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TECHNICAL REPORT

colour inside

Optical amplifiers –
Part 12: Fibre amplifiers for space division multiplexing transmission

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FOREWORD

IEC TR 61292-12 has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics. It is a Technical Report.

External document OITDA/TP 33/AM [1] [1]has served as a basis for the elaboration of this document.

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1 Numbers in square brackets refer to the Bibliography.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
86C/1807/DTR	86C/1819/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 61292 series, published under the general title *Optical amplifiers*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

Optical amplifiers (OAs) are essential components for designing long-haul optical transmission systems, for which many standards have been published. Recently, research has been conducted to develop higher data rate fibre optic transmission systems using space division multiplexing (SDM) with multi-core and few-mode optical fibres. A development effort is also underway to fabricate optical fibre amplifiers (OFAs) for SDM, which are necessary for extending the transmission distance. The OFAs varieties include multi-core optical fibre amplifiers, few-mode optical fibre amplifiers, and multi-core and few-mode optical fibre amplifiers. This document provides a better understanding of OFAs for SDM fibre transmission systems.

NOTE Few-mode fibres are special types of multimode fibres.

OPTICAL AMPLIFIERS –

Part 12: Fibre amplifiers for space division multiplexing transmission

1 Scope

This part of IEC 61292, which is a Technical Report, provides general information on optical fibre amplifiers for space division multiplexed transmission systems using multi-core, few-mode, and multi-core and few-mode optical fibres. This document describes the classification, concepts, configurations, and implementations of these amplifiers as well as state-of-the-art development technologies, specific features and measurement methods.

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 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 document, the terms and definitions given in IEC 60050-731, IEC 61291-1, IEC TR 61931, and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

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

[SOURCE: IEC TR 61292-3:2020, 3.1.1]

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

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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
MC&FMF	multi-core fibre with few-mode cores
MDG	mode-dependent gain
MDL	mode-dependent loss
MDM	mode-division multiplexing
MIMO	multi-input multi-output
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 OFAs

Fibre optic transmission systems using space division multiplexing (SDM) utilize multi-core fibre (MCF) transmission, few-mode fibre (FMF) transmission, or multi-core few-mode fibre (MC&FMF) transmission. These techniques are employed to overcome the capacity limits of conventional fibre transmission and can potentially achieve ultra-high transmission capacity per fibre (i.e., exabit/s). Long-haul transmission systems usually employ optical fibre amplifiers (OFAs) to maintain sufficiently high optical signal power along the fibre optic transmission line. SDM transmission systems typically use multi-core EDFAs (MC-EDFAs), few-mode EDFAs (FM-EDFAs), or multi-core few mode EDFAs (MC&FM-EDFAs). In contrast to conventional EDFAs, the input and output fibres of 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&FM-EDF) [2] to [45]. 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 scheme for SDM OFAs, which consists of MC-OFAs and FM-OFAs, as described in IEC TR 61292-3 [6]. MC-OFAs comprise MC-EDFAs and MC-FRAs, whereas FM-OFAs include FM-EDFAs and FM-FRAs. Furthermore, as various mode multiplexing techniques are under consideration for FMF transmission, FM-OFAs can have multiple mode types for amplification, such as linearly polarized (LP) modes, orbital-angular-momentum (OAM) modes, and coupled-core modes. MC&FM-OFAs can be made by combining MC and FM-OFA techniques.

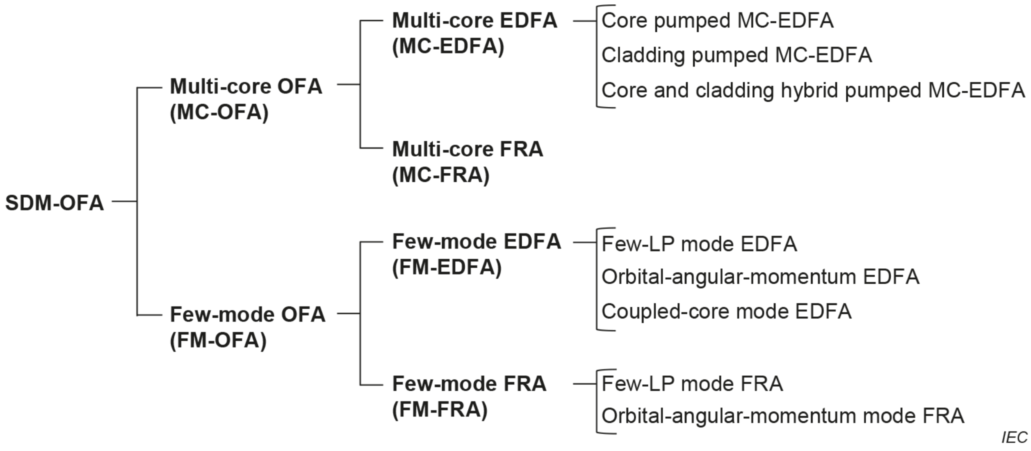


Figure 1 – Classification of SDM OFAs

5 Multi-core OFA technology

5.1 Outline of multi-core EDFAs

Figure 2 shows the concept of an MC-EDFA. In this case, the EDFA consists of an array of several conventional EDFAs (i.e., conventional gain blocks) with fan-out and fan-in elements for connecting the MC-EDFA to the output and input MCFs. Newer versions of MC-EDFAs are under development at the time of writing with the goal to improve performance through the integration of optical components (see IEC TR 61292-1 [7]) and EDF cores, without degradation in amplification properties and amplification efficiency. The amplification properties can be degraded, for example, by crosstalk (XT) between the optical signals propagating through the various amplifier cores.

Crosstalk characteristics are particularly important for MC-EDFAs, because several cores of EDFs need to be integrated with high density. Furthermore, it is important to achieve the same amplification characteristics for each core. It is expected that highly integrated MC-EDFA will lead to smaller amplifier systems, lower complexity/cost, and lower power consumption, compared with arrayed EDFAs.

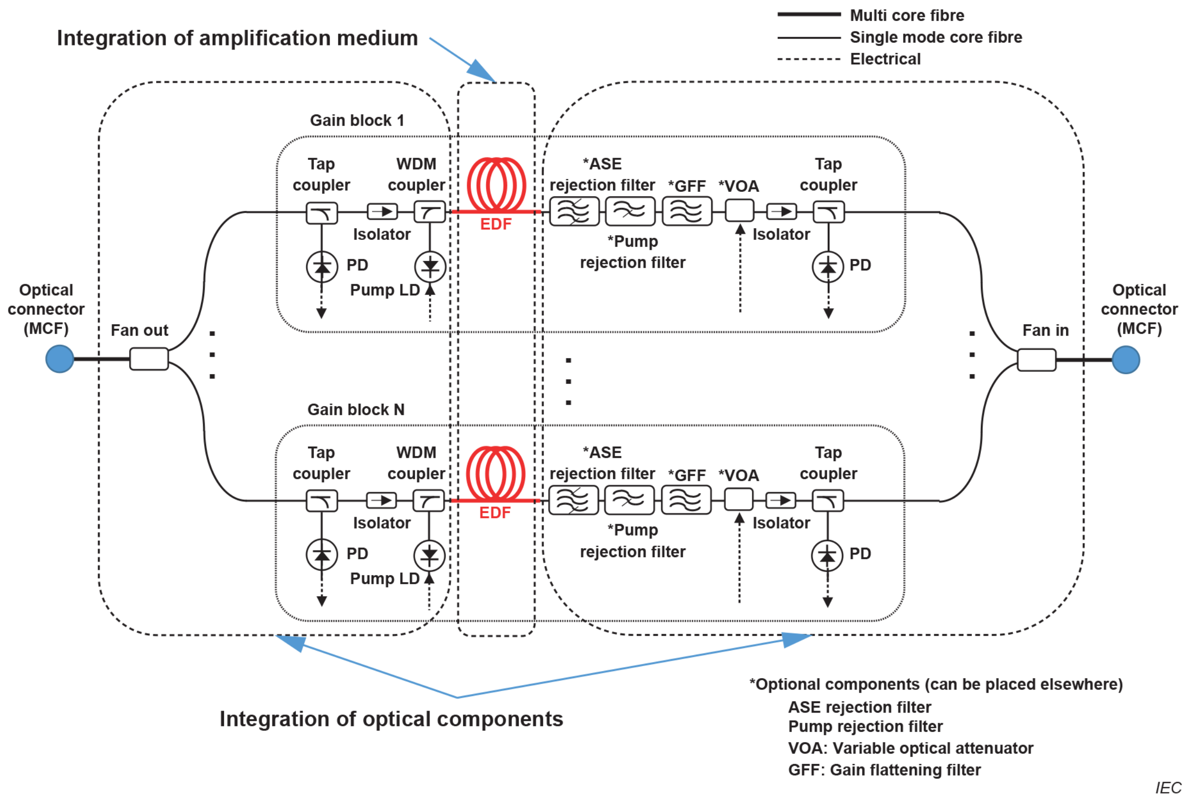
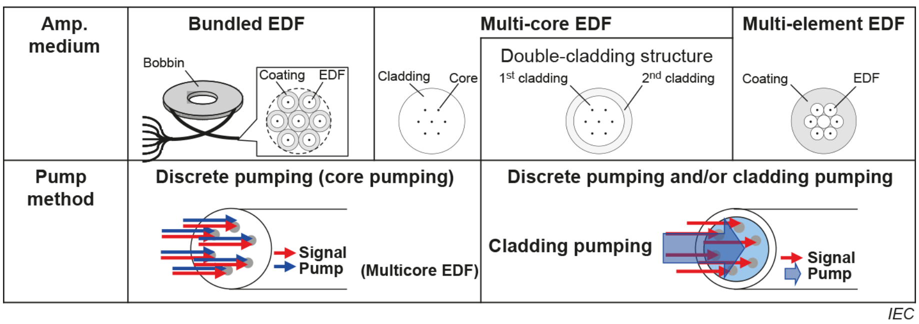


