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TECHNICAL REPORT

colour inside

Optical amplifiers –
Part 3: Classification, characteristics and applications

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OPTICAL AMPLIFIERS –

Part 3: Classification, characteristics and applications

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IEC TR 61292-3, which is a technical report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

This second edition cancels and replaces the first edition published in 2003. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) document architecture now focuses on EDFA, FRA and SOA;
b) the description of PDFA and TDFA has been moved to the annexes;
c) the EDWA description has been deleted;

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d) information on single channel amplification, multi-channel amplification, configuration and control method for EDFA, FRA and SOA has been added;

e) information on future amplifiers, arrayed amplifiers and SDM amplifiers has been added.

The text of this document is based on the following documents:

Draft TR	Report on voting
86C/1597/DTR	86C/1630/RVDTR

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

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

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 "http://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- withdrawn,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
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OPTICAL AMPLIFIERS –

Part 3: Classification, characteristics and applications

1 Scope

This part of IEC 61292, which is a Technical Report, establishes the classification of optical amplifiers (OAs). It also includes a brief description of each amplifier, its general properties, performance, configurations and applications.

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 – Part 731: Optical fibre communication* (available at www.electropedia.org)

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
rare earth-doped fibre amplifier, where the core of the fibre is doped with erbium ions

3.1.2
semiconductor optical amplifier
SOA
optical amplifier that uses a semiconductor to provide the gain medium

Note 1 to entry: These amplifiers have a similar structure to Fabry-Pérot laser diodes but with anti-reflection design elements at the end faces. The signal is amplified through the stimulated emission phenomenon of gain medium.

3.1.3
single channel amplifier
optical amplifier amplifying one signal

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3.1.4
multichannel amplifier
optical amplifier amplifying two or more signals whose wavelengths differ

3.1.5
remote optically pumped amplifier
ROPA
optical fibre amplifier in which pumping light(s) is transmitted remotely to active fibre through a transmission fibre

3.1.6
space division multiplexing amplifier
SDM amplifier
optical fibre amplifier that uses space division multiplexing (SDM) transmission system

Note 1 to entry: There are two types of SDM amplifier: one is a multi-core fibre amplifier, and the other is a few-mode fibre amplifier.

3.1.7
multi-core erbium-doped fibre amplifier
multi-core EDFA
space division multiplexing EDFA for multi-core transmission

3.1.8
few-mode erbium-doped fibre amplifier
few-mode EDFA
space division multiplexing EDFA for few-mode transmissions

3.1.9
arrayed amplifier
optical amplifier formed by arranging several semiconductor amplifiers and EDFAs in parallel

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3.2 Abbreviated terms

ACC	automatic current control
AGC	automatic gain control
ALC	automatic level control
APC	automatic power control
ASE	amplified spontaneous emission
DRA	distributed Raman amplifier
EDF	erbium-doped fibre
EDFA	erbium-doped fibre amplifier
EDFFA	erbium-doped fluoride fibre amplifier
EDSFA	erbium-doped silica fibre amplifier (commonly known as EDFA)
EDTFA	erbium-doped tellurite fibre amplifier
EDWA	erbium-doped waveguide amplifier
EYDFA	erbium ytterbium-doped fibre amplifier
EYDSFA	erbium ytterbium-doped silica fibre amplifier (commonly known as EYDFA)
FMF	few-mode fibre
FRA	fibre Raman amplifier
GFF	gain flattening filter
LD	laser diode
MCF	multi-core fibre

MQW multiple quantum well
NF noise figure
OA optical amplifier
OFA optical fibre amplifier
OSNR optical signal-to-noise ratio
OWGA optical waveguide amplifier
PD photo diode
PDFA praseodymium-doped fibre amplifier
PDFFA praseodymium-doped fluoride fibre amplifier (also known as PDFA)
PDG polarization-dependent gain
ROADM reconfigurable optical add/drop multiplexer
ROPA remote optically pumped amplifier
SDM space division multiplexing
SMF single-mode fibre
SOA semiconductor optical amplifier
TEC thermo-electric cooler
TDFA thulium-doped fibre amplifier
TDFFA thulium-doped fluoride fibre amplifier (also known as TDFA)
VOA variable optical attenuator
WDM wavelength division multiplexing
WSS wavelength selective switch

4 Classification

4.1 Types of OA

Figure 1 shows the classification of optical amplifiers. Optical amplifiers (OAs) are classified as optical fibre amplifiers (OFAs), semiconductor amplifiers (SOAs) and others (e.g. optical wave guide amplifiers (OWGA) such as Erbium doped waveguide amplifiers (EDWA)). Furthermore, OFAs are classified as rare earth-doped optical fibre amplifiers and fibre Raman amplifiers (FRAs), and rare earth-doped optical fibre amplifiers are classified as erbium-doped optical fibre amplifiers (EDFAs) and rare earth-doped optical fibre amplifiers with alternative dopants. From these various OAs, the OAs which are practically used are EDFAs, FRAs and SOAs. General properties, performance and configurations of EDFAs, FRAs and SOAs are described in Clause 5. OAs are also classified according to amplification form, application, etc., in addition to those in Figure 1. The various amplification forms and the application of optical amplifiers are explained in 4.2 and 4.3, respectively.

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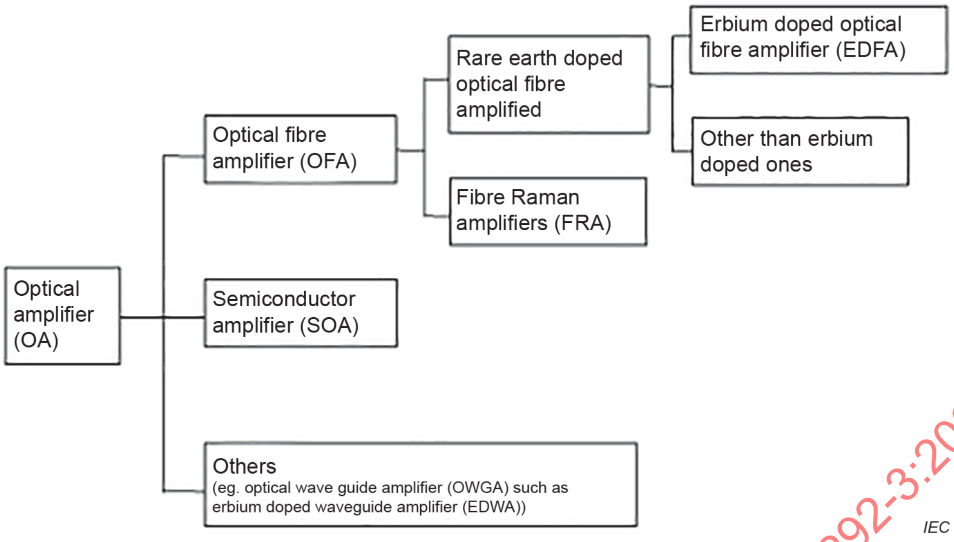

