TECHNICAL REPORT

IEC TR 61292-2

First edition
2003-01

Optical amplifier technical reports –

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

Reference number
IEC/TR 61292-2:2003(E)

Publication numbering

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PRICE CODE M

For price, see current catalogue

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

OPTICAL AMPLIFIER TECHNICAL REPORTS –

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

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the 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, the IEC publishes International Standards. 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. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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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- withdrawn;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.

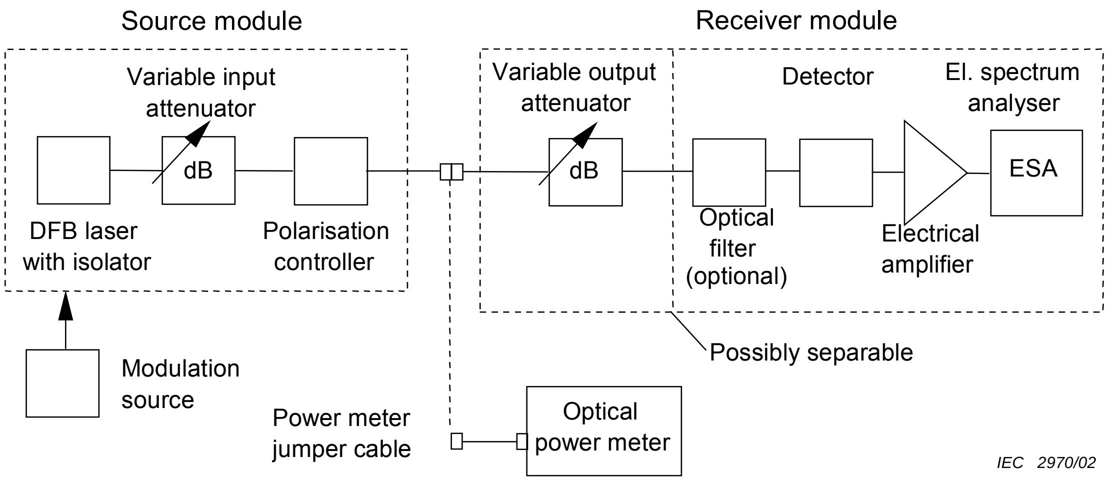

Figure 1 – Noise figure calibration setup

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:

$P_{\text{in},0}$ 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:

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

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

$N_{\text{shot},0}$ 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:

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

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

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

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

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

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

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

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

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

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

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:

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

Calculate the shot- and RIN contributions using:

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

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

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:

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

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:

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

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

3.2 Calculation of source RIN

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

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

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

Dividing the two equations yields:

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

and

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

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.

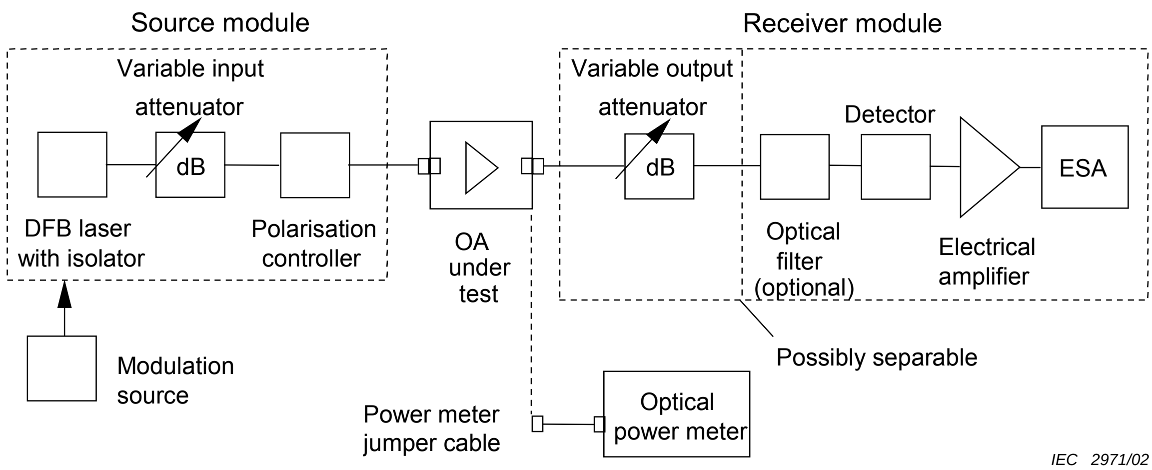

Figure 2 – Equipment for electrical noise figure test

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:

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

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

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.