Figure 2 – Concept of an MC-EDFA

Figure 3 shows several amplification media and pump methods for MC-EDFAs. Multi-core EDFs (MC-EDFs) are now actively under development [4], [5]. MC-EDFAs have the advantage that multi-core fibre fabrication techniques can be applied, so that complexity and size can be reduced through manufacturing. One of the challenges is to achieve uniform amplification characteristics in each core of the MC-EDFA. There are two types of MC-EDF. One type is designed for a single discrete pump laser; and the other type, which has a double cladding structure, is designed for cladding pumping. For the first type, the pump methods and optical components used for conventional EDFAs can be adapted. Additionally, this type has a highly efficient pumping capacity and high-speed controlling ability. The second type is targeted to have lower power consumption, and it can be downsized by decreasing the number of pump laser diodes (LDs) used. It has also been reported that bundled EDFs and multi-element EDFs can be used as amplification media for MC-EDFAs.



Source: TuS1-2, Photonics West 2014 [4], Figure 1, reproduced with the permission of SPIE.

Figure 3 – Amplification media and pump methods for MC-EDFAs

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

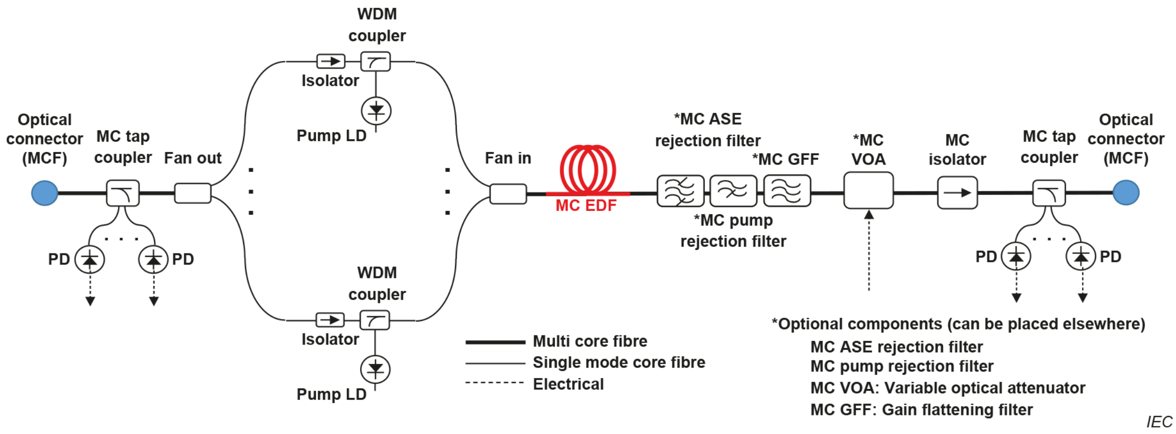
5.2.1 Core pumped multi-core EDFA

Figure 4 a) shows a typical configuration of a core-pumped MC-EDFA with MC-EDF and conventional WDM couplers, and Figure 4 b) shows a configuration with MC EDF and a multi-core WDM coupler. Other optical components used for MC-EDFAs include an MC tap coupler, which monitors the signal intensity in each core, an MC isolator, and other optional components such as MC ASE rejection filters, MC pump rejection filters, MC variable optical attenuators (MC VOA), and MC gain flattening filters (MC GFF). These optional components can be placed in different locations.

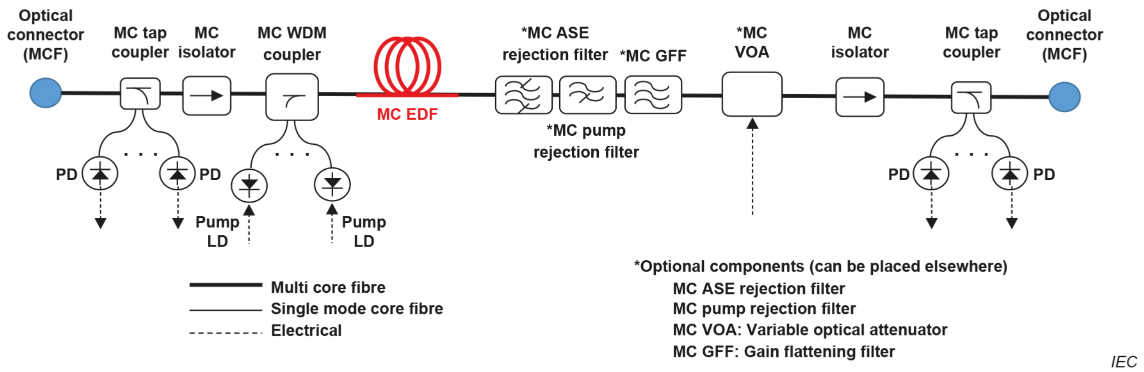
The most important component in Figure 4 a) and Figure 4 b) is the MC-EDF, which can be equipped with up to 19 cores, all having practical amplification characteristics, by using modified MCF fabrication techniques, according to previous reports [4], [5], [8] to [10]. One of the important characteristics of MC-EDFs is optical crosstalk between the various cores. Crosstalk is caused by mode coupling between cores. In general, the level of crosstalk depends on the spatial separation between the cores and on the EDF length. Since the length of the MC-EDF is much shorter than that of the MC transmission fibre, crosstalk in MC EDFs can be set to a larger value compared with other MCFs. In MC EDFs, acceptable levels of crosstalk can generally be achieved with a core pitch of 30 μm or larger.

Several prototypes have already been demonstrated, such as those equipped with a core-pumped MC-EDFA with MC EDF and conventional WDM couplers, and those with MC EDF and newly developed MC WDM couplers. Figure 5 shows an example of the configuration and amplification characteristics of a core-pumped MC-EDFA with a 7-core EDF and conventional WDM couplers [4], and Figure 6 shows the configuration and amplification characteristics of a core-pumped MC-EDFA with 19-core MC-EDF and MC WDM coupler [8].

Other prototypes that have been demonstrated include core-pumped MC-EDFAs with a bundled EDF and a multi-element EDF. For the purpose of developing a practical core-pumped MC-EDFA, uniform amplification characteristics are required for the various EDF cores. Moreover, multi-core optical components, such as MC tap couplers and MC GFFs, are indispensable, because these components have better performance and reliability as well as lower complexity/cost than arrays of conventional tap couplers and GFFs.

