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TECHNICAL REPORT

Optical amplifiers –
Part 1: Parameters of amplifier components

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Optical amplifiers –
Part 1: Parameters of amplifier components

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CONTENTS

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OPTICAL AMPLIFIERS –

Part 1: Parameters of amplifier components

FOREWORD

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IEC 61292-1, 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 1998. It is a technical revision with updates reflecting new technology.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86C/853/DTR	86C/871/RVC

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

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

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

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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- withdrawn,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

A bilingual version of this technical report may be published later.

OPTICAL AMPLIFIERS –

Part 1: Parameters of amplifier components

1 Scope and object

This part of IEC 61292, which is a technical report, applies to optical components of rare-earth doped fibre amplifiers. It provides information about the most relevant parameters of optical components especially for erbium doped fibre amplifiers (EDFAs).

The object of this technical report is to provide introductory information for a better understanding of EDFA operation and applications.

2 Normative references

The following referenced documents are indispensable for the application 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/TR 61931, *Fibre optic – Terminology*

ITU-T Recommendation G. 650.1, *Definition and test methods for linear, deterministic attributes of single-mode fibre and cable*

NOTE A list of informative references is given in the Bibliography.

3 Abbreviations

For the purposes of this document, the following abbreviations apply.

ASE	amplified spontaneous emission
EDFA	erbium-doped fibre amplifier
EDF	erbium-doped fibre
OFA	optical fibre amplifier
OA	optical amplifier
RMS(r.m.s)	root mean square
LD	laser diode
TEC	thermo-electric cooler
FBG	fibre Bragg grating
FWHM	full-width at half maximum
WDM	wavelength division multiplexing
GFF	gain flattening filter
PIN-PD	PIN-photodiode
VOA	variable optical attenuator
EDF	erbium doped fibre
PDL	polarization dependent loss (variation)
PMD	polarization mode dispersion
MTBF	mean time between failure

FIT failure in time

4 OFA components

The parameters relevant for a satisfactory understanding of OFA operation are covered by the following optical component definitions:

- active fibre;
- pump laser;
- wavelength division multiplexing (WDM) coupler;
- optical isolator;
- amplified spontaneous emission (ASE) rejection filter;
- pump rejection filter;
- gain flattening filter (GFF);
- tap coupler;
- PIN-photodiode (PIN-PD);
- variable optical attenuator (VOA);
- optical connectors.

Figure 1 provides an example of the component layout for an OFA.

