IEC/TR 61292-7

Edition 1.0 2011-11

TECHNICAL REPORT

Optical amplifiers –
Part 7: Four wave mixing effect in optical amplifiers

IEC/TR 61292-7:2011(E)

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

THIS PUBLICATION IS COPYRIGHT PROTECTED

Copyright © 2011 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester.
If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

Droits de reproduction réservés. Sauf indication contraire, aucune partie de cette publication ne peut être reproduite ni utilisée sous quelque forme que ce soit et par aucun procédé, électronique ou mécanique, y compris la photocopie et les microfilms, sans l'accord écrit de la CEI ou du Comité national de la CEI du pays du demandeur.
Si vous avez des questions sur le copyright de la CEI ou si vous désirez obtenir des droits supplémentaires sur cette publication, utilisez les coordonnées ci-après ou contactez le Comité national de la CEI de votre pays de résidence.

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland
Email: inmail@iec.ch
Web: www.iec.ch

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

- Catalogue of IEC publications: www.iec.ch/searchpub

The IEC on-line Catalogue enables you to search by a variety of criteria (reference number, text, technical committee,…). It also gives information on projects, withdrawn and replaced publications.

- IEC Just Published: www.iec.ch/online_news/justpub

Stay up to date on all new IEC publications. Just Published details twice a month all new publications released. Available on-line and also by email.

- Electropedia: www.electropedia.org

The world's leading online dictionary of electronic and electrical terms containing more than 20 000 terms and definitions in English and French, with equivalent terms in additional languages. Also known as the International Electrotechnical Vocabulary online.

- Customer Service Centre: www.iec.ch/webstore/custserv

If you wish to give us your feedback on this publication or need further assistance, please visit the Customer Service Centre FAQ or contact us:

Email: csc@iec.ch
Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

IEC/TR 61292-7

Edition 1.0 2011-11

TECHNICAL REPORT

Optical amplifiers –
Part 7: Four wave mixing effect in optical amplifiers

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

PRICE CODE **S**

ICS 33.160.10; 33.180.30

ISBN 978-2-88912-803-7

® Registered trademark of the International Electrotechnical Commission

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

CONTENTS

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

OPTICAL AMPLIFIERS –

Part 7: Four wave mixing effect in optical amplifiers

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example "state of the art".

IEC 61292-7, which is a technical report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

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

Enquiry draft	Report on voting
86C/1029/DTR	86C/1036/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.

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

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

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

The committee has decided that the contents of this publication will remain unchanged until the stability 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 publication may be issued at a later date.

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

INTRODUCTION

The four-wave mixing (FWM) effect is known as one of the major restrictions in DWDM transmission systems. Although observation, conditions for generation, and evaluation methods have been reported in the literature, no international standards have been published on this subject, and manufacturers and users evaluate this phenomenon using their own techniques.

This technical report is dedicated to the subject of four-wave mixing (FWM) effects in optical amplifiers. It provides an overview of the FWM effect and references information on test methods. The technology of optical amplifiers is quite new and still emerging; hence amendments and new editions to this technical report can be expected.

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

OPTICAL AMPLIFIERS –

Part 7: Four wave mixing effect in optical amplifiers

1 Scope and object

This part of IEC 61292, which is a technical report, applies to optical amplifiers (OAs) using active fibres and waveguides, containing rare-earth dopants, currently commercially available.

It provides guidance on crosstalk caused by the four-wave mixing (FWM) effect. The object of this technical report is to provide introductory information for understanding of the crosstalk issue raised by the FWM effect. This report also presents a measurement method in Annex A.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61290-10-4: *Optical amplifiers – Test methods – Part 10-4: Multichannel parameters – Interpolated source subtraction method using an optical spectrum analyzer*

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

3 Abbreviated terms

ASE	amplified spontaneous emission
AWG	arrayed waveguide
CW	continuous wave
DFB	distributed feed-back (laser diode)
DOP	degree of polarization
DWDM	dense wavelength division multiplexing
ECL	external cavity laser (diode)
EDF	erbium-doped fibre
EDFA	erbium-doped fibre amplifier
FWM	four-wave mixing
MUX	multiplexer
OA	optical amplifier
OFA	optical fibre amplifier
O-MUX	optical multiplexer
OSA	optical spectrum analyzer
ROADM	reconfigurable optical add/drop multiplexer
SPM	self-phase modulation
VOA	variable optical attenuator
WDM	wavelength division multiplexing
WSS	wavelength selective switch
XPM	cross-phase modulation

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

4 FWM effect in EDFAs

4.1 General

The EDFA is a crucial element to configure photonic network systems based on WDM transmission because the EDFA compensates for loss in node devices such as ROADMs and WSSs, and expands capacity and distance which leads to large scale networks. Therefore the EDFA is required to amplify many channels of dense WDM signals and is also required to produce higher power for respective channels in order to compensate for loss in node devices and transmission fibre. These demands have recently led to adverse deterioration of WDM signals caused by the nonlinear effect in the EDF. Previously this nonlinear effect was not thoroughly considered because the effect on signal deterioration was small.

As for the L-band EDFA, the emission cross section at 1,58 μm is extremely small as compared to that at 1,55 μm. As reported, the L-band amplifier requires a ten times longer EDF length in order to realize the 20-dB to 30-dB gain needed for practical use. Thus critical problems of signal deterioration by nonlinear effects were noted by the long fibre length amplification in L-band [1]. The FWM effect in multi-channel amplification is usually observed in an EDFA composed of long EDF, or in a high power EDFA. This technical report provides a method and procedure to measure crosstalk caused by the FWM (four-wave mixing) effect in the EDFA.

4.2 Introduction of the FWM effect

The nonlinear effects in EDF originate in the 3rd polarization of permittivity, the same as in transmission fibre, and lead four-wave mixing (FWM), cross-phase modulation (XPM) and self-phase modulation (SPM) [2][6]. In FWM, wavelength-multiplexed signals generate noise on other channels. Therefore, crosstalk is imposed between the signal and the noise products generated by FWM in DWDM transmission systems. Figure 1 is a schematic diagram explaining the generation of FWM products.

