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inside

Calibration of fibre-optic power meters

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INTERNATIONAL
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COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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CALIBRATION OF FIBRE-OPTIC POWER METERS

FOREWORD

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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

International Standard IEC 61315 has been prepared by IEC technical committee 86: Fibre optics.

This third edition cancels and replaces the second edition published in 2005. It constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) update of terms and definitions;
b) update of 5.1, including Table 1 (new type of source);
c) update of Annex A;
d) addition of Annex B on dB conversion.

The text of this International Standard is based on the following documents:

CDV	Report on voting
86/533/CDV	86/540A/RVC

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

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

In this document, the following print types are used:

– *terms defined in the document: in italic type.*

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

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• withdrawn,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

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INTRODUCTION

Fibre-optic power meters are designed to measure optical power from fibre-optic sources as accurately as possible. This capability depends largely on the quality of the *calibration* process. In contrast to other types of measuring equipment, the *measurement results* of *fibre-optic power meters* usually depend on many conditions of measurement. The conditions of measurement during the *calibration* process are called *calibration conditions*. Their precise description ~~must~~ is therefore ~~be~~ an integral part of the *calibration*.

This document defines all of the steps involved in the *calibration* process: establishing the *calibration conditions*, carrying out the *calibration*, calculating the uncertainty, and reporting the uncertainty, the *calibration conditions* and the *traceability*.

The absolute power *calibration* describes how to determine the ratio between the value of the input power and the power meter's result. This ratio is called *correction factor*. The measurement uncertainty of the *correction factor* is combined following Annex A from uncertainty contributions from the *reference meter*, the *test meter*, the setup and the procedure.

The calculations go through detailed characterizations of individual uncertainties. It is important to know that

a) ~~estimations of the individual uncertainties are acceptable~~ some uncertainties are type B estimations, experience-based,

b) a detailed uncertainty analysis is usually only ~~necessary~~ done once for each power meter type under test, and all subsequent *calibrations* ~~can be~~ are usually based on this one-time analysis, using the appropriate type A measurement contributions evaluated at the time of the *calibration*, and

c) some of the individual uncertainties ~~can~~ are simply ~~be~~ considered to be part of a checklist, with an actual value which can be neglected.

~~Calibration according to~~ Clause 5 defines absolute power *calibration*, which is mandatory for *calibration* reports referring to this document.

Clause 6 describes the evaluation of the measurement uncertainty of a calibrated power meter operated within *reference conditions* or within *operating conditions*. It depends on the *calibration* uncertainty of the power meter as calculated in 5.4, the conditions and its dependence on the conditions. It is usually performed by manufacturers in order to establish specifications and is not mandatory for reports referring to this document. One of these dependences, the *nonlinearity*, is determined in a separate *calibration* (Clause 7).

~~NOTE   Fibre-optic power meters measure and indicate the optical power in the air, at the end of an optical fibre. It is about 3,6 % lower than in the fibre due to Fresnel reflection at the glass-air boundary (with *N* = 1,47). This should be kept in mind when the power in the fibre has to be known.~~

CALIBRATION OF FIBRE-OPTIC POWER METERS

1 Scope

This document is applicable to instruments measuring *radiant power* emitted from sources that are typical for the fibre-optic communications industry. These sources include laser diodes, light emitting diodes (LEDs) and fibre-type sources. ~~The radiation may be divergent or collimated.~~ Both divergent and collimated radiations are covered. This document ~~describes~~ defines the *calibration* of power meters to be performed by *calibration* laboratories or by power meter manufacturers.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 60050-300, *International Electrotechnical Vocabulary – Electrical and electronic measurements and measuring instruments – Part 311: General terms relating to measurements – Part 312: General terms relating to electrical measurements – Part 313: Types of electrical measuring instruments – Part 314: Specific terms according to the type of instrument*~~

~~IEC 60359, *Electrical and electronic measurement equipment – Expression of performance*~~

IEC 60793-2, *Optical fibres – Part 2: Product specifications – General*

~~IEC 61300-3-12, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-12: Examinations and measurements – Polarization dependence of attenuation of a single-mode fibre optic component: Matrix calculation method*~~

~~IEC 61930, *Fibre optic graphical symbology*~~

IEC TR 61931:1998, *Fibre optic – Terminology*

ISO/IEC Guide 98-3:2008, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

~~ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*~~

~~BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, and OIML:1993, *International vocabulary of basic terms in metrology (VIM)*~~

~~BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, and OIML:1995, *Guide to the expression of uncertainty in measurement (GUM)*~~

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TR 61931 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/

- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
accredited calibration laboratory
calibration laboratory authorized by the appropriate national organization to issue *calibration* certificates with a minimum specified uncertainty, which demonstrate *traceability* to *national standards* (3.14)

3.2
adjustment
set of operations carried out on an instrument in order that it provides given indications corresponding to given values of the measurand

Note 1 to entry: When the instrument is made to give a null indication corresponding to a null value of the measurand, the set of operations is called zero adjustment.

Note 2 to entry: For more information, see ISO/IEC Guide 99:2007, 3.11.

[SOURCE: IEC 60050-311:2001, 311-03-16, modified – The words "of a measuring instrument" have been deleted from the term, and Note 2 to entry has been added. see also VIM 4.30]

3.3
calibration
set of operations that establish, under specified conditions, the relationship between the values of quantities indicated by a measuring instrument and the corresponding values realized by measurement standards

Note 1 to entry: The result of a *calibration* permits either the assignment of values of measurands to the indications or the determination of corrections with respect to indications.

Note 2 to entry: A *calibration* may also determine other metrological properties such as the effect of influence quantities.

Note 3 to entry: The result of a *calibration* may be recorded in a document, sometimes called a *calibration* certificate or a *calibration* report.

Note 4 to entry: See also ISO/IEC Guide 99:2007, 2.39.

[VIM, 6.11, modified]

3.4
calibration conditions
conditions of measurement in which the *calibration* is performed

3.5
centre centroidal wavelength
λ_{centre}
power-weighted mean wavelength of a light source in vacuum

Note 1 to entry: For a continuous spectrum, the centre *centroidal wavelength* is defined as:

$$\lambda_{\text{centre}} = \frac{1}{P_{\text{total}}} \int p(\lambda) \times \lambda \times d\lambda$$

and the total power is:

$$P_{\text{total}} = \int p(\lambda) \times d\lambda$$

where $p(\lambda)$ is the power spectral density of the source, for example in W/nm.

For a spectrum consisting of discrete lines, the centre wavelength is defined as:

$$\lambda_{\text{centre}} = \frac{\sum P_i \times \lambda_i}{\sum P_i}$$

where

P_i is the power of the ith discrete line, for example in W, and

λ_i is the vacuum wavelength of the ith discrete line.

$$\lambda_{\text{c}} = \frac{\int p(\lambda)\lambda d\lambda}{P_{\text{total}}} \qquad (1)$$

For a spectrum consisting of discrete lines, the *centroidal wavelength* is defined as:

$$\lambda_{\text{c}} = \frac{\sum_i P_i \lambda_i}{\sum_i P_i} \qquad (2)$$

where

$p(\lambda)$ is the power spectral density of the source, for example, in W/nm;

λ_i is the vacuum wavelength of the ith discrete line;

P_i is the power of the ith discrete line, for example, in W;

P_{total} is the total power, for example, in W.

Note 2 to entry: The above integrals and summations theoretically extend over the entire spectrum of the light source. However, it is usually sufficient to perform the integral or summation over the spectrum where the spectral density $p(\lambda)$ or power P_i is higher than 0,1 % of the maximum spectral density $p(\lambda)$ or power P_i.

3.6
correction factor
CF
numerical factor by which the uncorrected result of a measurement is multiplied to compensate for systematic error

Note 1 to entry: This note applies to the French language only.

[VIM, 3.16]

3.7
decibel
dB
submultiple of the bel (1 dB = 0,1 B), unit used to express values of power level on a logarithmic scale. The **power level** is always relative to a reference power P_0:

$$L_{P/P_0} = 10 \times \log_{10}\left(\frac{P}{P_0}\right) \quad (\text{dB})$$

where P and P_0 are expressed in the same linear units.

The reference power must always be reported, for example, the power level of 200 µW relative to 1 mW can be noted $L_{P/1\,\text{mW}}$ = –7 dB or L_P(re 1 mW) = –7 dB.

~~The linear ratio, R_lin, of two radiant powers, P_1 and P_2, can alternatively be expressed as a~~ **~~power level difference~~** ~~in decibels (dB):~~

~~$\Delta L_\text{P} = 10 \log_{10}(R_\text{lin}) = 10 \log_{10}(P_1/P_2) = 10 \log_{10}(P_1) – 10 \log_{10}(P_2).$~~

~~Similarly, relative uncertainties, U_lin, or relative deviations, can be alternatively expressed in~~ ~~decibels:~~

$$U_\text{dB} = \frac{10}{\ln 10} U_\text{lin} \cong 4{,}34 \times U_\text{lin} \text{ (dB)}$$

~~NOTE   ISO 31-2 and IEC 60027-3 should be consulted for further details. The rules of IEC 60027-3 do not permit attachments to unit symbols. However, the unit symbol dBm is widely used to indicate power levels relative to 1 mW and often displayed by fibre-optic power meters.~~

3.7
detector
element of the power meter that transduces the radiant optical power into a measurable, usually electrical, quantity

Note 1 to entry: In this document, the *detector* is assumed to be connected with the *optical input port* by an optical path.

Note 2 to entry: For more information, see ISO/IEC Guide 99:2007, 3.9.

~~[see IEC 61931 and VIM, 4.15]~~

3.8
deviation
D
~~for the purpose of this standard, the~~ relative difference between the power measured by the *test meter* (3.32) P_DUT and the reference power P_ref:

$$D = \frac{P_\text{DUT} - P_\text{ref}}{P_\text{ref}} \tag{3}$$

Note 1 to entry: This note applies to the French language only.

3.9
excitation
<fibre> description of the distribution of optical power between the modes in the fibre

Note 1 to entry: In context with multimode fibres, the fibre *excitation* is described by

a)   the *spot diameter* (3.31) on the surface of the fibre end, and

b)   the *numerical aperture* (3.17) of the radiation emitted from the fibre.

~~Full excitation means radiation characterized by a spot diameter which is approximately equal to the fibre's core diameter, and by a numerical aperture which is approximately equal to the fibre's numerical aperture.~~

Single-mode fibres are generally assumed to be excited by only one mode (the fundamental mode).

3.10
instrument state
set of parameters that can be chosen on an instrument

Note 1 to entry: Typical parameters of the *instrument state* are the optical power range, the wavelength setting, the display measurement unit and the output from which the *measurement result* is obtained (for example, display, interface bus, analogue output).

3.11
irradiance
quotient of the incremental *radiant power* ∂P incident on an element of the reference plane by the incremental area ∂A of that element:

$$E = \frac{\partial P}{\partial A} \quad \left(\text{W/m}^2 \right)$$

(4)

Note 1 to entry: For more information, see IEC TR 61931:1998, 2.1.15.

3.12
measurement result
y
(displayed or electrical) output of a power meter (or standard), after completing all actions suggested by the operating instructions, for example warm-up, ~~zeroing~~ zero adjustment and wavelength-correction

Note 1 to entry: *Measurement result* is expressed in watts (W). For the purposes of uncertainty ~~analysis~~, *measurement result*s in other units, for example volts, should be converted to watts. *Measurement results* in decibels (dB) should also be converted to watts, because the entire uncertainty accumulation is based on measurement results expressed in watts. See Annex B.

3.13
measuring range
set of values of measurands for which the error of a measuring instrument is intended to lie within specified limits

Note 1 to entry: In this document, the *measuring range* is the range of *radiant power* (part of the *operating range*), for which the uncertainty at *operating conditions* is specified. The term "dynamic range" should be avoided in this context.

Note 2 to entry: For more information, see ISO/IEC Guide 99:2007, 4.7.

~~[VIM, 5.4]~~

3.14
national measurement standard
national standard
standard recognized by a national decision to serve in a country as the basis for assigning values to other standards of the quantity concerned

Note 1 to entry: For more information, see ISO/IEC Guide 99:2007, 5.3.

~~[VIM, 6.3]~~

3.15
national standards laboratory
laboratory which maintains the *national standard* (3.14)

3.16
nonlinearity
NL
relative difference between the *response* (3.28) at a given power P and the *response* at a reference power P_0:

$$nl_{\text{P/P}_0} = \frac{r(P)}{r(P_0)} - 1$$

(5)

If expressed in decibels, the *nonlinearity* is:

$$NL_{P/P_0} = 10 \times \log_{10} \frac{r(P)}{r(P_0)} \text{ (dB)}$$

(6)

Note 1 to entry: The *nonlinearity* is equal to zero at the reference power.

Note 2 to entry: The term "local *nonlinearity*" is used for the relative difference between the *responses* at two different power levels (separated by 3,01 dB) obtained during the *nonlinearity calibration*. The term "global *nonlinearity*" is used for the result of summing up the local nonlinearities (in dB); it is identical to the *nonlinearity* defined here.

3.17
numerical aperture
description of the beam divergence of an optical source

Note 1 to entry: In this document, the *numerical aperture* is the sine of the (linear) half-angle at which the *irradiance* is 5 % of the maximum *irradiance*.

Note 2 to entry: Adapted from the definition of the *numerical aperture* of multimode graded-index fibres in IEC 60793-1-43:2015, Clause 3; in this document, the definition is used to describe the divergence of all divergent beams.

3.18
operating conditions
appropriate set of specified ranges of values of influence quantities usually wider than the *reference conditions* for which the uncertainties of a measuring instrument are specified (see VIM, 5.5)

Note 1 to entry: The *operating conditions* and uncertainty at *operating conditions* are usually specified by the manufacturer for the convenience of the user.

3.19
operating range
specified range of values of one of a set of *operating conditions* (3.18)

3.20
optical input port
physical input of the power meter (or standard) to which the *radiant power* is to be applied or to which the optical fibre end is to be connected

Note 1 to entry: An optical path (path of rays with or without optical elements, such as lenses, diaphragms, light guides, etc.) is assumed to connect the *optical input port* with the power meter's *detector*.

3.21
optical reference plane
plane on or near the *optical input port* (3.20) which is used to define the beam's *spot diameter* (3.31)

Note 1 to entry: The *optical reference plane* is usually assumed to be perpendicular to the beam propagation, and it should be described by appropriate mechanical dimensions relative to the power meter's *optical input port*.

3.22
polarization dependent response
PDR
variation in *response* of a power meter with respect to all possible polarization states of the input light:

$$PDR = 10 \times \log_{10} \left(\frac{r_{max}}{r_{min}} \right) \text{ (dB)}$$

(7)

where

r_{max} and r_{min} are the maximum and minimum *response* (3.28) taken over all polarization states

Note 1 to entry: *Polarization dependent response* is expressed in decibels.

Note 2 to entry: This note applies to the French language only.

3.23
fibre-optic power meter ~~(fibre-optic)~~
instrument capable of measuring *radiant power* from fibre-coupled sources such as lasers and LEDs, which are typical for the fibre-optic communications industry. ~~These sources include laser diodes, LEDs and fibres.~~

Note 1 to entry: The radiation may be divergent or collimated. The radiation is assumed to be incident on the *optical reference plane* within the specified conditions.

Note 2 to entry: A power meter may consist of either a single instrument or a main instrument and a separate sensing head. In the case of a separate sensing head, the head may be calibrated without the main instrument. However, if any analogue electronics are used in the main instrument, the sensing head shall be calibrated together with the main instrument.

~~NOTE   The measurement result may be influenced by the main instrument, particularly if any analog electronics is used in the main instrument. In such cases, the sensing head must be calibrated together with the main instrument.~~

Note 3 to entry: A *fibre-optic power meter* is usually capable of measuring the time-average of modulated optical power. An increased uncertainty may be observed, which depends on the duty cycle and the peak power of modulated optical power.

~~NOTE   All of the standards in this standard are power meters.~~

3.24
radiant power
P
power emitted, transferred, or received in the form of optical radiation [1][1]

Note 1 to entry: *Radiant power* is expressed in watts.

3.25
reference conditions
conditions of use prescribed for testing the performance of a measuring instrument or for intercomparison of results of measurements

Note 1 to entry: The *reference conditions* generally include reference values or reference ranges for the influence quantities affecting the measuring instrument.

~~[VIM, 5.7]~~

3.26
reference meter
standard which is used as the reference for the *calibration* (3.3) of a *test meter* (3.32)

3.27
reference standard
standard, generally having the highest metrological quality available at a given location or in a given organization, from which measurements made therein are derived

Note 1 to entry: For more information, see ISO/IEC Guide 99:2007, 5.6.

~~[VIM, 6.6]~~

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[1]   Numbers in square brackets refer to the Bibliography.

3.28
response
r

measurement result of a power meter, *y*, divided by the *radiant power* on the power meter's *optical reference plane*, *P*, at a given condition of measurement:

$$r = \frac{y}{P} \text{ (W/W, dimensionless)} \tag{8}$$

Note 1 to entry: An ideal power meter exhibits a *response* of 1 for all *operating conditions*.

3.29
spectral responsivity
responsivity
R

quotient of the *detector* output current *I* by the incident monochromatic optical power *P*:

$$R = \frac{I}{P} \text{ (A/W)} \tag{9}$$

Note 1 to entry: The *responsivity* depends on the conditions (wavelength, temperature, etc.). See Figure 1.

Note 2 to entry: This note applies to the French language only.

Key

Si   silicon

Ge   germanium

InGaAs   indium gallium arsenide

Figure 1 – Typical *spectral responsivity* of photoelectric *detectors*

3.30
spectral bandwidth
B

full-width at half-maximum (FWHM) of the source spectrum

~~If the spectrum is non-continuous, for example as in the case of a laser diode with a multi-longitudinal line spectrum, then the spectral bandwidth is defined with the help of the root-mean-square spectral bandwidth, *B*~rms~ :~~

$$B = M \times B_{\mathrm{rms}} = M \sqrt{\frac{\sum_i P_i \times \lambda_i^2}{\sum_i P_i} - \lambda_{\mathrm{centre}}^2} = M \sqrt{\frac{\sum_i P_i (\lambda_i - \lambda_{\mathrm{centre}})^2}{\sum_i P_i}}$$

where

M = $2\sqrt{2\ln 2} \simeq 2,35$ (calculated using a spectrum with a Gaussian envelope);

P_i is the power of the ith discrete line, for example in W;

λ_i is the vacuum wavelength of the ith discrete line;

$\lambda_{\mathrm{centre}}$ is the *centre wavelength.*

Note 1 to entry: If the source is a laser diode with a multiple-longitudinal mode spectrum, then the FWHM *spectral bandwidth B* is the RMS *spectral bandwidth*, multiplied by 2,35 (assuming the source has a Gaussian envelope):

$$B = 2{,}35 \sqrt{\frac{1}{P_{\mathrm{total}}} \sum_i P_i \left(\lambda_i - \lambda_c\right)^2} \tag{10}$$

$$P_{\mathrm{total}} = \sum_i P_i \tag{11}$$

where

λ_c is the *centroidal wavelength* (3.5) of the laser diode, in nm;

P_{total} is the total power, in W;

P_i is the power of ith longitudinal mode, in W;

λ_i is the vacuum wavelength of ith longitudinal mode, in nm.

Note 2 to entry: If the source emits at one wavelength only (single-line spectrum), it may be sufficient to specify an upper limit, for example *spectral bandwidth* < 1 nm.

Note 3 to entry: It is usually sufficient to perform the integral or summation over the spectrum where the power is higher than 0,1 % of the maximum power.

Note 4 to entry: This note applies to the French language only.

3.31
spot diameter
diameter of the irradiated area on the *optical reference plane*, defined by the (best-approximation) circle at which the *irradiance* (3.11) has dropped to 5 % of the peak *irradiance*

Note 1 to entry: The ratio of 5 % was adopted for reasons of compatibility with the definition of the *numerical aperture*. Other ratios are often used to describe laser beams, for example $1/e^2$ or $1/e$. In that case, the ratio shall be stated with the *spot diameter* value.

NOTE 2 The diameter of the *optical reference plane* must be larger than the spot diameter in order to measure the whole optical power.

3.32
test meter
fibre-optic power meter (3.23) (or standard) to be calibrated by comparison with the *reference meter* (3.26)

3.33
traceability
property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties

Note 1 to entry: For more information, see ISO/IEC Guide 99:2007, 2.41.

[VIM, 6.10]

3.34
traceability chain
unbroken chain of comparison (See Figure 2)

Note 1 to entry: For more information, see ISO/IEC Guide 99:2007, 2.42.
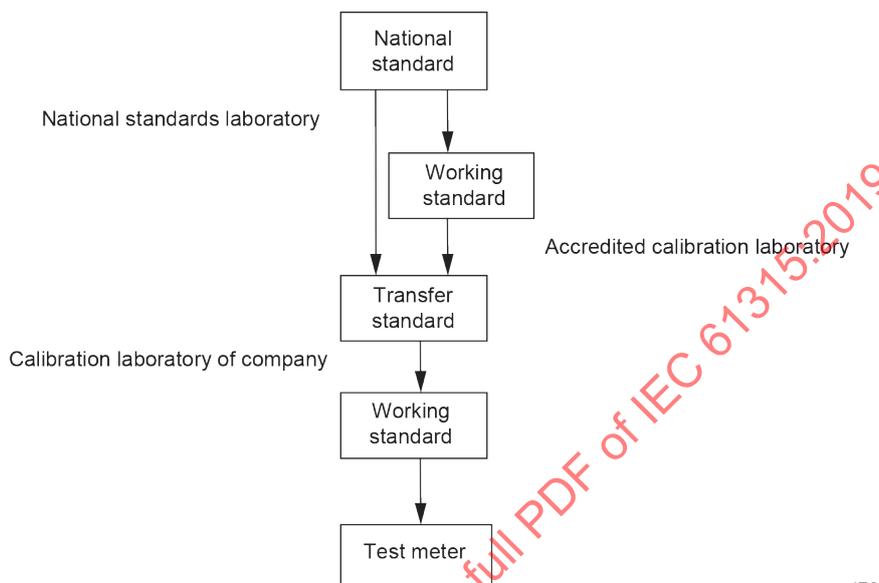
Figure 2 – Example of a *traceability chain*

[VIM 6.10]

3.35
working standard
standard that is used routinely to calibrate or check measuring instruments

Note 1 to entry: A *working standard* is usually calibrated against a *reference standard* (3.27).