Figure 1 – Classification of optical amplifiers

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Rare earth-doped optical fibre amplifiers other than erbium-doped ones have also been developed. Various rare earth-doped fibre amplifiers are often expressed as an abbreviation: X-Y-DFA. "X" indicates the type of rare earth, i.e., E, T, P, and "Y" represent erbium, thulium, praseodymium, and ytterbium, respectively. "Y" indicates the fibre type, i.e., S, F and T represent silica fibre, fluoride fibre and tellurite fibre, respectively. So, EDSFA, which is commonly known as EDFA, EDFFA and EDTFA indicate an erbium-doped silica fibre amplifier, an erbium-doped fluoride fibre amplifier and an erbium-doped tellurite fibre amplifier, respectively. When two kinds of rare earths are added, the notation X^1-X^2-Y-DFA is used. For example, EYSDFA (commonly known as EYDFA) indicates an erbium ytterbium-doped silica fibre amplifier. Although many rare earth-doped fibres have been developed, EDFA is the rare earth-doped fibre that is generally commercialized today. In addition, EYDFA is described as an EDFA that has high output characteristics in this classification. Furthermore, since praseodymium-doped fluoride fibre amplifiers (PDFFA, also known as PDFA) and thulium-doped fluoride fibre amplifiers (TDFFA, also known as TDFA) are used in special fields, they are introduced in Annex A. Furthermore, Annex B introduces SDM amplifiers that have recently appeared.

Figure 2 shows the amplification bandwidth of each type of amplifier. EDFA is used for amplification of C-band (amplification bandwidth: approximately 30 nm) and L-band (amplification bandwidth: approximately 30 nm) optical signals, and it is also applicable to amplification of a part of the S-band (amplification bandwidth: approximately 20 nm) optical signal. Rare earth-doped optical fibre amplifiers other than erbium-doped ones can achieve O-band, S-band and U-band amplification by using praseodymium and thulium as the dopant.

NOTE Spectral bands of O-band, S-band, C-band, L-band and U-band are defined in ITU-T G.Sup39.

FRAs and SOAs can realize amplification in the required band over the whole wavelength region by selecting the wavelength of the pump source and semiconductor composition. The amplification bandwidth of FRAs and SOAs is about 100 nm.

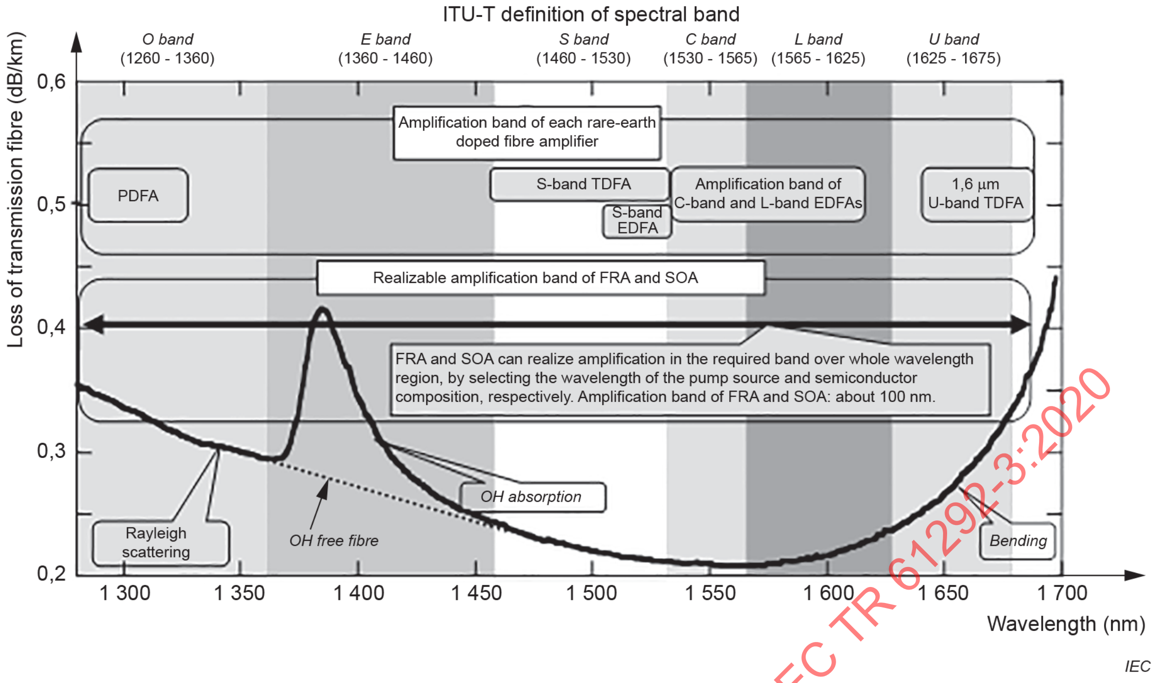

Figure 2 – Amplification bandwidth of each type of amplifier

4.2 Amplification forms

4.2.1 Lumped (or discrete) amplification and distributed amplification

In a transmission system, there are two amplification types: lumped (or discrete) amplification, which performs optical amplification between transmission fibres, and distributed amplification, which uses the transmission fibre itself as the amplification medium. EDFAs, other rare earth-doped optical fibre amplifiers and SOAs are applied to the former, and FRAs are used for both applications. However, an FRA is used as a distributed Raman amplifier (DRA) rather than a lumped (or discrete) amplifier because of its advantages and drawbacks. In addition, amplification in which an EDFA and Raman are combined is also applied in the system.

4.2.2 Single channel and multichannel amplification

OAs are classified according to the number of signals to be amplified with a single channel amplifier and a multichannel amplifier. The single channel amplifier amplifies only one signal, and the multichannel amplifier amplifies two or more signals whose wavelengths differ (that is, the WDM signal). EDFAs, other rare earth-doped optical fibre amplifiers and FRAs are applied as both amplifiers, and SOAs are generally used as single channel amplifiers due to the four wave-mixing effect.