When the signal lights of three different wavelengths are launched into EDFA, new lights (idler) are generated by the FWM effect. The newly generated wavelengths do not correspond with any of the above mentioned three wavelengths. When signal frequencies are f_{p}, f_{q}, and f_{r}, generated idler light caused by FWM is expressed as follows.

$$\begin{aligned} f_{\mathrm{F}} &= f_{\mathrm{p,q,r}} \\ &= f_{\mathrm{p}} + f_{\mathrm{q}} - f_{\mathrm{r}} \end{aligned} \tag{1}$$

The generated FWM products overlap with signal wavelength, and crosstalk is imposed on the signal.

Besides FWM idler generation by three wavelengths, FWM products are generated when two signals with different wavelengths are launched into EDFA. This FWM effect resulting from two signal wavelengths is called degenerate four-wave mixing.

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

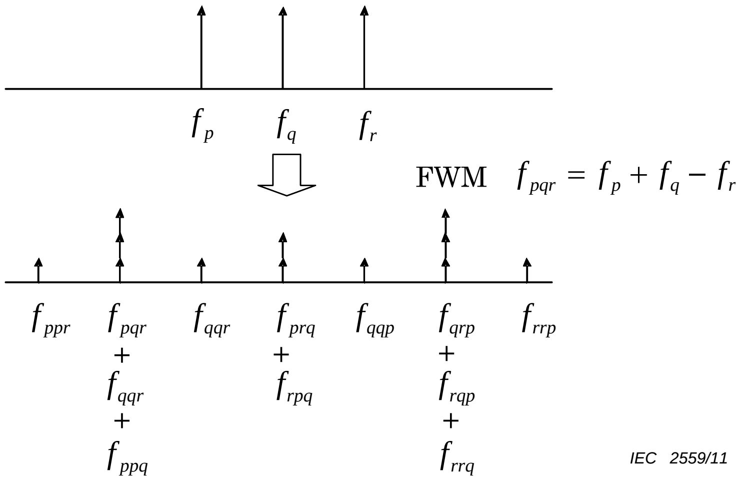

Figure 1 – Example of generation of FWM light

4.3 FWM crosstalk enhancement in EDFA

On a fundamental level, the origin of nonlinear response in the material is related to harmonic motion of bound electrons under the influence of an applied field. As a result, the induced polarization P from the electric dipoles is not linear in the electric field E, and is expressed in following Formula [2].

$$P = \chi_1 E + \chi_2 E \times E + \chi_3 E \times E \times E + \cdots \tag{2}$$

The first term represents the linear effect; the second term represents second order non-linearity; and third term represents third order non-linearity. χ_1, χ_2, χ_3 are first order, second order, and third order susceptibility.

The second order susceptibility χ_2 is responsible for such nonlinear effects as second-harmonic generation and sum-frequency generation. However it is nonzero only for media that lack inversion symmetry at the molecular level. Since SiO_2 is a symmetric molecule, χ_2 vanishes for silica glass. As a result, optical fibres do not normally exhibit second-order nonlinear effects.

The lowest-order nonlinear effects in optical fibres originate from the third order susceptibility χ_3 which is responsible for phenomena such as four-wave mixing. Hence the nonlinear effect which leads FWM is generated by third term in Formula (2).

From Formula (2), assuming signals with angular frequencies of ω_p, ω_q, and ω_r, and respective electric field $E(\omega_\mathrm{p},z)$, $E(\omega_\mathrm{q},z)$, $E(\omega_\mathrm{r},z)$, we can describe propagation equation of the electric field by FWM effect $E(\omega_\mathrm{F},z)$ as follows [4]. Notation z represents position along the fibre length.

$$\begin{aligned}\frac{\partial^2 E(\omega_\mathrm{F},z)}{\partial z^2} - \frac{n^2}{c^2}\frac{\partial^2 E(\omega_\mathrm{F},z)}{\partial t^2} - \frac{\varsigma^2}{c}\frac{\partial E(\omega_\mathrm{F},z)}{\partial t} \\ = \frac{4\pi}{c^2}\frac{\partial^2}{\partial t^2}(D\chi_3)\cdot E(\omega_\mathrm{p},z)\times E(\omega_\mathrm{q},z)\times E^*(\omega_r,z)\end{aligned} \tag{3}$$

Here, n is the refractive index of the core, c is velocity of light, and D is degeneration factor of FWM. The background loss of EDF is denoted by ζ.

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

When we assume a boundary condition of three signals which are launched into EDF as $E(\omega_p,0)$, $E(\omega_q,0)$, $E(\omega_r,0)$, considering gain distribution along the EDF length, FWM signal power which emits at $z = L$ is expressed as follows [5],[8].

$$P(\omega_F, L) = \frac{256\pi^4 \omega_F}{n^4 c^4} \left(\frac{D\chi_3}{A_{eff}} \right)^2 P(\omega_p, 0) \times P(\omega_q, 0) \times P(\omega_r, 0)$$
$$\times \left| e^{i\beta_F z} \int_0^L e^{i\Delta\Delta\, z} \sqrt{G(\omega_p)\Big|_0^z \times G(\omega_q)\Big|_0^z \times G(\omega_r)\Big|_0^z \times G(\omega_F)\Big|_z^L}\, dz \right|^2 \tag{4}$$

Here $P(\omega_p,0)$, $P(\omega_q,0)$, and $P(\omega_r,0)$ are input power to the EDF respectively, and β_F represents propagation constant of FWM light. $G(\omega_p)$, $G(\omega_q)$, and $G(\omega_r)$ represent gain evolution along the EDF at the frequency of ω_p, ω_q, and ω_r respectively. The propagation constant difference $\Delta\beta$ is given as follows [7],[8].

$$\Delta\beta = \frac{2\pi\lambda_r^4}{c} D_c \left(f_p - f_r\right)\left(f_q - f_r\right) \tag{5}$$

where $f_j = \omega_j / 2\pi$ (j = p,q,r), $\lambda_r = f_r / c$, and D_c is the chromatic dispersion of the EDF. $\Delta\beta$ represents the propagation constant difference of input powers with the angular frequency of ω_p, ω_q, and ω_r respectively. $\Delta\beta$ originates in the chromatic dispersion of EDF. Larger dispersion leads to larger $\Delta\beta$. As a result, FWM in an EDFA is enhanced with an increase of powers of signals $P(\omega_p,0)$, $P(\omega_q,0)$ and $P(\omega_r,0)$, and with an increase in the interaction length of fibre as shown above in Formula (4).