Note 2 to entry: For more information, see ISO/IEC Guide 99:2007, 5.7.

[VIM, 6.7]

3.36
zero error
measurement result of a power meter without *irradiation* of the *optical input port*

Note 1 to entry: For more information, see ISO/IEC Guide 99:2007, 4.28.

(VIM, 5.23)

4   Preparation for *calibration*

4.1   Organization

The calibration laboratory should satisfy requirements of ISO/IEC 17025.

The *calibration* laboratory should ensure that suitable requirements for *calibration* are followed.

NOTE   Guidance about good practices for *calibration* can be found in ISO/IEC 17025 [18].

There should be a documented measurement procedure for each type of *calibration* performed, giving step-by-step operating instructions and equipment to be used.

4.2   *Traceability*

~~The requirements of ISO/IEC 17025 should be met.~~

The *calibration* laboratory should ensure that suitable requirements are followed.

NOTE   Guidance about good practices for *calibration* can be found in ISO/IEC 17025 [18].

All standards used in the *calibration* process shall be calibrated according to a documented program with *traceability* to *national standards laboratories* or to *accredited calibration laboratories*. It is advisable to maintain more than one standard on each hierarchical level, so that the performance of the standard can be verified by comparisons on the same level. Make sure that any other test equipment which has a significant influence on the *calibration* results is calibrated. Upon request, specify this test equipment and its *traceability chain*(s). The re-*calibration* period(s) shall be defined and documented.

4.3   Advice for measurements and *calibrations*

4.3 gives general advice for all measurements and *calibrations* of optical and fibre-optic power meters.

The *calibration* should be made in a temperature-controlled room if non-temperature-controlled *detectors* are used. The recommended temperature is 23 °C. Humidity control may be necessary if humidity-sensitive optical *detectors* are used, or if there is the possibility of condensation on the components. A change of the laboratory's humidity may change the absorption of air and thereby change the power. This effect is relatively strong between 1 360 nm and 1 410 nm, especially when a sequential-type, open-beam *calibration* is used and the humidity changes between the steps. In parallel-type *calibrations* with open-beam paths of approximately the same lengths, the *measurement results* of both the *reference meter* and the *test meter* will change at approximately the same time, with negligible effect on the *calibration* result.

The laboratory should be kept clean. Connectors and *optical input ports* should always be cleaned before measurement. The quality and cleanness of the connector in front of the *detector* should be checked. All fibres should be moved as little as possible during the measurements; they can be fixed to the workbench if necessary. Sensors should be moved to the fibre rather than the fibre to the sensor.

The optical source that is used for the *excitation* of the power meter should be characterized for ~~centre~~ *centroidal wavelength* and *spectral bandwidth*. The *spectral bandwidth* should be narrow enough to avoid averaging over a wide range of wavelengths. Means to ensure the stability of the source, for example with the help of independent power monitoring, may be advisable.

Laser diodes are sensitive to back reflections. To improve the stability, it is advisable to use an optical attenuator or an optical isolator between the laser diode and the *test meter*. Because of their narrow *spectral bandwidths*, the combination of laser diode and multimode fibre is also capable of producing speckle patterns on the *optical reference plane*, resulting in an increased measurement uncertainty.

Fibre connectors and connector adapters are likely to produce errors in the *measurement result* [2] because of multiple reflections between the *optical input port* (or *detector*) and the connector-adapter combination (as part of the source). Therefore, connectors and adapters

with low reflectivity are recommended for the *calibration*. Otherwise, a *correction factor* and an increased uncertainty may have to be taken into account.

It is advisable to use *reference meters* with *detector* diameters of ≥ 3 mm, because they can easily be irradiated with an open beam, and they are less susceptible to contamination (dirt and dust). The *reference meter*'s surface reflections should be as small as possible. If the source emits a divergent beam, then a *reference meter* with an integrating sphere may be advisable. It is also acceptable to use meters with "flat" *detectors* and mathematical correction, based on multiplying the emitted far-field distribution with the measured angle-dependence of the *detector* of the *reference meter*, and integrating over the range of far-field angles.

Temperature control of the *detectors* should be considered for highly accurate *calibrations*, because *detectors* exhibit strong temperature dependence over some wavelength ranges.

4.4 Recommendations to ~~customers~~ users

It is recommended that the ~~customer (~~user of the power meter~~)~~ maintain at least one reference power meter, which allows comparison of the meters for confidence. These comparisons are particularly important before and after the meter is sent to recalibration, because they will allow the user to determine whether or not their scale has changed – for example due to transport – after the meter returns. Scale changes due to *adjustment* (3.2) (see IEC 60050-311:2001, 311-03-16 and ~~VIM~~ ISO/IEC Guide 99:2007, 4.30) will be reported on the *calibration* certificate.

A regular comparison of the *correction factors* (3.6), or of the *deviations* (3.8), will allow the user to screen out excessive ageing, and possibly to adjust the recalibration intervals.

5　Absolute power *calibration*

5.1　*Calibration* methods

The *calibration* of a power meter is usually achieved by exposing both the meter under test and a calibrated power meter with known uncertainty (the *reference meter*) to an optical radiation, and by transferring the *reference meter*'s (3.26) *measurement result* to the *test meter* (3.32).

The allowable *spectral bandwidth* (3.30) depends on the *test meter*'s *spectral responsivity* (3.29); the stronger its wavelength dependence, the narrower the *spectral bandwidth*. Usual bandwidths are ~~<15~~ ≤ 10 nm, which excludes the possibility of calibrating with wider-bandwidth LEDs. ~~Therefore, either laser diodes or combinations of "white" sources and narrow-bandwidth filters (for example monochromators) are typically used in optical power meter calibrations.~~ Therefore, one of the following is used in *fibre-optic power meter calibrations*: combinations of "white-light" sources and narrow-bandwidth filters (for example monochromators), laser diodes, or combinations of supercontinuum lasers with tuneable bandpass filters.

Depending on the type of source and the exciting beam geometry, ~~four~~ six most frequent *calibration* methods can be distinguished, as depicted in Table 1:
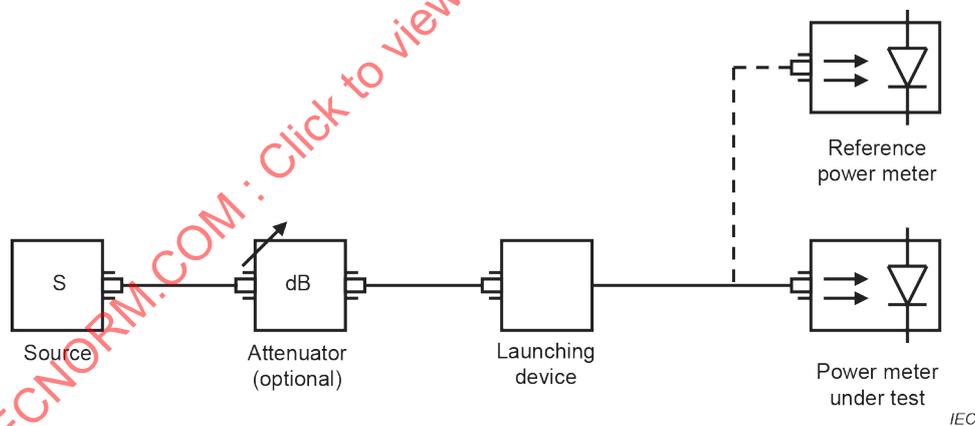
Table 1 – *Calibration* methods and correspondent typical power

Radiation source	Open-beam *calibration*	Fibre beam *calibration*
"White-light" with filter	$P \approx 10$ µW	$P \approx 10$ nW to 0,3 µW (MMF)
		$P \approx 2$ nW (SMF)
Laser diode	$P \approx 10$ µW to 1 a few mW	$P \approx 10$ µW to 1 a few mW (SMF and MMF)
Supercontinuum laser with filter	$P \approx 1$ µW to a few mW	$P \approx 1$ µW to 700 µW (SMF and MMF)
Key		
MMF: multimode fibre (usually graded-index fibre)		
SMF: single-mode fibre		

For *fibre-optic power meters*, fibre beam *calibration* is recommended. For open-beam *calibration*, a correction of the *calibration* results using a series of fibre beam laser *calibration* results at a few wavelengths should be performed.

One can distinguish between the sequential and the parallel measurement method. When the *reference meter* and *test meter* are sequentially exposed to the source, then the radiated power should be kept as constant as possible, for example by appropriate stabilization. For the parallel-type *calibration*, a beam splitter or a branching device is used to generate two beams that excite both the *reference meter* and the *test meter* simultaneously. In this case, the beam splitter or branching device ratio should shall be determined as accurately as possible, and its stability should shall be investigated.

As an example, a measurement setup for sequential, fibre-based *calibration* is illustrated in Figure 3. A launching device, for removal of the cladding modes and creation of an appropriate modal *excitation*, is included in the setup.

Figure 3 – Measurement setup for sequential, fibre-based *calibration*

5.2 Establishing the *calibration conditions*

The *calibration conditions* (3.4) are the measurement conditions during the *calibration* process. Establishing and maintaining the *calibration conditions* is an important part of the *calibration* (3.3), because any change of these conditions is capable of producing erroneous *measurement results*. The *calibration conditions* should be a close approximation to the intended *operating conditions* (3.18). This ensures that the (additional) uncertainty in the operating environment is as small low as possible. The *calibration conditions* should be specified in the form of nominal values with uncertainties when applicable. In order to meet the requirements of this document, the *calibration conditions* shall, at least a minimum, consist of the following:

a) the date of *calibration*;

b) the ambient temperature with uncertainty, for example 23 °C ± 1 °C;

c) the ambient relative humidity, if it has an influence; otherwise a relative humidity below the condensation point is assumed;

d) the nominal *radiant power* on the *optical reference plane* (3.21);

e) the beam geometry:

    1) an open (for example collimated) beam, described by the *spot diameter* (3.31) on the *optical reference plane*, the beam's *numerical aperture* (3.17) and the *irradiance* (3.11) distribution in the beam; typical *irradiance* distributions are: uniform, Gaussian or even irregular (speckled);

    2) the type of fibre and, if applicable, its degree of *excitation* (for example ~~fully excited~~ within encircled flux templates defined in IEC 61280-4-1 when using an A1a or A1b multimode fibre);

f) the connector-adapter combination: the connector type, polishing and adapter as part of the exciting source (if applicable);

g) the ~~*centre*~~ *centroidal wavelength* (3.5) of the exciting source ~~with its uncertainty~~;

h) the *spectral bandwidth* (3.30) of the exciting source ~~with its uncertainty~~;

i) the state of polarization: "unpolarized light" or "polarized light, undefinite state". If the latter is chosen, the uncertainty due to *polarization dependent response* (3.22) shall be taken into account in 5.4.3 and 5.4.5.

The above conditions may not be exhaustive. There ~~may~~ might be other parameters that have a significant influence on the *calibration* uncertainty and therefore shall be reported, too.

In the *calibration* with an open-beam, the power meter's *optical reference plane* (3.21) should be centrally irradiated with a beam diameter smaller than the active area of the *optical reference plane*.

In the *calibration* with a fibre, a single-mode fibre or a multimode fibre may be used. A single-mode fibre ~~may~~ can be advantageous because of its reproducible beam characteristics, but may not be available for all wavelengths. If a multimode fibre is used, then ~~full~~ *excitation* between 85 % and 95 % (slightly underfilled condition) is preferred because this *excitation* can be more easily reproduced (encircled flux templates defined in IEC 61280-4-1 are a good example of this condition). A launching device may be necessary to create the appropriate *excitation*. Note that multimode fibres will emit irregular beam patterns (speckle patterns) when driven by a laser diode; this will result in an increased *calibration* uncertainty. ~~Optical power in the cladding (cladding modes) should be removed with an appropriate mode stripper or launching device, if necessary.~~

A connector-adapter combination should only be reported if the power meter is calibrated with a fibre, ~~that is~~ and not with an open beam. It is recommended to use a combination of connector and adapter with sufficiently low reflections back to the power meter.

5.3 *Calibration* procedure

(1) Establish and record the appropriate *calibration conditions* (5.2). Switch on all instrumentation and ~~wait for~~ allow enough time for it to stabilize.

(2) Set up the *instrument state* (3.10) of the *reference meter* and *test meter* according to the instruction manual. Set the wavelength on all instruments for the source wavelength. Select appropriate power ranges. Record the *instrument states* of both meters. Adjust the zero of both meters if applicable.

(3) Measure the optical power with the *reference meter* $P_{std,1}$. Multiply the *measurement result* by the *correction factor* of the *reference meter* CF_{std} reported in its *calibration* certificate if it has not been adjusted. Multiply by the *correction factor* CF_{change} calculated in 5.4.4 if necessary. Record the *measurement result*, $P_{ref,1} = P_{std,1} \times CF_{std} \times CF_{change}$. ~~This is the best estimate of the true power.~~

(4) Measure the optical power with the *test meter*. Apply necessary corrections as suggested by the operating instructions. Record the *measurement result*, $P_{\text{DUT},1}$.

(5) Calculate the first of a series of *correction factors*:

$$CF_{\text{comparison},1} = \frac{P_{\text{ref},1}}{P_{\text{DUT},1}} \tag{12}$$

(6) Repeat steps (3) through (5) several times, with the result of obtaining several *correction factors*, $CF_{\text{comparison},1}$ to $CF_{\text{comparison},n}$.

(7) Calculate and record the average *correction factor*, CF_{DUT} from the individual *correction factors*:

$$CF_{\text{DUT}} = \frac{1}{n} \times \sum_{i=1}^{n} CF_{\text{comparison},i} \tag{13}$$

If desired, the *deviation D* can be calculated from the *correction factor*:

$$D = \frac{1}{CF_{\text{DUT}}} - 1 \tag{14}$$

In later use of the *test meter*, the *measurement results* shall be multiplied with CF_{DUT}. Alternatively, an *adjustment* (3.2) of the *test meter* can be made so that the *correction factor* is changed to 1. In this case, the comparison should be repeated for verification.

5.4 *Calibration* uncertainty

5.4.1 General

The *calibration* uncertainty is the measurement uncertainty of the *correction factor* CF_{DUT}. Calculate the combined standard uncertainty from:

$$u(CF_{\text{DUT}}) = \sqrt{u_{\text{setup}}^2 + u_{\text{ref}}^2 + u_{\text{DUT}}^2} \tag{15}$$

where

u_{setup} is the uncertainty due to the setup (5.4.2);

u_{ref} is the uncertainty of the *reference meter* (5.4.3);

u_{DUT} is the uncertainty due to the *test meter* (5.4.5).

NOTE Equation (15) is valid only if the input quantities are independent or uncorrelated. If some input quantities are significantly correlated, take the correlation must be taken into account. See GUM ISO/IEC Guide 98-3 for more detail.

Then calculate the expanded uncertainty from:

$$U(CF_{\text{DUT}}) = k \times u(CF_{\text{DUT}}) \tag{16}$$

where

k is the coverage factor.

See Annex A for more detail.

5.4.2 Uncertainty due to the setup

The following uncertainties may come from the setup.

a) Uncertainty due to the source power instability. In addition to the intrinsic variation of output power versus time, a laser source may react with unstable power to variations of back-reflections and variations of the state of polarisation of back-reflected light.

b) Uncertainty due to the beam splitter or branching device ratio (for parallel method), for example due to their polarization dependence.

c) Depending on the setup and method, other uncertainties may have to be taken into account.

Instability of the source power, of the beam splitter or branching device ratio (for parallel method) will cause a scatter in the measurement of the *correction factor*. The uncertainty due to these instabilities can be calculated from the experimental standard *deviation* of the *correction factors* $CF_{\text{comparison},1}$ to $CF_{\text{comparison},n}$ measured during the *calibration* (Equation (12)). The number of comparisons should be large to reduce this uncertainty. See Annex A for more detail on type A evaluation of uncertainty.

$$u_{\text{setup,typeA}} = \frac{s\left(CF_{\text{comparison}}\right)}{\sqrt{n}} \tag{17}$$

where

$s(CF_{\text{comparison}})$ is the experimental standard *deviation* of the *correction factors*;

n is the number of measurement cycles during the *calibration* process.

This uncertainty can also be calculated from a standard *deviation* evaluated once from measurements and used for all *calibrations* or from a type B evaluation. The instability should therefore not vary too much from one *calibration* to the next and not depend on the *test meter*. The number n in Equation (17) is always the number of measurement cycles during the current *calibration* process.

This type A evaluated uncertainty will also be influenced by the repeatability of the connection when using a sequential measurement method or by slight changes in the measurement conditions during the *calibration* process. It can (partially) take into account some of the uncertainties due to the *reference meter* (5.4.3) or *test meter* (5.4.5). Uncertainty components should not be taken into account twice but neither should they be forgotten.

Calculate the uncertainty due to the setup by combining all partial uncertainties described in 5.4.2:

$$u_{\text{setup}} = \sqrt{\sum_{i=1}^{m} u_{\text{setup,i}}^2} \tag{18}$$

5.4.3 Uncertainty of the *reference meter*

The uncertainty of the *reference meter* is mainly due to its *calibration*, the uncertainties of the current *calibration conditions* (3.4) and the dependence of the *reference meter* on these conditions.

The following uncertainties shall be evaluated. The evaluation can be made on the basis of measurements or estimations, or a mixture of both. The calculation of uncertainties is described in Annex A. The measurement of dependence on conditions is described in 6.3.2.

a) *Calibration* uncertainty of the *reference meter*. It shall be obtained from its *calibration* certificate.

b) Uncertainty due to the change from the conditions in which the *reference meter* was calibrated and the current *calibration conditions*, u_{change}, as calculated in 5.4.4.

c) Uncertainty due to temperature dependence of the *reference meter*.

d) Uncertainty due to dependence on relative humidity of the *reference meter*. Power meters with integrating sphere are particularly sensitive to absorption peaks of water when using narrow laser sources.

e) Uncertainty due to dependence on the beam geometry of the *reference meter*.

f) Uncertainty due to dependence on multiple reflections. Multiple reflections may exist between the *optical input port* and the radiation source (for example a connector-adapter combination). Different artefacts will change the measured power.

g) Uncertainty due to wavelength dependence of the *reference meter*.

h) Uncertainty due to dependence on source *spectral bandwidth* of the *reference meter*.

i) Uncertainty due to dependence on state of polarization of the *reference meter*, except if unpolarized or depolarized light is used for *calibration*.

j) Uncertainty due to optical interference. Fabry-Perot cavities can occur between the surface of the *detector*, of the window and the end of the connector, if used.

k) Uncertainty due to the resolution of the *reference meter*. If the resolution of the *reference meter* is δy_{ref}, the standard uncertainty is (see ~~GUM~~ISO/IEC Guide 98-3:2008, F.2.2.1):

$$u_{ref,resolution} = \frac{1}{2\sqrt{3}} \delta y_{ref} \tag{19}$$

l) Uncertainties due to other dependences of the *reference meter*. Depending on the type of *reference meter*, there may be other uncertainties of the *reference meter*. These should also be measured or estimated.

~~Note that ageing is considered as a change of condition, with the time being the influencing condition. The elapsed time Δt between the calibration of the reference meter and its usage in the calibration of the test meter is known and its uncertainty is $u(\Delta t) = 0$. The uncertainty due to ageing of the reference meter is calculated in 5.3.3.1 and is taken into account in point b).~~

m) Uncertainty due to ageing of the *reference meter*.

Then calculate the combined standard uncertainty of the *reference meter* from the n above standard uncertainties:

$$u_{ref} = \sqrt{\sum_{i=1}^{n} u_{ref,i}^2 + u_{change}^2} \tag{20}$$

where u_{change} is the uncertainty due to the change of conditions, as determined from 5.4.4.

5.4.4   *Correction factors* and uncertainty caused by the change of conditions

5.4.4.1   General

The *reference meter* may exhibit a different *response* because it was calibrated under conditions different from the current *calibration conditions*. Examples of differences between the two sets of measurement conditions are: parallel beam versus divergent beam, different source spectra, a non-reflecting setup versus a setup with multiple reflections, or a large time span between the two reference dates resulting in ageing of the standard.

If the conditions under which the *reference meter* was calibrated are nominally identical to the current *calibration conditions* (their uncertainties can be different) and if the ageing of the *reference meter* is negligible, 5.4.4 can be skipped (CF_{change} = 1).

As indicated in Figure 4, each change comprises the nominal change in conditions and the change in uncertainty.

Figure 4 – Change of conditions and uncertainty

For each of the potential error contributions (5.4.4.2 to 5.4.4.8), one should decide if it is sensible to calculate a *correction factor* or not. Alternative A includes the calculation of a *correction factor* with the result of a relatively small uncertainty. Alternative B means waiving the *correction factors* (or CF_{change} = 1) and taking larger uncertainties into account to embrace the worst-case conditions.