4.2.3 Fixed and variable gain amplification

Normally, since the gain characteristic of an OA is fixed, it may be called a fixed gain type OA. However, depending on the application, the OA may change its gain characteristics as necessary, and it may be called a variable gain type OA. An EDFA that can operate variable gain functions (this may be called a variable gain EDFA or gain switchable EDFA) can be achieved by changing EDF length that is used in the EDFA, or by using a multistage configuration (see 5.1.3.3).

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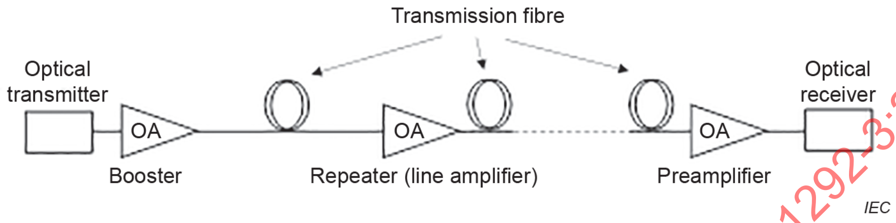
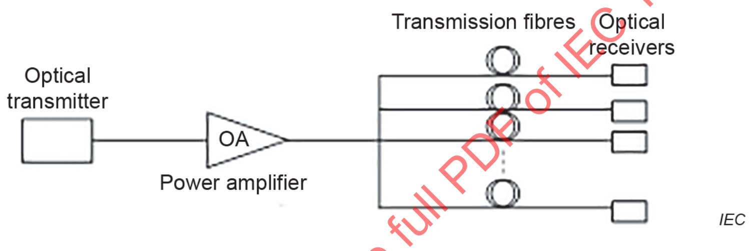
4.3 Application of optical amplifiers

There are three application forms of the lumped amplifier for use in a transmission system: booster, repeater (sometimes called line amplifier) and preamplifier, as shown in Figure 3 a). The booster amplifies a transmitted signal that is sent out to a transmission fibre. The repeater enlarges the signal intensity that became weak by fibre transmission and sends it out to the next transmission fibre. The preamplifier is installed in front of a receiver and amplifies the signal that became weak by transmission to a receiving level. When distributing a signal to two or more receiving points, the power amplifier acts as one of the lumped amplifiers and is installed in front of a branching point, as shown in Figure 3 b).



a) Booster amplifier, repeater (line) amplifier and preamplifier



b) Power amplifier

Figure 3 – Application forms of optical amplifiers in an optical transmission system

Recently, reconfigurable optical add/drop multiplexer (ROADM) technology for combining wavelength multiplexing and path management technology and successfully operating the ultra-high-speed/large-capacity optical network requires colourless, directionless and contention-less function. Details of ROADM are in IEC TR 62343-6-4.

To realize the function, it is necessary to construct a ROADM using a multi-port wavelength selective switch (WSS) and a multi-cast switch, as shown in Figure 4.

An arrayed amplifier, which is formed by arranging several semiconductor amplifiers and EDFAs in parallel, is used for loss compensation of WSS and multicast switches. The performance specification template of the multicast switch is standardized in IEC 62343-3-4.

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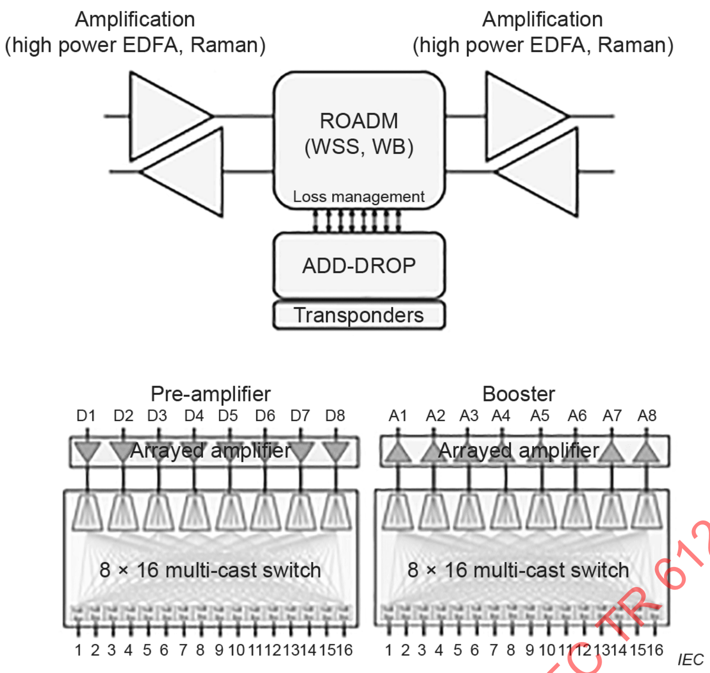

Figure 4 – Application forms of optical amplifiers in optical network (ROADM with colourless, directionless and contention-less function and arrayed amplifier)

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5 General properties, performance and configurations

5.1 Erbium-doped fibre amplifiers (EDFAs)

5.1.1 General properties

The concept of the optical fibre amplifier was proposed by Dr Snitzer in 1961. The EDFA concept was first demonstrated in 1985. Just when conventional un-repeated systems were approaching their peak performance, a research group at the University of Southampton showed that optical fibres could exhibit optical gain at wavelengths near 1 550 nm. These fibres were doped with a rare earth element, erbium, and were activated or pumped with low powers of visible light. EDFAs have since attracted considerable attention in the field of optical fibre communications because they conveniently operate in the preferred, i.e. low-loss, telecommunications spectral window at around 1 550 nm. EDFAs are the most widely used optical amplifiers today.

An EDFA can be optically pumped at several wavelengths, with optimum performances achieved at wavelengths of 980 nm and 1 480 nm. They provide gain at wavelengths from approximately 1 520 nm to 1 625 nm.

In its most basic configuration, a typical EDFA consists of a section of single-mode erbium-doped fibre, a pump laser, a WDM coupler for combining the signal and the pump power into the erbium fibre, input and output isolators and tap couplers and control electronics, as described in IEC TR 61292-1.

There are many energy levels for the erbium ion. However, only a small set of these energy levels is of interest to optical amplification in telecommunication systems. These include the ground state and a few of the lowest level states. The higher energy states represent transitions in the visible and ultra-violet part of the spectrum, and these states are essentially unoccupied in EDFA applications. Figure 5 shows the abridged energy levels for EDFAs and primary energy levels used in EDFAs.