Annex A
(informative)

List of symbols and abbreviations

B_e	calibrated, noise equivalent ESA electrical bandwidth (not necessarily the resolution bandwidth)
c	speed of light in vacuum, 299792458 m/s
e	electron charge
f	baseband frequency
F	(total) noise factor
$F_{\text{non-mpi}}$	frequency-independent contribution to total noise factor
F_{mpi}	noise factor contribution from multiple interference noise (OA internal reflections)
G	OA optical signal gain
H	Planck's constant
k	optical power reduction factor (default k = 0,5); it can be obtained by taking the square root of the electrical power reduction factor
ν	optical frequency = c/λ
$\Delta\nu$	source's FWHM linewidth with modulation on
$H_0(f)$	$S_{\text{esa}} / \Delta P_{\text{in}}^2$ = transfer function of receiver in watts^{-1}
H_0	same as $H_0(f)$
I_{mpi}	MPI figure of merit; the noise factor contribution caused by multiple path interference integrated over all baseband frequencies (0 to infinity);
I_{pd}	photodetector current
λ	wavelength in vacuum
m	the ratio of RMS optical power modulation amplitude to average optical power;
$N_{\text{OA,1}}$	(frequency dependent) OA noise power contribution to total ESA-measured noise power, after subtraction of thermal noise, shot noise, laser RIN noise
$N_{\text{OA,1}}^*$	(frequency dependent) OA noise power contribution to total noise power at OA output, after subtraction of thermal noise, shot noise, laser RIN noise, measured with ideal photodetector (quantum efficiency = 1)
$N_{\text{rin,0}}$	(frequency-dependent) ESA noise contribution caused by the laser's relative intensity noise, at calibration conditions
$N_{\text{rin,1}}$	(frequency-dependent) noise caused by the laser's relative intensity noise, measured with ESA
$N_{\text{shot,0}}$	(frequency-independent) shot noise caused by the optical input power, at calibration conditions, measured with ESA
$N_{\text{shot,1}}$	(frequency-independent) shot noise power due to total OA output power, measured with ESA
$N_{\text{shot,1}}^*$	(frequency independent) shot noise power due to total OA output power, measured with ideal photodetector
N_{th}	thermal noise level as measured with ESA (optical input port of receiver module closed)

N_0	(frequency-dependent) noise power measured with ESA with input and output attenuator set to 0 dB, thermal noise level subtracted, without OA test device
N_0'	(frequency-dependent) noise power measured with ESA with input attenuator set to $1/k$ ($k > 1$) and output attenuator set to 0 dB, thermal noise level subtracted, without OA test device
N_1	frequency-dependent noise power, with OA inserted, thermal noise level subtracted, measured with ESA
$r_0(f)$	effective photodetector responsivity through output attenuator at 0 dB setting
r_0	same as $r_0(f)$
P_{in}	optical input power = $T_{in}\ P_{in,0}$
	optical power radiated from the end of the input jumper cable
$P_{in,0}$	optical input power at 0 dB setting of input attenuator
$\Delta P_{in,\ rms}$	RMS optical power modulation amplitude = peak-to-peak optical power amplitude divided by $2\sqrt{2}$
P_{out}	total optical power radiated from the output port of the OA, including the ASE
R	resistance of photodetector
RIN_{source}	the source's relative intensity noise; generally, the square of the RMS optical power fluctuation divided by the (baseband) bandwidth and the square of the CW power
S_0	electrical power of the modulation signal at $T_{in} = 1$, measured with ESA, without OA
S_0^*	electrical power of the modulation signal at $T_{in} = 1$, measured with ideal photodetector, without OA
S_1	electrical power of the modulation signal, with OA inserted, measured with ESA
S_1^*	electrical power of the modulation signal, with OA inserted, measured with ideal photodetector
T_{in}	transmission factor of input attenuator relative to transmission at 0 dB setting, expressed in linear form
T_{out}	transmission factor of output attenuator relative to transmission at 0 dB setting, expressed in linear form
T_x	voltage amplification between detector output and ESA input; this quantity usually depends on the baseband frequency
ESA	electrical spectrum analyzer
FWHM	full width at half maximum
OA	optical fibre amplifier
RIN	relative intensity noise of the source, expressed in dB(Hz^{-1})

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ISBN 2-8318-6747-9

9 782831 867472

ICS 33.180.30; 33.160.10

Typeset and printed by the IEC Central Office
GENEVA, SWITZERLAND