If alternative A is chosen, the (cumulative) *correction factor* is:

$$CF_{change} = \frac{r_{previous}}{r_{current}} \tag{21}$$

or

$$CF_{change} = 1 - \Delta r \tag{22}$$

where

$r_{previous}$ is the *response* of the reference with *excitation* at the conditions at which it was calibrated;

$r_{current}$ is the *response* of the reference with *excitation* at the current *calibration conditions*;

Δr is the relative change of *response* ~~$\Delta r = (r_{previous} - r_{current}) / r_{current}$~~ $\Delta r = (r_{current} - r_{previous}) / r_{current}$.

Calculate the (cumulative) *reference meter*'s change-related *correction factor* by accumulating the partial *correction factors*, $CF_{change,i}$, outlined in 5.4.4.2 to 5.4.4.8. For each influencing quantity X_i, start with the calculation of the partial *correction factor*:

$$CF_{change,i} = 1 - \Delta r_i \tag{23}$$

The relative change of *response* Δr_i can be directly measured by changing the influencing quantity from the "previous" to the "current" *calibration conditions* or calculated from the nominal change of the influencing quantity Δx_i, and the *reference meter*'s nominal relative dependence on this quantity:

$$CF_{change,i} = 1 - c_i \times \Delta x_i \tag{24}$$

where

c_i is the partial derivate of the relative *response* on the influence quantity X_i, called sensitivity coefficient. See ISO/IEC Guide 98-3:2008, 5.1.3 and 5.1.4, for more detail.

If the sensitivity coefficient is not known very well, the following type B uncertainty ~~has to~~ should be taken into account:

$$u_{change,i} = u(c_i) \times \Delta x_i \tag{25}$$

where

$u(c_i)$ is the standard uncertainty of the sensitivity coefficient. The measurement of the dependences is discussed in 6.3.

Finally, calculate the *reference meter*'s cumulative *correction factor* from the above contributions:

$$CF_{change} = \prod_{i=1}^{n} CF_{change,i} \tag{26}$$

and the combined standard uncertainty due to the change of *calibration conditions*:

$$u_{change} = \sqrt{\sum_{i=1}^{n} u_{change,i}^2} \tag{27}$$

This *correction factor* corresponds to a known change of *response* of the *reference meter* caused by the two different sets of measurement conditions. It is a *correction factor* to apply to the power read by the *reference meter* (see 5.3).

~~5.3.3.1 Ageing~~

~~As mentioned in 5.3.2 the ageing is a change of condition. A correction factor is usually not calculated (CF = 1) except if the ageing coefficient of the reference meter is well known and stable and over a long time. The uncertainty should be calculated by multiplying the elapsed time Δt between the calibration of the reference meter and its use in the calibration of the test meter with the reference meter's ageing coefficient uncertainty $u(c_t)$.~~

$$\underline{u_{change,t} = u(c_t) \times \Delta t} ~~\tag{18}~~$$

~~Example: Only limits of ageing are known: ± 0,1 %/year. Following annex A, the ageing coefficient is c_t = 0 %/year and its uncertainty $u(c_t)$ = 0,1/ $\sqrt{3}$ %/year.~~

~~The uncertainty due to ageing of the reference meter one year after its calibration is then~~

$$\underline{u_{\text{change,t}} = u(c_{\text{t}}) \times \Delta t =} ~~\frac{0{,}1/\sqrt{3}}{}~~ ~~\%/\text{year} \times 1 \text{ year} = 0{,}06~\%~~ \tag{19}$$

5.4.4.2 *Correction factor* due to temperature change

The *correction factor* $CF_{\text{change},\Theta}$ should be calculated with the help of the nominal change between the "previous" and the "current" temperature $\Delta\Theta$ and the temperature sensitivity coefficient c_{Θ} of the *reference meter* (for example in %/°C).

$$CF_{\text{change},\Theta} = 1 - c_{\Theta} \times \Delta\Theta \tag{28}$$

5.4.4.3 *Correction factor* due to change of power level

The uncertainty should be calculated from the *nonlinearity* of the *reference meter* between the "previous" and the "current" power level. If necessary, a *correction factor* can be calculated from:

$$CF_{\text{change, }NL} = 10^{\frac{-NL}{10}} \tag{29}$$

where

NL is the *nonlinearity*, expressed in decibels (dB). Measurement of *nonlinearity* is described in Clause 7.

5.4.4.4 *Correction factor* due to change of beam geometry

The *correction factor* should be calculated from the change of *response* measured when changing the beam geometry.

5.4.4.5 *Correction factor* due to ~~dependence on multiple reflections~~ change of the connector-adapter combination

The *reference meter*'s *optical input port* should generally be assumed to be reflective. Such a reflection will travel back to the radiation source, for example, on an optical connector, be reflected again, and finally increase the displayed optical power level. This effect will give rise to a *correction factor* (usually < 1) and an increased uncertainty.

If, for example, the source used in the *calibration* of the *reference meter* ~~was~~ is non-reflective and the source used in the *calibration* of the *test meter* is reflective (caused by an optical connector), then the total power indicated by the *reference meter* is erroneous by the secondary reflection. If one assumes that the secondary reflection contributes an additional 5 % of the total power, then the individual *correction factor* is 0,95. This type of error can be reduced by using sources with highly absorptive enclosures, ~~respectively~~ or sources with low-reflectivity connector-adapter combinations.

The measurement method is described in 6.3.7.

5.4.4.6 *Correction factor* due to wavelength change

The *correction factor* should be calculated with the help of the nominal change of wavelength $\Delta\lambda$ and the *reference meter*'s nominal wavelength dependence c_{λ}.

$$CF_{\text{change},\lambda} = 1 - c_{\lambda} \times \Delta\lambda \tag{30}$$

5.4.4.7 *Correction factor* due to *spectral bandwidth* change

The *correction factor* should be calculated with the help of the nominal change of *spectral bandwidth* and the *reference meter*'s nominal dependence on the *spectral bandwidth*. Note that the *correction factor* remains 1 as long as the (uncorrected) wavelength-dependence is **linear** within the *spectral bandwidth* of the source. In the case that the wavelength dependence is curved, the *correction factor* can be computed with the help of the wavelength-dependence of the *reference meter* and the spectra of the two sources used in the *calibration* of the *reference meter* and in the *calibration* of the *test meter*.

5.4.4.8 Other *correction factors*

Depending on the type of *reference meter* and the *calibration conditions*, there may be other *correction factors*. These should also be measured or estimated as outlined ~~above~~ in 5.4.4.1.

5.4.5 Uncertainty due to the ~~test meter~~ *spectral bandwidths*

Uncertainties arising from the *test meter* are mainly due to the uncertainties of the *calibration conditions* and the dependence of the *test meter* on the conditions. The following uncertainties shall be evaluated. Their determination is similar to the evaluation described in 5.4.3. The calculation of uncertainties is described in Annex A, and the measurement of dependence on conditions is described in 6.3.2.

a) Uncertainty due to temperature dependence of the *test meter*.

b) Uncertainty due to dependence on relative humidity of the *test meter*. Power meters with integrating sphere are particularly sensitive to absorption peaks of water when using narrow laser sources.

c) Uncertainty due to dependence on beam geometry. This uncertainty comes from non-uniformity and angle-dependence of the *test meter*'s *optical input port*.

d) Uncertainty due to dependence on multiple reflections. Multiple reflections may exist between the *optical input port* and the radiation source (for example a connector-adapter combination). Different artefacts will change the measured power.

e) Uncertainty due to wavelength dependence of the *test meter*.

f) Uncertainty due to dependence on source *spectral bandwidth* of the *test meter*.

g) Uncertainty due to dependence on state of polarization of the *test meter*, except if unpolarized or depolarized light is used for *calibration*.

h) Uncertainty due to optical interference. Fabry-Perot cavities can occur between the surface of the *detector*, the window and the end of the connector, if used.

i) Uncertainty due to the resolution of the *test meter*. If the resolution of the *test meter* is δy_{DUT}, the standard uncertainty is (see ~~GUM~~ ISO/IEC Guide 98-3:2008, F.2.2.1):

$$u_{\text{DUT,resolution}} = \frac{1}{2\sqrt{3}}\delta y_{\text{DUT}} \tag{31}$$

j) Uncertainties due to other dependences of the *test meter*. Depending on the type of *test meter* and on the *calibration* process, there may be other conditions causing uncertainties.

Then calculate the combined standard uncertainty contribution of the *test meter* from the n above standard uncertainties:

$$u_{\text{DUT}} = \sqrt{\sum_{i=1}^{n} u_{\text{DUT,i}}^2} \tag{32}$$

5.5 Reporting the results

~~The results of each calibration should be reported as required by ISO/IEC 17025.~~

Suitable requirements for reporting the results of each *calibration* should be followed.

NOTE   Guidance about good practices for reporting the results of *calibration* can be found in ISO/IEC 17025 [18].

Calibration certificates or *calibration* reports referring to this document shall, at ~~least~~ a minimum, include the following information:

a)   all *calibration conditions* (3.4) as described in 5.2;

b)   the *test meter*'s *correction factor*(s) (3.6) or *deviation*(s) (3.8), if the *test meter* was not adjusted;

c)   on receipt *correction factors* or *deviations* and after *adjustment* (3.2) *correction factors* or *deviations* in the case that an *adjustment* was carried out;

d)   the *calibration* uncertainty in the form of an expanded uncertainty as described in 5.4;

e)   the *instrument state* (3.10) of the *test meter* during the *calibration*;

f)   evidence that the measurements are traceable (see ISO/IEC 17025~~:1999, 5.10.4.1 c)~~).

6   Measurement uncertainty of a calibrated power meter

6.1   Overview

The measurement uncertainty of a calibrated power meter is ~~greater~~ larger than its *calibration* uncertainty. It is the combination of the *calibration* uncertainty and of uncertainty contributions due to the dependence of the power meter on the conditions of measurement.

The determination of the measurement uncertainty of a calibrated power meter used at *reference conditions* or at *operating conditions* is not part of the *calibration* process. It is performed for example by manufacturers of power meters in order to establish specifications. It is not mandatory for *calibration* certificates or *calibration* reports referring to this document.

6.2   Uncertainty at *reference conditions*

Reference conditions (3.25) are used for testing the performance of a power meter or for intercomparisons. They are usually defined by manufacturers in order to specify the smallest uncertainty of a measuring instrument; therefore, they are often identical or close to its *calibration conditions*.

The uncertainty at *reference conditions* is the uncertainty on the result of a measurement taken by the calibrated and adjusted power meter when operated at *reference conditions*. It depends on the *calibration* uncertainty of the power meter, the *reference conditions* and the dependence of the power meter on the *reference conditions*. This is the reason why the uncertainty at *reference conditions* is always larger than the *calibration* uncertainty. Even when the *reference conditions* are identical to the *calibration conditions* (no uncertainty due to change of conditions), the *test* ~~(power)~~ *meter*'s dependences on the *reference conditions* have to be added (in quadrature) to the *calibration* uncertainty for a second time. Calculating the uncertainty at *reference conditions* of the calibrated *test meter* is similar to calculating the measurement uncertainty at *calibration conditions* of the *reference meter* described in 5.4.3:

$$u_{\text{DUT,ref\_conditions}} = \sqrt{u^2\left(CF_{\text{DUT}}\right) + u_{\text{DUT}}^2} \tag{33}$$

where

$u(CF_{DUT})$ is the *calibration* uncertainty of the *test meter*, as determined ~~from~~ in accordance with 5.4;

u_{DUT} is the uncertainty due to the dependence of the *test meter* on the *reference conditions*, as determined ~~from~~ in accordance with 5.4.5.

The description of the *reference conditions* should be made in the same way as the *calibration conditions* described in 5.2.

6.3 Uncertainty at *operating conditions*

6.3.1 General

The uncertainty at *operating conditions* (or operating instrumental uncertainty, see 3.2.11 of IEC 60359:2001) is the uncertainty on the result of a measurement taken by the calibrated and adjusted power meter when operated within a range of *operating conditions* (3.18). It depends on the *calibration* uncertainty, the *operating conditions* and the dependence of the power meter on the *operating conditions*:

$$u_{DUT,operating} = \sqrt{u^2(CF_{DUT}) + u^2_{extension}} \tag{34}$$

where

$u(CF_{DUT})$ is the *calibration* uncertainty of the *test meter*, as determined ~~from~~ according to 5.4.

$u_{extension}$ is the extension uncertainty, due to the dependence of the meter on the *operating conditions*, as determined from Equation (35).

Contrary to the *calibration conditions* (3.4) described in 5.2, each *operating condition* should be described by a range when possible. The set of *operating conditions* is specified by

a) the maximum time span between recalibrations,

b) the range of ambient temperatures,

c) the range of power levels (*measuring range*),

d) the range of beam geometries described by their *spot diameter* and *numerical aperture*, or the range of fibre types,

e) the applicable connector-adapter combinations, if any,

f) the range of wavelengths of the source, and

g) the maximum *spectral bandwidth* of the source.

All possible polarization states are included in the *operating conditions* by default. A relative humidity below the condensation point is also assumed.

The above conditions may be defined either by the power meter manufacturer or by the *calibration* laboratory in charge of the *calibration* for *operating conditions*.

To calculate the extension uncertainty, combine all uncertainties due to the dependences on the conditions:

$$u_{extension} = \sqrt{\sum_{i=1}^{n} u^2_{extension,i}} \tag{35}$$

where:

$u_{extension,i}$ are contributions to the extension uncertainty;

n   is the total number of contributions.

6.3.2   Determination of dependences on conditions

Each ~~individual~~ dependence should be recorded as relative change of the meter's *response*, caused by changing the relevant condition within its *operating range*. During the test, all other conditions should be kept at the *calibration conditions*. The zero point is defined by the *response* at *calibration conditions*. This way, each dependence can be specified by a range that is defined by the maximum positive and negative changes of the *response*. An asymmetric range about the zero point is the usual result, as shown in Figure 5.
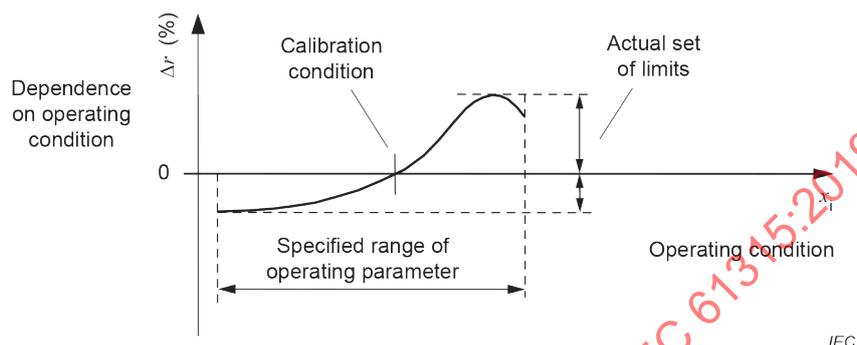

Figure 5 – Determining and recording an extension uncertainty

In order to obtain good measurement accuracy, the guidelines in Clause 4 should be observed. Uncertainties in the measurements should be ~~as small~~ low as possible, because the *measurement results* shall include these uncertainties. It is acceptable to use estimations instead of measurements if these estimations are based on known physical relations or on a sufficiently large number of characterizing measurements of the same type of *test meter*.

For the determination of the combined standard uncertainty of the *test meter* at *operating conditions*, the limits quantifying the individual dependences shall be converted to standard uncertainties using Equation (A.5).

The individual uncertainties are usually assumed to be independent. However, in some instances an uncertainty may be strongly dependent on more than one condition. Examples are outlined in 6.3.5, 6.3.7 and 6.3.8. If the extension uncertainty is substantially increased by changing the other conditions (within their specified *operating ranges*), this larger uncertainty shall be recorded. The calculation of the uncertainty shall then be based on these larger uncertainties.

6.3.3   Ageing

Ageing is the relative change of *response* ~~during~~ over a given period. It can be determined from the results of successive *calibrations* of the meter at the same conditions or from indications of the manufacturer.

For a manufacturer, the relative change of *response* ~~during~~ over a given period shall be determined with the assumption of careful use of the instrument. It is recommended to expose the power meter to its typical environmental conditions, for example ambient temperature (23 ± 1) °C for a laboratory-type instrument, *optical input port* non-irradiated, continuously repetitive cycles of power-on 12 h, power-off 12 h, with a total test time equal to the given period. The change of *response* should be measured by comparison with a *working standard*. Regular and traceable recalibration of the *working standard* will be necessary, in order to exclude ageing of the *working standard*. As always, the measurement uncertainty, in this case mostly the uncertainty of the *working standard*, shall be taken into account.

It is recommended to calculate the ageing uncertainty from a rectangular distribution obtained as described above (see Clause A.3). If, for example, a *detector* is known to increase its *response* by a maximum of 0,1 % per year at a certain wavelength, then the ageing uncertainty is characterized by a rectangle that extends from 0 % (at time 0) to +0,1 % (at time 1 year).

6.3.4 Dependence on temperature

The relative change of *response* against the *response* at the *calibration conditions* should be measured by changing the temperature within the operating temperature range. The rectangular uncertainty distribution is then defined by the most negative and the most positive relative changes of the *response*. Only the extremes of the *response* as a function of the temperature are relevant, not the *responses* at the extremes of temperature (see Figure 5).

Note that the temperature dependence of the *spectral responsivity* of semiconductor *detectors* depends on the wavelength.

6.3.5 Dependence on the power level (*nonlinearity*)

The relative change of *response* against the *response* at the *calibration* power level should be measured in accordance with Clause 7.

6.3.6 Dependence on the type of fibre or on the beam geometry

6.3.6.1 General

Fibre-optic power meters may be designed to accept fibres or open beams. It is assumed that the *response* of the power meter depends on the geometry of the light beam because, for example, of non-uniformity and angle-dependence of the meter's *optical input port*.

The relative change of *response* should be measured with a *working standard* that exhibits

- negligible angle-dependence,
- negligible surface reflections, and
- a sufficiently large active area to capture the fibre beams or the open beams.

~~A good choice of working standard may be a well-characterized power meter with an integrating sphere.~~
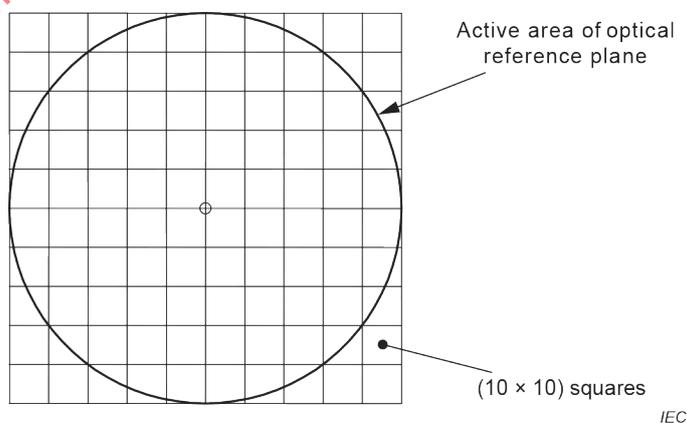

Figure 6 – Possible subdivision of the *optical reference plane* into 10 × 10 squares, for the measurement of the spatial *response*

Another possibility is evaluating the uncertainties with a mathematical analysis, based on the assumption that all uncertainties are caused by non-uniform spatial *responses* of the *test meter*'s reference plane. In preparation of this analysis, the active area of the *optical reference plane* should be subdivided into an array of squares, for example, 10×10 squares as in Figure 6.

Then two types of measurements should be carried out:

a) measurements of the spatial power density, together with the angles of incidence, on the *optical reference plane* as generated by the applicable beam geometries;

b) measurements of the *test meter*'s spatial *response*, weighted with appropriate multipliers which characterize the meter's dependence on oblique incidence (angle dependence), on the *test meter*'s reference plane: the spatial *response* should be measured with a beam diameter equal to the length of the square.

The change of *response* upon changing the beam parameters can then be evaluated on the basis of modelling the necessary *measurement results*, by multiplying the (spatial) power levels with the spatial *responses* and adding all products. Note that the spatial *responses* are usually wavelength-dependent.

6.3.6.2   Measurement of the fibre dependence

~~In the test of fibre-related uncertainties, the fibres under test should be fully excited, both in terms of the core diameter and of the numerical aperture. An approximate fibre length of 2 m is recommended. Optical power in the cladding (cladding modes) should be removed with appropriate mode strippers if necessary.~~ In the test of fibre-related uncertainties, multimode fibres under test should be slightly underfilled (see 5.2). The fibres should be terminated by the connector-adapter combination defined by the *calibration conditions*. Both the connector and the adapter should exhibit a low reflectivity, so that multiple reflections between the connector-adapter combination and the *detector* do not influence the *measurement results*. The *spectral bandwidth* of the source should be narrow enough to avoid averaging over a wide range of wavelengths.

Step 1: the output of the reference fibre is measured with both the *working standard* and the *test meter*, and the difference is (mathematically) adjusted to zero.

Step 2: the above procedure is applied to

a) a standard single-mode fibre as defined by IEC 60793-2, and

b) the (specified) fibre with the largest core diameter, the fibre with the largest *numerical aperture*, or both.

The intention of the test is to measure the dependence of the *test meter* on the type of fibre and on the mode volume. The largest relative change of *response* against step 1 (positive and negative) should be used to determine the fibre-related uncertainty. The uncertainty shall also include the uncertainty in measuring the fibre outputs with the *working standard*, caused for example by the effects of non-uniformity, beam divergence and multiple reflections on the *working standard*.