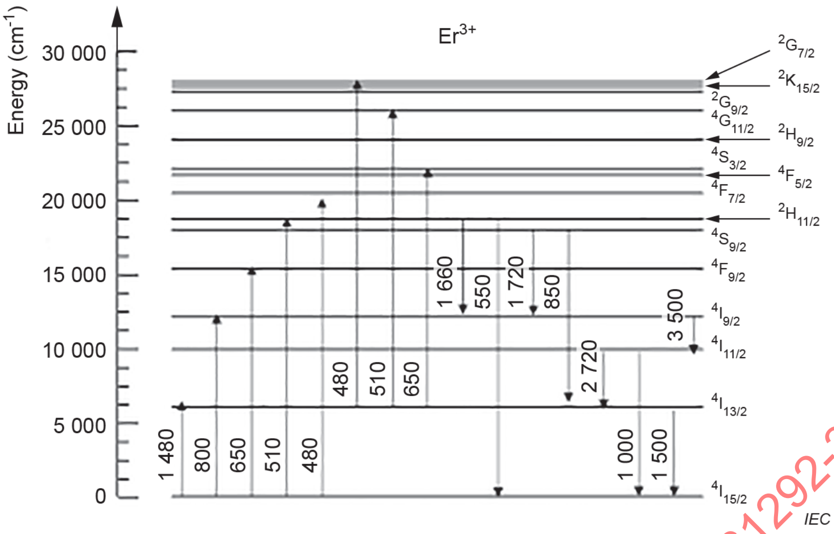

Figure 5 – Abridged and primary energy levels for erbium ion

EDFAs have been shown to exhibit low polarization-sensitive gain, immunity to inter-channel cross-talk, a high saturation output power and low noise close to the quantum limit. EDFAs can simultaneously amplify weak signals at wavelengths across the operating range of 1 520 nm to 1 625 nm. This operating range varies with amplifier design, but this capability is crucial for wavelength division multiplexing (WDM). EDFAs provide all optical amplification in the 1 550-nm region, where silica transmission fibre has its minimum loss. Erbium has excellent spectroscopic properties, including a radiative decay limited metastable lifetime and conveniently located auxiliary energy levels. As a result, it has been possible to produce amplifiers that operate within fractions of a dB of the quantum limits of noise figure and power conversion efficiency. Erbium-doped fibre amplifiers have made it possible to increase the capacity of optical transmission systems dramatically while reducing system costs. Capacity increases are possible because the high output powers afforded by EDFAs can be used to support a higher number of channels, while their broad bandwidth and slow gain dynamics allow transparent multichannel operation. A variety of host glasses, dopants and fibre designs continue to be investigated with the aim of optimizing amplifier characteristics such as pump efficiency and spectral bandwidth.

5.1.2 Typical performance

EDFAs have been demonstrated to provide about 50 dB or more gain, noise figures a few tenths of a dB above the quantum limit, output powers of > 1 W, and gain variations of under 0,2 dB on bandwidths greater than 40 nm by applying gain band flattening technology. Gain, noise figure, output power, power conversion efficiency and gain variation over the required operating band constitute the primary optical parameters that describe the performance of an EDFA. The above parameters, however, tend to require different operating conditions for their respective optimization. Good noise performance requires a high average inversion, while the best power conversion efficiency is available at lower inversions in highly saturated amplifiers. High gain can interfere with noise performance if the backward propagating amplified spontaneous emission (ASE) begins to significantly deplete the inversion in the front end of the EDFA. Many gain-flattening techniques reduce noise performance and/or power conversion efficiency. Commercial systems, however, typically require strong performance on all the essential parameters, but some amount of compromise is needed to achieve this. Any amplifier design will still require some trade-off between parameters of interest. The final design decisions naturally are made in the context of the transmission system in which the amplifier is to be used.

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5.1.3 Configurations

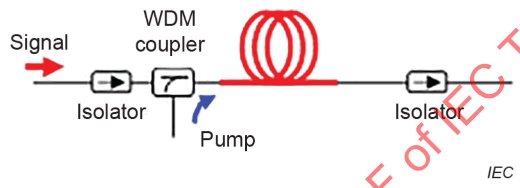
5.1.3.1 General

In 5.1.3.2 and 5.1.3.3, the typical pumping method is explained. Furthermore, the multistage configuration that is used to realize the desired characteristic and the style of business dealings is described.

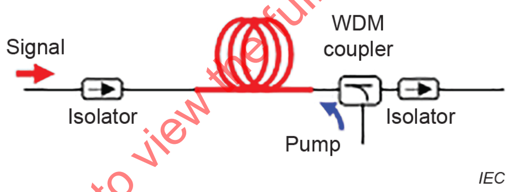
5.1.3.2 Pumping method

5.1.3.2.1 Pumping direction

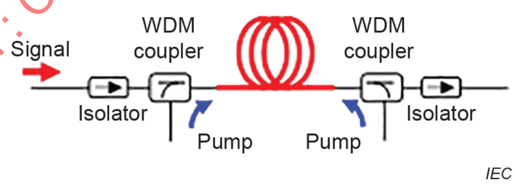
Basic EDFA components are a pump source, an EDF, optical isolators and a WDM coupler. To realize the EDFAs, how the pumping light is launched into the EDF combining those components is important. There are three pumping directions: forward pumping, backward pumping and bidirectional pumping, as shown in Figures 6 a), b) and c). In general, forward pumping is superior in noise characteristic, and backward pumping is superior in high output characteristic. Bidirectional pumping can realize both characteristics.



a) Forward pumping



b) Backward pumping



c) Bidirectional pumping

Figure 6 – Pumping configurations of optical fibre amplifier

5.1.3.2.2 Core and cladding pumping

There is core pumping, which launches pumping light into the EDF core directly, and cladding pumping, which launches pumping light into the EDF clad. There is also core and cladding hybrid pumping that combines core pumping and cladding pumping, as shown in Figures 7 a), b) and c). To achieve cladding pumping, double cladding EDF are required. In general, cladding pumping is applied for achieving high power EDFA by using erbium ytterbium-doped fibre (this is called EYDFA). Detailed information on high power EDFA is in IEC TR 61292-8.