Figure 2 shows FWM generation in two EDFAs which are composed of different EDF respectively [3]. The case of conventional EDF is shown in the figure on the left, and FWM generation with amplified signals is observed. The figure on the right shows the case of optimized EDF to suppress FWM generation. FWM generation of optimized EDF is mitigated as compared with conventional EDF. FWM generation is suppressed by appropriate EDF design as shown in the figure on the right.

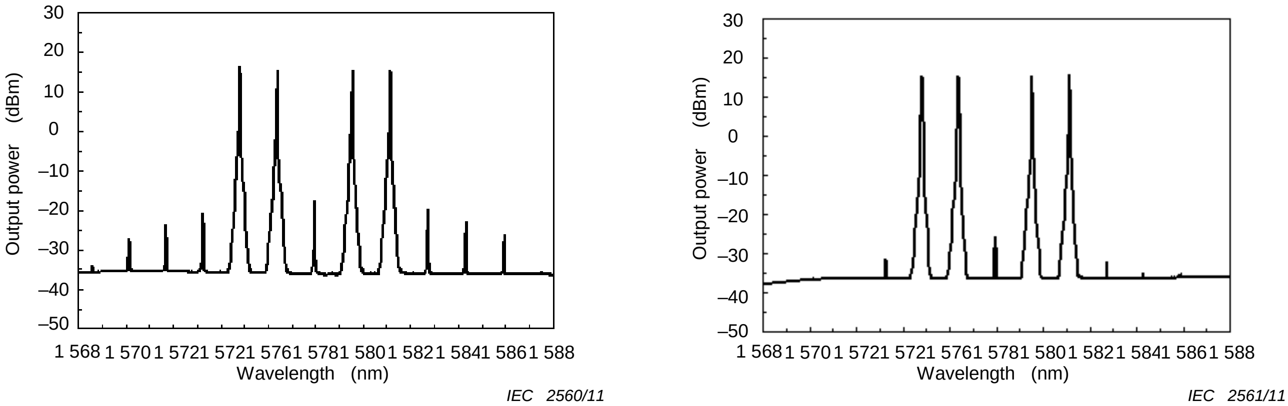

Figure 2 – Examples of EDFA with FWM effect

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

Annex A
(informative)

A technique for measurement of four wave mixing effect in OAs

A.1 Overview

N channels of signal which are equally spaced for frequencies (f_1,f_2,..., f_N) are normally launched into an OA which amplifies multiple WDM signals. However if amplification characteristics with N channel input are observed, FWM light cannot be separated from signal light since FWM light was generated on signal frequencies.

In this measurement method, a single channel at wavelength f_k is removed from a block of N input channels, and N-1 signal wavelengths are launched into the OA. The power of the FWM product at wavelength f_k where signal wavelength is removed and the amplified signal power at adjacent wavelengths $f_{k+/-1}$ are measured. Crosstalk caused by the FWM effect in the OA is estimated by measuring amplification of signals of N-1 channels, assuming amplification of N channels of the WDM array.

A.2 Apparatus

A.2.1 Basic measurement set-up

A.2.1.1 General

The basic measurement set-up is shown in Figure A.1.

The test setup, recommended test condition, and the procedure are described in following sections.