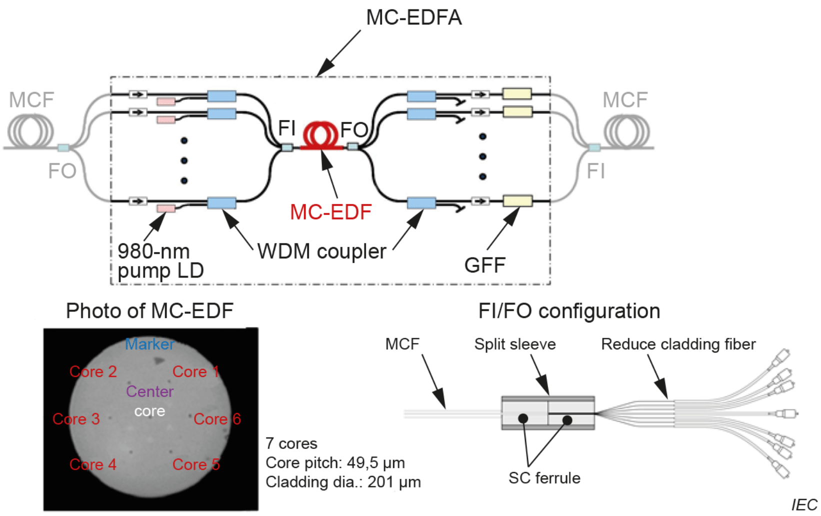


a) Using conventional WDM couplers

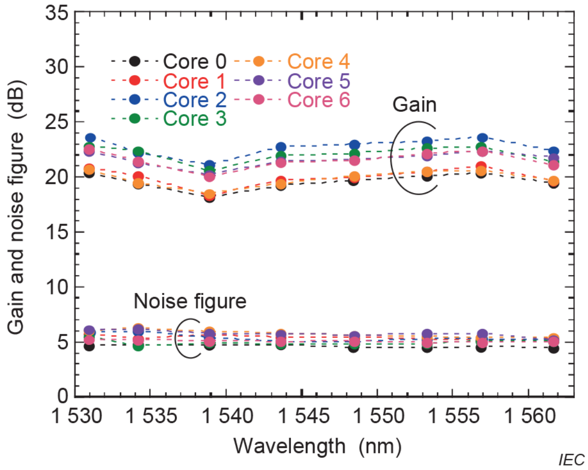


b) Using MC WDM couplers

Figure 4 – Configurations of core-pumped MC-EDFAs



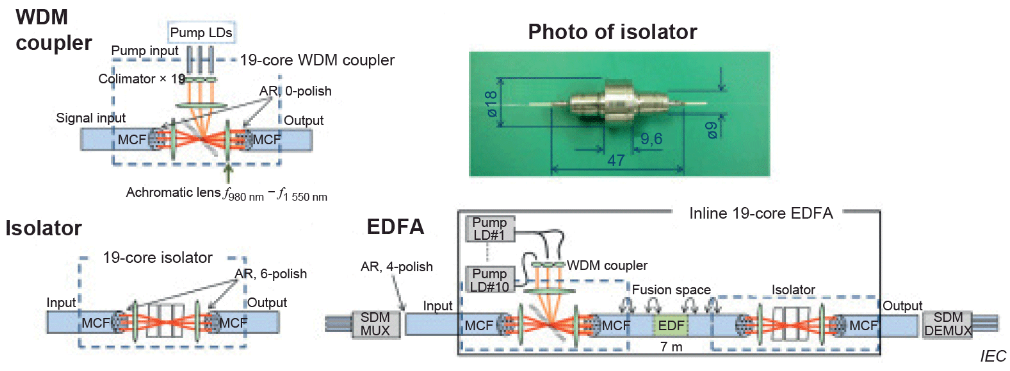
a) Configuration



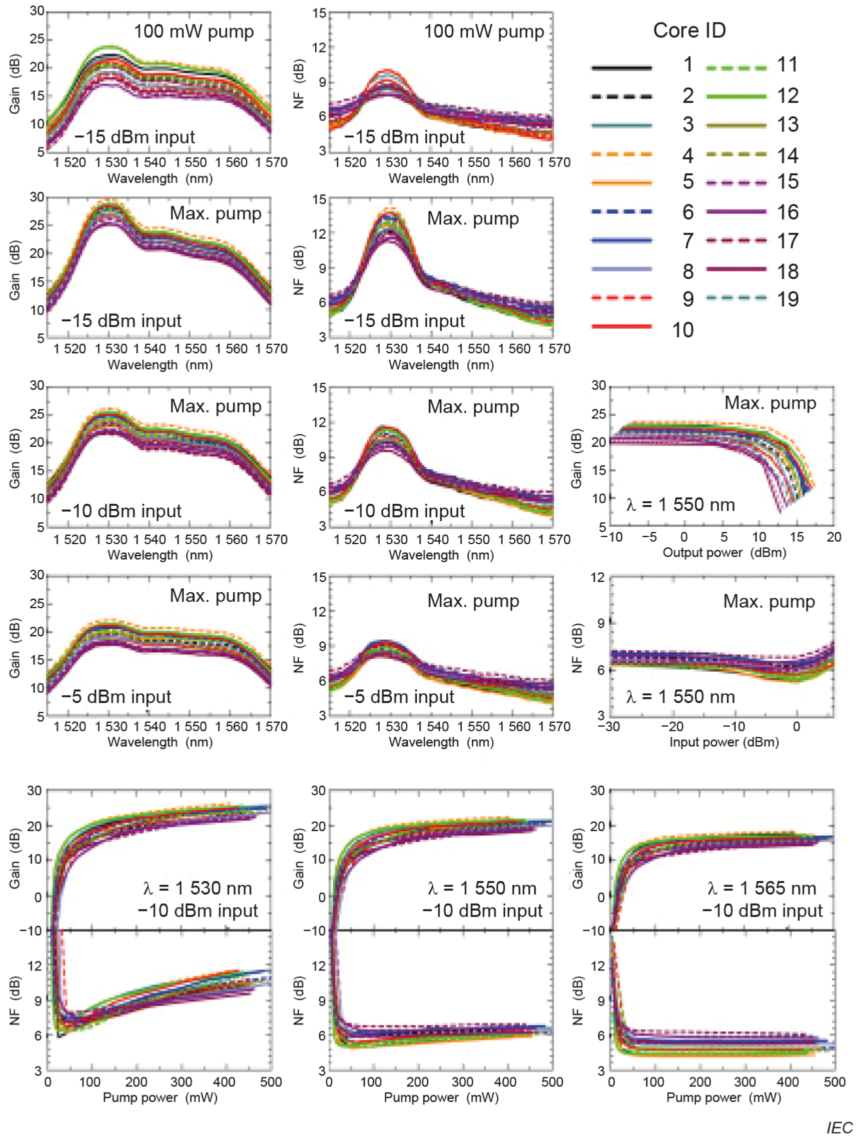
b) Amplification characteristics

Source: TuS1-2, Figure 3, Photonics West 2014 [4], reproduced with the permission of SPIE.

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



a) Configuration



b) Amplification characteristics

Source: Optics Express 22, p. 90 (2014) [8], Figure 3 and Figure 4, reproduced with the permission of Optica Publishing Group. © The Optical Society.

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

5.2.2 Cladding pumped multi-core EDFA

Figure 7 shows a typical configuration of a cladding-pumped MC-EDFA. In addition to the optical components shown for the core-pumped MC-EDFA, this amplifier requires an MC-EDF designed for cladding pumping as well as a special pump light combiner.

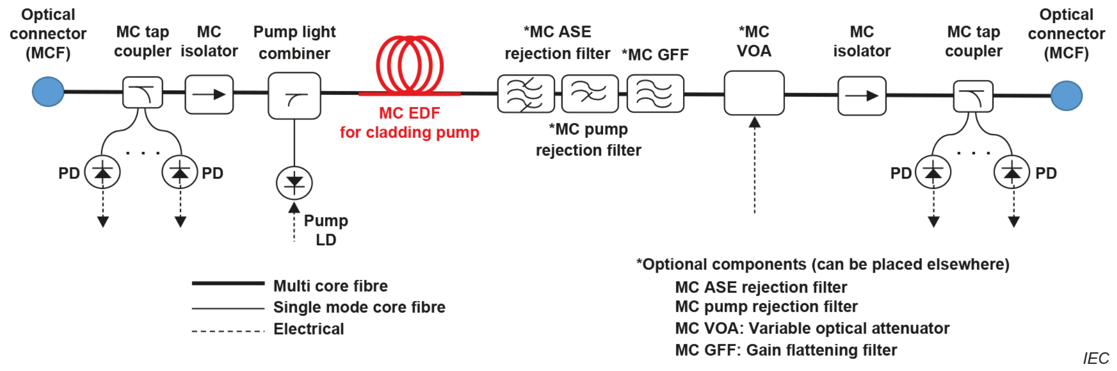


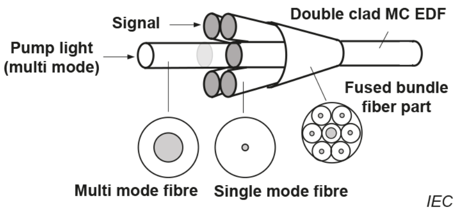
Figure 7 – Configuration of a cladding-pumped MC-EDFA

The cladding pump technique is used to increase the output power of optical amplifiers, as described in IEC TR 61292-8 [11]. It is believed that cladding pumping can reduce the complexity and power consumption of an MC-EDFA because the various EDF cores can be pumped collectively.

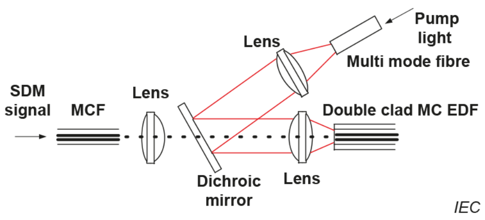
An MC-EDF designed for cladding pumping has a double cladding structure that comprises the cores, an inner cladding, and outer claddings. It has been reported that an MC-EDF with cladding pumping can have up to 32-cores [4], [5], [9], [10], [13], [14].