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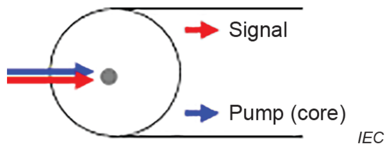
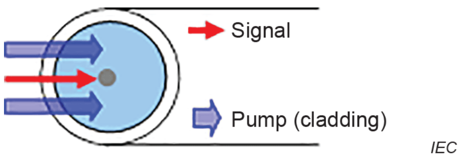
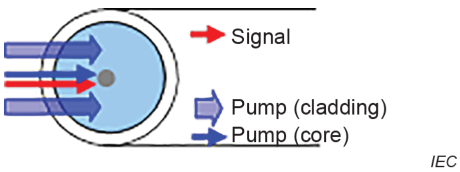


a) Core pumping



b) Cladding pumping



c) Core and cladding hybrid pumping

Figure 7 – Core and cladding pumping configurations

5.1.3.2.3 Remote optically pumped amplifier (ROPA)

ROPA is the method that supplies pump light remotely to the amplification unit consisting of EDF and passive components via the transmission fibre. Two types of ROPA configuration are used:

a) with backward pumping (i.e. the pumping is provided from the receiver side); and
b) with forward pumping (i.e. the pumping is provided from the transmitter side).

Figure 8 shows ROPA forward pumping. In the ROPA, a 1 480-nm pump is generally used.

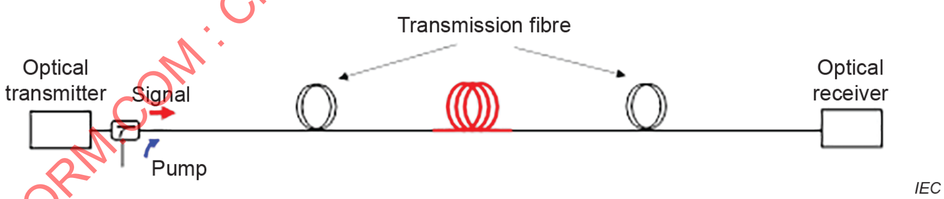


Figure 8 – Configuration of ROPA

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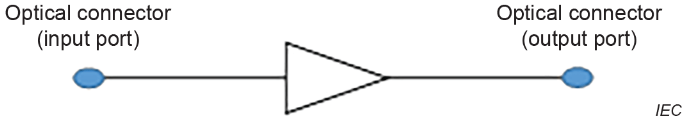
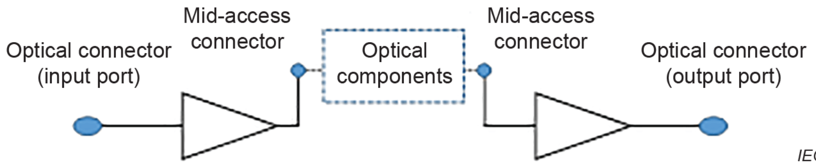
5.1.3.3 Multistage configuration

In order for EDFA to realize the desired characteristics, multistage configuration is used. Figures 9 a) and b) show single stage and double stage configuration, respectively. By using double stage configuration, low-noise and high-power characteristics are realized by combining the low-noise amplifier and high-power amplifier (when the mid-access connectors are optically connected directly). Furthermore, it is possible to add various functions into the EDFA by inserting various optical parts between mid-access connectors. For example, by using a variable attenuator, WDM signal amplification can maintain flat gain characteristics and constant channel output. Also, by inserting dispersion compensating fibre, a dispersion compensating function is introduced with least impact on the amplifier and therefore system performance.



a) Single stage configuration



b) Double stage configuration

Figure 9 – Single stage and double stage configurations

5.1.4 Control scheme

To operate an EDFA stably, there are the three control methods shown in Figures 10 a), b) and c): automatic current control (ACC), automatic power control (APC), and automatic gain control (AGC). APC is sometimes called automatic level control (ALC). The drive current of the pumping source in EDFA is uniformly controlled by ACC. For ALC, the output signal is monitored by a tap coupler and is controlled to obtain constant intensity by adjusting the drive current of the pumping source in EDFA. For AGC, the input and output signal intensities are monitored by tap couplers, and the drive current is controlled to obtain constant signal gain.

When remote control of EDFA is realized, the interface for delivering and receiving information from the control unit is carried in EDFA. The control commands used with this interface are described in IEC 61291-6-1.

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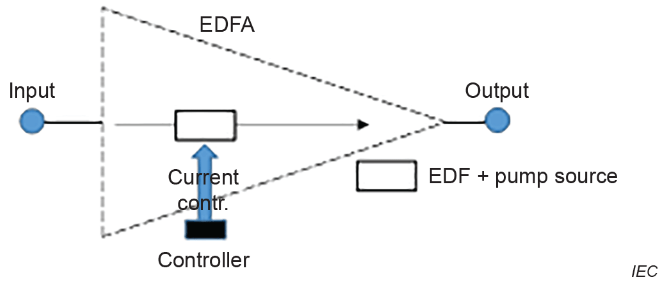
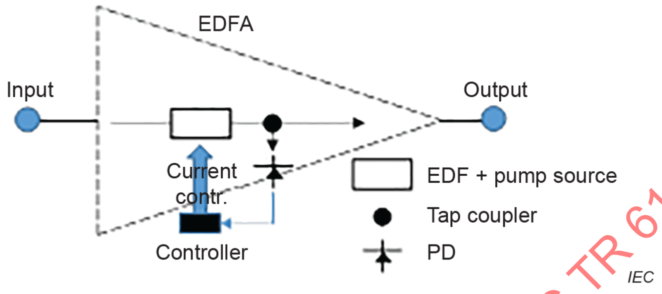
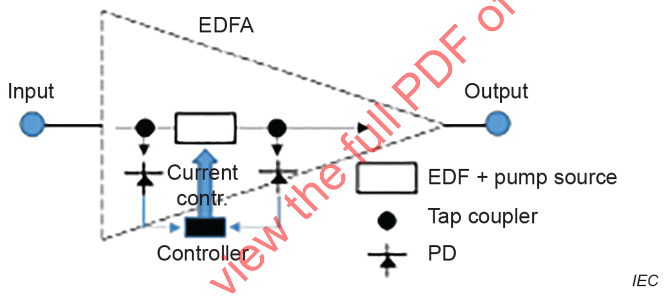


a) Automatic current control (ACC) method



b) Automatic power control (APC) method/automatic level control (ALC) method



c) Automatic gain control (AGC) method

Figure 10 – Control schemes of EDFA

5.1.5 Product configurations and application

EDFA is widely used in applications such as booster, repeater, preamplifier and power amplifier (see 4.2.3). In commercial dealings of EDFA between the manufacturer and the user, there are various styles:

- gain block without active device: consisting of EDF and several passive components;
- gain block: consists of EDF, several passive components and pump source;
- gain module: consists of gain block and pump controller;
- desktop: consists of gain block, LD controller and AC/DC convertor; used mainly for experiments;
- gain module with input/output (IO): consists of gain module and IO interface;
- desktop with IO: consists of desktop and IO interface; used mainly for experiments.