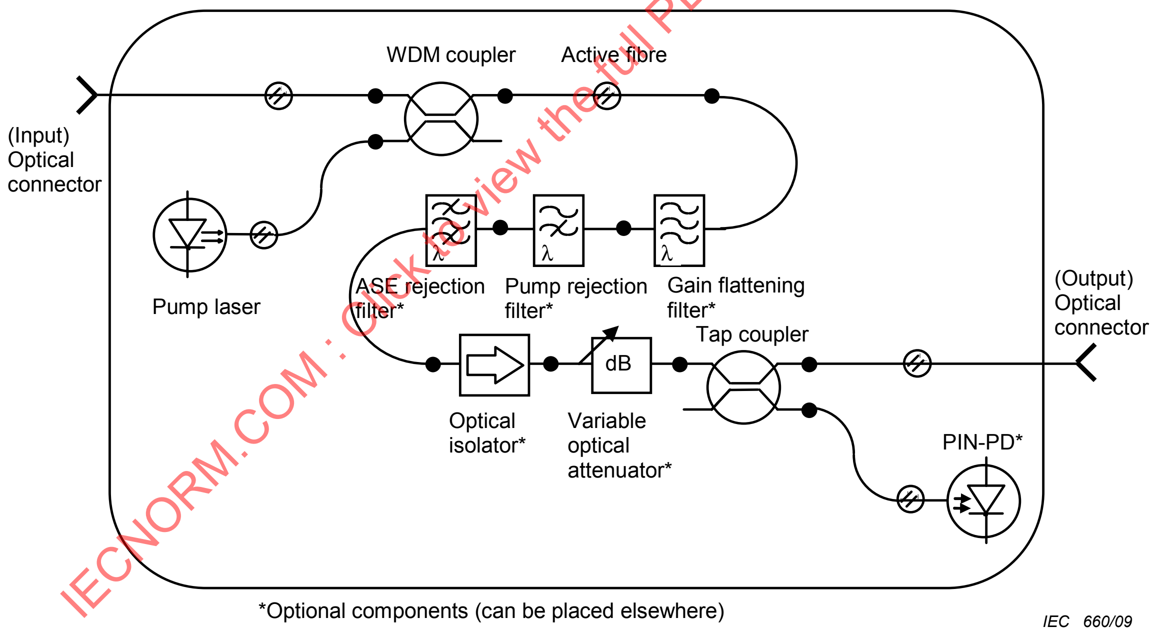

Figure 1 – Example of the components inside an EDFA operating in a co-propagating pumping scheme

5 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

5.1 Active fibre

The active fibre is used as gain media in OFA. Rare earth ion is generally doped in the core region of fibre to produce signal amplification, an Er^{3+} ion is applied for 1550-nm band OFA such as an erbium doped fibre amplifier (EDFA). Erbium doped fibre (EDF) absorbs light with a wavelength of 980 nm or 1 480 nm for pumping, and emits infrared light with a wavelength in the 1 550-nm region. Optical amplification is realized utilizing stimulated emission of 1 530-nm luminescence.

5.1.1
active fibre maximum input signal power
optical power level associated with the input signal above which the active fibre gets damaged, causing impossibility of normal operation

5.1.2
active fibre insertion loss at out-of-band wavelength
active fibre insertion loss for a signal at out-of-band wavelength

5.1.3
active fibre polarization-dependent gain variation
maximum fibre gain variation due to variation of the state of polarization of the input signal

5.1.4
active fibre PMD
maximum PMD at the signal wavelength which is launched into the input port of the active fibre and exits from signal output port of the active fibre, expressed in ps (pico second)

NOTE 1 When an optical signal travels through an optical fibre, optical component or subsystem (such as an OFA), the change in the shape and width of the pulse due to the differential group delay (DGD) (the propagation delay difference between the two principal states of polarization (PSPs)) and to the waveform distortion for each PSP, is due to PMD. PMD, together with polarization dependent loss (PDL) and polarization dependent gain (PDG), may introduce large waveform distortions leading to an unacceptable bit error ratio increase.

NOTE 2 The level of PMD may depend on temperature and operating conditions.

5.1.5
active fibre mode field diameter
as in ITU-T Recommendation G.650.1 and IEC/TR 61931

5.1.6
active fibre cut-off wavelength
as in ITU-T Recommendation G.650.1 and IEC/TR 61931

5.1.7
active fibre cladding diameter
as in ITU-T Recommendation G.650.1 and IEC/TR 61931

5.1.8
active fibre cladding non-circularity
as in ITU-T Recommendation G.650.1 and IEC/TR 61931

5.1.9
active fibre mode field concentricity error
as in ITU-T Recommendation G.650.1 and IEC/TR 61931

5.1.10
active fibre composition
composition of the active fibre, intended as the host glass composition as well as the dopant element and its concentration

5.1.11
active fibre length
length of the active fibre. Changing fibre length can optimize gain characteristics of EDFA

5.1.12
active fibre dopant distribution
concentration of dopant rare-earth ions in the fibre as a function of the fibre radial coordinate

5.1.13
pumping efficiency
for a given active fibre, the slope of the gain versus pump optical power curve under specified operating conditions

5.1.14
saturation pump power
for a given active fibre, the pump optical power level above which the small-signal gain shows no further increase

