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Optical amplifier technical reports –

Part 2: Theoretical background for noise figure evaluation using the electrical spectrum analyzer

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CONTENTS

FOREWORD 3
INTRODUCTION 4

1 Scope and object 5
2 Normative references 5
3 Theoretical background of calibration 5
 3.1 Calculation for photocurrent measurement alternative 7
 3.2 Calculation of source RIN 7
4 Theoretical background of noise factor calculation 8

Annex A (informative) List of symbols and abbreviations 11

Figure 1 – Noise figure calibration setup 5
Figure 2 – Equipment for electrical noise figure test 8

INTERNATIONAL ELECTROTECHNICAL COMMISSION

OPTICAL AMPLIFIER TECHNICAL REPORTS –

Part 2: Theoretical background for noise figure evaluation using the electrical spectrum analyzer

FOREWORD

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IEC 61292-2, 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/418/DTR	86C/474/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.

The committee has decided that the contents of this publication will remain unchanged until 2008. At this date, the publication will be

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- withdrawn;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

INTRODUCTION

This Technical Report should be read in conjunction with IEC 61290-3-2. To enhance the clarity of this document, some of the text in document 61290-3-2 is repeated here. Definitions of many terms and parameters contained in this Technical Report can be found in IEC 61291-1.

Each abbreviation introduced in this Technical Report is generally explained in the text the first time it appears. However, for an easier understanding of the whole text, a list of the abbreviations used in this Technical Report is given in Annex A.

OPTICAL AMPLIFIER TECHNICAL REPORTS –

Part 2: Theoretical background for noise figure evaluation using the electrical spectrum analyzer

1 Scope and object

This Technical Report applies to all commercially available optical amplifiers (Oas) including optical fibre amplifiers (OFAs) using active fibres and semiconductor optical amplifiers (SOAs) using semiconductor gain media.

The object of this Technical Report is to provide the theoretical background to Clause 6 (Calculation) of IEC 61290-3-2.

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 61290-3: *Optical fibre amplifiers – Basic specification – Test methods for noise figure parameters*

IEC 61290-3-2: *Optical fibre amplifier test methods – Part 3-2: Noise figure parameters – Electrical spectrum analyzer method*

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

3 Theoretical background of calibration

The calibration setup is shown in Figure 1.

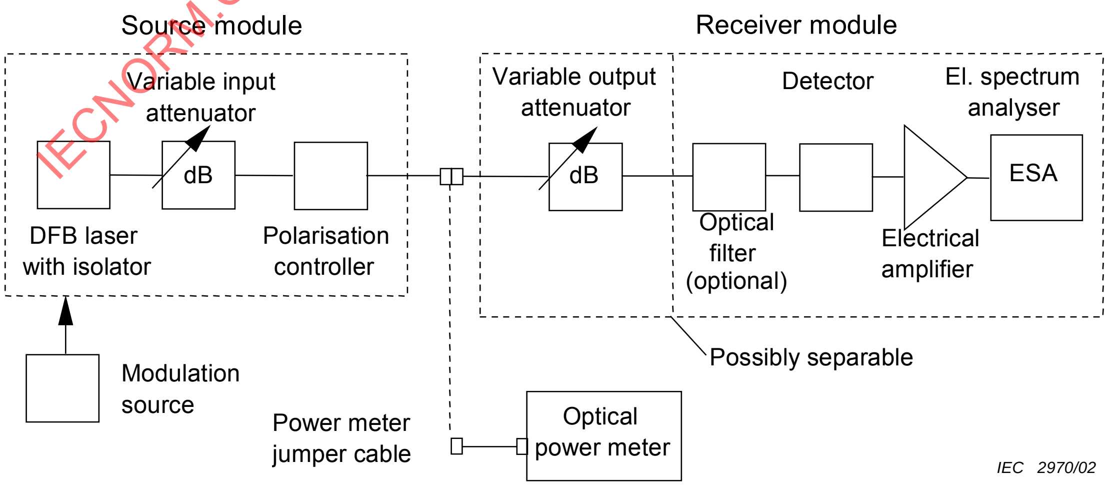

Figure 1 – Noise figure calibration setup

The following quantities are obtained during the calibration process; notice that all noise measurement results are to be understood as ESA power levels after subtraction of the thermal noise level:

$P_{in,0}$ is optical input power at 0 dB setting of input attenuator.