To accomplish cladding pumping, the pump light is coupled to an inner cladding of the MC-EDF with the help of a specially designed pump light combiner. Since the inner cladding area is much larger than the core area, a high-power multimode LD can be used to inject the pump light into the inner cladding. The pump light combiner is known from other cladding pumping techniques and can be either a fused bundled fibre pump combiner, a lens system combiner, or a tapered fibre side-coupled combiner, as shown in Figure 8 a), Figure 8 b) and Figure 8 c). Several prototypes of the cladding-pumped MC-EDFAs have been reported [3], [4], [6] to [9]. Figure 9 shows an example of the configuration and amplification characteristics of an EDFA with a 32-core cladding-pumped MC-EDF [13].

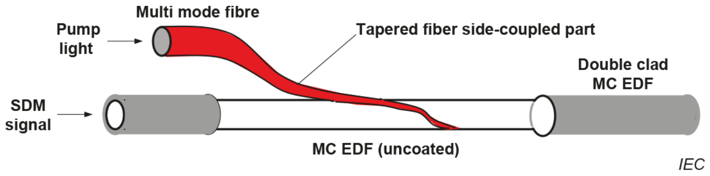
A practical cladding-pumped MC-EDFA ideally has uniform amplification characteristics in the various EDF cores, and its optical components have good performance and reliability.



a) **Fused bundled fibre pump combiner**

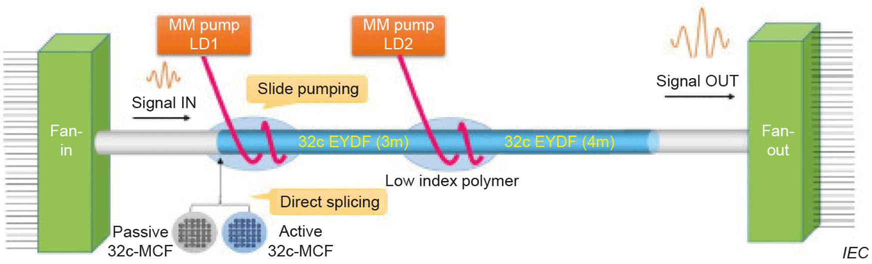


b) **Lens system combiner**

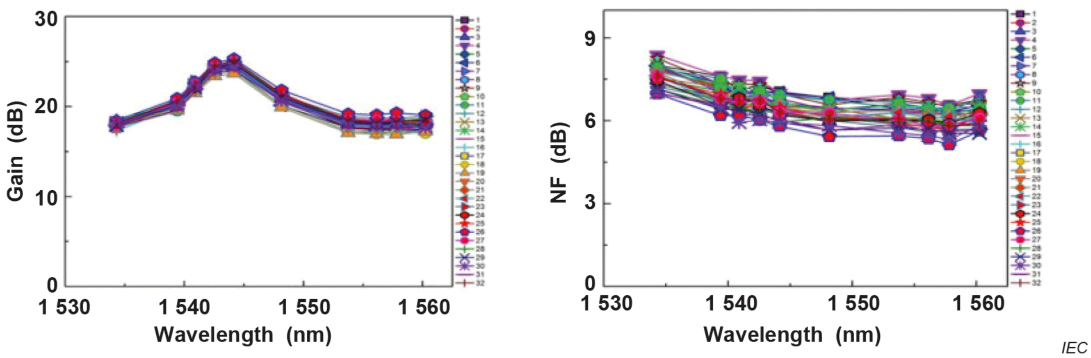


c) **Tapered fibre side-coupled combiner**

Figure 8 – Pump light combiner



a) **Configuration**



b) **Amplification characteristics**

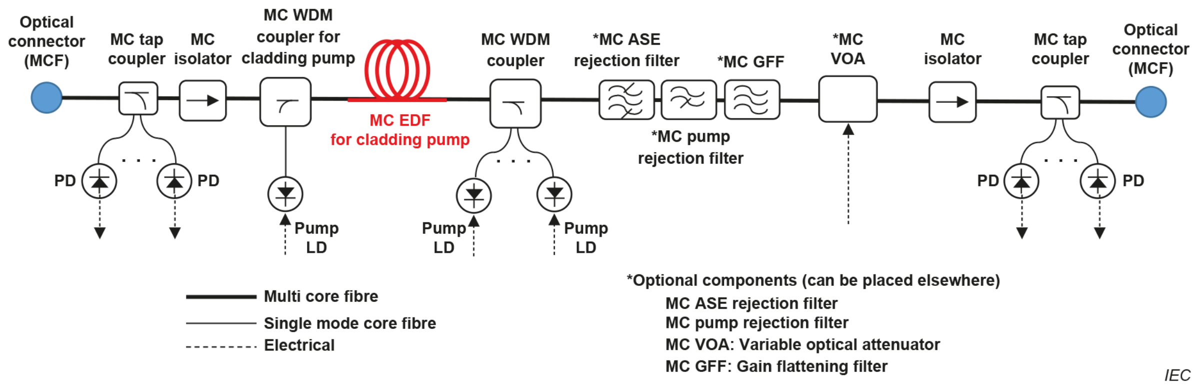
Source: Optics Express 25, p. 32887 (2017) [13], Figure 2 and Figure 3, reproduced with the permission of Optica Publishing Group. © The Optical Society.

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

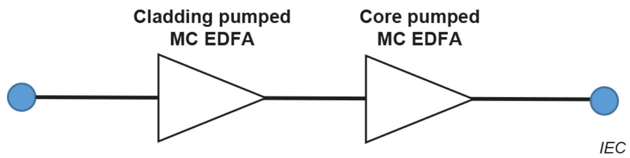
5.2.3 Core and cladding hybrid pumped MC-EDFA

Cladding-pumped MC-EDFAs pump all the cores simultaneously and therefore have the potential to reduce power consumption. However, they usually cannot adjust the pump power individually in each core, because the performance of each core changes, depending on the number of input signal channels and incident signal power. MC-EDFAs using a hybrid pumping scheme with simultaneous core and a cladding pumping can ideally achieve low power consumption (via cladding pumping) and individual adjustment of the pump power in each core (via core pumping) [15].

Figure 10 shows the configurations of two types of hybrid core and cladding-pumped multi-core EDFA. In type 1, shown in Figure 10 a), a single MC-EDF designed for cladding pumping is pumped from both ends, with one end pumping the cladding and the other end the core. In type 2, shown in Figure 10 b), a cladding pumped MC-EDFA and a core pumped MC-EDFA are connected in series. Both types of prototypes have already been developed, and an MC-EDFA with low power consumption and excellent controllability of each core has already been demonstrated. Currently, efforts are underway to further reduce power consumption by optimizing the distribution ratio between the cladding pump power and the core pump power.



a) Type 1

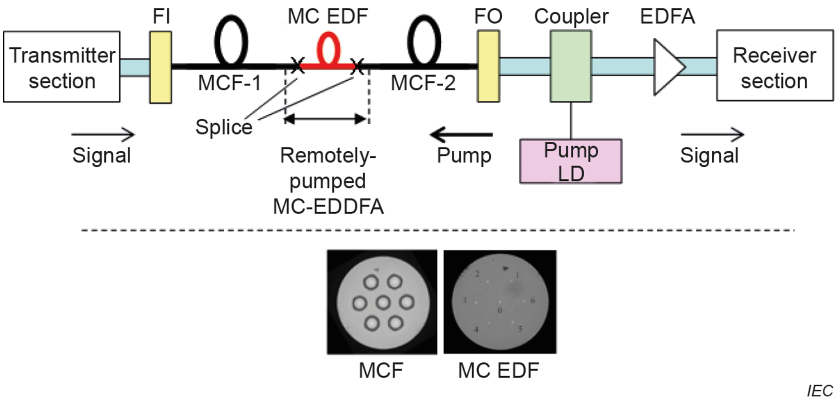


b) Type 2

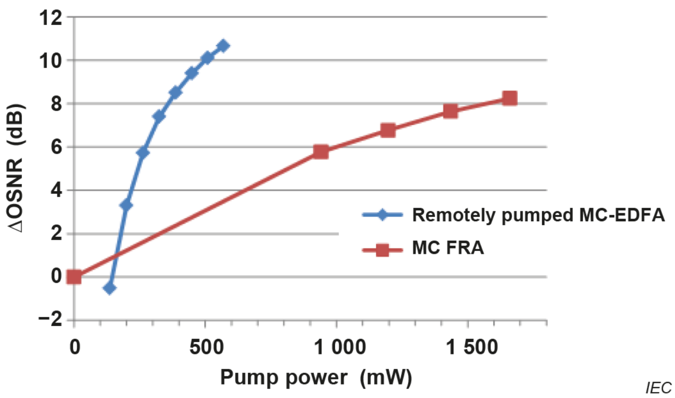
Figure 10 – Configuration of core and cladding hybrid-pumped MC-EDFA

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

Remotely pumped MC-EDFAs and MC-FRAs use optical fibre amplification technologies that have already been commercialized with conventional EDFAs and FRAs. A remotely pumped MC-EDFA is obtained by stimulating a remotely located MC-EDF (which is placed somewhere along the length of the transmission MCFs) with a distant pump. On the other hand, an MC-FRA is obtained by pumping the individual cores of the transmission MCF, which introduces Raman gain. It has been confirmed that FRAs can efficiently improve the signal-to-noise ratio (SNR) of the transmitted signal by Raman amplification. Figure 11 a) shows the configuration of a remotely pumped MC-EDFA, and Figure 11 b) shows the optical signal-to-noise ratio (OSNR) improvements achieved by a remotely pumped MC-EDFA and an MC-FRA [16].



a) **Configuration**



b) **OSNR improvement**

Source: WC3.3, Summer Topical Meeting on SDM (2013) [16], Figure 1 and Figure 4, reproduced with the permission of IEEE. © 2013 IEEE.