5.1.15
threshold pump power
the minimum pump optical power necessary to reach a small-signal gain equal to 1 in a given active fibre when the fibre length is short enough so that the pump optical power remains constant along the fibre

5.1.16
active fibre operating temperature
temperature to be maintained for normal operating condition, given in the relevant detail specification

NOTE Amplification characteristics of active fibre strongly depend on its temperature. Thus, EDF in the many EDFA unit is maintained with the certain constant temperature. Many EDFA units include heater device or TEC in order to control active fibre temperature. Fibre operating temperatures of 40 ˚C ~ 70 ˚C are usually specified as operating temperature. Some of fixed gain EDFAs (especially smaller packaged EDFA), do not include this feature.

5.2 Pump laser

A pump laser is used to provide excitation energy for active fibre. By introducing the strong pumping light from a pump laser to active fibre, the signal light will be amplified by stimulated emission from a rare-earth ion such as Er^{3+} in EDF.

5.2.1
pumping wavelength
nominal wavelength of the emission spectrum of the pump laser. In EDFA, 980 nm and 1 480 nm are commonly used for pumping wavelength

5.2.2
pumping scheme
set-up of the EDFA characterized by the direction of pump optical power propagation with respect to signal direction

NOTE Usually, three schemes are used: co-propagating, where the pump and the signal propagate through the active fibre in the same direction; counter-propagating, where the signal and the pump propagate through the active fibre in opposite directions; bi-directional, where two pumps propagate simultaneously through the active fibre in both directions. Regarding pumping schemes other than pump direction, a polarization combining scheme and a wavelength combining scheme are considered for detailed design to enlarge pump power. However, a single laser diode pump scheme is described as a classic example in this technical report.

5.2.3
pumping power
optical power associated with the pump, injected into the active fibre

5.2.4
centre wavelength
pump efficiency of EDF depends on the overlap integral of EDF absorption spectrum and pump LD spectrum, so the centre wavelength of pump laser is crucial for EDF pumping

a) centroidal wavelength

Regarding many pump LDs of 980 nm and 1 480 nm, centroidal wavelength λ_{avg} is applied for centre wavelength λ_c. The centroidal wavelength is the mean or average wavelength of an optical spectrum of pump LD. The definition of centroidal wavelength is described as follows:

$$\lambda_{\text{avg}} = \left(\frac{1}{P_0}\right)\sum_{i=1}^{N} P_i \lambda_i$$

where

λ_i is the wavelength of the i^{th} peak point (nm) ;

i corresponds to mode number for output spectra of pump LD;

P_i is the power of the i^{th} peak point (nW) ; and

P_0 is the total power summed for all peak points (nW):

$$P_0 = \sum_{i=1}^{N} P_i$$

N is the number of peak points.

b) peak wavelength

Regarding some pump LDs of 980 nm and 1 480 nm with FBG stabilizer, peak wavelength λ_{peak} is applied for centre wavelength λ_c. The peak wavelength corresponds to the maximum power value of the optical spectrum of pump LD. The definition of peak wavelength is described as follows:

$$\lambda_c = \lambda_{peak}$$

NOTE Refer to IEC 61280-1-3 for details.

5.2.5
pumping spectral width
pump efficiency of EDF depends on the overlap integral of EDF absorption spectrum and pump LD spectrum, so the pumping spectral width of pump laser is crucial term for EDF pumping in order to quantify power band width of pump LD.

a) RMS spectral width

Regarding many pump LDs of 980 nm and 1 480 nm, RMS spectral width $\Delta\lambda_{rms}$ is applied for spectral width. The definition of RMS spectral width is described as follows:

$$\Delta\lambda_{\text{rms}} = \left[\frac{1}{P_0}\sum_{i=1}^{N} P_i(\lambda_i - \lambda_c)^2\right]^{\frac{1}{2}}$$

b) full-width at half maximum

Regarding some pump LDs of 980 nm and 1 480 nm with FBG stabilizer, full-width at half maximum (FWHM) $\Delta\lambda_{fwhm}$ is applied for spectral width. The definition of FWHM spectral width is described as follows:

1) The positive difference of the closest spaced wavelengths, one above and one below the peak wavelength λ_{peak}, at which the spectral power density is 3 dB down from its peak value.
2) The difference of the half-power wavelengths can be determined as follows; since the laser may not have modes at these wavelengths, they may be obtained by interpolation.
3) Connect the tip of each mode to the tips of adjacent modes; draw a horizontal line 3-dB down from the peak power point.
4) The two or more intersection points define the half-power wavelengths. The maximum difference in half-power wavelengths is $\Delta\lambda_{fwhm}$.

NOTE Refer to IEC 61280-1-3 for details.

5.2.6
wavelength stability
rate of variation of pumping wavelength with respect to operating and environmental conditions

5.2.7
threshold current
driving current at which the pump laser starts to lase. Practically, this value is specified as the crossing condition between the spontaneous emission and lasing regions

5.2.8
maximum allowed current
maximum driving current which may cause irreversible damage to the pump laser. A current, derated from the absolute maximum rating, is generally applied

5.2.9
pump LD chip temperature
temperature of chip to be controlled for normal operation, where performance of pump LD ensured

NOTE The output power and operating wavelength are affected by laser chip temperature. Therefore ordinary pump LD module includes a TEC in order to maintain LD chip temperature. The temperature range of 25 ˚C ~ 45 ˚C is commonly specified by LD vendors. Previous generation chips are specified at 25 ˚C, and some more recent chips are specified to operate at 35 ˚C or 45 ˚C.

5.2.10
pump LD case temperature
operative temperature range of LD case within which the pump laser module can be operated while still meeting all its specified parameter values, given in the relevant detail specification

NOTE Power consumption of temperature controlled pump LD module with TEC features differs for various case temperatures, since TEC is operated to maintain LD chip temperature against various (high or low) temperatures. The case temperature also affects center wavelength and wavelength stability of pump laser with FBG wavelength stabilizer, since reflection wavelength of FBG is varied for its case temperature. Therefore pump LD case temperature is specified by LD vender to ensure normal operation of all the related performance. Most of LD module is specified for case temperature range around 0 ˚C ~ 75 ˚C.

5.2.11
chip temperature dependence of threshold current
threshold current dependence on pump laser chip temperature

5.2.12
case temperature dependence of wavelength
wavelength dependence of the center wavelength of the laser on the pump laser case temperature, expressed in nm/˚C

5.2.13
device reliability
probability of performing required functions at specified operating and environmental conditions. The reliability of a pump laser is expressed by either of the following two parameters: mean time between failure (MTBF) or failure in time (FIT):

MTBF is the mean period of continuous operation without any failure at specified operating and environmental conditions

FIT is the number of failures expected in 10^9 device-hours at specified operating and environmental conditions

5.3 WDM coupler

A WDM coupler is used to unify pump light with signal light and to guide combined light to active fibre. Thin film technology or tapered fused coupler technology is commonly applied to the WDM coupler.

5.3.1
WDM coupler signal insertion loss
fraction of the optical power associated with the input signal and launched into the signal input port of the coupler which does not exit from the signal output port of the coupler, expressed in dB

5.3.2
WDM coupler pump insertion loss
fraction of the optical power associated with the pump and launched into the pump input port of the coupler which does not exit from the signal output port of the coupler, expressed in dB

5.3.3
WDM coupler PDL
maximum insertion loss variation due to the change of the input light state of polarization, expressed in dB. This term is defined for both signal input port and pump input port

5.3.4
WDM coupler signal reflectance
fraction of the optical power associated with the input signal which is reflected by the signal from input port of the coupler, expressed in dB

5.3.5
WDM coupler PMD
maximum PMD at the signal wavelength which is launched into the input port of the coupler and exits from signal output port of the coupler, expressed in ps (picosecond)