S_0 is electrical power of the modulation signal at 0 dB setting of input attenuator.

N_0 is noise power measured with ESA with input and output attenuator at 0 dB.

N_0' is noise power measured with ESA with input attenuator set to 1/k (k > 1) and output attenuator set to 0 dB.

N_0 can be expressed as:

$$N_0 = N_{rin,0} + N_{shot,0} \ \text{[W]} \tag{1}$$

$N_{rin,0}$ is (frequency-dependent) ESA noise contribution caused by the laser's relative intensity noise (RIN);

$N_{shot,0}$ is (frequency-independent) ESA noise contribution caused by the photodetector's shot noise.

N_0', obtained after k-fold reduction of the input power, can be expressed as:

$$N_0' = k^2 N_{rin,0} + k N_{shot,0} \tag{2}$$

For subtraction purposes, re-write equation (2) in two different forms:

$$\frac{1}{k^2} N_0' = N_{rin,0} + \frac{1}{k} N_{shot,0} \tag{3}$$

$$\frac{1}{k} N_0' = k N_{rin,0} + N_{shot,0} \tag{4}$$

Subtraction (3) – (1) yields the shot noise contribution to the ESA noise power:

$$N_{shot,0}\left(\frac{1}{k} - 1\right) = \frac{1}{k^2} N_0' - N_0$$

$$N_{shot,0} = \frac{N_0' - k^2 N_0}{k(1-k)} \tag{5}$$

Subtraction (1) – (4) also yields the contribution from the source's RIN to the ESA noise power:

$$N_{rin,0}(1-k) = N_0 - \frac{1}{k} N_0'$$

$$N_{rin,0} = \frac{k N_0 - N_0'}{k(1-k)} \tag{6}$$

3.1 Calculation for photocurrent measurement alternative

The effective photodetector responsivity (which includes the loss of the output attenuator at 0 dB attenuation) can be calculated from:

$$r_0 = \frac{I_{\mathrm{pd,0}}}{P_{\mathrm{in,0}}}$$

Calculate the shot- and RIN contributions using:

$$N_{\mathrm{shot,0}} = 2er_0\, P_{\mathrm{in,0}}\, RT_x{}^2\, B_e = \frac{2e}{r_0} H_0\, P_{\mathrm{in,0}}\, B_e \qquad (7)$$

$$S_0 = H_0\, m^2\, P_{\mathrm{in,0}}{}^2 \qquad 8)$$

in which m is the ratio of RMS optical power modulation amplitude to average optical power, and the following was used as receiver transfer function:

$$H_0 = \frac{S_{\mathrm{esa}}}{\Delta P_{\mathrm{in}}{}^2} = r_0{}^2\, T_x{}^2\, R \qquad (9)$$

where

r_0 is effective photodetector responsivity in A/W through output attenuator at 0 dB setting; this quantity may depend on the baseband frequency, and

T_x is voltage amplification between resistor R and ESA input; this quantity usually depends on the baseband frequency.

Dividing the two equations yields:

$$\frac{N_{\mathrm{shot,0}}}{S_0} = \frac{2e}{r_0} \frac{H_0\, P_{\mathrm{in,0}}\, B_e}{H_0\, m^2\, P_{\mathrm{in,0}}{}^2} = \frac{2e}{r_0} \frac{B_e}{m^2\, P_{\mathrm{in,0}}} \qquad (10)$$

$$N_{\mathrm{shot,0}} = \frac{2e}{r_0} \frac{B_e\, S_0}{m^2\, P_{\mathrm{in,0}}} \qquad (11)$$