Figure 11 – Configuration and performance of remotely pumped MC-EDFA and MC-FRA

5.4 Specific features and measurements

Basic optical characteristics of MC-EDFAs include signal gain and noise characteristics. These characteristics can be evaluated as described in the IEC 61290-1 series [17], the IEC 61290-3 series [18], and the IEC 61290-5 series [19], by using optical fan-in and fan-out devices as shown in Figure 12.

NOTE A minimum set of relevant performance parameters for optical amplifiers is defined in IEC 61291-2 [22] for single channel applications and in IEC 61291-4 [23] for multichannel applications.

The characteristics of core-pumped MC-EDFAs can be measured by individually pumping each of the cores. In cladding-pumped MC-EDFAs and in hybrid-pumped MC-EDFAs, the characteristics of the measured core are affected by the presence of signals injected into the other cores. Therefore, it is necessary to closely monitor these effects when evaluating cladding-pumped and hybrid-pumped MC-EDFAs.

When several cores in MC-EDFAs are embedded in a common cladding, the signals can experience optical crosstalk (XT) from other cores. Thus, XT evaluation methods are required to measure the crosstalk components precisely. There are two methods for evaluating XT, both of which can identify crosstalk resulting from a signal incident on other cores by wavelength or time analysis. Figure 13 shows the concept of these two methods, using either different wavelengths (Figure 13 a)) or wavelength and time multiplexing (Figure 13 b)). In the first method, the IEC 61290-1 series [17] can be used to analyse the output signal intensity ratio for each wavelength [24], and in the second method, IEC 61290-10-1 [20] and IEC 61290-10-2 [21] can be used to analyse the output signal intensity ratio as a function of time to evaluate the signal crosstalk.

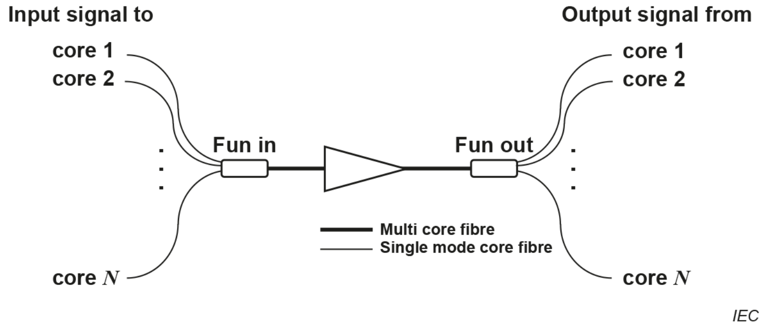
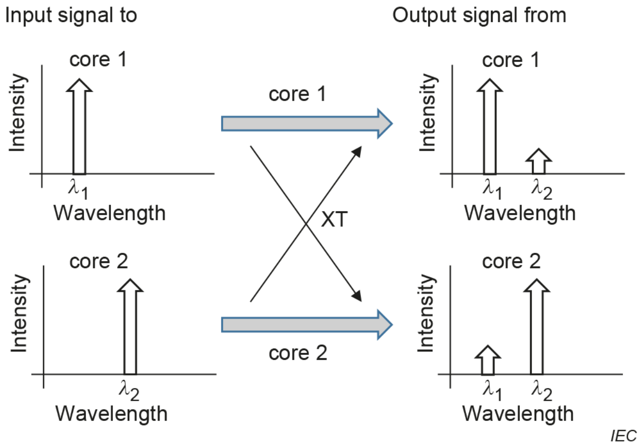
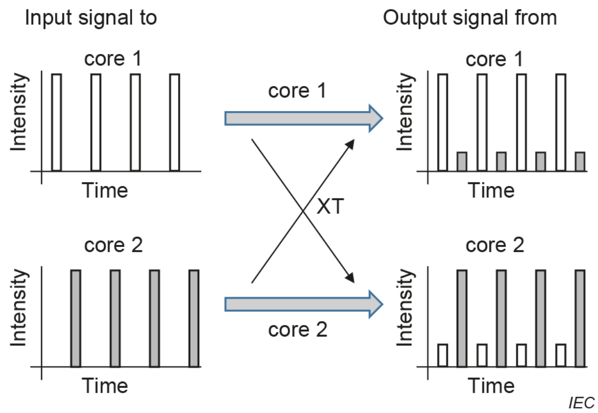


Figure 12 – Multi-core EDFA evaluation setup for basic optical characteristics



a) Using different wavelengths



b) By time separation of signals

Figure 13 – XT evaluation methods with different wavelengths

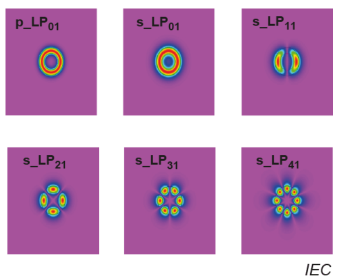
6 Few-mode OFA technology

6.1 Outline of few-mode EDFA

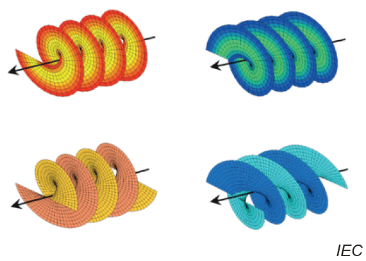
Conventional single-mode fibre optic communication systems typically use only the LP_{01} mode of the transmission fibre to carry information. However, it is possible to increase the transmission capacity of a single fibre by replacing the single-mode fibre with a few-mode fibre (FMF); information can then be transmitted on each of the various modes of the FMF. Mode-division multiplexing (MDM) of multiple modes is used to transmit data over FMFs. LP modes, OAM modes, and coupled-core modes are candidates for mode-division multiplexing (see Figure 14) [3], [9], [25] to [27]. Additionally, MDM generally uses MIMO (multiple-input multiple-output) techniques at the receiver to remove signal distortions caused by mode crosstalk and to restore the original signals. It has been pointed out that the performance of MIMO systems is affected by a mode-dependent loss (MDL) and mode-dependent gain (MDG). Accordingly, optical amplifiers for MDM systems need to control MDG in addition to satisfying the basic requirements for amplifiers such as a gain and noise figure.

Figure 15 shows the configuration of a typical FM-EDFA. Optical components required for such amplifiers include an FM-EDF with equal amplification characteristics for each mode having a low MDG, an FM WDM coupler capable of amplification characteristics for each mode, an FM tap coupler that monitors the signal intensity of each mode, an FM isolator, and other optional components, which could be placed elsewhere, such as an FM ASE rejection filter, an FM pump rejection filter, or an FM VOA, and an FM GFF.

To achieve the desired low MDG, it is necessary to use components that have low MDG characteristics. Particularly, it is essential to have an FM-EDF with excellent performance. In addition, an FM VOA with adjustable MDG could be required in many cases to change the loss for each mode.