5.3.6
pump leakage at the signal input port
fraction of the optical power associated with the pump injected into the coupler which exits from the signal input port, expressed in dB

5.3.7
WDM coupler temperature and vibration stability
range of temperature and vibration level within which the coupler maintains its nominal specifications

5.3.8
WDM coupler insertion loss at out-of-band wavelength
fraction of the optical power associated with a carrier at out-of-band wavelength which is injected in the signal input port and which does not exit from the signal output port of the coupler, expressed in dB

5.4 Optical isolator

An optical isolator is an optical component that makes the light direction one way. OFA operation becomes unstable and generates noise when returned light enters. The optical isolator utilizes the Faraday effect to cut off the returned beam and stabilize the operation of the amplifiers.

5.4.1
isolation
fraction of the optical power launched into the output port exiting the input port of the isolator, expressed in dB

5.4.2
optical isolator insertion loss
fraction of the optical power at the signal wavelength launched into the input port of the isolator which does not exit from the output port, expressed in dB

5.4.3
optical isolator input signal reflectance
fraction of the optical power associated with the input signal which is reflected by the signal from input port of the isolator, expressed in dB

5.4.4
optical isolator output signal reflectance
fraction of the optical power associated with the reverse propagating light which is reflected by the signal from output port of the isolator, expressed in dB

5.4.5
optical isolator PMD
maximum PMD at the signal wavelength which is launched into the input port of the isolator and exits from signal output port of the isolator, expressed in ps (pico second)

5.4.6
optical isolator wavelength bandwidth
wavelength interval within which the isolation is less than 3 dB below the maximum isolation

5.4.7
polarization-dependent isolation
maximum isolation variation due to the change of the input signal state of polarization, expressed in dB

5.4.8
optical isolator PDL
maximum insertion loss variation due to the change of the input signal state of polarization, expressed in dB

5.4.9
optical isolator temperature and vibration stability
range of temperature and vibration conditions within which the isolator maintains its nominal specifications

5.4.10
optical isolator insertion loss at out-of-band wavelength
fraction of the optical power at out-of-band wavelength, coupled into the input port of the isolator which does not exit from the output port, expressed in dB

5.5 ASE rejection filter

An ASE rejection filter is a rejection filter used to suppress unnecessary ASE power at the output of an OFA. Large ASE power degrades noise performance of OFAs. A band pass filter, notch suppression filter or long wavelength pass filter is generally applied for ASE rejection filtering with thin film technology.

5.5.1
ASE rejection filter insertion loss
fraction of the optical power associated with the input signal which does not exit from the output port of the filter, expressed in dB

5.5.2
ASE rejection filter input signal optical reflectance
fraction of the optical power associated with the input signal which is reflected by the input port of the filter, expressed in dB

5.5.3
ASE rejection filter output signal optical reflectance
fraction of the optical power associated with the reverse propagating light which is reflected by the output port of the filter, expressed in dB

5.5.4
ASE rejection filter PDL
maximum insertion loss variation due to the change of the input light state of polarization, expressed in dB

5.5.5
ASE rejection filter PMD
maximum PMD at the signal wavelength which is launched into the input port of the filter and exits from signal output port of the filter, expressed in ps (picosecond)

5.5.6
ASE rejection filter peak wavelength
wavelength at which the insertion loss of the ASE rejection filter is minimum

5.5.7
ASE rejection filter wavelength bandwidth
wavelength interval within which the insertion loss is less than 3 dB over the minimum insertion loss

5.5.8
ASE rejection filter tunability
wavelength interval over which the peak wavelength can be set

5.5.9
ASE rejection filter insertion loss at out-of-band wavelength
fraction of the optical power at out-of-band wavelength launched into the filter and which does not exit from its output port, expressed in dB

5.6 Pump rejection filter

A pump rejection filter is used to reject remnant pump power at output of OFA. Excessive remnant pump power interferes with the power monitor accuracy of the power level control of an OFA using PIN-PD. A band pass filter, notch suppression filter or long wavelength pass filter is generally applied for pump rejection filtering with thin film technology or fibre grating technology.