3.2 Calculation of source RIN

The following derivation can be used to estimate the laser RIN:

$$N_{\mathrm{rin,0}} = H_0\, B_e\, P_{\mathrm{in,0}}{}^2\, RIN_{\mathrm{source}} \qquad (12)$$

$$N_{\mathrm{shot,0}} = 2er_0\, P_{\mathrm{in,0}}\, RT_x{}^2\, B_e = \frac{2e}{r_0} H_0\, P_{\mathrm{in,0}}\, B_e \qquad (13)$$

Dividing the two equations yields:

$$\frac{N_{\text{rin},0}}{N_{\text{shot},0}} = \frac{H_0 B_e P_{\text{in},0}{}^2 RIN_{\text{source}}}{\frac{2e}{r_0} H_0 P_{\text{in},0} B_e} = \frac{r_0 P_{\text{in},0} RIN_{\text{source}}}{2e} \tag{14}$$

and

$$RIN_{\text{source}} = 10\lg\left(\frac{2e}{r_0 P_{\text{in},0}} \frac{N_{\text{rin},0}}{N_{\text{shot},0}}\right) \quad [\text{dB(Hz}^{-1})] \tag{15}$$

For the purpose of this procedure, it is sufficient to know the approximate RIN value. Therefore, it may be sufficient to estimate the value of r_0 in the equation above.

4 Theoretical background of noise factor calculation

Purpose and strategy: subtract shot noise and RIN contributions from the measured electrical spectrum analyzer (ESA) noise powers, then add the theoretical shot noise contribution of an ideal photodetector with quantum efficiency = 1. Notice that the shot noise and spontaneous-spontaneous mixing contributions caused by the amplified source spontaneous emission are neglected.

In the following, subscript 0 denotes source quantities and subscript 1 denotes quantities when the OA is inserted. An asterisk * denotes quantities measured with an ideal photodetector with quantum efficiency = 1.

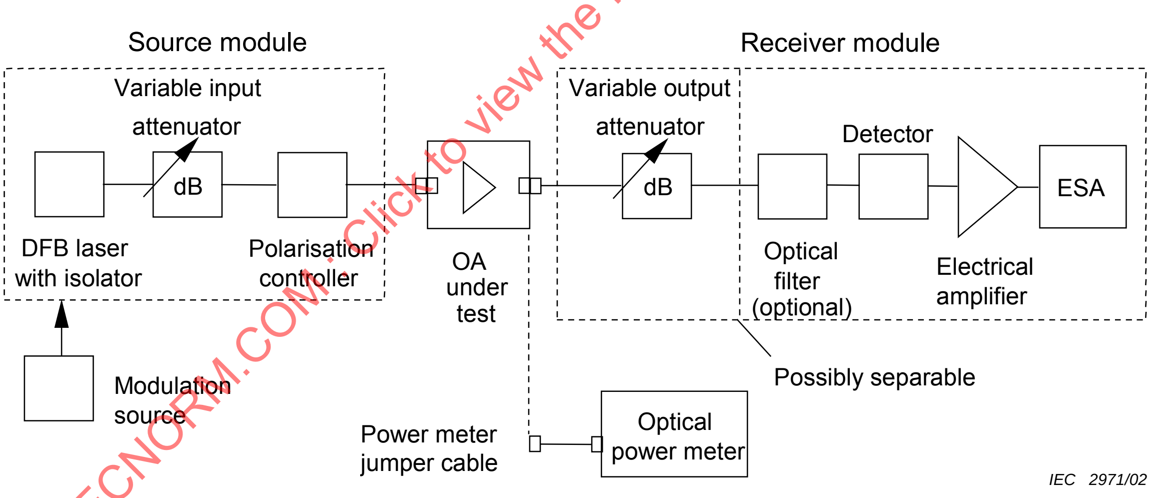

Figure 2 – Equipment for electrical noise figure test

Most equations in this clause are in linear, not logarithmic form.

The equations below make use of previous measurement and calibration results.