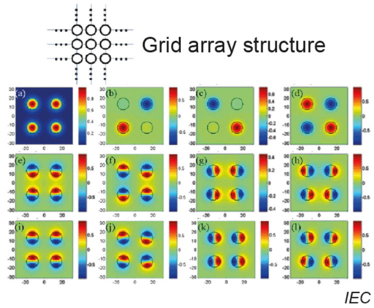


a) LP modes



Source: Phys. Rev. Lett. 96, p. 163905-1 (2006) [26], Figure 1, reproduced with the permission of the American Physical Society. © 2006 APS

b) OAM modes



Source: IEEE JSTQE 22, p. 196 (2016) [27], Figure 12, reproduced with the permission of IEEE. © 2016 IEEE

c) Coupled-core modes

Figure 14 – Image of each mode propagating through the core

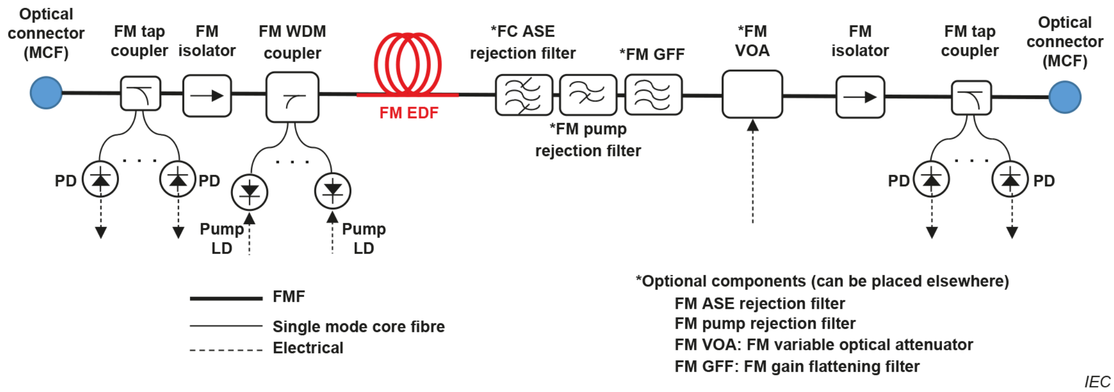
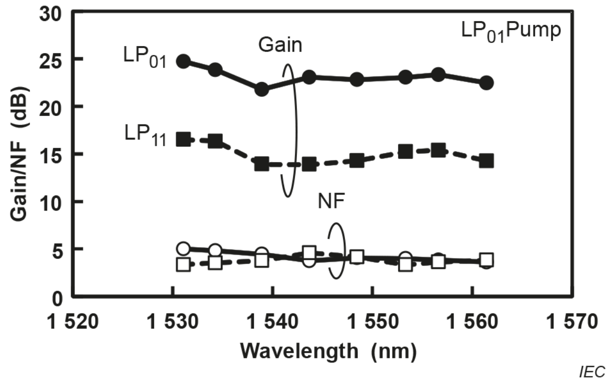


Figure 15 – Configuration of an FM-EDFA

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 under development at the time of writing, and proper pumping methods for FM-EDFs have been studied. Mode amplification beyond the LP_{01} mode can be achieved by increasing the core diameter of the conventional EDFs, for example, with step-index core and step erbium doping profile structure, although the MDG can become large in this case (with 10 dB higher MDG in the LP_{01} signal mode compared to the LP_{11} signal mode; see Figure 16 [28]). Therefore, it is necessary to reduce the MDG. Large MDG is due to the difference in the overlap integral of the different mode profiles with the activated erbium-ion profile. While conventional EDFs have the same erbium doping profile as the optical index profiles, the power distribution of these two modes is quite different. If the EDF is pumped with light from an LP_{01} mode, the activated erbium doping profile is expected to be close to the pumping light. The gain that a mode experiences in an EDF depends on the overlap integral of the signal power profile with the activated erbium doping profile. This explains the large MDG found in few-mode EDFAs using conventional EDFs.



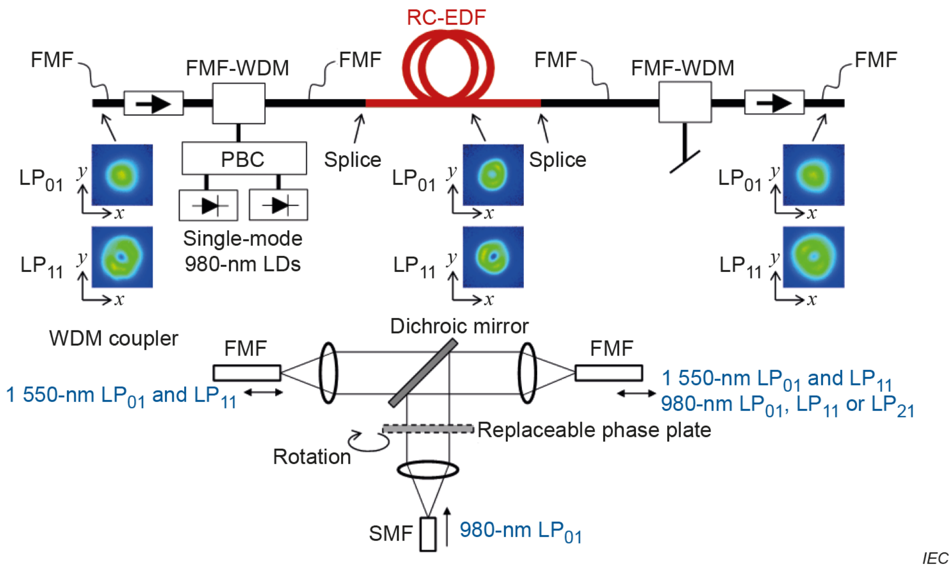
Source: Electron. Lett. 51, p. 172 (2014) [28], Figure 4, reproduced with the permission of John Wiley and Sons. © 2014 John Wiley and Sons

Figure 16 – Example of gain and NF of a 2-LP FM-EDFA (large core, step core index and step erbium doping profile structured as in a conventional EDF)

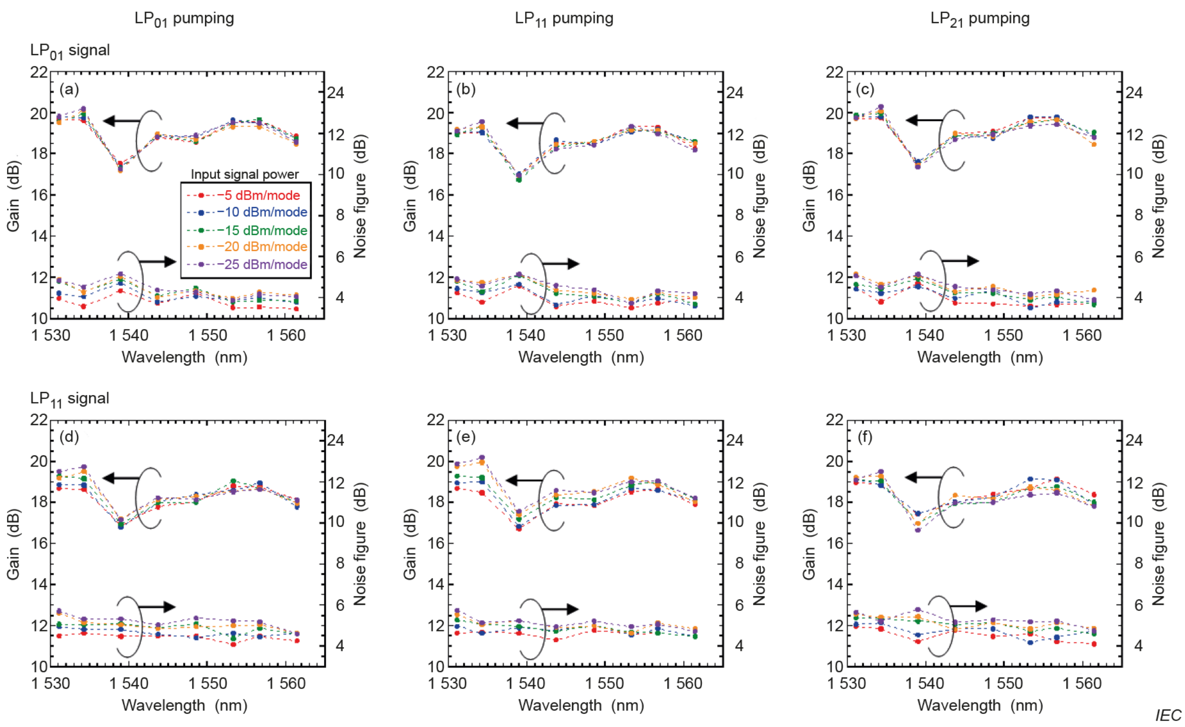
Two approaches have been proposed to reduce the MDG of an FM-EDF. One approach is to apply pump light from a higher order intensity mode [29], [30]. The activated erbium-ion profile varies with the pumping power distribution. For example, when using the LP_{21} mode for pumping, the gain of the LP_{11} signal mode could be larger than that of the LP_{01} mode. MDGs of 2,5 dB and 1 dB were obtained in an FM-EDF with step-index core profile by applying LP_{11} and LP_{21} mode pumping, respectively. The other approach is to change the erbium doping profile and the core index of the FM-EDF [28], [31] to [33]. In theory, if the erbium doping profile is adjusted to the pump light intensity of higher-order modes, similar to a ring erbium doping profile, 4-LP signal mode amplification with 1 dB MDG can be expected. Furthermore, another proposal has been made to use 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 and Figure 18 show configurations and amplification characteristics of two FM-EDFAs designed for 2-LP signal modes [31], [32]. An EDFA prototype that consists of a ring-core FM-EDF, an FM WDM coupler and two FM isolators has achieved an MDG of less than 1,0 dB between the LP_{01} and LP_{11} signal modes [31]. Similar results have been obtained with three-mode EDFAs [32].

