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TECHNICAL REPORT

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

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FOREWORD

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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.

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- withdrawn,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.

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.

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

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.

$$\begin{aligned} f_F &= f_{p,q,r} \\ &= f_p + f_q - f_r \end{aligned} \tag{1}$$

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.

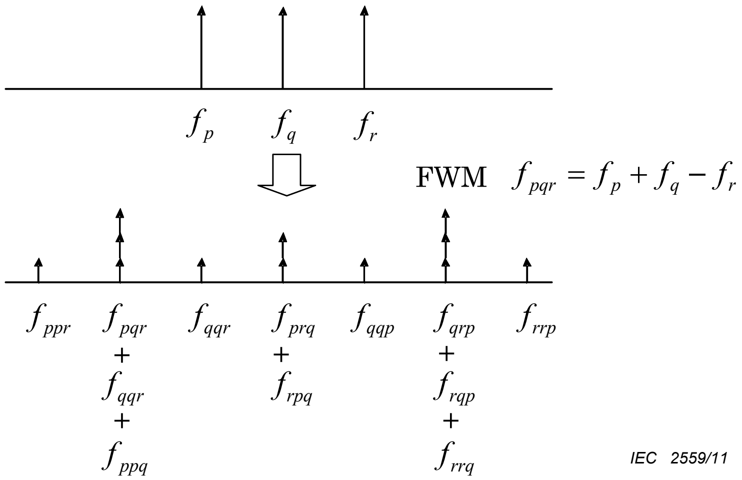


Figure 1 – Example of generation of FWM light

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].

$$P = \chi_1 E + \chi_2 E \times E + \chi_3 E \times E \times E + \cdots \qquad (2)$$

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 $E(\omega_p,z)$, $E(\omega_q,z)$, $E(\omega_r,z)$, we can describe propagation equation of the electric field by FWM effect $E(\omega_F,z)$ as follows [4]. Notation z represents position along the fibre length.

$$\frac{\partial^2 E(\omega_F,z)}{\partial z^2} - \frac{n^2}{c^2}\frac{\partial^2 E(\omega_F,z)}{\partial t^2} - \frac{\varsigma^2}{c}\frac{\partial E(\omega_F,z)}{\partial t} = \frac{4\pi}{c^2}\frac{\partial^2}{\partial t^2}(D\chi_3)\cdot E(\omega_p,z)\times E(\omega_q,z)\times E^*(\omega_r,z) \qquad (3)$$

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.

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].

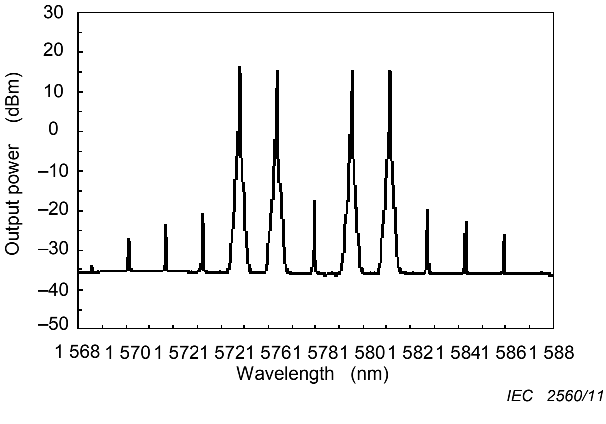
$$P(\omega_F,L)=\frac{256\pi^4\omega_F}{n^4c^4}\left(\frac{D\chi_3}{A_{eff}}\right)^2 P(\omega_p,0)\times P(\omega_q,0)\times P(\omega_r,0)$$
$$\times\left|e^{i\beta_F z}\int_0^L e^{i\Delta\Delta z}\sqrt{G(\omega_p)\big|_0^z\times G(\omega_q)\big|_0^z\times G(\omega_r)\big|_0^z\times G(\omega_F)\big|_z^L}\,dz\right|^2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

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].

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

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.



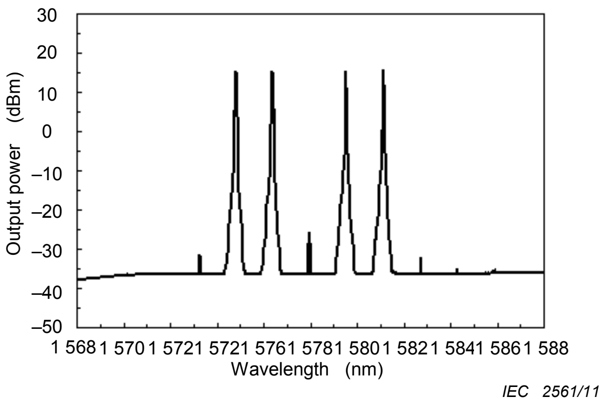


Figure 2 – Examples of EDFA with FWM effect