Results obtained from the calibration: $P_{\text{in},0}$, N_{th}, S_0, $N_{\text{shot},0}$, $N_{\text{rin},0}$, B_e .

Results obtained from measurement: T_{in}, T_{out}, P_{out}, S_1, N_1 .

a) Calculate the (frequency-dependent) total noise factor as outlined in the noise figure theory of IEC 61290-3:

$$F = \frac{SNR_{\text{in}}{}^{*}}{SNR_{\text{out}}{}^{*}} = \frac{S_0{}^{*}}{N_{\text{shot,0}}{}^{*}} \frac{N_{\text{shot,1}}{}^{*} + N_{\text{OA,1}}{}^{*}}{S_1{}^{*}} \tag{16}$$

b) The first ratio of the noise factor can be expressed in photocurrents from an ideal photodetector:

$$\frac{S_0{}^{*}}{N_{\text{shot,0}}{}^{*}} = \left(\frac{e}{h\nu}\right)^2 m^2 P_{\text{in}}{}^2 \frac{h\nu}{2e^2 P_{\text{in}} B_e} = \frac{m^2 P_{\text{in}}}{2h\nu B_e} \tag{17}$$

where $\frac{e}{h\nu}$ is the responsivity of an ideal photodetector,

and $P_{\text{in}} = T_{\text{in}} P_{\text{in,0}}$ is the input power.

c) The second ratio of the noise factor can be re-written by replacing the OA-term with ESA measurement results; it does not depend on the quantum efficiency of the photodetector:

$$\frac{N_{\text{shot,1}}{}^{*} + N_{\text{OA,1}}{}^{*}}{S_1{}^{*}} = \frac{N_{\text{shot,1}}{}^{*}}{S_1{}^{*}} + \frac{N_{\text{OA,1}}}{S_1} \tag{18}$$

1) Analysis of the first term, expressed in photocurrents from an ideal photodetector:

$$\frac{N_{\text{shot,1}}{}^{*}}{S_1{}^{*}} = \frac{2e^2 P_{\text{out}} B_e}{h\nu} \frac{1}{\left(\frac{e}{h\nu}\right)^2 m^2 G^2 P_{\text{in}}{}^2} = \frac{2h\nu B_e P_{\text{out}}}{m^2 G^2 P_{\text{in}}{}^2} \tag{19}$$

where: $G = \frac{1}{T_{\text{in}} T_{\text{out}}} \sqrt{\frac{S_1}{S_0}}$ = optical gain.

2) Analysis of the second term, expressed in ESA-measured noise powers.

Calculate the (frequency-dependent) OA contribution to the measured total noise:

$$N_{\text{OA,1}} = N_1 - N_{\text{rin,0}} \frac{S_1}{S_0} - N_{\text{shot,0}} \frac{T_{\text{out}} P_{\text{out}}}{P_{\text{in,0}}} \tag{20}$$

Summarizing the results for the second term:

$$\frac{N_{\text{OA,1}}}{S_1} = \frac{N_1}{S_1} - \frac{N_{\text{rin,0}}}{S_0} - \frac{N_{\text{shot,0}}}{S_1} \frac{T_{\text{out}} P_{\text{out}}}{P_{\text{in,0}}} \tag{21}$$

d) Finally, the noise factor can be calculated on the basis of equation (16) using the results obtained above:

$$F = \frac{m^2 P_{\text{in}}}{2h\nu B_e} \left(\frac{2h\nu B_e P_{\text{out}}}{m^2 G^2 P_{\text{in}}{}^2} + \frac{N_{\text{OA,1}}}{S_1} \right) \tag{22}$$

$$F = \frac{P_{\text{out}}}{G^2 P_{\text{in}}} + \frac{m^2 P_{\text{in}}}{2h\nu B_e} \frac{N_{\text{OA},1}}{S_1} \tag{23}$$

Notice that only ratio type measurements are used in these equations. An absolute calibration of the transfer function of the receiver module is not necessary.