In addition, an FM VOA is under development using a spatial light modulator and a long-period fibre grating. The MDG can be controlled between –7 dB to +5 dB by changing the ratio of the LP_{01} to LP_{11} pump modes with a long-period fibre grating [34]. Currently, research is underway to further increase the number of modes.



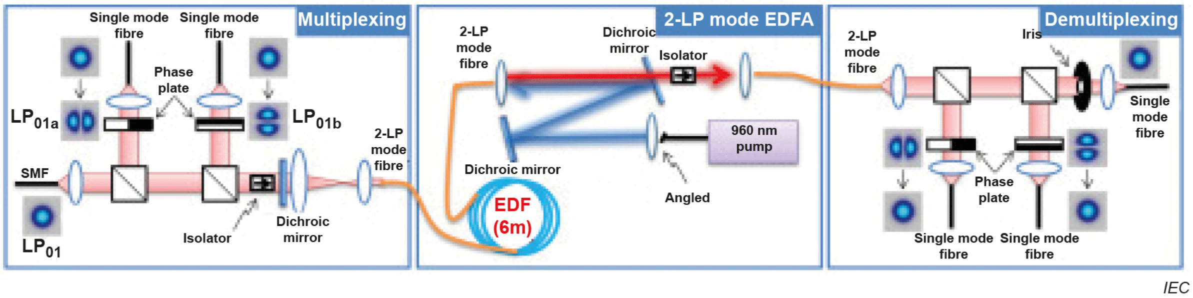
a) **Configuration**



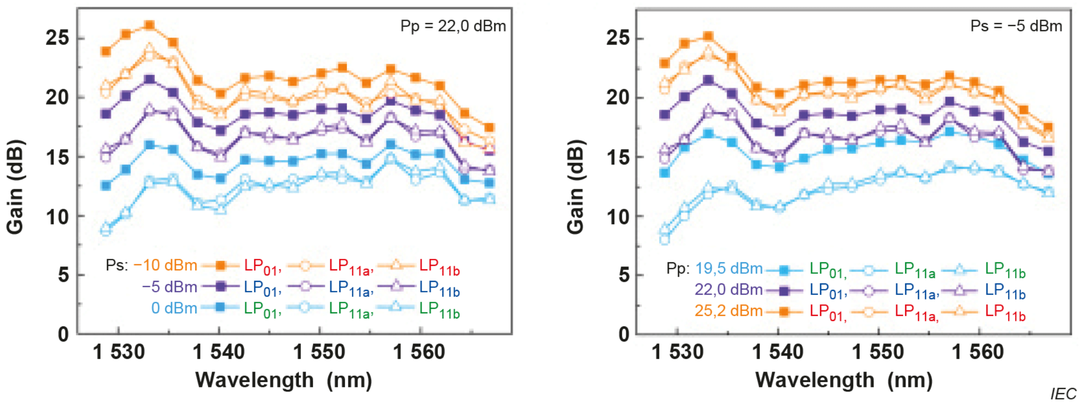
b) **Amplification characteristics**

Source: Optics Express 23, p. 27450 (2015) [31], Figure 11 and Figure 14, reproduced with the permission of Optica Publishing Group. © 2015 The Optical Society.

Figure 17 – Configuration and amplification characteristics of a 2-LP mode EDFA prototype consisting of a ring-core FM-EDF, FM WDM coupler, and two FM isolators



a) **Configuration**



b) **Amplification characteristics**

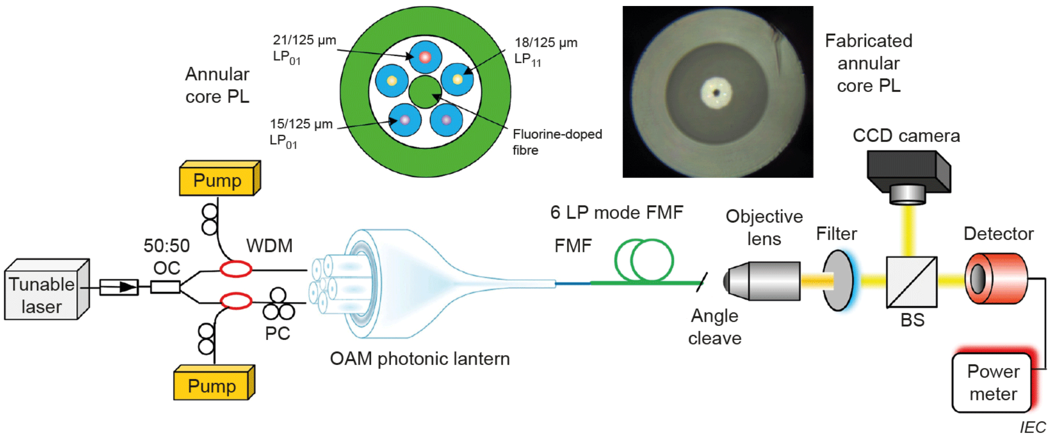
Source: Optics Express 21, p. 10383 (2015) [32], Figure 1 (d) and Figure 3, reproduced with the permission of Optica Publishing Group. © 2013 The Optical Society.

Figure 18 – Configuration and amplification characteristics of a 3-mode EDFA prototype using 2-LP signal modes employing a ring-core FM-EDF

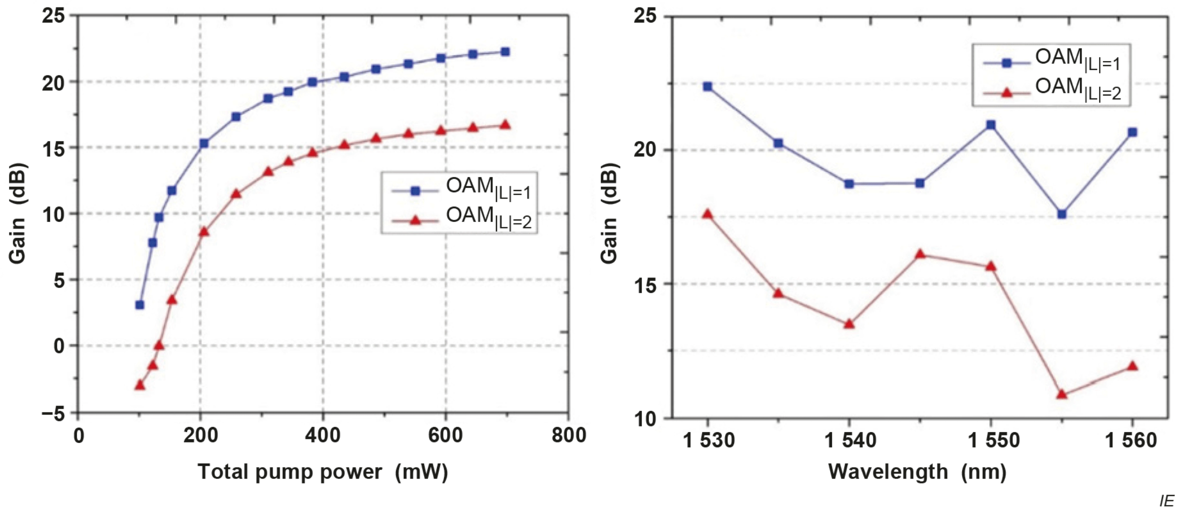
6.2.2 OAM mode EDFA and Coupled-core mode EDFA

EDFAs for OAM modes have been reported that use either a ring-core EDF structure, or an annular-core photonic lantern structure and FMFs [35] to [37]. In the former, simulations have shown that 18-OAM mode amplification with low MDG can be achieved. Some experiments have also been conducted for 2-OAM mode amplification. In the latter, there are still issues with MDG, although experiments of 2-OAM mode amplification have been conducted (see Figure 19 [37]). In addition, an OAM-mode OFA for one OAM mode has been reported that uses a PbS-doped ring-core fibre with approximately 3 dB of on/off signal gain at 1 550 nm [38].

Moreover, coupled-core-mode EDFAs have been reported that use a coupled-core EDF [39], [40]. Experiments have demonstrated that coupled-core amplification can be achieved either with a core or a cladding pump.



a) **Experimental setup**



b) **Amplification characteristics**

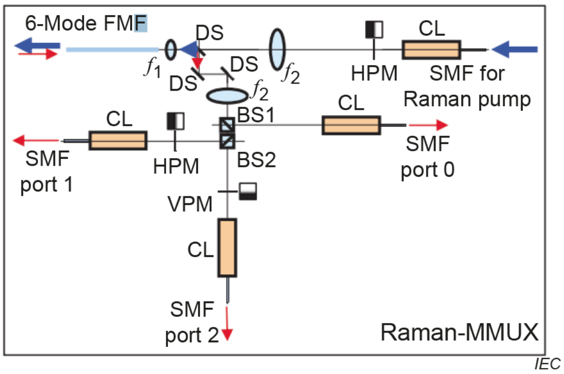
Source: STu4K.4, CLEO 2017 [37], Figure 1 and Figure 2, reproduced with the permission of the authors.