5.6.1
pump rejection filter insertion loss
fraction of the optical power associated with the input signal which does not exit from the output port of the filter, expressed in dB

5.6.2
pump rejection filter input signal optical reflectance
fraction of the optical power associated with the input signal which is reflected by the input port of the filter, expressed in dB

5.6.3
pump rejection filter output signal optical reflectance
fraction of the optical power associated with the reverse propagating light which is reflected by the output port of the filter, expressed in dB

5.6.4
pump rejection filter PDL
maximum insertion loss variation due to the change of the input signal state of polarization, expressed in dB

5.6.5
pump rejection filter PMD
maximum PMD at the signal wavelength which is launched into the input port of the filter and exits from signal output port of the filter, expressed in ps (picosecond)

5.6.6
pump rejection filter cutoff wavelength
for fibre filters, the wavelength greater than the ratio between the total optical power (including launching high order modes) and the fundamental-mode optical power which has decreased to less than a specified value (currently 0,1 dB), the modes being substantially uniformly excited

5.6.7
pump rejection filter extinction ratio
fraction of the optical power associated with the pump which is not transmitted by the filter, expressed in dB

5.6.8
pump rejection filter extinction wavelength range
wavelength interval within which the extinction ratio is less than 3 dB below the maximum extinction ratio

5.6.9
pump rejection filter insertion loss at out-of-band wavelength
fraction of the optical power at out-of-band wavelength launched into the filter and which does not exit from its output port, expressed in dB

5.7 Gain flattening filter (GFF)

A gain flattening filter is a spectral device that equalizes either the output or gain spectrum of OFAs. The inverted loss profile of the gain profile of an OFA is generally designed. Thin film technology or fibre grating technology is commonly used to implement a GFF.

5.7.1
gain flattening filter wavelength range
wavelength interval within which the signal gain of the OFA is adjusted to be flattened by the GFF

5.7.2
gain flattening filter insersion loss
fraction of the optical power associated with the input signal which does not exit from the output port of the filter, expressed in dB. This value is generally defined as the minimum value within the GFF wavelength range

5.7.3
gain flattening filter error function
difference between design target loss profile and actual loss profile of the filter within the GFF wavelength range, expressed in dB, i.e. $(\text{error func.})_{dB} = (\text{actual loss})_{dB} - (\text{target loss})_{dB}$

5.7.4
gain flattening filter PDL
maximum loss variation due to the change of the input signal state of polarization, expressed in dB

5.7.5
gain flattening filter input signal optical reflectance
fraction of the optical power associated with the input signal which is reflected by the input port of the GFF, expressed in dB

5.7.6
gain flattening filter output signal optical reflectance
fraction of the optical power associated with the reverse propagating light which is reflected by the output port of the GFF, expressed in dB

5.7.7
gain flattening filter filter PMD
maximum PMD at the signal wavelength which is launched into the input port of the filter and exits from signal output port of the filter, expressed in ps (picosecond)

5.8 Tap coupler

A tap coupler is usually a 1 × 2 splitter device, dividing input power into two separate ports. One port is used to signal the line, and the other is used to tap the line. Monitor functionality is generally composed of a tap port and a PIN-PD.