In these measurements, a significant type A uncertainty may be caused by "speckles", in conjunction with the non-uniformity of the *optical input port*. Speckles are irregular *irradiance* distributions caused by interference between different modes in a multimode fibre. This effect occurs particularly when the fibre is excited by the (highly coherent) radiation from a laser diode. This uncertainty can be reduced by averaging a series of *measurement results*, in which each sample is taken after a slight movement of the fibre. Fibre movement will change the speckle pattern. Note this may be accompanied by a change of the total *radiant power*, because of a change of the reflected power and the laser diode sensitivity to reflected power.

Speckles do not exist in single-mode fibres when the exciting wavelength is sufficiently longer than the fibre's cut-off wavelength. Another possibility of eliminating the speckle pattern is using a less coherent source, such as a filtered LED or a filtered "white" radiation source.

6.3.6.3   Measurement of open-beam dependence

Similar to measuring the fibre dependence, the dependence on the *spot diameter* (3.31) and the *numerical aperture* (3.17) of an open beam can be evaluated by comparison with a *working standard* that exhibits a uniform large area *detector* and negligible angle dependence.

To address the problem of combined dependence on *spot diameter* and *numerical aperture*, it may be sufficient to evaluate

a) the relative change of *response* (against the *response* at *calibration conditions*) due to *excitation* with the specified smallest *spot diameter* – smallest *numerical aperture*, and

b) the relative change of *response* due to *excitation* with the specified largest *spot diameter* – largest *numerical aperture*.

6.3.7   Dependence on the connector-adapter combination

6.3.7 discusses the *test meter*'s dependence on ~~multiple~~ reflections ~~between the optical input port and~~ from the radiation source (for example an optical connector or other mechanical parts in the beam path between the source and the *optical input port*). Note that the reflections may be specular or diffuse.

The relative change of *response* should be measured with the help of a *working standard* that exhibits negligible angle-dependence and surface reflections. The fibre should be the one ~~of~~ used for the *calibration* ~~conditions~~. It is advisable to hold the fibre end in place during the measurement, in order to avoid any bending-induced changes of the power level. The source used should not be too coherent to avoid Fabry-Perot type interference (see 6.3.8.2): it should be broad enough, for example, 1 nm or more.

Step 1:   the reference beam geometry ~~(respectively~~ exiting the source or the reference fibre~~)~~, (together with the reference connector-adapter combination), is measured with both the *working standard* and the *test meter*, and the difference is (mathematically) adjusted to zero.

Step 2:   the step 1 procedure is applied to all specified connector-adapter combinations, by repeating each connection several times to reduce type A uncertainties. The largest relative change of *response* against step 1 (positive and negative) should be used to determine the uncertainty. The uncertainty shall also include the type B uncertainty in measuring the various combinations with the *working standard*, caused for example by ~~multiple~~ the reflections ~~on~~ when using the *working standard*.

~~Referring to~~ In accordance with the last paragraph of 6.3.2, it may also be necessary to ~~additionally~~ measure the dependence with the highest-order fibre, as listed in 6.3.6.2. A high-order fibre will create a larger image on the *optical reference plane*, and therefore make limitations in the positioning accuracy more obvious. In this case, an increased dependence should be recorded.

6.3.8   Dependence on wavelength

6.3.8.1   General

The relative change of spectral *response* against the *response* at the *calibration* wavelength should be measured. These measurements will normally be carried out using a spectrally continuous source imaged through a spectrally discriminating instrument, for example a monochromator or a number of spectral filters. The stray light, that is light not at the selected wavelength, should be evaluated, in order to ensure accurate *measurement results*. The ~~centre~~ *centroidal wavelength*(s) and the *spectral bandwidth*(s) should also be measured. The bandwidth should be narrow, because a wide bandwidth in conjunction with a strong curvature of the *test meter*'s wavelength dependence is capable of producing erroneous *measurement results*. Note that extremely narrow *spectral bandwidth* may cause optical interference problems, which is comb-like wavelength dependence, when the beam path contains one or more optical resonators.

The beam geometry should be ~~one of the calibration conditions~~ appropriate for the determination of this dependence. It may be possible to substitute a fibre beam using a combination of lenses and apertures. In this case, care should be taken to match the irradiated *spot diameter* and position on the *optical reference plane* with those achieved using a fibre input. Care should also be taken to ensure that back reflections from the *optical input port* do not add uncertainties to the *measurement results*.

The measurement should be carried out by direct comparison with a *working standard* by using the substitution technique. The *working standard* should have been calibrated for relative spectral *response*.

Because of the relatively low power levels in these measurements, zero adjustment of both power meters is essential. If the instrument comprises means of correction, for example a *calibration* curve or a table stored in a memory, the relative change of *response* from the corrected *response* has to be measured.

Changing the temperature may strongly influence the wavelength-dependence. For example, the wavelength-dependence of a germanium photodiode at 1 550 nm is much stronger at 0 °C than at room temperature. In general, the wavelength uncertainty shall be calculated on the basis of the largest wavelength-dependence, in this case the one at 0 °C.

6.3.8.2 Dependence on wavelength due to Fabry-Perot type interference

When using a narrow *spectral bandwidth* laser ($B \ll 1$ nm), the spectral *response* can sometimes vary rapidly with respect to wavelength, as depicted in Figure 7. This is usually caused by Fabry-Perot cavity(ies) in the optical path to the *detector*. Fabry-Perot cavities can occur between the two faces of the window in the *detector* cap, between one face of the window and the *detector* itself, or, if a fibre is used, between the end of the fibre and any of the other surfaces.
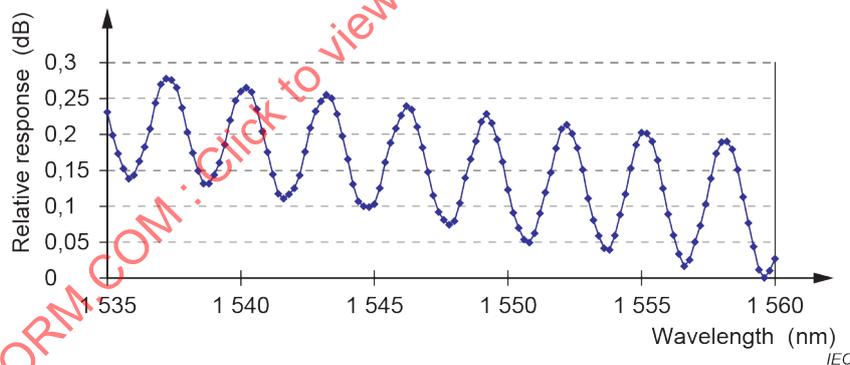

Figure 7 – Wavelength dependence of *response* due to Fabry-Perot type interference

In Figure 7, the peak-to-peak variation reaches $\Delta_{dB} = 0{,}2$ dB ($\Delta_\% = 4{,}6$ %), which is significant. The standard uncertainty due to optical interference is the standard *deviation* of the sine pattern.

$$u_{int} = \frac{1}{\sqrt{2}} \times \frac{\Delta_\%}{2} = 1{,}6 \text{ %} \tag{36}$$

6.3.9 Dependence on *spectral bandwidth*

This dependence increases with the curvature of the *detector*'s wavelength dependence. The relative change of *response* as a function of the *spectral bandwidth* of the source has to be tested within the specified range of *spectral bandwidths*. A monochromator can be used to generate a variable *spectral bandwidth*; the actual power level should be measured with a

working standard with negligible wavelength-dependence. The spectral-bandwidth dependence can also be evaluated by mathematical analysis, based on the known spectral *response* of the *test meter* and on the known spectral characteristics of the source.

6.3.10   Dependence on polarization

A method of evaluation of the *polarization dependent response* (PDR) (3.22) of the *test meter* is to measure the *response* of the meter multiple times at different states of polarization. A stable light source polarized to nearly 100 % should be used, otherwise use a polarizer after the source as shown in Figure 8. A polarization controller is used to convert the fixed input polarization state to all possible output states.
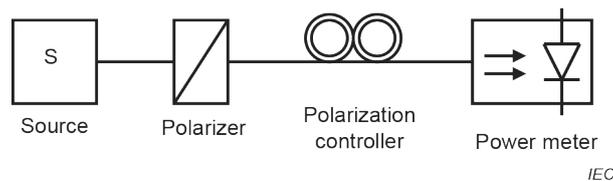

Figure 8 – Measurement setup of *polarization dependent response*

The source power instability and the loss variation of the polarization controller should be far ~~smaller~~ lower than the polarization dependence of the *test meter*. This should be verified by replacing the *test meter* with a *detector* with a very low *polarisation dependent response*.

~~NOTE~~ The laser sources may react with unstable power when light with a varying polarization state is back-reflected; therefore, an attenuator or isolator may have to be inserted between the source and the polarization controller.

Another PDR measurement method, the matrix method, can be adapted from the polarization dependent loss (PDL) ~~measurement~~ Mueller matrix method in ~~IEC 61300-3-12~~ IEC 61300-3-2:2009, as described in [3].

6.3.11   Other dependences

Depending on the type of *test meter*, there may be dependences on other parameters. These should also be characterized as relative changes of *response* against the *response* at the *calibration conditions*.

One example may be including intensity-modulated optical signals into the *operating conditions*, in the form of specifying a range of modulation frequencies and duty cycles, and evaluating the type B uncertainty due to the modulation. ~~Be aware~~ It is important to take into account that extreme duty cycles are capable of saturating the *detector*, the electronics, or both.

7   *Nonlinearity calibration*

7.1   General

The *nonlinearity* (3.16) of the power meter should be calibrated to ensure accurate measurements at power levels away from the *calibration* level and for relative measurements such as loss and gain measurements. The *calibration* should be made by increasing and decreasing the power level to detect nonlinearities at the boundaries of each amplifier range or, whenever possible, to include *measurement results* at both sides of each range boundary, in order to include nonlinearities at these boundaries. ~~Be aware~~ It is important to note that the *detector nonlinearity* is dependent on the wavelength. As an example, an InGaAs *detector* that is linear at 1 310 nm and 1 550 nm may be nonlinear at 850 nm.

Several methods are possible. The superposition method is the reference method, as it is the most accurate and does not require a *reference standard* (self-calibrating method). ~~However, the used power steps of 2 (about 3 dB) might be too large to detect nonlinearities that might appear at amplifier range boundaries. This limitation may be avoided by starting the calibration from several reference powers, or by taking separate measurements of the same power level on both sides of the amplifier range boundaries.~~

All methods use sources with selectable power level, for example (stabilized) laser diode sources and variable attenuators. The generated power levels should cover the specified *measuring range* (3.13). During the test, the maximum permissible *irradiance* of the input port should be defined by the optical power at the upper end of the *measuring range* and by single-mode fibre *excitation*.
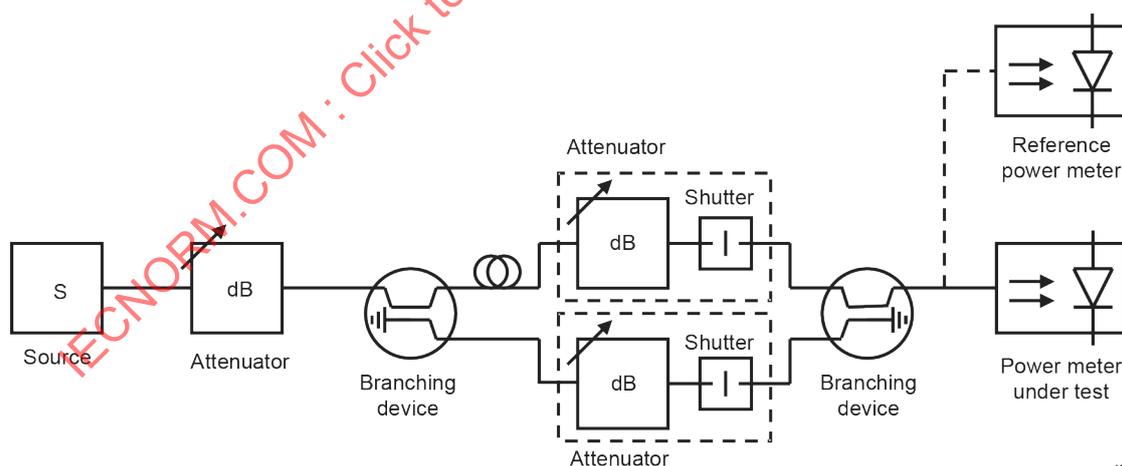
The power level saturating the *detector* is dependent on the beam geometry. A small *spot diameter* may saturate the *detector* at lower power than a larger *spot diameter*.

NOTE Extreme ambient temperatures may increase the *nonlinearity*. ~~Referring to the statement on "dependence on more than one operating condition" in 6.2, it may be necessary to additionally~~ As stated in the last paragraph of 6.3.2, some uncertainties can be dependent on more than one operating condition, and it can additionally be necessary to measure the *nonlinearity* at the extremes of the operating temperature range, and to record an increased uncertainty at *operating conditions*.

7.2 *Nonlinearity calibration* based on superposition

7.2.1 General

Highly accurate *nonlinearity calibration* is possible with the superposition method (also known as the "addition method") [4] [5]. A "fibred" version of the open-beam double aperture method [6] [7] may be used with single-mode fibres. A possible setup is illustrated in Figure 9. The power is split into two different paths where shutters are located and then recombined on the power meter under test.

Figure 9 – *Nonlinearity calibration* based on superposition

Stable, optically-isolated (to reduce sensitivity to reflections) distributed feedback (DFB) lasers can be used, provided that the linewidth is broadened to yield an optimized coherence, as with the procedure for the absolute *calibration*. The two paths of the setup should have different lengths (around 100 m for DFB lasers) to avoid (Mach-Zehnder-type) interference fluctuations, and unused branches of branching devices ~~must~~ shall be terminated. The drawback of this method is its higher insertion loss: typically around 1,5 dB for the first attenuator, 0,5 dB for the first branching device, 1,5 dB for the second attenuator~~s~~ and about 3,5 dB for the combining branching device for a total of about 7 dB. For higher power measurements, an optional optical

amplifier (like an EDFA – erbium doped fibre amplifier – for the 1,55 µm band) can be inserted between the source and the first attenuator.

7.2.2 Procedure

(1) Set the attenuators in the two paths so that the power measured on the meter is the same when light is coming from one path or from the other path.

(2) Open both shutters and measure the total power from both paths simultaneously: $P_{ab,i}$.

(3) Close the shutter on path b and measure the power from path a: $P_{a,i}$.

(4) Close the shutter on path a, open the shutter on path b and measure the power from path b: $P_{b,i}$.

(5) If the sum of the individual powers is not equal to the total power, there is a *nonlinearity*:

$$NL_i = 10 \times \log_{10} \frac{P_{ab,i}}{P_{a,i} + P_{b,i}} (dB) \tag{37}$$

(6) Using the first attenuator, attenuate the total power by a factor 2 ($10 \log_{10} 2 \cong 3,01$ dB) to the level of the individual powers of the preceding step.

(7) Repeat steps (2) to (6) through all the desired range.

(8) At the end, the global *nonlinearity* is the sum of all the local nonlinearities expressed in decibels (dB), starting calculations from the reference power level where the *nonlinearity* is zero (higher order terms are neglected).

$$NL_{global}(P_n) = -\sum_{i=0}^{n+1} NL_i \text{ for } n = -1, -2, -3, \text{ etc.} \tag{38}$$

$$NL_{global}(P_0) = 0 \text{ (reference power)}$$

$$NL_{global}(P_n) = +\sum_{i=1}^{n} NL_i \text{ for } n = 1, 2, 3, \text{ etc.}$$

where

$n < 0$ indicates power levels lower than the reference power;

$n > 0$ indicates power levels higher than the reference power;

NL_i is the local *nonlinearity* for the ith step ($i = 0$ for the step where P_{ab} is the reference power).

The result is a list of global nonlinearities for the whole power range in steps of 3,01 dB as seen in Table 2:

Table 2 – *Nonlinearity*

i	$P_{a,i}$ W	$P_{b,i}$ W	$P_{a,i} + P_{b,i}$ W	$P_{ab,i}$ W	NL_i dB	$NL_{global}(P_{ab,i})$ dB
2					NL_2	$NL_1 + NL_2$
1					NL_1	NL_1
0				P_0	NL_0	0
−1					NL_{-1}	$-NL_0$
−2					NL_{-2}	$-NL_0 - NL_{-1}$

The largest *nonlinearity* relative to the reference power is:

$$NL_{max} = \pm \max(|NL_{global}|) \text{ (dB)} \tag{39}$$

This result of the *nonlinearity calibration* can be included in the *test meter*'s *calibration* certificate or *calibration* report described in 5.5. If desired, NL_{max} may be reported separately, together with its applicable uncertainty, as calculated in 7.2.3.

Using 3 dB power steps might be too large to detect nonlinearities that might appear at amplifier range boundaries. This limitation can be avoided by starting the *calibration* from several reference powers, or by taking separate measurements of the same power level on both sides of the amplifier range boundaries.

7.2.3   Uncertainties

Typical possible uncertainties of this method include all possible power fluctuations during a set of the three measurements such as source fluctuations due to drifts or sensitivity to changing reflections, instabilities due to interference if the coherence length of the laser is too large, polarization sensitivity and resolution of the power meter. These errors for each step are cumulative and will add to the errors of the preceding steps.

Another uncertainty is the inequivalence between the individual powers of each step and also with the total power of the next step. If the individual powers are not properly balanced, the result will not be reliable. For this last reason, the use of the optional attenuator in each path is recommended, as shown in Figure 9 (the shutter is usually included in the attenuator). They allow the power in each path to be balanced at the beginning of the measurements. Another version of the setup uses this approach, but employs two separate laser sources directly connected to the second and third attenuators respectively. It has the advantage to start measurements at higher powers but it requires communication with the *test meter* to adjust the attenuators at each step.

Calculate first the combined standard uncertainty for the local *nonlinearity* (one step) $u(NL_i)$ by root-sum-squaring all relevant standard uncertainty contributions. Then calculate the standard uncertainty of the global *nonlinearity* with:

$$u\left(NL_{global}\right) = \sqrt{n} \times u\left(NL_i\right) \text{ (dB)} \tag{40}$$

where

n is the number of 3,01 dB steps counted from the reference level.

7.3 *Nonlinearity calibration* based on comparison with a calibrated power meter

7.3.1 General

One possible measurement method is direct comparison of the *test meter* with a *reference meter* by using the substitution technique. The *reference meter* is used to determine the output power. Then the *reference meter* is replaced by the *test meter*. The *measurement results* of both meters are recorded. In this case, errors can be due to the repeatability of the attenuator, its PDL, the source power stability and the *nonlinearity* of the *reference meter*. The *nonlinearity* of the *reference meter* should have been calibrated using a more accurate method.

It is advisable to repeat the measurements with the *working standard* to check for drifts in the measurement. In order to extend the measurements to low power levels, it is recommended that the *reference meter* incorporate a low noise *detector*.

Instead of the substitution, simultaneous *excitation* of both the standard *reference meter* and the *test meter*, with the help of an appropriate beam splitter or branching device, is also possible, as depicted in Figure 10. A beam splitter/branching device with an asymmetric ratio, or the use of a second attenuator, will allow an extension of the dynamic range of the measurement in both directions. The dependence of the ratio to the power level and polarization has to be investigated.
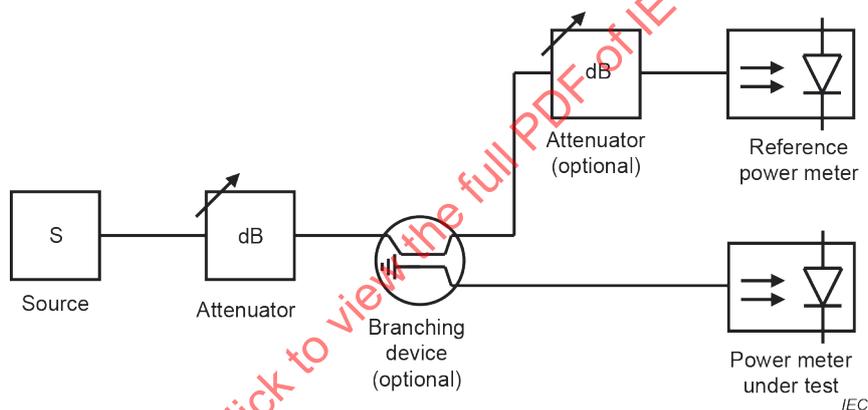
Figure 10 – Measurement setup for *nonlinearity calibration* by comparison

7.3.2 Procedure

(1) Set the desired reference power with the help of the first attenuator.

(2) Measure the *radiant power* with the *reference meter* $P_{ref,0}$ and with the *test meter* $P_{DUT,0}$.

(3) Increase (or decrease) the power with the help of the first attenuator and record the power measured with the *reference* meter $P_{ref,i}$ and with the *test meter* $P_{DUT,i}$.

(4) Calculate the *nonlinearity*:

$$NL_i = 10 \times \log_{10} \frac{P_{DUT,i}}{P_{DUT,0}} - 10 \times \log_{10} \frac{P_{ref,i}}{P_{ref,0}} \ \text{(dB)} \tag{41}$$

(5) Repeat steps (3) to (4) to cover the measurement range.

7.3.3 Uncertainties

Possible sources of measurement uncertainties are given in the following list, which may not be complete exhaustive. Additional contributions may have to be taken into account, depending on the measurement setup and procedure. The mathematical basis, Annex A, should be used to calculate and state the uncertainties.

a) *nonlinearity* of the linearity standard (usually calibrated by the superposition method);

b) source instability (back-reflections may cause source instability);

c) optical interference (the coherence length of the source should be smaller than the distance between reflection points);

d) polarization dependence of the components;

e) resolution of the *test meter*;

f) stability of the ratio of the beam splitter or the branching device if used;

g) depending on the procedure, the repeatability of the attenuator.