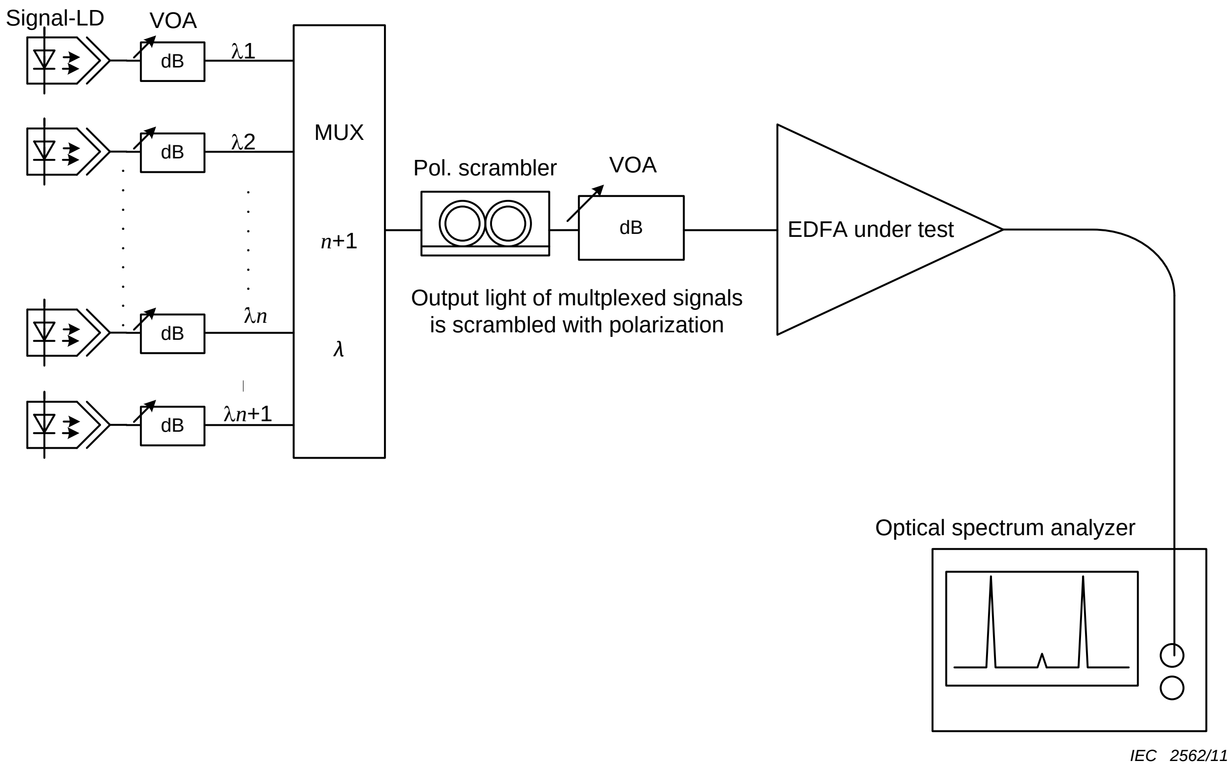

Figure A.1 – Basic measurement set-up

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

A.2.1.2 Signal-LD

Any lasers whose wavelengths are adjustable and have a linewidth of approximately 5 MHz are recommended. The conventional DFB-LD is applicable. Multiple signal-LDs simultaneously output the light in CW mode. Wavelengths of the signal-LDs are spaced with equal frequency. The signal-LDs shall be provided with the function that the output power is adjustable in order for output levels from signal-LDs to be uniform. The VOA at output port of respective signal-LDs may be applied for output level adjustment.

A.2.1.3 O-MUX

O-MUX is used to combine the respective lights from signal-LDs. The device shall have low insertion loss and small crosstalk. An AWG shall be used for this function.

A.2.1.4 Polarization scrambler

A polarization scrambler is inserted at the output port of the O-MUX. The polarization states of the WDM signals are scrambled. The device shall be able to randomize the polarization state of input signal light with all possible states of polarization (linear, elliptical and circular). The device needs to be operated in a randomizing mode in which the polarization is scrambled at a rate faster than scanning time or averaging time of the OSA. The rate shall be faster than the time in which the OSA scans single point. As a result, the time-averaged DOP of signals shall be reduced to nearly zero during the measurement.

A.2.1.5 VOA

This device is inserted in input port of the OA under test. The device attenuates the input signal to an appropriate level under operating condition of the OA.

A.2.1.6 OSA

An OSA is used to measure the amplified signal and the light generated by the FWM effect in the OA. The resolution bandwidth shall be set to a much narrower bandwidth than the wavelength interval of the signal LDs, e.g. 0,1 nm or narrower bandwidth shall be required when signal LDs are allocated with 100-GHz intervals. The scanning speed of the OSA needs to be adjusted for the randomizing rate of polarization scrambler to be faster than the time in which the OSA scans a single point.

A.2.2 Test condition

A.2.2.1 General

The basic recommended test conditions are given in Table A.1.

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

Table A.1 – Recommended test conditions

Item	Recommendation	Comments
Number of channel	40 ch (100-GHz spacing) or 80 ch (50-GHz space)	Maximum applicable number of channels in which OA under test is used.
Wavelength interval	100 GHz or 50 GHz	Same interval of WDM signals in which OA under test is used.
Wavelength accuracy of light source	± 12,5 GHz (± 100 pm)	± 12,5 GHz requirement is generic requirement to 100-GHz spaced tuneable DFB laser.
Input power flatness (multi-channel power variation)	± 0,2 dB	[Max. power channel] – [Min. power channel]
Linewidth of signal-LD	Typ.5 MHz (conventional DFB-LD)	Conventional DFB-LD with wider line width instead of narrow linewidth tuneable laser is more suitable.
Total input power to OA	It depends on OA specification.	Identical to the specification of OA under test.
Total output power of OA	It depends on OA specification.	Identical to the specification of OA under test.
Polarization scrambler	Output light of multiplexed signals is scrambled with polarization.	See A.2.2.4

A.2.2.2 Number of channels

Crosstalk caused by the FWM effect in an OA is estimated by measuring amplification of signals of N-1 channels, assuming amplification of N channels of WDM signals in this measurement method. Thus FWM light at wavelength f_k generated by removed signal at wavelength f_k (missing channel) cannot be observed. Therefore crosstalk shall be underestimated in cases where the number of signal wavelengths is small (details are described in Annex B). In order to avoid underestimation owing to a small set of signal wavelengths, the number of signal wavelengths shall be as large as the actual WDM amplification in the field. It is reported that error from true value is mitigated within 0,2 dB in the case of more than 40 input channels.

A.2.2.3 Wavelength interval

The wavelength interval shall be identical to the interval of the operating condition of the WDM transmission system for which the OA under test is applied. A 40-channel input with 100-GHz spacing or an 80-channel input with 50-GHz spacing is recommended.

A.2.2.4 Wavelength accuracy of light source

The wavelength accuracy of the light source shall be better than ± 12,5 GHz (± 100 pm). The accuracy requirement within ± 12,5 GHz is a generic requirement for a 100-GHz spaced tuneable DFB laser.

A.2.2.5 Input power flatness (multi-channel power variation)

Input power flatness to the OA shall be better than ± 0,2 dB because the deviation of the input power causes the deviation of the output with constant gain operation, which results in an error from the true value. It is suggested that the OA operating condition, such as multichannel gain variation (gain flatness), is less than 1,0 dB peak-to-peak.

A.2.2.6 Linewidth of signal-LD

The linewidth of signal-LD is recommended to be approximately 5 MHz, which is the typical value of the DFB-LD. The use of conventional DFB-LD with wider linewidth instead of a narrow linewidth tuneable laser is more suitable to demonstrate actual use.