5.8.1
tap coupler coupling ratio
split ratio between the fraction of the optical power launched into the input port which exits from the signal output port of the coupler and the fraction of the optical power launched into the input port which exits from the tap port of the coupler, expressed in percent

5.8.2
tap coupler insertion loss
fraction of the optical power associated with the input signal which does not exit from the signal output port of the coupler, expressed in dB

5.8.3
tap coupler PDL in the signal path
maximum insertion loss variation due to the change of the input signal state of polarization, expressed in dB. This term is defined for the path between signal input port and signal output port

5.8.4
tap coupler PDL in the tap path
maximum insertion loss variation due to the change of the input signal state of polarization, expressed in dB. This term is defined for the path between signal input port and signal tap port

5.8.5
tap coupler wavelength and temperature dependent loss variation in the signal path
insertion loss variation between the signal input port and the signal output port due to change of signal wavelength and change of temperature, expressed in dB

5.8.6
tap coupler wavelength and temperature dependent loss variation in the tap path
insertion loss variation between the signal input port and the signal tap port due to change of signal wavelength and change of temperature, expressed in dB

5.8.7
tap coupler input signal reflectance
fraction of the optical power associated with the input signal which is reflected by the signal from input port of the coupler, expressed in dB

5.8.8
tap coupler output signal reflectance
fraction of the optical power associated with the reverse propagating light which is reflected by the signal from output port of the coupler, expressed in dB

5.8.9
tap coupler tap port reflectance
fraction of the optical power associated with the tap port signal which is reflected by the signal from tap port of the coupler, expressed in dB

5.8.10
tap coupler PMD
maximum PMD at the signal wavelength which is launched into the input port of the coupler and exits from signal output port of the coupler, expressed in ps (picosecond)

5.9 PIN-photodiode (PIN-PD)

A PIN-photodiode (PIN-PD) converts detected optical power to photo-current. A PIN-PD is a monitor device of optical power for input or output of OFAs. By using detected photo-current, the OFA can monitor power level and control power level with a pump laser.

5.9.1
PIN-photodiode wavelength range
wavelength interval within which the PIN-PD normally operates in its nominal specification

5.9.2
PIN-photodiode reverse voltage
operative reverse bias voltage applied to the PIN-PD

5.9.3
PIN-photodiode responsivity
current conversion efficiency of the optical power into photo-current, expressed in A/W, or mA/mW

5.9.4
PIN-photodiode back reflectance
fraction of the optical power associated with the input signal which is reflected by the facet of PIN-PD, expressed in dB

5.9.5
PIN-photodiode dark current
leakage random current that flows to the PIN-PD when the specified reverse voltage is applied without any light input into PIN-PD, expressed in nA. The dark current increases when the temperature of the PIN-PD rises

5.9.6
PIN-photodiode capacitance
junction capacitance when specified reverse bias voltage is applied, expressed in pF

5.10 Variable optical attenuator (VOA)

A variable optical attenuator (VOA) produces attenuation within any value in its nominal specification. VOA is utilized to control either output level or gain value of an OFA. VOA is sometimes inserted between two separated OFA stages in order to adjust gain tilt of the OFA.

5.10.1
variable optical attenuator wavelength range
wavelength interval within which the VOA normally operates in its nominal specification

5.10.2
variable optical attenuator insertion loss
fraction of the optical power associated with the input signal which does not exit from the output port of the VOA, expressed in dB, generally defined in minimum attenuation condition

5.10.3
variable optical attenuator PDL
maximum insertion loss variation due to the change of the input signal state of polarization, expressed in dB

5.10.4
variable optical attenuator PMD
maximum PMD at the signal wavelength which is launched into the input port of the VOA and exits from signal output port of the VOA, expressed in ps (picosecond)

5.10.5
variable optical attenuator attenuation range
attenuation range or total loss range that can be set at the VOA in its nominal specification

5.10.6
variable optical attenuator response speed
maximum time needed to change the attenuation from the beginning loss status until the end of the change. This value is practically defined under the condition that attenuation is changed from minimum value to maximum value in its nominal specification

5.10.7
variable optical attenuator repeatability
uncertainty in reproducing the attenuation (or total loss) after randomly changing and re-setting the attenuation by the VOA

5.10.8
variable optical attenuator input signal reflectance
fraction of the optical power associated with the input signal which is reflected by the signal from input port of the VOA, expressed in dB