7.4   *Nonlinearity calibration* based on comparison with an attenuator

The simplest but least accurate method to measure the *nonlinearity* is based on varying the power level with a calibrated attenuator. The *traceability chain* (3.34) of the attenuator shall be determined. Care shall be taken in the calculation of the uncertainty since the *calibration* of the attenuator is itself based on the linearity of a calibrated power meter. This method does not require a second power meter; instead, the reference power levels can then be calculated with the known attenuation of the attenuator. The main errors arise from the *nonlinearity* of the variable attenuator, its PDL in the case of single-mode fibres and the source power stability. Be also aware of It is also important to take into account the attenuator's repeatability and wavelength dependence. This method is nevertheless useful when high accuracy is not necessary because it is simple and because the low insertion loss (only the loss of the attenuator) permits measurement at higher power than other methods (up to the maximum input power at which the attenuator remains linear).

7.5   *Calibration* of power meter for high power measurement

Most photoelectric *detectors* become nonlinear above an optical power of about 10 mW. Sensors designed to measure power at higher power usually incorporate an attenuator in front of the *detector*.

Absolute power *calibration* at high power [8] is not always available widely. When not possible, it is then necessary to calibrate the *nonlinearity* of the power meter up to high power. In this context, high power is defined as powers greater than 10 mW. It is not straightforward to use the same setup as described in the previous clauses 7.2 to 7.4 since several components may exhibit nonlinear effects. The behaviour at high power of all elements in the *calibration* setup (connectors, attenuators, branching devices, etc.) should be investigated. The superposition method is the preferred method, since it does not rely on a *reference standard*, but note that the use of a long length of fibre in one path of the superposition system is not desirable at high powers due to the possibility of nonlinear effects causing apparent *nonlinearity* of the power meter.

Annex A
(normative)

Mathematical basis for measurement uncertainty calculations

A.1 General

Annex A summarises the form of evaluating, combining and reporting the uncertainty of measurement. ~~It is based on the "Guide to the expression of uncertainty in measurement" (GUM). It does not relieve the need to consult this guide for more advice.~~ It is based on ISO/IEC Guide 98-3. Annex A shall be read in conjunction with ISO/IEC Guide 98-3 for additional information.

This document distinguishes two types of evaluation of uncertainty of measurement. Type A is the method of evaluation of uncertainty by the statistical analysis of a series of measurements on the same measurand. Type B is the method of evaluation of uncertainty based on other knowledge.

A.2 Type A evaluation of uncertainty

Type A evaluation of standard uncertainty can be applied when several independent observations have been made for a quantity under the same conditions of measurement.

For a quantity X estimated from n independent repeated observations X_k, the arithmetic mean is:

$$\overline{X} = \frac{1}{n}\sum_{k=1}^{n} X_k \tag{A.1}$$

This mean is used as the estimate of the quantity, that is $x = \overline{X}$. The experimental standard *deviation* of the observations is given by:

$$s(X) = \left[\frac{1}{n-1}\sum_{k=1}^{n}\left(X_k - \overline{X}\right)^2\right]^{1/2} \tag{A.2}$$

where

$\overline{X}$ is the arithmetic mean of the observed values;

X_k are the measurement samples of a series of measurements;

n is the number of measurements; it is assumed to be large, for example, $n \geq 10$.

The type A standard uncertainty $u_{\text{typeA}}(x)$ associated with the estimate x is the experimental standard *deviation* of the mean:

$$u_{\text{typeA}}(x) = s\left(\overline{X}\right) = \frac{s(X)}{\sqrt{n}} \tag{A.3}$$

A.3   Type B evaluation of uncertainty

Type B evaluation of standard uncertainty is the method of evaluating the uncertainty by means other than the statistical analysis of a series of observations. It is evaluated by scientific judgement based on all available information on the variability of the quantity.

If the estimate x of a quantity X is taken from a manufacturer's specification, *calibration* certificate, handbook, or other source and its quoted uncertainty $U(x)$ is stated to be a multiple k of a standard *deviation*, the standard uncertainty $u(x)$ is simply the quoted value divided by the multiplier.

$$u(x) = U(x) \,/\, k \tag{A.4}$$

If only upper and lower limits X_{max} and X_{min} can be estimated for the value of the quantity X ~~(for example a manufacturer's specifications or a temperature range)~~, a rectangular probability distribution is assumed~~, the estimated value is~~.

$$x = \frac{1}{2}(X_{max} + X_{min}) \tag{A.5}$$

~~and the standard uncertainty is~~

$$u(x) = \frac{1}{2\sqrt{3}}(X_{max} - X_{min}) \tag{A.6}$$

The standard uncertainty is

$$u(x) = \frac{\left(\left|X_{max} - x\right|, \left|X_{min} - x\right|\right)_{MAX}}{\sqrt{3}} \tag{A.5}$$

The contribution to the standard uncertainty associated with the output estimate y resulting from the standard uncertainty associated with the input estimate x is

$$u(y) = c \times u(x) \tag{A.6}$$

where

c is the sensitivity coefficient associated with the input estimate x, that is the partial derivative of the model function $y(x)$, evaluated at the input estimate x.

$$c = \frac{\partial y}{\partial x} \tag{A.7}$$

The sensitivity coefficient c describes the extent to which the output estimate y is influenced by variations of the input estimate x. It can be evaluated by Equation (A.7) or by using numerical methods, that is by calculating the change in the output estimate y due to a change in the input estimate x from a model function. Sometimes, it may be more appropriate to find the change in the output estimate y due to the change in x from an experiment.

A.4   Determining the combined standard uncertainty

The combined standard uncertainty is used to collect a number of individual uncertainties into a single number. The combined standard uncertainty is based on statistical independence of the

individual uncertainties; it is calculated by root-sum-squaring all standard uncertainties obtained from type A and type B evaluation:

$$u_c(y) = \sqrt{\sum_{i=1}^{n} u_i^2(y)} \tag{A.8}$$

where

i is the current number of individual contributions;

$u_i(y)$ are the standard uncertainty contributions;

n is the number of uncertainties.

NOTE ~~It is acceptable to neglect~~ Uncertainty contributions ~~to~~ in this equation that are smaller than 1/10 of the largest contribution are negligible, because squaring them will reduce their significance to 1/100 of the largest contribution.

When the quantities above are to be used as the basis for further uncertainty computations, then the combined standard uncertainty, u_c, can be re-inserted into Equation (A.8). Despite its partial~~ly~~ type A origin, u_c should be considered as describing an uncertainty of type B.

A.5   Reporting

In *calibration* reports and technical data sheets, combined standard uncertainties shall be reported in the form of expanded uncertainties, together with the applicable level of confidence. *Correction factors* or *deviations* shall be reported. The expanded uncertainty U is obtained by multiplying the standard uncertainty $u_c(y)$ by a coverage factor k:

$$U = k \times u_c(y) \tag{A.9}$$

For a level of confidence of approximately 95 %, the default level, then $k = 2$. If a level of confidence of approximately 99 % is chosen, then $k = 3$. The above values for k are valid under some conditions (see ~~GUM,~~ ISO/IEC Guide 98-3); if these conditions are not met, larger coverage factors are to be used to reach these levels of confidence.

Annex B
(informative)

Linear to dB scale conversion of uncertainties

B.1 Definition of decibel

The decibel is a submultiple of the bel (1 dB = 0,1 B). This unit is used to express values of power level on a logarithmic scale. The power level is always relative to a reference power P_0:

$$L_{P/P_0} = 10 \times \log_{10}\left(\frac{P}{P_0}\right) \text{ (dB)} \tag{B.1}$$

where

P and P_0 are expressed in the same linear units.

B.2 Conversion of relative uncertainties

Similar to the definition in Clause B.1, relative uncertainties, U_{lin}, or relative *deviations*, can be expressed in decibels:

$$U_{dB} = 10 \times \log_{10}(1 + U_\%) \tag{B.2}$$

Reciprocally, U_{lin} can be expressed in % using:

$$U_\% = \left[10^{\frac{U_{dB}}{10}} - 1\right] \times 100 \tag{B.3}$$

For small values of U_{lin}, the first term of the applicable Taylor series can be used. Having:

$$\ln(1+x) = \sum_{n=1}^{\infty} \frac{-1^{n+1}}{n} x^n \text{ and } \log_{10} x = \frac{\ln x}{\ln(10)} \tag{B.4}$$

that leads to:

$$U_{dB} = \frac{10}{\ln(10)} \sum_{n=1}^{\infty} \frac{-1^{n+1}}{n} U_{lin}{}^n \approx \frac{10}{\ln(10)} U_{lin} \tag{B.5}$$

and to two useful expressions:

$$U_{dB} \approx 4,34 \times U_{lin} \Leftrightarrow U_{lin} \approx 0,23 \times U_{dB} \tag{B.6}$$

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[14]   IEC 61280-4-1, *Fibre-optic communication subsystem test procedures – Part 4-1: Installed cable plant – Multimode attenuation measurement*

[15]   IEC TR 61930, *Fibre optic graphical symbology*

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[2] This publication has been withdrawn, but for the purpose of this document, it is given as a reference.

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[17]   IEC 60359:2001, *Electrical and electronic measurement equipment – Expression of performance*

[18]   ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

[19]   ISO/IEC Guide 99:2007, *International vocabulary of metrology – Basic and general concepts and associated terms (VIM)*

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IEC 61315

INTERNATIONAL STANDARD

NORME INTERNATIONALE

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inside

Calibration of fibre-optic power meters

Étalonnage de wattmètres pour dispositifs à fibres optiques

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION
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CALIBRATION OF FIBRE-OPTIC POWER METERS

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.

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International Standard IEC 61315 has been prepared by IEC technical committee 86: Fibre optics.

This third edition cancels and replaces the second edition published in 2005. It constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) update of terms and definitions;

b) update of 5.1, including Table 1 (new type of source);

c) update of Annex A;

d) addition of Annex B on dB conversion.

The text of this International Standard is based on the following documents:

CDV	Report on voting
86/533/CDV	86/540A/RVC

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

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

In this document, the following print types are used:

– *terms defined in the document: in italic type.*

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

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

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

Fibre-optic power meters are designed to measure optical power from fibre-optic sources as accurately as possible. This capability depends largely on the quality of the *calibration* process. In contrast to other types of measuring equipment, the *measurement results* of *fibre-optic power meters* usually depend on many conditions of measurement. The conditions of measurement during the *calibration* process are called *calibration conditions*. Their precise description is therefore an integral part of the *calibration*.

This document defines all of the steps involved in the *calibration* process: establishing the *calibration conditions*, carrying out the *calibration*, calculating the uncertainty, and reporting the uncertainty, the *calibration conditions* and the *traceability*.

The absolute power *calibration* describes how to determine the ratio between the value of the input power and the power meter's result. This ratio is called *correction factor*. The measurement uncertainty of the *correction factor* is combined following Annex A from uncertainty contributions from the *reference meter*, the *test meter*, the setup and the procedure.

The calculations go through detailed characterizations of individual uncertainties. It is important to know that

a) some uncertainties are type B estimations, experience-based,

b) a detailed uncertainty analysis is usually only done once for each power meter type under test, and all subsequent *calibrations* are usually based on this one-time analysis, using the appropriate type A measurement contributions evaluated at the time of the *calibration*, and

c) some of the individual uncertainties are simply considered to be part of a checklist, with an actual value which can be neglected.

Clause 5 defines absolute power *calibration*, which is mandatory for *calibration* reports referring to this document.

Clause 6 describes the evaluation of the measurement uncertainty of a calibrated power meter operated within *reference conditions* or within *operating conditions*. It depends on the *calibration* uncertainty of the power meter as calculated in 5.4, the conditions and its dependence on the conditions. It is usually performed by manufacturers in order to establish specifications and is not mandatory for reports referring to this document. One of these dependences, the *nonlinearity*, is determined in a separate *calibration* (Clause 7).

CALIBRATION OF FIBRE-OPTIC POWER METERS

1 Scope

This document is applicable to instruments measuring *radiant power* emitted from sources that are typical for the fibre-optic communications industry. These sources include laser diodes, light emitting diodes (LEDs) and fibre-type sources. Both divergent and collimated radiations are covered. This document defines the *calibration* of power meters to be performed by *calibration* laboratories or by power meter manufacturers.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 60793-2, *Optical fibres – Part 2: Product specifications – General*

IEC TR 61931:1998, *Fibre optic – Terminology*

ISO/IEC Guide 98-3:2008*, Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC TR 61931 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
accredited calibration laboratory
calibration laboratory authorized by the appropriate national organization to issue *calibration* certificates with a minimum specified uncertainty, which demonstrate *traceability* to *national standards* (3.14)

3.2
adjustment
set of operations carried out on an instrument in order that it provides given indications corresponding to given values of the measurand

Note 1 to entry: When the instrument is made to give a null indication corresponding to a null value of the measurand, the set of operations is called zero adjustment.

Note 2 to entry: For more information, see ISO/IEC Guide 99:2007, 3.11.

[SOURCE: IEC 60050-311:2001, 311-03-16, modified – The words "of a measuring instrument" have been deleted from the term, and Note 2 to entry has been added.]

**3.3
calibration**
set of operations that establish, under specified conditions, the relationship between the values of quantities indicated by a measuring instrument and the corresponding values realized by measurement standards

Note 1 to entry: The result of a *calibration* permits either the assignment of values of measurands to the indications or the determination of corrections with respect to indications.

Note 2 to entry: A *calibration* may also determine other metrological properties such as the effect of influence quantities.

Note 3 to entry: The result of a *calibration* may be recorded in a document, sometimes called a *calibration* certificate or a *calibration* report.

Note 4 to entry: See also ISO/IEC Guide 99:2007, 2.39.

**3.4
calibration conditions**
conditions of measurement in which the *calibration* is performed

**3.5
centroidal wavelength**
λ_c
power-weighted mean wavelength of a light source in vacuum

Note 1 to entry: For a continuous spectrum, the *centroidal wavelength* is defined as:

$$\lambda_c = \frac{\int p(\lambda)\lambda d\lambda}{P_{total}} \tag{1}$$

For a spectrum consisting of discrete lines, the *centroidal wavelength* is defined as:

$$\lambda_c = \frac{\sum_i P_i \lambda_i}{\sum_i P_i} \tag{2}$$

where

$p(\lambda)$ is the power spectral density of the source, for example, in W/nm;

λ_i is the vacuum wavelength of the ith discrete line;

P_i is the power of the ith discrete line, for example, in W;

P_{total} is the total power, for example, in W.

Note 2 to entry: The above integrals and summations theoretically extend over the entire spectrum of the light source. However, it is usually sufficient to perform the integral or summation over the spectrum where the spectral density $p(\lambda)$ or power P_i is higher than 0,1 % of the maximum spectral density $p(\lambda)$ or power P_i.

**3.6
correction factor**
CF
numerical factor by which the uncorrected result of a measurement is multiplied to compensate for systematic error

Note 1 to entry: This note applies to the French language only.

3.7
detector
element of the power meter that transduces the radiant optical power into a measurable, usually electrical, quantity

Note 1 to entry: In this document, the *detector* is assumed to be connected with the *optical input port* by an optical path.

Note 2 to entry: For more information, see ISO/IEC Guide 99:2007, 3.9.

3.8
deviation
D
relative difference between the power measured by the *test meter* (3.32) P_{DUT} and the reference power P_{ref}:

$$D = \frac{P_{DUT} - P_{ref}}{P_{ref}} \tag{3}$$

Note 1 to entry: This note applies to the French language only.

3.9
excitation
<fibre> description of the distribution of optical power between the modes in the fibre

Note 1 to entry: In context with multimode fibres, the fibre *excitation* is described by

a)   the *spot diameter* (3.31) on the surface of the fibre end, and

b)   the *numerical aperture* (3.17) of the radiation emitted from the fibre.

Single-mode fibres are generally assumed to be excited by only one mode (the fundamental mode).

3.10
instrument state
set of parameters that can be chosen on an instrument

Note 1 to entry: Typical parameters of the *instrument state* are the optical power range, the wavelength setting, the display measurement unit and the output from which the *measurement result* is obtained (for example, display, interface bus, analogue output).

3.11
irradiance
quotient of the incremental *radiant power* ∂P incident on an element of the reference plane by the incremental area ∂A of that element:

$$E = \frac{\partial P}{\partial A} \quad \left(W/m^2 \right) \tag{4}$$

[Note 1 to entry: For more information, see IEC TR 61931:1998, 2.1.15.

3.12
measurement result
y
(displayed or electrical) output of a power meter (or standard), after completing all actions suggested by the operating instructions, for example warm-up, zero adjustment and wavelength-correction

Note 1 to entry: *Measurement result* is expressed in watts (W). For the purposes of uncertainty, *measurement result*s in other units, for example volts, should be converted to watts. *Measurement results* in decibels (dB) should

also be converted to watts, because the entire uncertainty accumulation is based on measurement results expressed in watts. See Annex B.

3.13
measuring range
set of values of measurands for which the error of a measuring instrument is intended to lie within specified limits

Note 1 to entry: In this document, the *measuring range* is the range of *radiant power* (part of the *operating range*), for which the uncertainty at *operating conditions* is specified. The term "dynamic range" should be avoided in this context.

Note 2 to entry: For more information, see ISO/IEC Guide 99:2007, 4.7.

3.14
national measurement standard
national standard
standard recognized by a national decision to serve in a country as the basis for assigning values to other standards of the quantity concerned

Note 1 to entry: For more information, see ISO/IEC Guide 99:2007, 5.3.

3.15
national standards laboratory
laboratory which maintains the *national standard* (3.14)

3.16
nonlinearity
NL
relative difference between the *response* (3.28) at a given power P and the *response* at a reference power P_0:

$$nl_{P/P_0} = \frac{r(P)}{r(P_0)} - 1 \tag{5}$$

If expressed in decibels, the *nonlinearity* is:

$$NL_{P/P_0} = 10 \times \log_{10} \frac{r(P)}{r(P_0)} \ \text{(dB)} \tag{6}$$

Note 1 to entry: The *nonlinearity* is equal to zero at the reference power.

Note 2 to entry: The term "local *nonlinearity*" is used for the relative difference between the *responses* at two different power levels (separated by 3,01 dB) obtained during the *nonlinearity calibration*. The term "global *nonlinearity*" is used for the result of summing the local nonlinearities (in dB); it is identical to the *nonlinearity* defined here.

3.17
numerical aperture
description of the beam divergence of an optical source

Note 1 to entry: In this document, the *numerical aperture* is the sine of the (linear) half-angle at which the *irradiance* is 5 % of the maximum *irradiance*.

Note 2 to entry: Adapted from the definition of the *numerical aperture* of multimode graded-index fibres in IEC 60793-1-43:2015, Clause 3; in this document, the definition is used to describe the divergence of all divergent beams.

3.18
operating conditions
appropriate set of specified ranges of values of influence quantities usually wider than the *reference conditions* for which the uncertainties of a measuring instrument are specified

Note 1 to entry: The *operating conditions* and uncertainty at *operating conditions* are usually specified by the manufacturer for the convenience of the user.

3.19
operating range
specified range of values of one of a set of *operating conditions* (3.18)

3.20
optical input port
physical input of the power meter (or standard) to which the *radiant power* is to be applied or to which the optical fibre end is to be connected

Note 1 to entry: An optical path (path of rays with or without optical elements, such as lenses, diaphragms, light guides, etc.) is assumed to connect the *optical input port* with the power meter's *detector*.

3.21
optical reference plane
plane on or near the *optical input port* (3.20) which is used to define the beam's *spot diameter* (3.31)

Note 1 to entry: The *optical reference plane* is usually assumed to be perpendicular to the beam propagation, and it should be described by appropriate mechanical dimensions relative to the power meter's *optical input port*.

3.22
polarization dependent response
PDR
variation in *response* of a power meter with respect to all possible polarization states of the input light:

$$PDR = 10 \times \log_{10}\left(\frac{r_{\max}}{r_{\min}}\right) \text{ (dB)} \tag{7}$$

where

$r_{\max}$ and $r_{\min}$ are the maximum and minimum *response* (3.28) taken over all polarization states

Note 1 to entry: *Polarization dependent response* is expressed in decibels.

Note 2 to entry: This note applies to the French language only.

3.23
fibre-optic power meter
instrument capable of measuring *radiant power* from fibre-coupled sources such as lasers and LEDs, which are typical for the fibre-optic communications industry

Note 1 to entry: The radiation may be divergent or collimated. The radiation is assumed to be incident on the *optical reference plane* within the specified conditions.

Note 2 to entry: A power meter may consist of either a single instrument or a main instrument and a separate sensing head. In the case of a separate sensing head, the head may be calibrated without the main instrument. However, if any analogue electronics are used in the main instrument, the sensing head shall be calibrated together with the main instrument.

Note 3 to entry: A *fibre-optic power meter* is usually capable of measuring the time-average of modulated optical power. An increased uncertainty may be observed, which depends on the duty cycle and the peak power of modulated optical power.

3.24
radiant power
P

power emitted, transferred, or received in the form of optical radiation [1][1]

Note 1 to entry: *Radiant power* is expressed in watts.

3.25
reference conditions
conditions of use prescribed for testing the performance of a measuring instrument or for intercomparison of results of measurements

Note 1 to entry: The *reference conditions* generally include reference values or reference ranges for the influence quantities affecting the measuring instrument.

3.26
reference meter
standard which is used as the reference for the *calibration* (3.3) of a *test meter* (3.32)

3.27
reference standard
standard, generally having the highest metrological quality available at a given location or in a given organization, from which measurements made therein are derived

Note 1 to entry: For more information, see ISO/IEC Guide 99:2007, 5.6.