Figure 11 shows the configuration when one EDF is used, but two EDFs are used for the double stage configuration.

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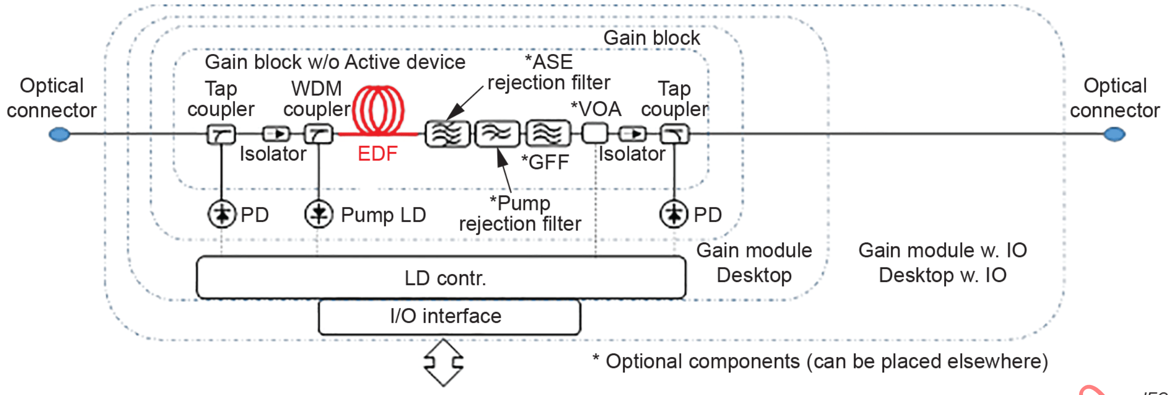

Figure 11 – Product configurations

5.2 Fibre Raman amplifiers (FRAs)

5.2.1 General properties

The spontaneous Raman effect was discovered by C.V. Raman in 1928. R.H. Stolen first reported on stimulated Raman emission in silica fibres in 1972. Fibre Raman amplifiers (FRA) with the potential of very low noise were investigated intensively in the 1980's. Raman amplifiers require high pump powers, and initially only pulsed high-power pumps had sufficient power to pump Raman amplifiers. Due to Raman inefficiency and much better performance of emerging EDFAs, interest in FRAs had dwindled. However, the FRA has attracted much interest as a distributed Raman amplifier (DRA) in the recent decade, because a DRA improves the optical signal-to-noise ratio (OSNR) in a long-haul transmission system, preventing the signal from being attenuated to very low powers where noise power relative to signal power is significantly high. Developments in high power continuous wave (CW) laser diodes have also stimulated interest in using DRA. Additional interest in FRA is due to its potential for wide-gain bandwidth of a lumped (or discrete) amplifier. Since Raman amplification does not rely on the fluorescence of an atom, an FRA may be used at any wavelength, including a window outside the erbium gain band, so long as a high-power pump laser of the appropriate wavelength can be developed.

The physical mechanism providing the gain in FRAs differs in various aspects from that of EDFAs. Whereas EDFAs rely on the fluorescence of the erbium atom, FRAs use a weak non-linear scattering mechanism of Raman process to generate their gain. The Raman amplification process is described in IEC TR 61292-6:2010, 4.2. This scattering process has a response time of the order of femto-seconds, which can be compared to the fluorescent lifetime in erbium of 0,5 ms to 10 ms. Consequently, FRAs may suffer from cross-channel saturation interference. This can result in FRAs behaving as nonlinear devices when operated in the saturated regime, which will give poor performance in WDM systems. The Raman gain process is very polarization dependent, which ideally aligns signal and pump polarizations to obtain maximum gain. However, this is impractical in a deployed system with multiple signals with differing polarizations. Thus, the Raman pump source will be depolarised before being introduced into the fibre span to achieve as good an alignment as feasible as the pump and signal interact along the fibre span. The measure of depolarization is known as degree of polarization (DOP) (IEC TR 61292-6:2010, 6.2.3). Typically, a target of < 10 % DOP is required.

Since the Raman effect is small in silica fibre, lengths of fibre on the order of tens of kilometres or more are required, as are pump powers from a few hundred milliwatts up to several watts. FRAs are currently being investigated in two different configurations:

a) as DRA using the transmission fibre as the gain medium; and

b) as a lumped amplifier or a discrete amplifier, where the gain fibre has been selected for high gain.

The pumps may be several discrete diodes at the appropriate wavelength, providing high pump power. These can be wavelength and polarization multiplexed to give higher pump powers.

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Pump wavelength multiplexing can be used to broaden gain spectrum, as described in IEC TR 61292-6:2010, 4.4. Pump polarization multiplexing can also be used to minimize polarization-dependent gain as described in the following.

Raman effect is also polarization-dependent so that an orthogonally polarized signal and pump will produce no gain. In both counter and co-pumped systems, the pump and signal polarization states will vary slowly with respect to each other as they propagate, and this variation may also be unstable with time. The use of an unpolarized pump, polarization multiplexed pumps, or a system where the relative state of polarization between the pump and signal varies significantly will produce an amplifier with low polarization-dependent gain.

In a co-propagating scheme, pump fluctuations will cause gain fluctuations, which will appear as amplitude noise on the signal. Additionally, adding gain to optical channels already at high power could cause non-linearities in high power signals. For these reasons, pump light is generally counter-propagating with respect to the signal in the Raman fibre. This averages the transfer of amplitude noise from the pump to the signal, thus minimising gain fluctuations and keeping signal powers lower than non-linear thresholds. Inserting counter-propagating Raman pumps is implemented by using a wavelength-dependent coupler, or by using optical circulators that have a wide bandwidth of operation, also providing input and output isolation.