Figure 19 – Configuration and amplification characteristics of a 2-OAM mode EDFA

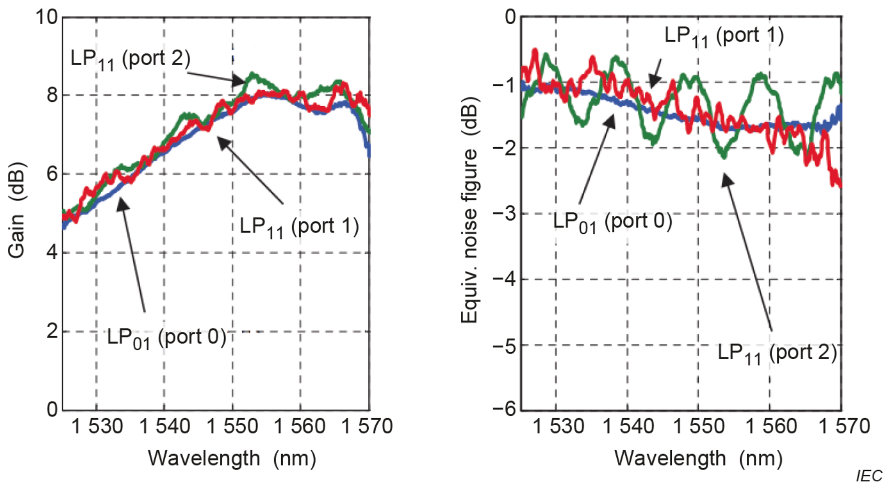
6.3 State-of-the-art FM-FRA development technology

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

An FRA for 2-LP modes has been demonstrated in an FMF transmission experiment (see Figure 20) [41]. This experiment has shown that MDG can 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 of more than 2-LP modes [42]. Studies on OAM FRAs also have commenced, and some experiments resulted in several dB of on/off signal gains for 2-OAM modes [43], [44].



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



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

Source: Th.13.K.5, ECOC 2011 [41], Figure 1, reproduced with the permission of Nokia Corporation.

Figure 20 – 2-LP-mode FM-FRA experiment

6.4 Specific feature and measurement

Basic optical characteristics of FM-EDFAs include signal gain and noise characteristics. These characteristics can be evaluated based on the IEC 61290-1 series [17], the IEC 61290-3 series [18], and the IEC 61290-5 series [19] by using appropriate mode converters, a mode combiner, and a mode splitter, as shown in Figure 21.

NOTE A minimum set of relevant performance parameters for optical amplifiers is defined in IEC 61291-2 [22] for single channel applications and in IEC 61291-4 [23] for multichannel applications.

However, the amplifier configuration illustrated in Figure 15 cannot discriminate between different LP modes in the output signal when mixed intra-modes occur, such as LP_{11a} and LP_{11b}. Thus, when characterising the MDG, the amplitude and phase transfer matrix of the amplifier is measured for all input/output pairs and across all wavelengths [45].

The crosstalk characteristics between the modes can be evaluated using either different wavelengths or time multiplexing, similar to the evaluation of MC-EDFA (see Figure 13). The wavelength separation method in the IEC 61290-1 series [17] can be used. For comparing the output signal intensity ratios for each wavelength, IEC 61290-10-1 [20] and IEC 61290-10-2 [21] can be used in the time separating method to compare the output signal intensity ratios for each time unit for the purpose of evaluating crosstalk (XT).

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

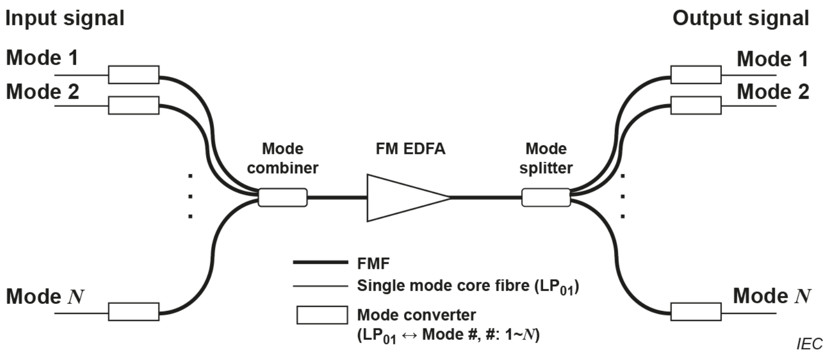
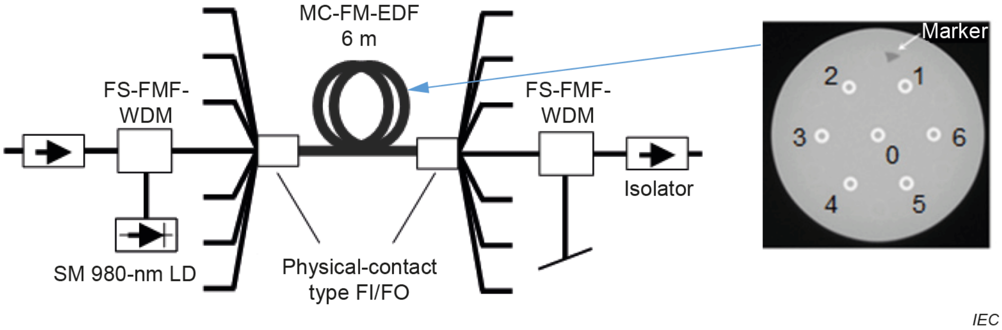


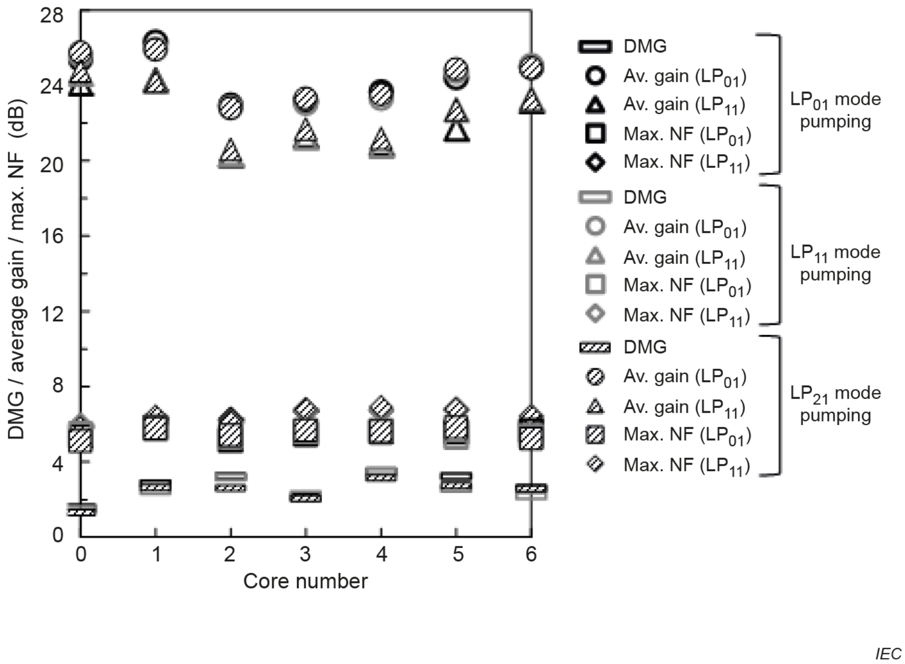
Figure 21 – FM-EDFA evaluation setup for basic optical characteristics

7 Combined MC and FM-OFA technology

EDFAs that combine MC-EDF and FM-EDF technologies are also under development [46] to [49]. An example of such MC&FM-EDFA is displayed in Figure 22, showing multiple cores in a ring configuration. It has been confirmed that seven cores with low MDG and 2-LP mode amplification can be achieved, as shown in Figure 22. As the technology advances, the number of modes and cores are expected to increase. For example, amplification using MC&FM-EDFs with 7 cores and 6 modes has been demonstrated. It is believed that the number of EDF cores and modes will continue to increase in the future. It will be necessary to develop specially designed optical components for these amplifiers.



a) **Configuration**



b) **Amplification characteristics**

Source: IEEE Photon. Technol. Lett. 29, p. 2163 (2017) [47], Figure 3 and Figure 4, reproduced with the permission of IEEE. © 2017 IEEE.

Figure 22 – MC-EDFA with FM cores

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