3.28
response
r

measurement result of a power meter, y, divided by the *radiant power* on the power meter's *optical reference plane*, P, at a given condition of measurement:

$$r = \frac{y}{P} \text{ (W/W, dimensionless)} \tag{8}$$

Note 1 to entry: An ideal power meter exhibits a *response* of 1 for all *operating conditions*.

3.29
spectral responsivity
responsivity
R
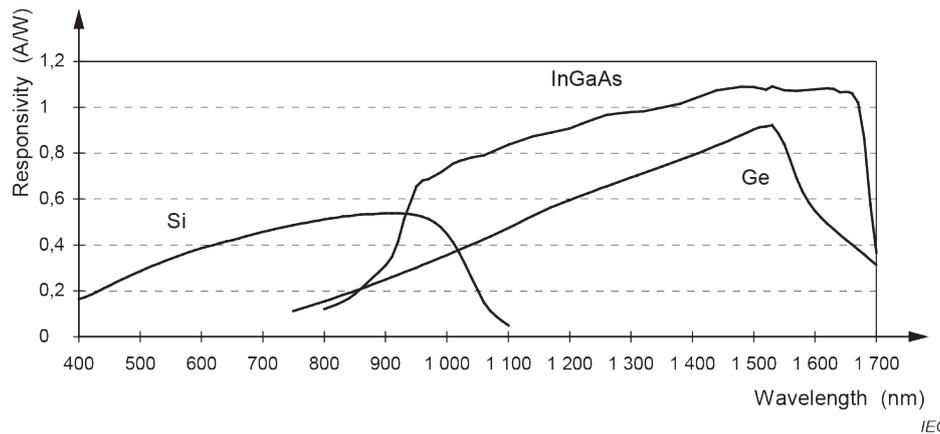
quotient of the *detector* output current I by the incident monochromatic optical power P:

$$R = \frac{I}{P} \text{ (A/W)} \tag{9}$$

Note 1 to entry: The *responsivity* depends on the conditions (wavelength, temperature, etc.). See Figure 1.

Note 2 to entry: This note applies to the French language only.

_____

[1]   Numbers in square brackets refer to the Bibliography.

Key

Si   silicon

Ge   germanium

InGaAs   indium gallium arsenide

Figure 1 – Typical *spectral responsivity* of photoelectric *detectors*

3.30
spectral bandwidth
B
full-width at half-maximum (FWHM) of the source spectrum

Note 1 to entry: If the source is a laser diode with a multiple-longitudinal mode spectrum, then the FWHM *spectral bandwidth* B is the RMS *spectral bandwidth*, multiplied by 2,35 (assuming the source has a Gaussian envelope):

$$B = 2,35 \sqrt{\frac{1}{P_{\text{total}}} \sum_i P_i \left(\lambda_i - \lambda_c\right)^2} \tag{10}$$

$$P_{\text{total}} = \sum_i P_i \tag{11}$$

where

λ_c is the *centroidal wavelength* (3.5) of the laser diode, in nm;

P_{total} is the total power, in W;

P_i is the power of ith longitudinal mode, in W;

λ_i is the vacuum wavelength of ith longitudinal mode, in nm.

Note 2 to entry: If the source emits at one wavelength only (single-line spectrum), it may be sufficient to specify an upper limit, for example *spectral bandwidth* < 1 nm.

Note 3 to entry: It is usually sufficient to perform the integral or summation over the spectrum where the power is higher than 0,1 % of the maximum power.

Note 4 to entry: This note applies to the French language only.

3.31
spot diameter
diameter of the irradiated area on the *optical reference plane*, defined by the (best-approximation) circle at which the *irradiance* (3.11) has dropped to 5 % of the peak *irradiance*

Note 1 to entry: The ratio of 5 % was adopted for reasons of compatibility with the definition of the *numerical aperture*. Other ratios are often used to describe laser beams, for example $1/e^2$ or $1/e$. In that case, the ratio shall be stated with the *spot diameter* value.

3.32
test meter
fibre-optic power meter (3.23) (or standard) to be calibrated by comparison with the *reference meter* (3.26)

3.33
traceability
property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties

Note 1 to entry: For more information, see ISO/IEC Guide 99:2007, 2.41.

3.34
traceability chain
unbroken chain of comparison (see Figure 2)

Note 1 to entry: For more information, see ISO/IEC Guide 99:2007, 2.42.
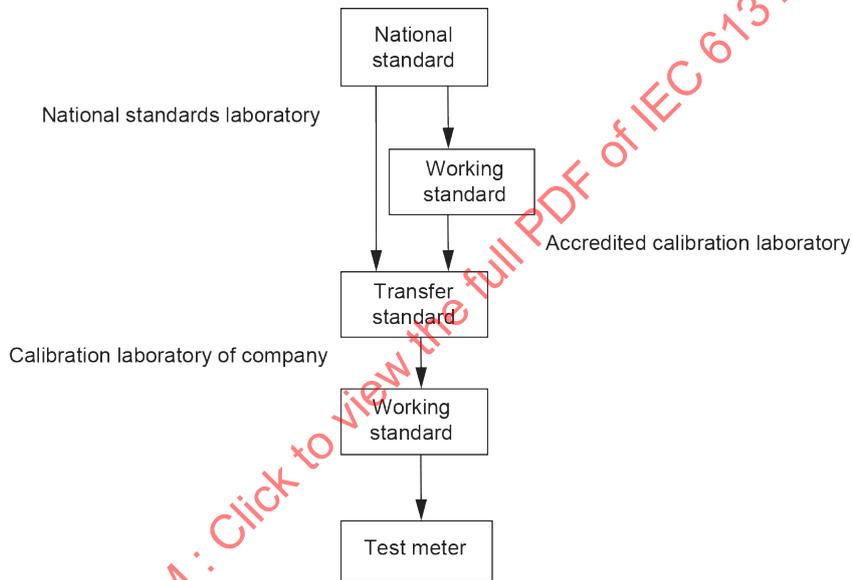
Figure 2 – Example of a *traceability chain*

3.35
working standard
standard that is used routinely to calibrate or check measuring instruments

Note 1 to entry: A *working standard* is usually calibrated against a *reference standard* (3.27).

Note 2 to entry: For more information, see ISO/IEC Guide 99:2007, 5.7.

3.36
zero error
measurement result of a power meter without *irradiation* of the *optical input port*

Note 1 to entry: For more information, see ISO/IEC Guide 99:2007, 4.28.

4 Preparation for *calibration*

4.1 Organization

The *calibration* laboratory should ensure that suitable requirements for *calibration* are followed.

NOTE   Guidance about good practices for *calibration* can be found in ISO/IEC 17025 [18].

There should be a documented measurement procedure for each type of *calibration* performed, giving step-by-step operating instructions and equipment to be used.

4.2 *Traceability*

The *calibration* laboratory should ensure that suitable requirements are followed.

NOTE   Guidance about good practices for *calibration* can be found in ISO/IEC 17025 [18].

All standards used in the *calibration* process shall be calibrated according to a documented program with *traceability* to *national standards laboratories* or to *accredited calibration laboratories*. It is advisable to maintain more than one standard on each hierarchical level, so that the performance of the standard can be verified by comparisons on the same level. Make sure that any other test equipment which has a significant influence on the *calibration* results is calibrated. Upon request, specify this test equipment and its *traceability chain*(s). The re-*calibration* period(s) shall be defined and documented.

4.3 Advice for measurements and *calibrations*

4.3 gives general advice for all measurements and *calibrations* of optical and fibre-optic power meters.

The *calibration* should be made in a temperature-controlled room if non-temperature-controlled *detectors* are used. The recommended temperature is 23 °C. Humidity control may be necessary if humidity-sensitive optical *detectors* are used, or if there is the possibility of condensation on the components. A change of the laboratory's humidity may change the absorption of air and thereby change the power. This effect is relatively strong between 1 360 nm and 1 410 nm, especially when a sequential-type, open-beam *calibration* is used and the humidity changes between the steps. In parallel-type *calibrations* with open-beam paths of approximately the same lengths, the *measurement results* of both the *reference meter* and the *test meter* will change at approximately the same time, with negligible effect on the *calibration* result.

The laboratory should be kept clean. Connectors and *optical input ports* should always be cleaned before measurement. The quality and cleanness of the connector in front of the *detector* should be checked. All fibres should be moved as little as possible during the measurements; they can be fixed to the workbench if necessary. Sensors should be moved to the fibre rather than the fibre to the sensor.

The optical source that is used for the *excitation* of the power meter should be characterized for *centroidal wavelength* and *spectral bandwidth*. The *spectral bandwidth* should be narrow enough to avoid averaging over a wide range of wavelengths. Means to ensure the stability of the source, for example with the help of independent power monitoring, may be advisable.

Laser diodes are sensitive to back reflections. To improve the stability, it is advisable to use an optical attenuator or an optical isolator between the laser diode and the *test meter*. Because of their narrow *spectral bandwidths*, the combination of laser diode and multimode fibre is also capable of producing speckle patterns on the *optical reference plane*, resulting in an increased measurement uncertainty.

Fibre connectors and connector adapters are likely to produce errors in the *measurement result* [2] because of multiple reflections between the *optical input port* (or *detector*) and the connector-adapter combination (as part of the source). Therefore, connectors and adapters with low reflectivity are recommended for the *calibration*. Otherwise, a *correction factor* and an increased uncertainty may have to be taken into account.

It is advisable to use *reference meters* with *detector* diameters of ≥ 3 mm, because they can easily be irradiated with an open beam, and they are less susceptible to contamination (dirt and dust). The *reference meter*'s surface reflections should be as small as possible. If the source emits a divergent beam, then a *reference meter* with an integrating sphere may be advisable. It is also acceptable to use meters with "flat" *detectors* and mathematical correction, based on multiplying the emitted far-field distribution with the measured angle-dependence of the *detector* of the *reference meter*, and integrating over the range of far-field angles.

Temperature control of the *detectors* should be considered for highly accurate *calibrations*, because *detectors* exhibit strong temperature dependence over some wavelength ranges.

4.4   Recommendations to users

It is recommended that the user of the power meter maintain at least one reference power meter, which allows comparison of the meters for confidence. These comparisons are particularly important before and after the meter is sent to recalibration, because they will allow the user to determine whether or not their scale has changed – for example due to transport – after the meter returns. Scale changes due to *adjustment* (3.2) (see IEC 60050-311:2001, 311-03-16 and ISO/IEC Guide 99:2007, 4.30) will be reported on the *calibration* certificate.

A regular comparison of the *correction factors* (3.6), or of the *deviations* (3.8), will allow the user to screen out excessive ageing, and possibly to adjust the recalibration intervals.

5   Absolute power *calibration*

5.1   *Calibration* methods

The *calibration* of a power meter is usually achieved by exposing both the meter under test and a calibrated power meter with known uncertainty (the *reference meter*) to an optical radiation, and by transferring the *reference meter*'s (3.26) *measurement result* to the *test meter* (3.32).

The allowable *spectral bandwidth* (3.30) depends on the *test meter*'s *spectral responsivity* (3.29); the stronger its wavelength dependence, the narrower the *spectral bandwidth*. Usual bandwidths are ≤ 10 nm, which excludes the possibility of calibrating with wider-bandwidth LEDs. Therefore, one of the following is used in *fibre-optic power meter calibrations*: combinations of "white-light" sources and narrow-bandwidth filters (for example monochromators), laser diodes, or combinations of supercontinuum lasers with tuneable bandpass filters.

Depending on the type of source and the exciting beam geometry, six most frequent *calibration* methods can be distinguished, as depicted in Table 1:

Table 1 – *Calibration* methods and correspondent typical power

Radiation source	Open-beam *calibration*	Fibre beam *calibration*
"White-light" with filter	$P \approx 10$ µW	$P \approx 10$ nW to 0,3 µW (MMF) $P \approx 2$ nW (SMF)
Laser diode	$P \approx 10$ µW to a few mW	$P \approx 10$ µW to a few mW (SMF and MMF)
Supercontinuum laser with filter	$P \approx 1$ µW to a few mW	$P \approx 1$ µW to 700 µW (SMF and MMF)

Radiation source	Open-beam *calibration*	Fibre beam *calibration*
Key MMF: multimode fibre (usually graded-index fibre) SMF: single-mode fibre		

For *fibre-optic power meters*, fibre beam *calibration* is recommended. For open-beam *calibration*, a correction of the *calibration* results using a series of fibre beam laser *calibration* results at a few wavelengths should be performed.

One can distinguish between the sequential and the parallel measurement method. When the *reference meter* and *test meter* are sequentially exposed to the source, then the radiated power should be kept as constant as possible, for example by appropriate stabilization. For the parallel-type *calibration*, a beam splitter or a branching device is used to generate two beams that excite both the *reference meter* and the *test meter* simultaneously. In this case, the beam splitter or branching device ratio shall be determined as accurately as possible, and its stability shall be investigated.

As an example, a measurement setup for sequential, fibre-based *calibration* is illustrated in Figure 3. A launching device, for removal of the cladding modes and creation of an appropriate modal *excitation*, is included in the setup.

Figure 3 – Measurement setup for sequential, fibre-based *calibration*

5.2 Establishing the *calibration conditions*

The *calibration conditions* (3.4) are the measurement conditions during the *calibration* process. Establishing and maintaining the *calibration conditions* is an important part of the *calibration* (3.3), because any change of these conditions is capable of producing erroneous *measurement results*. The *calibration conditions* should be a close approximation to the intended *operating conditions* (3.18). This ensures that the (additional) uncertainty in the operating environment is as low as possible. The *calibration conditions* should be specified in the form of nominal values with uncertainties when applicable. In order to meet the requirements of this document, the *calibration conditions* shall, at a minimum, consist of the following:

a) the date of *calibration*;

b) the ambient temperature with uncertainty, for example 23 °C ± 1 °C;

c) the ambient relative humidity, if it has an influence; otherwise a relative humidity below the condensation point is assumed;

d) the nominal *radiant power* on the *optical reference plane* (3.21);

e) the beam geometry:

   1) an open (for example collimated) beam, described by the *spot diameter* (3.31) on the *optical reference plane*, the beam's *numerical aperture* (3.17) and the *irradiance* (3.11)

distribution in the beam; typical *irradiance* distributions are: uniform, Gaussian or even irregular (speckled);

2) the type of fibre and, if applicable, its degree of *excitation* (for example within encircled flux templates defined in IEC 61280-4-1 when using an A1a or A1b multimode fibre);

f) the connector-adapter combination: the connector type, polishing and adapter as part of the exciting source (if applicable);

g) the *centroidal wavelength* (3.5) of the exciting source;

h) the *spectral bandwidth* (3.30) of the exciting source;

i) the state of polarization: "unpolarized light" or "polarized light, undefinite state". If the latter is chosen, the uncertainty due to *polarization dependent response* (3.22) shall be taken into account in 5.4.3 and 5.4.5.

The above conditions may not be exhaustive. There might be other parameters that have a significant influence on the *calibration* uncertainty and therefore shall be reported, too.

In the *calibration* with an open-beam, the power meter's *optical reference plane* (3.21) should be centrally irradiated with a beam diameter smaller than the active area of the *optical reference plane*.

In the *calibration* with a fibre, a single-mode fibre or a multimode fibre may be used. A single-mode fibre can be advantageous because of its reproducible beam characteristics, but may not be available for all wavelengths. If a multimode fibre is used, then *excitation* between 85 % and 95 % (slightly underfilled condition) is preferred because this *excitation* can be more easily reproduced (encircled flux templates defined in IEC 61280-4-1 are a good example of this condition). A launching device may be necessary to create the appropriate *excitation*. Note that multimode fibres will emit irregular beam patterns (speckle patterns) when driven by a laser diode; this will result in an increased *calibration* uncertainty.

A connector-adapter combination should only be reported if the power meter is calibrated with a fibre, and not with an open beam. It is recommended to use a combination of connector and adapter with sufficiently low reflections back to the power meter.

5.3   *Calibration* procedure

(1) Establish and record the appropriate *calibration conditions* (5.2). Switch on all instrumentation and allow enough time for it to stabilize.

(2) Set up the *instrument state* (3.10) of the *reference meter* and *test meter* according to the instruction manual. Set the wavelength on all instruments for the source wavelength. Select appropriate power ranges. Record the *instrument states* of both meters. Adjust the zero of both meters if applicable.

(3) Measure the optical power with the *reference meter* $P_{std,1}$. Multiply the *measurement result* by the *correction factor* of the *reference meter* CF_{std} reported in its *calibration* certificate if it has not been adjusted. Multiply by the *correction factor* CF_{change} calculated in 5.4.4 if necessary. Record the *measurement result*, $P_{ref,1} = P_{std,1} \times CF_{std} \times CF_{change}$.

(4) Measure the optical power with the *test meter*. Apply necessary corrections as suggested by the operating instructions. Record the *measurement result*, $P_{DUT,1}$.

(5) Calculate the first of a series of *correction factors*:

$$CF_{comparison,1} = \frac{P_{ref,1}}{P_{DUT,1}} \tag{12}$$

(6) Repeat steps (3) through (5) several times, with the result of obtaining several *correction factors*, $CF_{\text{comparison,1}}$ to $CF_{\text{comparison,n}}$.

(7) Calculate and record the average *correction factor*, CF_{DUT} from the individual *correction factors*:

$$CF_{\text{DUT}} = \frac{1}{n} \times \sum_{i=1}^{n} CF_{\text{comparison,i}} \qquad (13)$$

If desired, the *deviation D* can be calculated from the *correction factor*:

$$D = \frac{1}{CF_{\text{DUT}}} - 1 \qquad (14)$$

In later use of the *test meter*, the *measurement results* shall be multiplied with CF_{DUT}. Alternatively, an *adjustment* (3.2) of the *test meter* can be made so that the *correction factor* is changed to 1. In this case, the comparison should be repeated for verification.

5.4 *Calibration* uncertainty

5.4.1 General

The *calibration* uncertainty is the measurement uncertainty of the *correction factor* CF_{DUT}. Calculate the combined standard uncertainty from:

$$u\left(CF_{\text{DUT}}\right) = \sqrt{u_{\text{setup}}^2 + u_{\text{ref}}^2 + u_{\text{DUT}}^2} \qquad (15)$$

where

u_{setup} is the uncertainty due to the setup (5.4.2);

u_{ref} is the uncertainty of the *reference meter* (5.4.3);

u_{DUT} is the uncertainty due to the *test meter* (5.4.5).

Equation (15) is valid only if the input quantities are independent or uncorrelated. If some input quantities are significantly correlated, take the correlation into account. See ISO/IEC Guide 98-3 for more detail.

Then calculate the expanded uncertainty from:

$$U\left(CF_{\text{DUT}}\right) = k \times u\left(CF_{\text{DUT}}\right) \qquad (16)$$

where

k is the coverage factor.

See Annex A for more detail.

5.4.2 Uncertainty due to the setup

The following uncertainties may come from the setup.

a) Uncertainty due to the source power instability. In addition to the intrinsic variation of output power versus time, a laser source may react with unstable power to variations of back-reflections and variations of the state of polarisation of back-reflected light.

b) Uncertainty due to the beam splitter or branching device ratio (for parallel method), for example due to their polarization dependence.

c) Depending on the setup and method, other uncertainties may have to be taken into account.

Instability of the source power, of the beam splitter or branching device ratio (for parallel method) will cause a scatter in the measurement of the *correction factor*. The uncertainty due to these instabilities can be calculated from the experimental standard *deviation* of the *correction factors* $CF_{\text{comparison,1}}$ to $CF_{\text{comparison,n}}$ measured during the *calibration* (Equation (12)). The number of comparisons should be large to reduce this uncertainty. See Annex A for more detail on type A evaluation of uncertainty.

$$u_{\text{setup,typeA}} = \frac{s\left(CF_{\text{comparison}}\right)}{\sqrt{n}} \tag{17}$$

where

$s(CF_{\text{comparison}})$ is the experimental standard *deviation* of the *correction factors*;

n is the number of measurement cycles during the *calibration* process.

This uncertainty can also be calculated from a standard *deviation* evaluated once from measurements and used for all *calibrations* or from a type B evaluation. The instability should therefore not vary too much from one *calibration* to the next and not depend on the *test meter*. The number n in Equation (17) is always the number of measurement cycles during the current *calibration* process.

This type A evaluated uncertainty will also be influenced by the repeatability of the connection when using a sequential measurement method or by slight changes in the measurement conditions during the *calibration* process. It can (partially) take into account some of the uncertainties due to the *reference meter* (5.4.3) or *test meter* (5.4.5). Uncertainty components should not be taken into account twice but neither should they be forgotten.

Calculate the uncertainty due to the setup by combining all partial uncertainties described in 5.4.2:

$$u_{\text{setup}} = \sqrt{\sum_{i=1}^{m} u_{\text{setup,i}}^2} \tag{18}$$

5.4.3 Uncertainty of the *reference meter*

The uncertainty of the *reference meter* is mainly due to its *calibration*, the uncertainties of the current *calibration conditions* (3.4) and the dependence of the *reference meter* on these conditions.