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

A.2.2.7 Total input power to OA

Total input power shall be identical to the total input power with which the OA under test is specified. It is generally recommended that total input power is adjusted to the maximum level within the specified range for which the OA under test is applied in order for generated FWM power to be maximized.

A.2.2.8 Total output power of OA

The total output power shall be identical to the total output power with which the OA-under - test is specified. It is generally recommended that total output power is adjusted to the maximum level within the specified range for which the OA-under-test is applied in order for the generated FWM power to be maximized.

A.2.2.9 Polarization scrambler

This device needs to be operated in a randomizing mode in which the polarization is scrambled at a rate faster than the scanning time or averaging time of the OSA. The rate shall be faster than the time in which the OSA scans a single point in order to reduce the time-averaged DOP of signals to nearly zero during measurement.

A.3 Test sample

The OA shall operate at nominal operating conditions with WDM signal input. If the OA is likely to cause laser oscillations due to unwanted reflections, the use of optical isolators is recommended at the input and output of the OA-under-test. This will minimize signal instability and measurement inaccuracy.

Input power and output power of the OA shall be identical to the relevant specification of the OA under test in order to quantify crosstalk under actual operating conditions of the OA in a WDM transmission system.

A.4 Procedure

A.4.1 General

A.4.1.1 Test procedures

The test procedure consists of 8 parts.

A.4.1.2 Wavelengths setting of signal-LDs

Wavelengths of signal LDs shall be set in accordance with A.2.2. Only one wavelength is turned off from the WDM array in order to observe FWM light generated in the OA under test.

A.4.1.3 Power setting of signal-LDs

Output powers of signal LDs shall be adjusted. The VOA at the output port of signal LDs shall be used to attenuate signal light with appropriate power level. Input power flatness to the OA under test shall be in accordance with A.2.2.

A.4.1.4 Setting the polarization scrambler

The polarization scrambler shall be set in accordance with A.2.2.

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

A.4.1.5 OA input power adjustment

Total input power of the OA under test shall be adjusted. The VOA at the input port of the OA shall be used to attenuate total input power with the appropriate level. Refer to the details in section A.2.2.

A.4.1.6 OA output power adjustment

The total output power of the OA under test shall be adjusted. Refer to the details in section A.2.2.

A.4.1.7 Measurement by OSA (signal light)

Amplified signal light level shall be measured by OSA. Refer to the details in A.4.2.

A.4.1.8 Measurement by OSA (FWM light)

Output level of FWM light generated in the OA under test shall be measured by OSA. Refer to the details in A.4.2.

A.4.1.9 Calculation of crosstalk

Crosstalk shall be calculated by use of the measured amplified signal level and generated FWM light. Refer to the details in A.4.2.

The measurement flow is shown in Figure A.2.

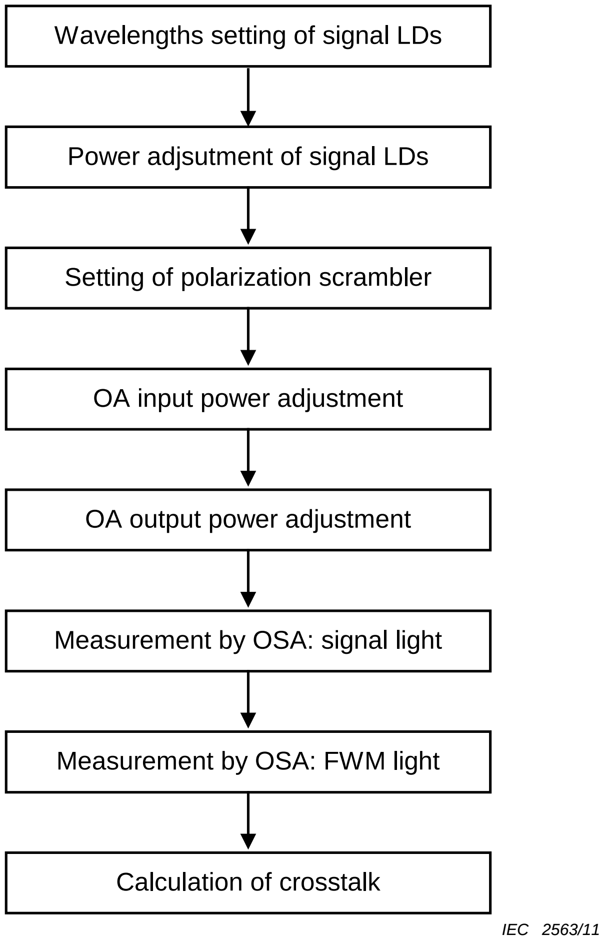

Figure A.2 – Measurement flow chart

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

A.4.2 Measurement by OSA and crosstalk calculation

The details of measurement by the OSA and crosstalk calculation are described in this section.

For better understanding of measurement by OSA, refer to IEC 61290-10-4.

a) Turn off only one wavelength of signal LDs

Only one wavelength is turned off from the signals arranged at 40-ch and 100-GHz intervals, for example, and the FWM light that appears at this wavelength is observed for the crosstalk calculation.

b) Estimate signal power at the wavelength where FWM light appears

$P_{SIG}(\lambda_{n-1})$: Amplified output signal power of the N-1 channel in equally spaced WDM array, [mW]

$$P_{SIG}(\lambda_{n-1}) = S_{n-1} - ASE_{n-1}$$

Subtract ASE factor ASE_{n-1} from the measured level S_{n-1} to quantify real signal power at the wavelength λ_{n-1}

S_{n-1}: measured level containing ASE factor of the wavelength λ_{n-1} [mW]

ASE_{n-1}: interpolated ASE level at the wavelength λ_{n-1} [mW]

$P_{SIG}(\lambda_{n+1})$: Amplified output signal power of $n+1$ channel in equally spaced signal set [mW]

$$P_{SIG}(\lambda_{n+1}) = S_{n+1} - ASE_{n+1}$$

Subtract ASE factor ASE_{n+1} from the measured level S_{n+1} to quantify real signal power at the wavelength λ_{n+1}

S_{n+1}: measured level containing ASE factor of the wavelength λ_{n+1} [mW]

ASE_{n+1}: interpolated ASE level at the wavelength λ_{n+1} [mW]

1) Estimation of signal power at the wavelength, Method A: Average level

Calculate the average power between adjacent signals of FWM light.