5.2.2 Typical performance

The performance of FRAs can be characterized by a similar set of parameters to those used for EDFAs.

The gain spectrum for silica fibre is not flat and has a double peak shape. This can be compensated for by gain flattening filters or by using multiple pumps to build a wide-bandwidth composite gain shape. Typical DRA performance of C-band amplification in SMF is described in IEC TR 61292-6:2010, 4.6, in which a backward-pumped DRA with triple pump with the wavelengths of 1 424 nm (two pumps) and 1 452 nm (one pump) are presented. In a DRA, the on-off gain and equivalent noise figure are evaluated. Details of the on-off gain and equivalent noise figure are described in IEC TR 61292-6:2010, 6.3. For a lumped FRA, by using eight wavelength distributed pump lasers, 4 dB gain has been shown using a 45-km distributed amplifier with a flatness of 1,1 dB p-p ripple over 100 nm. Using multiple pumps can help extend the bandwidth but there is also interaction between the pumps as they travel along the fibre. Shorter wavelengths transfer power to longer wavelengths, and this shall be compensated for by varying the pump input powers and careful selection of pump wavelength.

The dominant noise source in a well-designed FRA is signal-spontaneous beating. The ASE level due to the Raman effect is inherently low, and the signal-spontaneous beating noise may be compared to that of a completely inverted erbium amplifier. There may be a small amount of passive loss from the gain fibre or from the couplers, though external noise figures of less than 4,5 dB are achievable. If the amplifier gain is high, then noise from Rayleigh scattering can become dominant. There are two possible causes: first, single Rayleigh scattering of the backward propagating ASE can cause an increase in the forward propagating ASE – this will manifest itself as an increase in signal-spontaneous beating noise; second, the forward propagating signal may be Rayleigh scattered twice – this is double Rayleigh scattering (DRS) and will cause an increase in the multi-path interference. In a lumped FRA, Rayleigh scattering may be decreased by dividing the amplifier into two or more isolated stages of lower gain. It should be noted that amplifiers can exhibit a low optical noise figure but be useless for optical communications due to high multi-path interference. Electrical noise measurements are therefore also necessary.

Low signal-signal crosstalk is important for WDM applications. Crosstalk may occur when the amplifier is operated in saturation through the depletion of the pump, since the amplifier has fast gain dynamics. The counter-pumped configuration will average pump depletion effects over the transit time of the amplifier and can reduce signal-signal crosstalk at higher frequencies. In general, most high-gain FRAs are operated out of saturation.

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5.2.3 Configuration

An FRA can be used as a distributed Raman amplifier (DRA) rather than a lumped (or discrete) Raman amplifier because it does not require a dopant ion in a fibre, which allows use of a transmission fibre as the amplification medium. However, a discrete Raman amplifier requires specially designed highly non-linear fibre and has multi-path interference that limits the amplifier gain. Details are described in IEC TR 61292-6:2010, 4.3.

A DRA is deployed in either a forward (co-propagating) configuration or a backward (counter-propagating) configuration. Details, including a comparison between the two configurations, are described in IEC TR 61292-6:2010, 4.5.

5.2.4 Control scheme

Since the Raman gain depends on an individual transmission fibre, the DRA requires an automatic gain control (AGC) to maintain the Raman gain while keeping the gain flatness. A typical AGC system has a feedback loop that monitors the amplified power and then adjusts the Raman pump power. The monitored power can be a total output power, an amplified signal power, or a power of ASE. The DRA with the AGC enables the correct Raman gain in any kind of fibres and non-ideal fibres degraded over time.

5.2.5 Product configurations and application

Utilization of a DRA is limited by its drawbacks. Applications are limited to areas where the DRA offers significant advantages and is the unique solution. DRA application includes all-Raman systems and hybrid EDFA Raman systems. Details are in IEC TR 61292-6:2010, Clause 5.

5.3 Semiconductor amplifiers (SOAs)

5.3.1 General properties

The physical mechanism providing gain in semiconductor optical amplifiers differs in various aspects from that of optical fibre amplifiers. In the first place, like LDs, the stimulated emission of photons in SOAs occurs via electron-hole recombination processes induced by signal photons with wavelengths sitting in the amplification band of the semiconductor material. Population inversion is generated in the active region by injecting an electrical current. Compared with LDs, the most distinctive feature of SOAs is that the SOA chip has an anti-reflection coating on both facets to avoid optical feedback between the facets. The incremental (or local) gain of semiconductor materials is much greater than that of rare earth-doped fibres. This accounts for the very short lengths of these devices: 0,5 mm versus tens of meters for rare earth-doped fibres. Therefore, SOAs are generally very simple and compact devices compared to optical fibre amplifiers, where long active fibres, laser sources for optical pumping and various fibre-optic components are required.

In the second place, SOAs feature fast gain-dynamics. The characteristic time required for the gain to recover completely is typically 200 ps in an SOA compared to 0,5 ms to 10 ms in an OFA. Consequently, SOAs may suffer from cross-saturation interference and saturation-induced waveform distortion. This implies that SOAs are non-linear devices, especially when operated in the saturation regime. This feature, which may be detrimental for applications of SOA as in-line amplifiers in WDM systems, can be turned to advantage in the implementation of important system functionalities, such as wavelength conversion, optical switching and demultiplexing.

Moreover, the geometry and dimensions of SOA active guides generally do not match with those of optical fibres. This implies that solutions should be implemented to reduce coupling losses with the fibres of the line and to minimize polarization-dependent gain, which may originate from the rectangular symmetry of the SOA active waveguide transverse section.

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Finally, SOAs are very flexible in terms of operating wavelength. By varying the composition of the semiconductor material, SOAs working in the wavelength regions around 1 310 nm or 1 550 nm (or others) can be manufactured without introducing substantial changes in the manufacturing process. Amplification bandwidth is typically of the order of 100 nm.

Another specific feature of SOA chips is their integration with other semiconductor devices such as tuneable LDs, electro-absorption modulators and passive waveguides on a single chip. The integrated SOAs are used, for example, as booster amplifiers in tuneable LDs and line amplifiers (loss compensators) in photonic integrated circuits.

Compared to an EDFA, an SOA has higher NF, lower saturation power and gain ripple issues when used across multiple wavelengths. Additionally, the faster response time of an SOA can lead to cross-modulation across signal channels.

In summary, SOAs have completely different physical mechanisms for amplification and for the configuration of the device compared to OFAs. Details are in IEC TR 61292-9:2017, 4.1.