The following uncertainties shall be evaluated. The evaluation can be made on the basis of measurements or estimations, or a mixture of both. The calculation of uncertainties is described in Annex A. The measurement of dependence on conditions is described in 6.3.2.

a) *Calibration* uncertainty of the *reference meter*. It shall be obtained from its *calibration* certificate.

b) Uncertainty due to the change from the conditions in which the *reference meter* was calibrated and the current *calibration conditions*, u_{change}, as calculated in 5.4.4.

c) Uncertainty due to temperature dependence of the *reference meter*.

d) Uncertainty due to dependence on relative humidity of the *reference meter*. Power meters with integrating sphere are particularly sensitive to absorption peaks of water when using narrow laser sources.

e) Uncertainty due to dependence on the beam geometry of the *reference meter*.

f) Uncertainty due to dependence on multiple reflections. Multiple reflections may exist between the *optical input port* and the radiation source (for example a connector-adapter combination). Different artefacts will change the measured power.

g) Uncertainty due to wavelength dependence of the *reference meter*.

h) Uncertainty due to dependence on source *spectral bandwidth* of the *reference meter*.

i) Uncertainty due to dependence on state of polarization of the *reference meter*, except if unpolarized or depolarized light is used for *calibration*.

j) Uncertainty due to optical interference. Fabry-Perot cavities can occur between the surface of the *detector*, of the window and the end of the connector, if used.

k) Uncertainty due to the resolution of the *reference meter*. If the resolution of the *reference meter* is δy_{ref}, the standard uncertainty is (see ISO/IEC Guide 98-3:2008, F.2.2.1):

$$u_{\text{ref,resolution}} = \frac{1}{2\sqrt{3}} \delta y_{\text{ref}} \qquad (19)$$

l) Uncertainties due to other dependences of the *reference meter*. Depending on the type of *reference meter*, there may be other uncertainties of the *reference meter*. These should also be measured or estimated.

m) Uncertainty due to ageing of the *reference meter*.

Then calculate the combined standard uncertainty of the *reference meter* from the n above standard uncertainties:

$$u_{\text{ref}} = \sqrt{\sum_{i=1}^{n} u_{\text{ref,i}}^2 + u_{\text{change}}^2} \qquad (20)$$

where u_{change} is the uncertainty due to the change of conditions, as determined from 5.4.4.

5.4.4 *Correction factors* and uncertainty caused by the change of conditions

5.4.4.1 General

The *reference meter* may exhibit a different *response* because it was calibrated under conditions different from the current *calibration conditions*. Examples of differences between the two sets of measurement conditions are: parallel beam versus divergent beam, different source spectra, a non-reflecting setup versus a setup with multiple reflections, or a large time span between the two reference dates resulting in ageing of the standard.

If the conditions under which the *reference meter* was calibrated are nominally identical to the current *calibration conditions* (their uncertainties can be different) and if the ageing of the *reference meter* is negligible, 5.4.4 can be skipped ($CF_{\text{change}} = 1$).

As indicated in Figure 4, each change comprises the nominal change in conditions and the change in uncertainty.
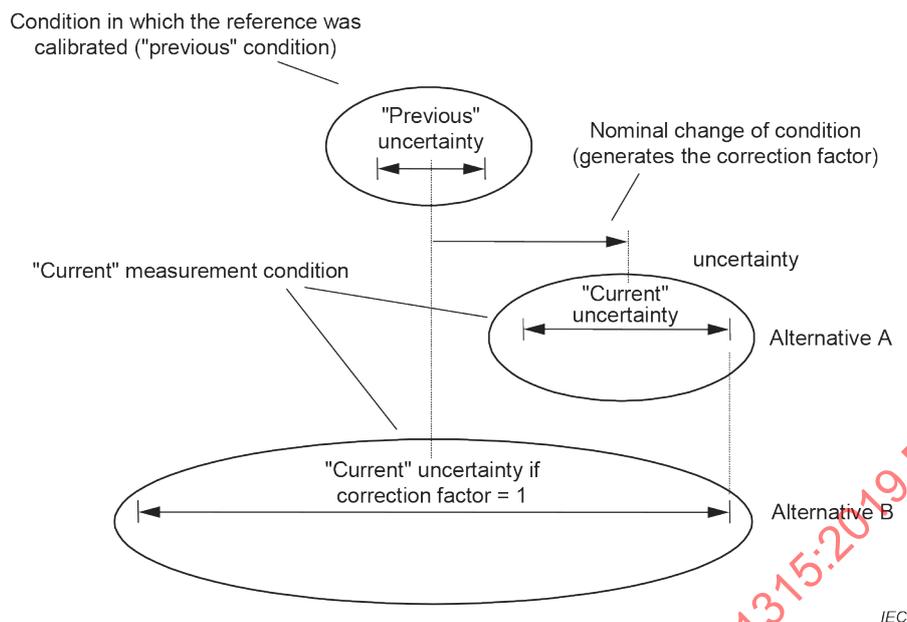
Condition in which the reference was
calibrated ("previous" condition)

"Previous"
uncertainty

Nominal change of condition
(generates the correction factor)

uncertainty

"Current" measurement condition

"Current"
uncertainty

Alternative A

"Current" uncertainty if
correction factor = 1

Alternative B

IEC

Figure 4 – Change of conditions and uncertainty

For each of the potential error contributions (5.4.4.2 to 5.4.4.8), one should decide if it is sensible to calculate a *correction factor* or not. Alternative A includes the calculation of a *correction factor* with the result of a relatively small uncertainty. Alternative B means waiving the *correction factors* (or CF_{change} = 1) and taking larger uncertainties into account to embrace the worst-case conditions.

If alternative A is chosen, the (cumulative) *correction factor* is:

$$CF_{change} = \frac{r_{previous}}{r_{current}} \qquad (21)$$

or

$$CF_{change} = 1 - \Delta r \qquad (22)$$

where

$r_{previous}$ is the *response* of the reference with *excitation* at the conditions at which it was calibrated;

$r_{current}$ is the *response* of the reference with *excitation* at the current *calibration conditions*;

Δr is the relative change of *response* $\Delta r = (r_{current} - r_{previous}) / r_{current}$.

Calculate the (cumulative) *reference meter*'s change-related *correction factor* by accumulating the partial *correction factors*, $CF_{change,i}$, outlined in 5.4.4.2 to 5.4.4.8. For each influencing quantity X_i, start with the calculation of the partial *correction factor*:

$$CF_{change,i} = 1 - \Delta r_i \qquad (23)$$

The relative change of *response* Δr_i can be directly measured by changing the influencing quantity from the "previous" to the "current" *calibration conditions* or calculated from the nominal change of the influencing quantity Δx_i, and the *reference meter*'s nominal relative dependence on this quantity:

$$CF_{\text{change,i}} = 1 - c_i \times \Delta x_i \tag{24}$$

where

c_i is the partial derivate of the relative *response* on the influence quantity X_i, called sensitivity coefficient. See ISO/IEC Guide 98-3:2008, 5.1.3 and 5.1.4, for more detail.

If the sensitivity coefficient is not known very well, the following type B uncertainty should be taken into account:

$$u_{\text{change,i}} = u(c_i) \times \Delta x_i \tag{25}$$

where

$u(c_i)$ is the standard uncertainty of the sensitivity coefficient. The measurement of the dependences is discussed in 6.3.

Finally, calculate the *reference meter*'s cumulative *correction factor* from the above contributions:

$$CF_{\text{change}} = \prod_{i=1}^{n} CF_{\text{change,i}} \tag{26}$$

and the combined standard uncertainty due to the change of *calibration conditions*:

$$u_{\text{change}} = \sqrt{\sum_{i=1}^{n} u_{\text{change,i}}^2} \tag{27}$$

This *correction factor* corresponds to a known change of *response* of the *reference meter* caused by the two different sets of measurement conditions. It is a *correction factor* to apply to the power read by the *reference meter* (see 5.3).

5.4.4.2 *Correction factor* due to temperature change

The *correction factor* $CF_{\text{change},\Theta}$ should be calculated with the help of the nominal change between the "previous" and the "current" temperature $\Delta\Theta$ and the temperature sensitivity coefficient c_Θ of the *reference meter* (for example in %/°C).

$$CF_{\text{change},\Theta} = 1 - c_\Theta \times \Delta\Theta \tag{28}$$

5.4.4.3 *Correction factor* due to change of power level

The uncertainty should be calculated from the *nonlinearity* of the *reference meter* between the "previous" and the "current" power level. If necessary, a *correction factor* can be calculated from:

$$CF_{\text{change, }NL} = 10^{\frac{-NL}{10}} \tag{29}$$

where

NL is the *nonlinearity*, expressed in decibels (dB). Measurement of *nonlinearity* is described in Clause 7.

5.4.4.4   *Correction factor* due to change of beam geometry

The *correction factor* should be calculated from the change of *response* measured when changing the beam geometry.

5.4.4.5   *Correction factor* due to change of the connector-adapter combination

The *reference meter*'s *optical input port* should generally be assumed to be reflective. Such a reflection will travel back to the radiation source, for example, on an optical connector, be reflected again, and finally increase the displayed optical power level. This effect will give rise to a *correction factor* (usually < 1) and an increased uncertainty.

If, for example, the source used in the *calibration* of the *reference meter* is non-reflective and the source used in the *calibration* of the *test meter* is reflective (caused by an optical connector), then the total power indicated by the *reference meter* is erroneous by the secondary reflection. If one assumes that the secondary reflection contributes an additional 5 % of the total power, then the individual *correction factor* is 0,95. This type of error can be reduced by using sources with highly absorptive enclosures, or sources with low-reflectivity connector-adapter combinations.

The measurement method is described in 6.3.7.

5.4.4.6   *Correction factor* due to wavelength change

The *correction factor* should be calculated with the help of the nominal change of wavelength $\Delta\lambda$ and the *reference meter*'s nominal wavelength dependence c_λ.

$$CF_{\text{change},\lambda} = 1 - c_\lambda \times \Delta\lambda \qquad (30)$$

5.4.4.7   *Correction factor* due to *spectral bandwidth* change

The *correction factor* should be calculated with the help of the nominal change of *spectral bandwidth* and the *reference meter*'s nominal dependence on the *spectral bandwidth*. Note that the *correction factor* remains 1 as long as the (uncorrected) wavelength-dependence is **linear** within the *spectral bandwidth* of the source. In the case that the wavelength dependence is curved, the *correction factor* can be computed with the help of the wavelength-dependence of the *reference meter* and the spectra of the two sources used in the *calibration* of the *reference meter* and in the *calibration* of the *test meter*.

5.4.4.8   Other *correction factors*

Depending on the type of *reference meter* and the *calibration conditions*, there may be other *correction factors*. These should also be measured or estimated as outlined in 5.4.4.1.

5.4.5   Uncertainty due to the *spectral bandwidths*

Uncertainties arising from the *test meter* are mainly due to the uncertainties of the *calibration conditions* and the dependence of the *test meter* on the conditions. The following uncertainties shall be evaluated. Their determination is similar to the evaluation described in 5.4.3. The calculation of uncertainties is described in Annex A, and the measurement of dependence on conditions is described in 6.3.2.

a) Uncertainty due to temperature dependence of the *test meter*.

b) Uncertainty due to dependence on relative humidity of the *test meter*. Power meters with integrating sphere are particularly sensitive to absorption peaks of water when using narrow laser sources.

c) Uncertainty due to dependence on beam geometry. This uncertainty comes from non-uniformity and angle-dependence of the *test meter*'s *optical input port*.

d) Uncertainty due to dependence on multiple reflections. Multiple reflections may exist between the *optical input port* and the radiation source (for example a connector-adapter combination). Different artefacts will change the measured power.

e) Uncertainty due to wavelength dependence of the *test meter*.

f) Uncertainty due to dependence on source *spectral bandwidth* of the *test meter*.

g) Uncertainty due to dependence on state of polarization of the *test meter*, except if unpolarized or depolarized light is used for *calibration*.

h) Uncertainty due to optical interference. Fabry-Perot cavities can occur between the surface of the *detector*, the window and the end of the connector, if used.

i) Uncertainty due to the resolution of the *test meter*. If the resolution of the *test meter* is δy_{DUT}, the standard uncertainty is (see ISO/IEC Guide 98-3:2008, F.2.2.1):

$$u_{DUT,resolution} = \frac{1}{2\sqrt{3}} \delta y_{DUT} \tag{31}$$

j) Uncertainties due to other dependences of the *test meter*. Depending on the type of *test meter* and on the *calibration* process, there may be other conditions causing uncertainties.

Then calculate the combined standard uncertainty contribution of the *test meter* from the *n* above standard uncertainties:

$$u_{DUT} = \sqrt{\sum_{i=1}^{n} u_{DUT,i}^2} \tag{32}$$

5.5 Reporting the results

Suitable requirements for reporting the results of each *calibration* should be followed.

NOTE   Guidance about good practices for reporting the results of *calibration* can be found in ISO/IEC 17025 [18].

Calibration certificates or *calibration* reports referring to this document shall, at a minimum, include the following information:

a) all *calibration conditions* (3.4) as described in 5.2;

b) the *test meter*'s *correction factor*(s) (3.6) or *deviation*(s) (3.8), if the *test meter* was not adjusted;

c) on receipt *correction factors* or *deviations* and after *adjustment* (3.2) *correction factors* or *deviations* in the case that an *adjustment* was carried out;

d) the *calibration* uncertainty in the form of an expanded uncertainty as described in 5.4;

e) the *instrument state* (3.10) of the *test meter* during the *calibration*;

f) evidence that the measurements are traceable (see ISO/IEC 17025).

6   Measurement uncertainty of a calibrated power meter

6.1   Overview

The measurement uncertainty of a calibrated power meter is larger than its *calibration* uncertainty. It is the combination of the *calibration* uncertainty and of uncertainty contributions due to the dependence of the power meter on the conditions of measurement.

The determination of the measurement uncertainty of a calibrated power meter used at *reference conditions* or at *operating conditions* is not part of the *calibration* process. It is performed for example by manufacturers of power meters in order to establish specifications. It is not mandatory for *calibration* certificates or *calibration* reports referring to this document.

6.2   Uncertainty at *reference conditions*

Reference conditions (3.25) are used for testing the performance of a power meter or for intercomparisons. They are usually defined by manufacturers in order to specify the smallest uncertainty of a measuring instrument; therefore, they are often identical or close to its *calibration conditions*.

The uncertainty at *reference conditions* is the uncertainty on the result of a measurement taken by the calibrated and adjusted power meter when operated at *reference conditions*. It depends on the *calibration* uncertainty of the power meter, the *reference conditions* and the dependence of the power meter on the *reference conditions*. This is the reason why the uncertainty at *reference conditions* is always larger than the *calibration* uncertainty. Even when the *reference conditions* are identical to the *calibration conditions* (no uncertainty due to change of conditions), the *test meter*'s dependences on the *reference conditions* have to be added (in quadrature) to the *calibration* uncertainty for a second time. Calculating the uncertainty at *reference conditions* of the calibrated *test meter* is similar to calculating the measurement uncertainty at *calibration conditions* of the *reference meter* described in 5.4.3:

$$u_{\text{DUT,ref\_conditions}} = \sqrt{u^2\left(CF_{\text{DUT}}\right) + u_{\text{DUT}}^2} \tag{33}$$

where

$u(CF_{\text{DUT}})$ is the *calibration* uncertainty of the *test meter*, as determined in accordance with 5.4;

u_{DUT} is the uncertainty due to the dependence of the *test meter* on the *reference conditions*, as determined in accordance with 5.4.5.

The description of the *reference conditions* should be made in the same way as the *calibration conditions* described in 5.2.

6.3   Uncertainty at *operating conditions*

6.3.1   General

The uncertainty at *operating conditions* (or operating instrumental uncertainty, see 3.2.11 of IEC 60359:2001) is the uncertainty on the result of a measurement taken by the calibrated and adjusted power meter when operated within a range of *operating conditions* (3.18). It depends on the *calibration* uncertainty, the *operating conditions* and the dependence of the power meter on the *operating conditions*:

$$u_{\text{DUT,operating}} = \sqrt{u^2(CF_{\text{DUT}}) + u_{\text{extension}}^2} \tag{34}$$

where

$u(CF_{\text{DUT}})$ is the *calibration* uncertainty of the *test meter*, as determined according to 5.4;

$u_{\text{extension}}$ is the extension uncertainty, due to the dependence of the meter on the *operating conditions*, as determined from Equation (35).

Contrary to the *calibration conditions* (3.4) described in 5.2, each *operating condition* should be described by a range when possible. The set of *operating conditions* is specified by

a) the maximum time span between recalibrations,

b) the range of ambient temperatures,

c) the range of power levels (*measuring range*),

d) the range of beam geometries described by their *spot diameter* and *numerical aperture*, or the range of fibre types,

e) the applicable connector-adapter combinations, if any,

f) the range of wavelengths of the source, and

g) the maximum *spectral bandwidth* of the source.

All possible polarization states are included in the *operating conditions* by default. A relative humidity below the condensation point is also assumed.

The above conditions may be defined either by the power meter manufacturer or by the *calibration* laboratory in charge of the *calibration* for *operating conditions*.

To calculate the extension uncertainty, combine all uncertainties due to the dependences on the conditions:

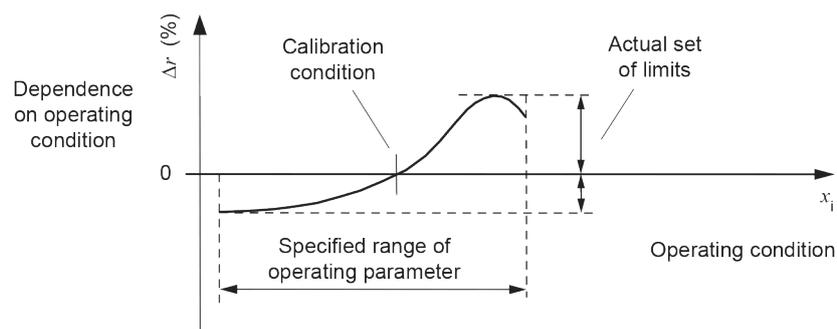$$u_{\text{extension}} = \sqrt{\sum_{i=1}^{n} u_{\text{extension,i}}^2} \qquad (35)$$

where:

$u_{\text{extension,i}}$ are contributions to the extension uncertainty;

n is the total number of contributions.

6.3.2   Determination of dependences on conditions

Each dependence should be recorded as relative change of the meter's *response*, caused by changing the relevant condition within its *operating range*. During the test, all other conditions should be kept at the *calibration conditions*. The zero point is defined by the *response* at *calibration conditions*. This way, each dependence can be specified by a range that is defined by the maximum positive and negative changes of the *response*. An asymmetric range about the zero point is the usual result, as shown in Figure 5.

Figure 5 – Determining and recording an extension uncertainty

In order to obtain good measurement accuracy, the guidelines in Clause 4 should be observed. Uncertainties in the measurements should be as low as possible, because the *measurement results* shall include these uncertainties. It is acceptable to use estimations instead of measurements if these estimations are based on known physical relations or on a sufficiently large number of characterizing measurements of the same type of *test meter*.

For the determination of the combined standard uncertainty of the *test meter* at *operating conditions*, the limits quantifying the individual dependences shall be converted to standard uncertainties using Equation (A.5).

The individual uncertainties are usually assumed to be independent. However, in some instances an uncertainty may be strongly dependent on more than one condition. Examples are outlined in 6.3.5, 6.3.7 and 6.3.8. If the extension uncertainty is substantially increased by changing the other conditions (within their specified *operating ranges*), this larger uncertainty shall be recorded. The calculation of the uncertainty shall then be based on these larger uncertainties.

6.3.3   Ageing

Ageing is the relative change of *response* over a given period. It can be determined from the results of successive *calibrations* of the meter at the same conditions or from indications of the manufacturer.

For a manufacturer, the relative change of *response* over a given period shall be determined with the assumption of careful use of the instrument. It is recommended to expose the power meter to its typical environmental conditions, for example ambient temperature (23 ± 1) °C for a laboratory-type instrument, *optical input port* non-irradiated, continuously repetitive cycles of power-on 12 h, power-off 12 h, with a total test time equal to the given period. The change of *response* should be measured by comparison with a *working standard*. Regular and traceable recalibration of the *working standard* will be necessary, in order to exclude ageing of the *working standard*. As always, the measurement uncertainty, in this case mostly the uncertainty of the *working standard*, shall be taken into account.

It is recommended to calculate the ageing uncertainty from a rectangular distribution obtained as described above (see Clause A.3). If, for example, a *detector* is known to increase its *response* by a maximum of 0,1 % per year at a certain wavelength, then the ageing uncertainty is characterized by a rectangle that extends from 0 % (at time 0) to +0,1 % (at time 1 year).

6.3.4   Dependence on temperature

The relative change of *response* against the *response* at the *calibration conditions* should be measured by changing the temperature within the operating temperature range. The rectangular uncertainty distribution is then defined by the most negative and the most positive relative changes of the *response*. Only the extremes of the *response* as a function of the temperature are relevant, not the *responses* at the extremes of temperature (see Figure 5).

Note that the temperature dependence of the *spectral responsivity* of semiconductor *detectors* depends on the wavelength.

6.3.5   Dependence on the power level (*nonlinearity*)

The relative change of *response* against the *response* at the *calibration* power level should be measured in accordance with Clause 7.

6.3.6 Dependence on the type of fibre or on the beam geometry

6.3.6.1 General

Fibre-optic power meters may be designed to accept fibres or open beams. It is assumed that the *response* of the power meter depends on the geometry of the light beam because, for example, of non-uniformity and angle-dependence of the meter's *optical input port*.

