Ercan, A. Vel´aquez-Benitez1, S. H. Chang, R. Ryf, A. Schulzgen, J. C. A. Zaharias, P. Sillard, C. Gonnet, J. E. A. Lopez2, and R. Amezcua-Correa, "*Multi-mode optical fiber amplifier supporting over 10 spatial modes*," 2016 Optical Fiber Communication Conference (OFC 2016), Th5A.4, 2016.

[35] K. Shibahara, D. Lee, T. Kobayashi, T. Mizuno, H. Takara, A. Sano, H. Kawakami, Y. Miyamoto, H. Ono, M. Oguma, Y. Abe, T. Matsui, R. Fukumoto, Y. Amma, T. Hosokawa, S. Matsuo, K. Saitoh, M. Yamada, and Toshio Morioka, “*Transmission Over 1050-km Few-Mode Fiber Basedon Bidirectional Distributed Raman Amplification*,” IEEE J. Lightwave Technol., Vol. 34, No. 1, pp. 196-204, 2016.

[36] Y. Amma, T. Hosokawa, H. Ono; K. Ichii, K. Takenaga; S. Matsuo, and M. Yamada, “*Ring-Core Multicore Few-Mode Erbium-Doped Fiber Amplifier*,” IEEE Photonics Technology Letters, vol. 29, no. 24, pp. 2163-2166, 2017.

[37] Y. Jung, M. Wada, K. Shibahara, S. Jain, I. A. Davidson, P. Barua, J. R. Hayes, T. Sakamoto, T. Mizuno, Y. Miyamoto, Y. Sasaki, K. Saitoh, K. Nakajima, and D. J. Richardson, “*High Spatial Density 6-Mode 7-Core Fiber Amplifier for L-Band Operation*,” IEEE J. Lightwave Technol., Vol. 38, No. 11, pp. 2938-2943, 2020.

[38] Y. Wakayama, D. Soma, S. Beppu, S. Sumita, K. Igarashi, and T. Tsuritani, “*266.1-Tbit/s Transmission Over 90.4-km 6-Mode Fiber With Inline Dual C+L-Band 6-Mode EDFA*,” IEEE J. Lightwave Technol., Vol. 37, No. 2, pp. 404-410, 2019.

OITDA/TP 33/AM : 2021

Optical fibre amplifier for space division multiplex transmission

解　説

この解説は，本体に記載した事柄を説明するもので，技術資料（TP）の一部ではない。

1　制定の趣旨

この技術資料は, 長距離の SDM 光ファイバ通信システムを構築する際に必要となる SDM アンプについての情報を提供する。

2　制定の経緯

シングルモードファイバ(SMF) を用いた従来の光ファイバ通信システムでは，時分割多重，波長多重，デジタルコヒーレント技術を用いることで伝送容量の拡大が図られてきた。しかし，通信トラフィックの増加に伴い，更なる光ファイバ通信システムの伝送容量の更なる増加が必要となっている。近年，通信容量の飛躍的な増加を目的に，マルチコアファイバやマルチモードファイバを伝送路として用いる空間分割多重(SDM) の研究・開発が進められている。

本資料が，日本国内の光ファイバ増幅器の製造者ならびにユーザ，光ファイバ増幅器の部品製造者などにとって，次世代の光増幅器の 1 つとして考えられている SDM アンプについての有益な情報が提供できるものと考える。同文書は，

- ✓ SDM アンプの分類およびその概要
- ✓ 最先端の開発技術および開発された増幅器構成と増幅特性例
- ✓ SDM アンプの測定方法

について解説している。

本 OITDA 技術資料は, 2020 年 4 月から 2021 年 2 月に光増幅器及びダイナミックモジュール標準化部会で審議された。

3　審議中に特に問題となった事項

この技術資料の作成にあたり，審議中に問題となった事項及び審議結果は，次のとおりである。

a) マルチコアファイバ技術及びフュー（few）モード技術を中心に記載することにしていたが，読者の理解を促進するため，利得，出力，雑音指数などの性能例を記載する必要があるとの意見があった。審議の結果，国内研究機関の事例だけでなく，海外研究機関の事例を，出典を明確にすることでデータ

を引用することにした。

4 構成要素

主な項目は次のとおりである。

a) Scope（**箇条 1**）

この技術資料は，マルチコアファイバ技術及びフューモードファイバ技術を適用した SDM 増幅器についてまとめた。

b) Normative references（**箇条 2**）

関連する IEC 61290 規格群，IEC 61291 規格群，IEC 61292 規格群及び IEC 60050-731 を引用した。

c) Teams, definitions and abbreviated teams（**箇条 3**）

この TP に記載する主な SDM 光増幅器の用語及び定義を規定した。

d) Classification of SDM OFA（**箇条 4**）

SDM OFA の分類を記載した。

e) Multi-core OFA technology（**箇条 5**）

マルチコア光ファイバ増幅器の技術を記載した。

f) Few-mode OFA technology（**箇条 6**）

フューモード光ファイバ増幅器の技術を記載した。

g) MC and FM OFA technology（**箇条 7**）

マルチコアファイバ技術及びフューモードファイバ技術を用いた光ファイバ増幅器の技術例を記載した。

5 その他

本技術資料は，IEC/TC 86/SC86C に TR 原稿として提案を予定している。

6 TP 作成・検討メンバ

TP 作成・検討メンバの構成表を，次に示す。

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高　橋　英　憲	株式会社ＫＤＤＩ総合研究所
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小　野　浩　孝	湘南工科大学

（執筆者　山田 誠）

7　原案作成部会の構成表

原案作成部会の構成表（一般財団法人光産業技術振興協会 光増幅器及びダイナミックモジュール標準化部会）を，次に示す。

光増幅器及びダイナミックモジュール標準化部会　構成表

	氏名	所属
（議長）	山　田　　　誠	大阪府立大学
（メンバ）	小　熊　健　史	日本電気株式会社
	小　島　　　学	横河計測株式会社
	佐　藤　功　紀	古河電気工業株式会社
	鹿　間　光　太	日本電信電話株式会社
	渋　谷　　　隆	株式会社白山
	清　水　　　誠	NTT エレクトロニクス株式会社
	鈴　木　裕　一	富士通株式会社
	高　橋　英　憲	株式会社 KDDI 総合研究所
	田　中　正　人	住友電気工業株式会社
	長谷川　清　智	三菱電機株式会社
	藤　崎　文　雄	パナソニックシステムソリューションズジャパン株式会社
	三　浦　寿太郎	日本モレックス合同会社
	水　本　哲　弥	東京工業大学
	宮　内　　　彰	IEC/TC 86 委員
	八重樫　浩　樹	沖電気工業株式会社
	吉　田　　　実	近畿大学
（オブザーバ）	磯　野　秀　樹	富士通オプティカルコンポーネンツ株式会社
	岡　田　直　也	経済産業省商務情報政策局
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	森　　　高　章	一般財団法人光産業技術振興協会
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（執筆者　山田 誠）

この OITDA 規格の TP（技術資料）は，一般財団法人光産業技術振興協会ファイバオプティクス標準化部会 光ファイバセンサ専門部会で審議・取纏めたものである。
この資料についてのご意見又はご質問は，下記にご連絡ください。

TP（技術資料）:

空間分割多重伝送用光ファイバ増幅器
（Optical fibre amplifier for space division multiplexing transmission）

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