$P_{SIG}(\lambda_n)$: Estimated amplified output signal power at the wavelength n channel where FWM light appears [mW]

$$P_{SIG}(\lambda_n) = \frac{1}{2}\left(P_{SIG}(\lambda_{n-1}) + P_{SIG}(\lambda_{n+1})\right)$$

2) Estimation of signal power at the wavelength, Method B: Minimum level

Take the minimum signal level of adjacent signals of the FWM light.

$P_{SIG}(\lambda_n)$: Estimated amplified output signal power at the n channel where FWM light appears [mW]

$$P_{SIG}(\lambda_n) = \mathrm{Min}\left(P_{SIG}(\lambda_{n-1}), P_{SIG}(\lambda_{n+1})\right)$$

Process b)1) or b)2) shall be applied to estimate signal power at the wavelength λ_n.

c) Estimate FWM power at the wavelength

$$P_{FWM}(\lambda_n) = S_n - ASE_n$$

$P_{FWM}(\lambda_n)$: FWM output level at the wavelength n ch. λ_n [mW]

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

S_n : measured level containing ASE factor of the wavelength λ_n [mW]

ASE_n : interpolated ASE level at the wavelength λ_n [mW]

d) Calculate FWM Xtalk level from signal power and FWM power

$$Xtalk(\lambda_n) = 10 \times \mathrm{Log}_{10}\left(\frac{P_{Sig}(\lambda_n)}{P_{FWM}(\lambda_n)}\right) > 0$$

e) Change the signal wavelength that is turned off from the equally spaced signal set (e.g.; 40-channel with 100GHz space). Repeat steps (a) through (h) described in section A.4.1.

An example of the OSA spectra, WDM signal power and FWM power is shown in Figure A.3.

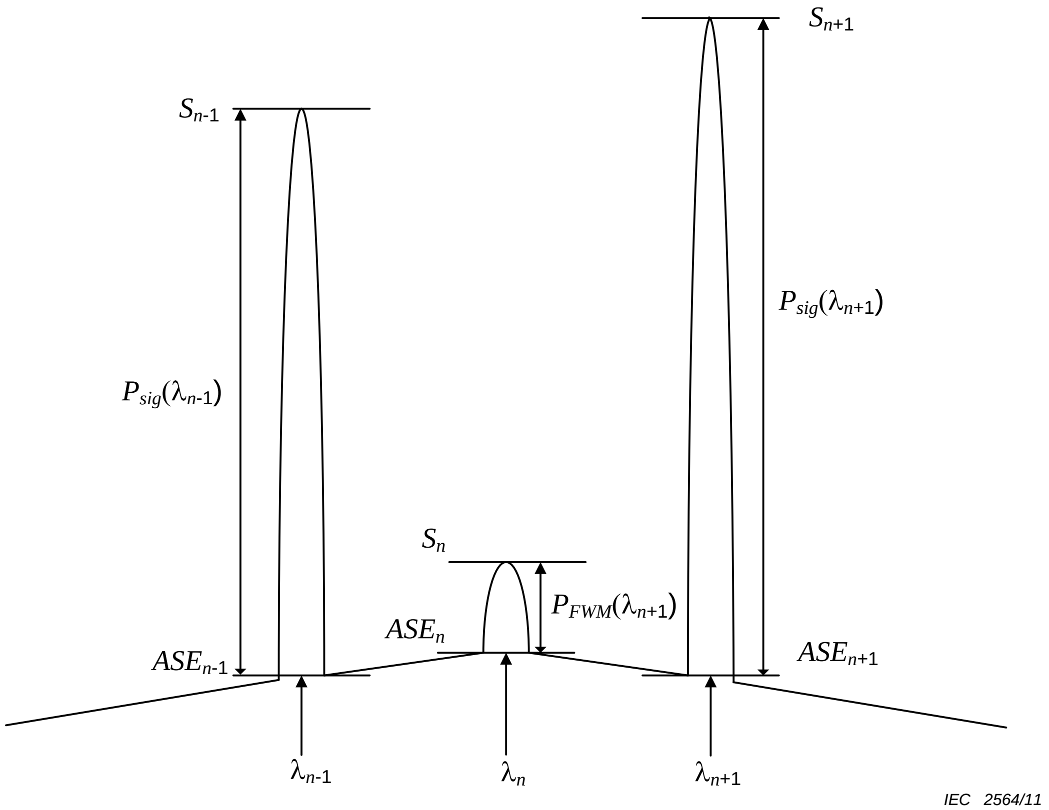

Figure A.3 – Calculation of crosstalk

A.5 Test results

A.5.1 Information to be provided with each measurement

The following test results and relevant information shall be provided with each measurement.

a) test sample identification
b) wavelength range of channels (signal-LDs)
c) number of channel
d) wavelength interval
e) wavelength turned off for crosstalk measurement
f) total input power to OA
g) total output power of OA
h) calculated crosstalk

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

A.5.2 Information available upon request

a) description of the equipment set-up

b) flatness (multi-channel power variation) of input power to OA

c) flatness (multi-channel power variation) of output power to OA

d) scrambling rate of polarization scrambler

e) resolution bandwidth of OSA

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

Annex B
(informative)

Underestimation of FWM crosstalk by reduced number of WDM inputs

B.1 Outline

The FWM signal power is usually measured by turning off the source of the signal channel in which the FWM signal is generated. This means that the measured FWM signal power does not include the contribution of the signal channel whose source is turned off. That is, for an N-channel WDM signals, the measured FWM signal is affected by only $N-1$ channels. However, the required FWM signal power should be contributed by all the signal channels (N-channels). In this annex, the differences are shown between the FWM signal powers with and without the contribution of a signal channel with the same frequency as the FWM signal, and are revealed to be very similar [8].