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5.3.2 Typical performance

SOA performance can be characterized by a set of parameters similar to those already defined for optical fibre amplifiers, which are (spectral) gain parameters, (spectral) noise parameters and output power parameters. However, care should be taken, since all of these parameters do actually depend on the operation temperature and may depend on the polarization state of input light. A distinctive parameter of SOAs, which does not apply to OFAs, is spectral gain ripple, caused by residual reflectivity of the end facets of the chip.

Different active layer designs have been developed to achieve polarization-insensitive gain using both bulk and multiple quantum well (MQW) semiconductor material (square waveguide section, use of tensile strained materials). In state-of-the-art SOAs, polarization dependence of the gain is so low (typically a fraction of a dB) that it no longer constitutes a serious problem. The coupling efficiency with the fibres of the line has been substantially improved by means of integrated mode-field profile converters. This is beneficial to the overall noise figure of the SOA module. By using MQW structures, SOA module noise figures of the order of 6 dB to 8 dB can be achieved. Modules with 30 dB optical gain and more than 10 mW of saturated output power are now commercially available. Reliable, accurate and reproducible deposition processes of anti-reflection coatings have been devised, making it possible to obtain very low reflectivity with an acceptable yield and to reduce spectral gain ripples in commercial devices to less than 0,2 dB in depth.

As far as the gain linearity issue is concerned, very promising results have been achieved by means of the gain-clamping technique. In this technique, the amplifier is made to oscillate at a wavelength outside the desired spectral interval (but still inside the gain profile of the SOA) by means of a suitable integrated Bragg reflector (like that used for the fabrication of DFB lasers). The laser action clamps the inversion of the active medium and thus the gain of the SOA, inhibiting (to a certain extent) most of the processes originating the non-linear response of the device. Gain clamping has been recently implemented in commercially available devices. Details are in IEC TR 61292-9:2017, Clause 4.

5.3.3 Configurations

5.3.3.1 SOA modules

An SOA chip, a TEC and optical lenses may be assembled in a butterfly package that has fibre pigtails for the input and output ports. This is the most common package for SOA modules, and its size is almost the same as that of 14-pin butterfly LD modules. Details are described in IEC TR 61292-9:2017, 4.2.

5.3.3.2 Integrated SOA chips

Since SOA chips can be integrated with other semiconductor devices, integrated SOA chips are widely used in photonic integrated circuits (PICs) as boosters and line amplifiers. An example of integrated SOA chips is described in IEC TR 61292-9:2017, Clause A.5.

5.3.4 Product configurations and applications

Conventionally, SOA modules were not generally applied in commercially available optical network systems. This was because several characteristics of SOAs, such as polarization-dependent gain (PDG) and NF, did not meet the system requirements. Also, SOAs were not applicable for systems that required a large saturation output power, because the gain length of SOAs was typically as short as 1,5 mm. However, recently, PDG and NF characteristics have been improved, and use in the wavelength region that cannot be realized by EDFA has started. Furthermore, since SOA chips can be integrated with other semiconductor devices, integrated SOA chips are widely used in PICs as boosters and line amplifiers. Details of product configurations and applications are in IEC TR 61292-9:2017, Annex A.

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Annex A
(informative)

Other rare earth-doped fibre amplifiers

A.1 General

Two types of rare earth-doped optical fibre amplifiers, praseodymium-doped fibre amplifiers and thulium-doped fibre amplifiers, different from EDFA, have been developed. In Annex A, their characteristics are described.

A.2 Praseodymium-doped fibre amplifier (PDFA)

The PDFA is an optical fibre amplifier for the operating wavelength at around 1 300 nm. The PDFA has advantages of high-saturation output power, polarization-independent gain, low distortion and low noise figure compared to other amplifiers at this wavelength, and therefore has been recognized as a most promising candidate for 1 300-nm transmission systems.

The amplification mechanism of PDFAs is classified as a four-level amplification system as shown in Figure A.1. It is based on the stimulated emission of the $^1G_4$ level to the $^3H_5$ level of praseodymium ions. Pump photon ground state absorption occurs between the $^3H_4$ level and the $^1G_4$ level. Peak absorption wavelength is about 1 015 nm. The excited praseodymium ions of the $^1G_4$ level descend to the $^3F_4$ level very easily due to multi-phonon relaxation, because an energy difference between both levels is only about 3 000 cm^{-1}. The most effective way of improving this quantum efficiency is to select a low phonon energy glass as the fibre host. Amongst the glasses with low-phonon energies, fluoride glass is the most promising candidate as the host glass matrix for the praseodymium ions. In addition, praseodymium-doped fibre (PDF) with small-core diameter structure could be used for achieving highly efficient amplification.

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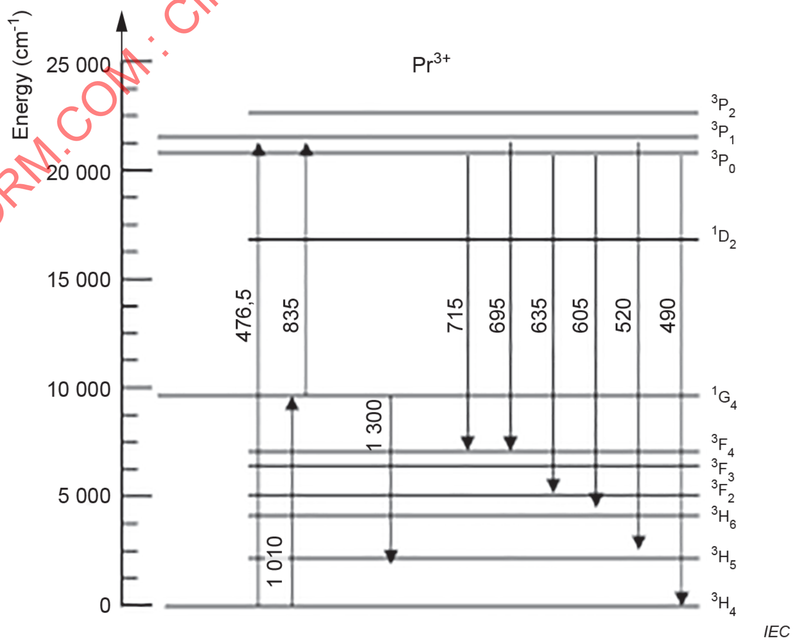

Figure A.1 – Abridged and primary energy levels for praseodymium ion