B.2 Number of combinations which generate FWM

Figure B.1 shows the total number of combinations and number of combinations without the FWM channel that contribute to the FWM product generation at each channel number. In the combinations without the FWM channel, f_F coincides with f_r, $f_F = f_p + f_q - f_r = f_r$. There are 44 input signal channels in our estimation. The figure also shows the ratio of the number of combinations without the FWM channel over the total number of combinations contributing to the FWM signal generation. The ratio has its maximum value at the centre of the channel band and is zero at the band edge. Figure B.2 shows the total channel number dependence of the maximum ratio of the number of the combinations when $f_F = f_r$ over the total number of the combinations. The ratio decreases as the total number of channels increases and is less than a few percent (approximately 0,2 dB) for a total channel number in the tens. Thus, excluding the FWM signal channel input has little effect on the FWM signal power measurement when tens of WDM signal are launched into the EDFA.

B.3 Simulated FWM power

For confirmation the FWM signal power was calculated for the two kinds of signal inputs, namely the signal with all the channels and the signal without the FWM channel. Figure B.3 shows the spectra of the calculated FWM signal power for the signal with all the channels and those for the signal excluding the channel that coincides with the FWM generated channel. The input signal is a 44-channel, 100-GHz spaced L-band signal with a channel power of –15 dBm/ch. The simulated EDFA is pumped at 1 480 nm in a forward pumping scheme, and peak absorption of the EDF is 24 dB/m at 1 530 nm. The EDF chromatic dispersion values are 5 ps/nm × km and 50 ps/nm × km. The numerical model is based on [6]. The FWM signal power spectra are smaller for the signal without the FWM channel than those for the signal with all the channels. However, the difference between the FWM power spectra around the wavelength range where the FWM signal power reaches its maximum value for the two kinds of signal is less than 0,2 dB. The effects of the EDF chromatic dispersion and the total channel number on the difference in the FWM signal powers are shown in Figure B.4. This figure illustrates the dependence of the difference between the FWM signal powers on the total channel number for various EDF dispersion values. The differences increase as the total channel number decreases because the maximum ratio of the number of the combinations when $f_F = f_r$ over the total number of the combination increases. This dependence of the FWM signal power difference on the total channel number is large when the EDF dispersion is large because the phase mismatching has a greater effect on the FWM signal generation. However, the FWM signal power differences are smaller than around 0,2 dB for 10 to 40 channels depending on the EDF dispersion.

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

B.4 Conclusion

For estimation of the worst FWM crosstalk, the use of 40 or more signal sources reduces the effect caused by turning off the source of the FWM channel on the generated FWM signal power. If necessary, an additional 0,1dB to 0,2 dB is sufficient to compensate for the FWM signal power.

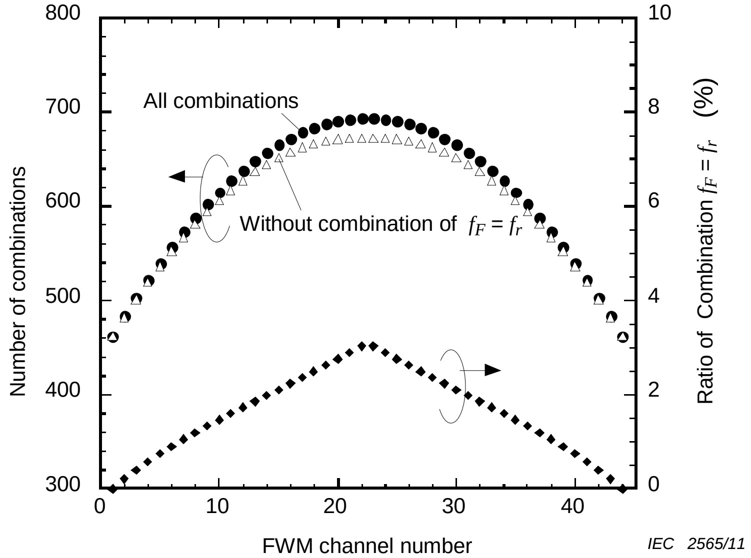

Figure B.1 – Total number of combinations and number of combinations without the FWM channel that contribute to the FWM product generation for each channel number

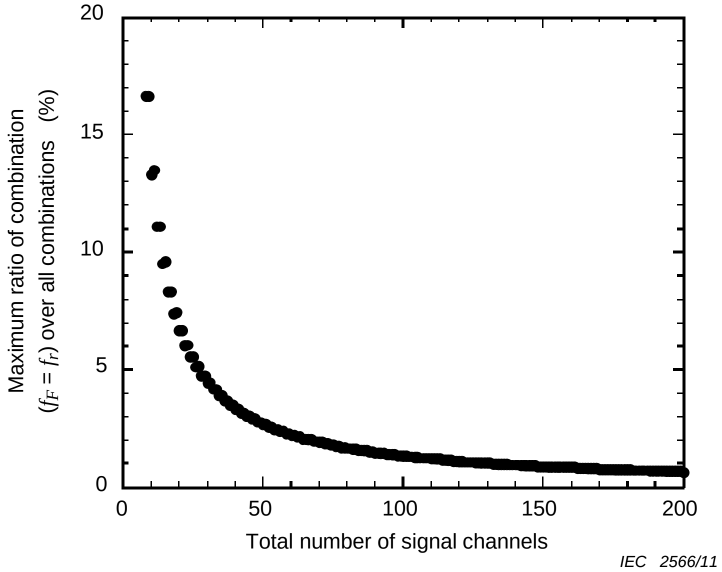

Figure B.2 – Total channel number dependence of the ratio of the number of the combinations under the condition $f_F = f_r$ over the total number of combinations

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

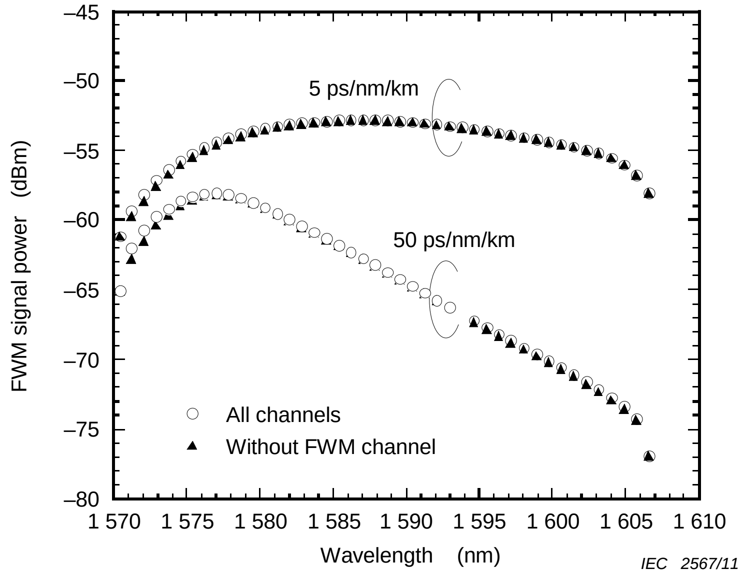

Figure B.3 – Calculated FWM signal power when all the signal channels are input and excluding the channel that coincides with the FWM channel

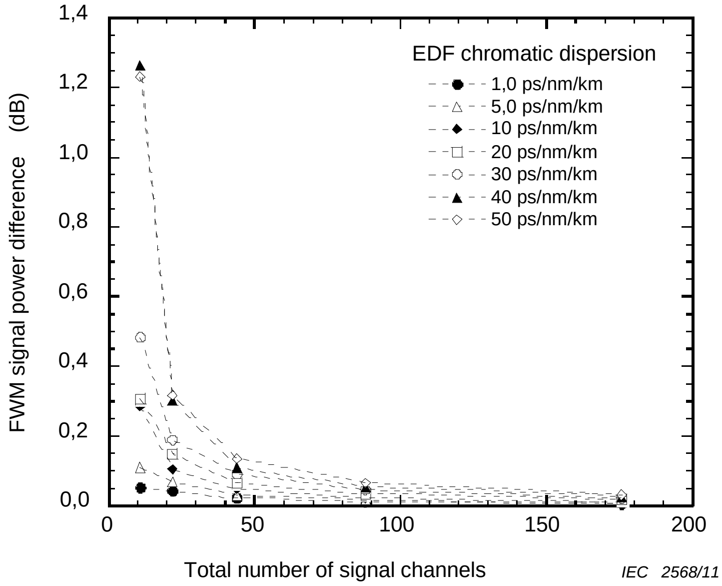

Figure B.4 – Dependence of the difference between the FWM signal powers for signals with all the channels and without the FWM channel on the total channel number for various EDF dispersion values

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

Bibliography

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

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

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

[1] Y. Liu et al, *"Four-wave mixing in EDFAs", Tech. Digest OFC'2000*, Baltimore, paper WG4 (2000)

[2] G. P. Agrawal, *Nonlinear Fiber Optics: Second Edition*, Academic Press, (1995).

[3] K. Aiso et al, *"Erbium Lanthanum co-doped fiber for L-band amplifier with high efficiency, low non-linearity and low*," *Tech. Digest OFC'2001*, Anaheim, paper TuA6 (2001)

[4] K. Inoue, *"Polarization Effect on Four-Wave Mixing Efficiency in a Single-Mode Fiber", J. Quantum Electronics.,* Vol.28, No.4. Apr., pp.883, (1992)

[5] S. Radic, G. Pendock, A. Srivastava, P. Wysocki, and A. R. Chraplyvy, *"Four-Wave Mixing in Optical Links Using Quasi-Distributed Optical Amplifiers", J. Lightwave Technol.* Vol.19, No.5. May, pp.636, (2001)

[6] A. R. Charplyvy, *"Limitations on Lightwave Communications Imposed by Optical-Fiber Nonlinearities", J. Lightwave Technol.* Vol.8, No.10. Oct., pp.1553, (1990)

[7] N. Shibata, R. P. Braun, and R. G. Waarts, *"Phase-mismatch dependence of efficiency of wave generation through four-wave mixing in a single-mode fiber,,," IEEE J. Quantum Electron.,* vol. 23, Jul., pp.1205, (1987)

[8] H. Ono, and M. Yamada, *"Four-Wave Mixing Crosstalk Measurement in a Highly Doped L-Band Erbium-Doped Fiber Amplifier by Using Half of the Signal Channels", J. Lightwave Technol.,* Vol.26, No.14. Jul., pp.2175, (2008)

[9] IEC/TR 61292-5: *Optical amplifiers – Part 5: Polarization mode dispersion parameter – General information*

[10] Optoelectronic Industry and Technology Development Association (OITDA) Technical Paper – TP07/AM-2009: Application guide for Four-wave mixing effect in optical amplifiers – Technical Paper

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

3, rue de Varembé
PO Box 131
CH-1211 Geneva 20
Switzerland

Tel: + 41 22 919 02 11
Fax: + 41 22 919 03 00
info@iec.ch
www.iec.ch

Copyrighted material licensed to BR Demo by Thomson Reuters (Scientific), Inc., subscriptions.techstreet.com, downloaded on Nov-28-2014 by James Madison. No further reproduction or distribution is permitted. Uncontrolled when print