The relative change of *response* should be measured with a *working standard* that exhibits

– negligible angle-dependence,

– negligible surface reflections, and

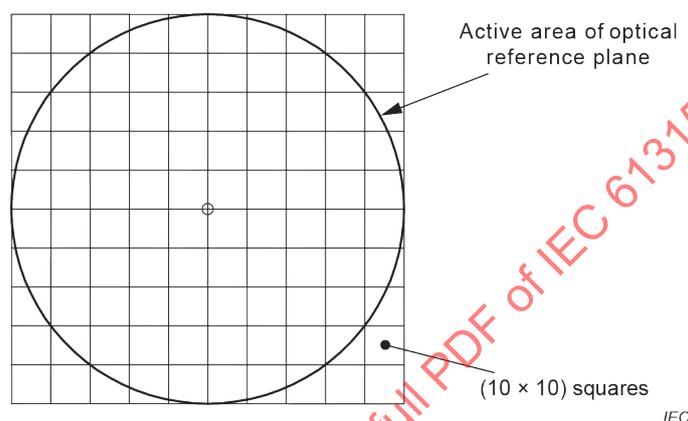– a sufficiently large active area to capture the fibre beams or the open beams.

Figure 6 – Possible subdivision of the *optical reference plane* into 10 × 10 squares, for the measurement of the spatial *response*

Another possibility is evaluating the uncertainties with a mathematical analysis, based on the assumption that all uncertainties are caused by non-uniform spatial *responses* of the *test meter*'s reference plane. In preparation of this analysis, the active area of the *optical reference plane* should be subdivided into an array of squares, for example, 10 × 10 squares as in Figure 6.

Then two types of measurements should be carried out:

a) measurements of the spatial power density, together with the angles of incidence, on the *optical reference plane* as generated by the applicable beam geometries;

b) measurements of the *test meter*'s spatial *response*, weighted with appropriate multipliers which characterize the meter's dependence on oblique incidence (angle dependence), on the *test meter*'s reference plane: the spatial *response* should be measured with a beam diameter equal to the length of the square.

The change of *response* upon changing the beam parameters can then be evaluated on the basis of modelling the necessary *measurement results*, by multiplying the (spatial) power levels with the spatial *responses* and adding all products. Note that the spatial *responses* are usually wavelength-dependent.

6.3.6.2 Measurement of the fibre dependence

In the test of fibre-related uncertainties, multimode fibres under test should be slightly underfilled (see 5.2). The fibres should be terminated by the connector-adapter combination defined by the *calibration conditions*. Both the connector and the adapter should exhibit a low reflectivity, so that multiple reflections between the connector-adapter combination and the

detector do not influence the *measurement results*. The *spectral bandwidth* of the source should be narrow enough to avoid averaging over a wide range of wavelengths.

Step 1: the output of the reference fibre is measured with both the *working standard* and the *test meter*, and the difference is (mathematically) adjusted to zero.

Step 2: the above procedure is applied to

    a) a standard single-mode fibre as defined by IEC 60793-2, and

    b) the (specified) fibre with the largest core diameter, the fibre with the largest *numerical aperture*, or both.

The intention of the test is to measure the dependence of the *test meter* on the type of fibre and on the mode volume. The largest relative change of *response* against step 1 (positive and negative) should be used to determine the fibre-related uncertainty. The uncertainty shall also include the uncertainty in measuring the fibre outputs with the *working standard*, caused for example by the effects of non-uniformity, beam divergence and multiple reflections on the *working standard*.

In these measurements, a significant type A uncertainty may be caused by "speckles", in conjunction with the non-uniformity of the *optical input port*. Speckles are irregular *irradiance* distributions caused by interference between different modes in a multimode fibre. This effect occurs particularly when the fibre is excited by the (highly coherent) radiation from a laser diode. This uncertainty can be reduced by averaging a series of *measurement results*, in which each sample is taken after a slight movement of the fibre. Fibre movement will change the speckle pattern. Note this may be accompanied by a change of the total *radiant power*, because of a change of the reflected power and the laser diode sensitivity to reflected power.

Speckles do not exist in single-mode fibres when the exciting wavelength is sufficiently longer than the fibre's cut-off wavelength. Another possibility of eliminating the speckle pattern is using a less coherent source, such as a filtered LED or a filtered "white" radiation source.

6.3.6.3   Measurement of open-beam dependence

Similar to measuring the fibre dependence, the dependence on the *spot diameter* (3.31) and the *numerical aperture* (3.17) of an open beam can be evaluated by comparison with a *working standard* that exhibits a uniform large area *detector* and negligible angle dependence.

To address the problem of combined dependence on *spot diameter* and *numerical aperture*, it may be sufficient to evaluate

    a) the relative change of *response* (against the *response* at *calibration conditions*) due to *excitation* with the specified smallest *spot diameter* – smallest *numerical aperture*, and

    b) the relative change of *response* due to *excitation* with the specified largest *spot diameter* – largest *numerical aperture*.

6.3.7   Dependence on the connector-adapter combination

6.3.7 discusses the *test meter*'s dependence on reflections from the radiation source (for example an optical connector or other mechanical parts in the beam path between the source and the *optical input port*). Note that the reflections may be specular or diffuse.

The relative change of *response* should be measured with the help of a *working standard* that exhibits negligible angle-dependence and surface reflections. The fibre should be the one used for the *calibration*. It is advisable to hold the fibre end in place during the measurement, in order to avoid any bending-induced changes of the power level. The source used should not be too coherent to avoid Fabry-Perot type interference (see 6.3.8.2): it should be broad enough, for example, 1 nm or more.

Step 1:   the reference beam geometry exiting the source or the reference fibre (together with the reference connector-adapter combination), is measured with both the

working standard and the *test meter*, and the difference is (mathematically) adjusted to zero.

Step 2: the step 1 procedure is applied to all specified connector-adapter combinations, by repeating each connection several times to reduce type A uncertainties. The largest relative change of *response* against step 1 (positive and negative) should be used to determine the uncertainty. The uncertainty shall also include the type B uncertainty in measuring the various combinations with the *working standard*, caused for example by the reflections when using the *working standard*.

In accordance with the last paragraph of 6.3.2, it may also be necessary to measure the dependence with the highest-order fibre, as listed in 6.3.6.2. A high-order fibre will create a larger image on the *optical reference plane*, and therefore make limitations in the positioning accuracy more obvious. In this case, an increased dependence should be recorded.

6.3.8 Dependence on wavelength

6.3.8.1 General

The relative change of spectral *response* against the *response* at the *calibration* wavelength should be measured. These measurements will normally be carried out using a spectrally continuous source imaged through a spectrally discriminating instrument, for example a monochromator or a number of spectral filters. The stray light, that is light not at the selected wavelength, should be evaluated, in order to ensure accurate *measurement results*. The *centroidal wavelength*(s) and the *spectral bandwidth*(s) should also be measured. The bandwidth should be narrow, because a wide bandwidth in conjunction with a strong curvature of the *test meter*'s wavelength dependence is capable of producing erroneous *measurement results*. Note that extremely narrow *spectral bandwidth* may cause optical interference problems, which is comb-like wavelength dependence, when the beam path contains one or more optical resonators.

The beam geometry should be appropriate for the determination of this dependence. It may be possible to substitute a fibre beam using a combination of lenses and apertures. In this case, care should be taken to match the irradiated *spot diameter* and position on the *optical reference plane* with those achieved using a fibre input. Care should also be taken to ensure that back reflections from the *optical input port* do not add uncertainties to the *measurement results*.

The measurement should be carried out by direct comparison with a *working standard* by using the substitution technique. The *working standard* should have been calibrated for relative spectral *response*.

Because of the relatively low power levels in these measurements, zero adjustment of both power meters is essential. If the instrument comprises means of correction, for example a *calibration* curve or a table stored in a memory, the relative change of *response* from the corrected *response* has to be measured.

Changing the temperature may strongly influence the wavelength-dependence. For example, the wavelength-dependence of a germanium photodiode at 1 550 nm is much stronger at 0 °C than at room temperature. In general, the wavelength uncertainty shall be calculated on the basis of the largest wavelength-dependence, in this case the one at 0 °C.

6.3.8.2 Dependence on wavelength due to Fabry-Perot type interference

When using a narrow *spectral bandwidth* laser ($B \ll 1$ nm), the spectral *response* can sometimes vary rapidly with respect to wavelength, as depicted in Figure 7. This is usually caused by Fabry-Perot cavity(ies) in the optical path to the *detector*. Fabry-Perot cavities can occur between the two faces of the window in the *detector* cap, between one face of the window and the *detector* itself, or, if a fibre is used, between the end of the fibre and any of the other surfaces.
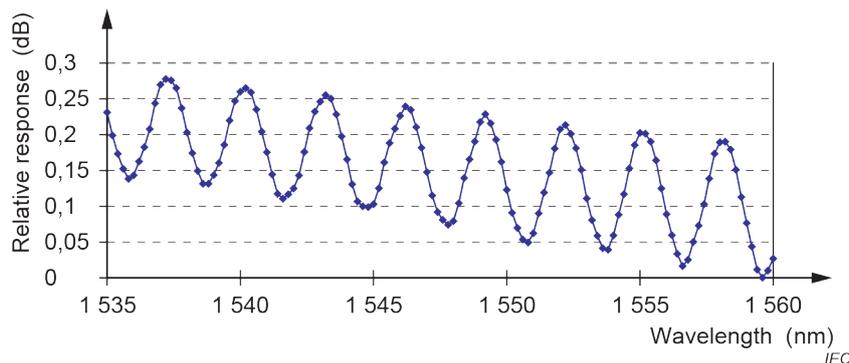
Figure 7 – Wavelength dependence of *response* due to Fabry-Perot type interference

In Figure 7, the peak-to-peak variation reaches Δ_{dB} = 0,2 dB ($\Delta_{\%}$ = 4,6 %), which is significant. The standard uncertainty due to optical interference is the standard *deviation* of the sine pattern.

$$u_{int} = \frac{1}{\sqrt{2}} \times \frac{\Delta_{\%}}{2} = 1,6\ \% \tag{36}$$

6.3.9 Dependence on *spectral bandwidth*

This dependence increases with the curvature of the *detector*'s wavelength dependence. The relative change of *response* as a function of the *spectral bandwidth* of the source has to be tested within the specified range of *spectral bandwidths*. A monochromator can be used to generate a variable *spectral bandwidth*; the actual power level should be measured with a *working standard* with negligible wavelength-dependence. The spectral-bandwidth dependence can also be evaluated by mathematical analysis, based on the known spectral *response* of the *test meter* and on the known spectral characteristics of the source.

6.3.10 Dependence on polarization

A method of evaluation of the *polarization dependent response* (PDR) (3.22) of the *test meter* is to measure the *response* of the meter multiple times at different states of polarization. A stable light source polarized to nearly 100 % should be used, otherwise use a polarizer after the source as shown in Figure 8. A polarization controller is used to convert the fixed input polarization state to all possible output states.
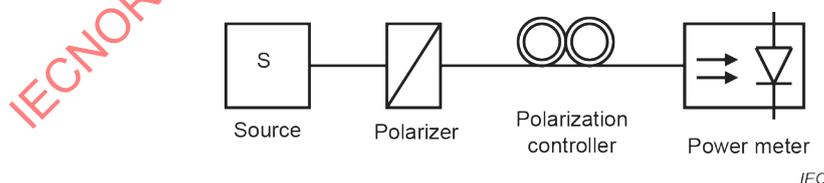

Figure 8 – Measurement setup of *polarization dependent response*

The source power instability and the loss variation of the polarization controller should be far lower than the polarization dependence of the *test meter*. This should be verified by replacing the *test meter* with a *detector* with a very low *polarisation dependent response*.

The laser sources may react with unstable power when light with a varying polarization state is back-reflected; therefore, an attenuator or isolator may have to be inserted between the source and the polarization controller.

Another PDR measurement method, the matrix method, can be adapted from the polarization dependent loss (PDL) Mueller matrix method in IEC 61300-3-2:2009, as described in [3].

6.3.11 Other dependences

Depending on the type of *test meter*, there may be dependences on other parameters. These should also be characterized as relative changes of *response* against the *response* at the *calibration conditions*.

One example may be including intensity-modulated optical signals into the *operating conditions*, in the form of specifying a range of modulation frequencies and duty cycles, and evaluating the type B uncertainty due to the modulation. It is important to take into account that extreme duty cycles are capable of saturating the *detector*, the electronics, or both.

7 *Nonlinearity calibration*

7.1 General

The *nonlinearity* (3.16) of the power meter should be calibrated to ensure accurate measurements at power levels away from the *calibration* level and for relative measurements such as loss and gain measurements. The *calibration* should be made by increasing and decreasing the power level to detect nonlinearities at the boundaries of each amplifier range or, whenever possible, to include *measurement results* at both sides of each range boundary, in order to include nonlinearities at these boundaries. It is important to note that the *detector nonlinearity* is dependent on the wavelength. As an example, an InGaAs *detector* that is linear at 1 310 nm and 1 550 nm may be nonlinear at 850 nm.

Several methods are possible. The superposition method is the reference method, as it is the most accurate and does not require a *reference standard* (self-calibrating method).

All methods use sources with selectable power level, for example (stabilized) laser diode sources and variable attenuators. The generated power levels should cover the specified *measuring range* (3.13). During the test, the maximum permissible *irradiance* of the input port should be defined by the optical power at the upper end of the *measuring range* and by single-mode fibre *excitation*.

The power level saturating the *detector* is dependent on the beam geometry. A small *spot diameter* may saturate the *detector* at lower power than a larger *spot diameter*.

Extreme ambient temperatures may increase the *nonlinearity*. As stated in the last paragraph of 6.3.2, some uncertainties can be dependent on more than one operating condition, and it can additionally be necessary to measure the *nonlinearity* at the extremes of the operating temperature range, and to record an increased uncertainty at *operating conditions*.

7.2 *Nonlinearity calibration* based on superposition

7.2.1 General

Highly accurate *nonlinearity calibration* is possible with the superposition method (also known as the "addition method") [4] [5]. A "fibred" version of the open-beam double aperture method [6] [7] may be used with single-mode fibres. A possible setup is illustrated in Figure 9. The power is split into two different paths where shutters are located and then recombined on the power meter under test.
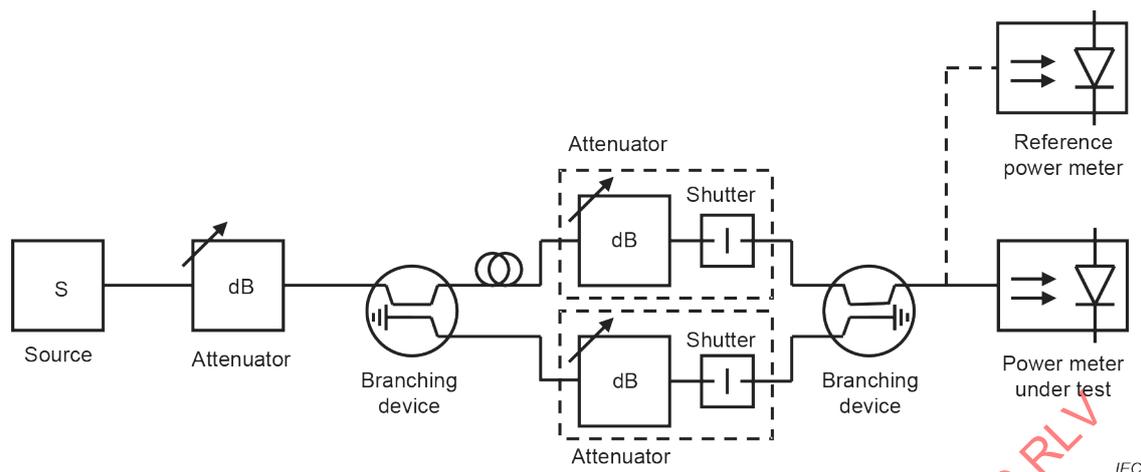
Figure 9 – *Nonlinearity calibration* based on superposition

Stable, optically-isolated (to reduce sensitivity to reflections) distributed feedback (DFB) lasers can be used, provided that the linewidth is broadened to yield an optimized coherence, as with the procedure for the absolute *calibration*. The two paths of the setup should have different lengths (around 100 m for DFB lasers) to avoid (Mach-Zehnder-type) interference fluctuations, and unused branches of branching devices shall be terminated. The drawback of this method is its higher insertion loss: typically around 1,5 dB for the first attenuator, 0,5 dB for the first branching device, 1,5 dB for the second attenuator and about 3,5 dB for the combining branching device for a total of about 7 dB. For higher power measurements, an optional optical amplifier (like an EDFA – erbium doped fibre amplifier – for the 1,55 μm band) can be inserted between the source and the first attenuator.

7.2.2   Procedure

(1) Set the attenuators in the two paths so that the power measured on the meter is the same when light is coming from one path or from the other path.

(2) Open both shutters and measure the total power from both paths simultaneously: $P_{ab,i}$.

(3) Close the shutter on path b and measure the power from path a: $P_{a,i}$.

(4) Close the shutter on path a, open the shutter on path b and measure the power from path b: $P_{b,i}$.

(5) If the sum of the individual powers is not equal to the total power, there is a *nonlinearity*:

$$NL_i = 10 \times \log_{10} \frac{P_{ab,i}}{P_{a,i} + P_{b,i}} \, (\text{dB}) \tag{37}$$

(6) Using the first attenuator, attenuate the total power by a factor 2 (10 $\log_{10}$ 2 ≅ 3,01 dB) to the level of the individual powers of the preceding step.

(7) Repeat steps (2) to (6) through all the desired range.

(8) At the end, the global *nonlinearity* is the sum of all the local nonlinearities expressed in decibels (dB), starting calculations from the reference power level where the *nonlinearity* is zero (higher order terms are neglected).

$$NL_{\text{global}}(P_n) = -\sum_{i=0}^{n+1} NL_i \quad \text{for } n = -1, -2, -3, \text{ etc.} \tag{38}$$

$$NL_{\text{global}}(P_0) = 0 \, (\text{reference power})$$

$$NL_{\text{global}}\left(P_{\text{n}}\right) = +\sum_{i=1}^{n} NL_{\text{i}} \text{ for } n = 1, 2, 3, \text{ etc.}$$

where

$n < 0$ indicates power levels lower than the reference power;

$n > 0$ indicates power levels higher than the reference power;

NL_{i} is the local *nonlinearity* for the ith step ($i = 0$ for the step where P_{ab} is the reference power).

The result is a list of global nonlinearities for the whole power range in steps of 3,01 dB as seen in Table 2:

Table 2 – *Nonlinearity*

i	$P_{\text{a,i}}$ W	$P_{\text{a,i}}$ W	$P_{\text{a,i}} + P_{\text{b,i}}$ W	$P_{\text{ab,i}}$ W	NL_{i} dB	$NL_{\text{global}}(P_{\text{ab,i}})$ dB
2					NL_2	$NL_1 + NL_2$
1					NL_1	NL_1
0				P_0	NL_0	0
−1					NL_{-1}	$-NL_0$
−2					NL_{-2}	$-NL_0 - NL_{-1}$

The largest *nonlinearity* relative to the reference power is:

$$NL_{\text{max}} = \pm \max(|NL_{\text{global}}|) \text{ (dB)} \tag{39}$$

This result of the *nonlinearity calibration* can be included in the *test meter*'s *calibration* certificate or *calibration* report described in 5.5. If desired, NL_{max} may be reported separately, together with its applicable uncertainty, as calculated in 7.2.3.

Using 3 dB power steps might be too large to detect nonlinearities that might appear at amplifier range boundaries. This limitation can be avoided by starting the *calibration* from several reference powers, or by taking separate measurements of the same power level on both sides of the amplifier range boundaries.

7.2.3   Uncertainties

Typical possible uncertainties of this method include all possible power fluctuations during a set of the three measurements such as source fluctuations due to drifts or sensitivity to changing reflections, instabilities due to interference if the coherence length of the laser is too large, polarization sensitivity and resolution of the power meter. These errors for each step are cumulative and will add to the errors of the preceding steps.

Another uncertainty is the inequivalence between the individual powers of each step and also with the total power of the next step. If the individual powers are not properly balanced, the result will not be reliable. For this last reason, the use of the optional attenuator in each path is recommended, as shown in Figure 9 (the shutter is usually included in the attenuator). They allow the power in each path to be balanced at the beginning of the measurements. Another version of the setup uses this approach, but employs two separate laser sources directly connected to the second and third attenuators respectively. It has the advantage to start measurements at higher powers but it requires communication with the *test meter* to adjust the attenuators at each step.

Calculate first the combined standard uncertainty for the local *nonlinearity* (one step) $u(NL_i)$ by root-sum-squaring all relevant standard uncertainty contributions. Then calculate the standard uncertainty of the global *nonlinearity* with:

$$u\left(NL_{\text{global}}\right) = \sqrt{n} \times u\left(NL_i\right) \ (\text{dB}) \tag{40}$$

where

n is the number of 3,01 dB steps counted from the reference level.

7.3   *Nonlinearity calibration* based on comparison with a calibrated power meter

7.3.1   General

One possible measurement method is direct comparison of the *test meter* with a *reference meter* by using the substitution technique. The *reference meter* is used to determine the output power. Then the *reference meter* is replaced by the *test meter*. The *measurement results* of both meters are recorded. In this case, errors can be due to the repeatability of the attenuator, its PDL, the source power stability and the *nonlinearity* of the *reference meter*. The *nonlinearity* of the *reference meter* should have been calibrated using a more accurate method.

It is advisable to repeat the measurements with the *working standard* to check for drifts in the measurement. In order to extend the measurements to low power levels, it is recommended that the *reference meter* incorporate a low noise *detector*.

Instead of the substitution, simultaneous *excitation* of both the *reference meter* and the *test meter*, with the help of an appropriate beam splitter or branching device, is also possible, as depicted in Figure 10. A beam splitter/branching device with an asymmetric ratio, or the use of a second attenuator, will allow an extension of the dynamic range of the measurement in both directions. The dependence of the ratio to the power level and polarization has to be investigated.
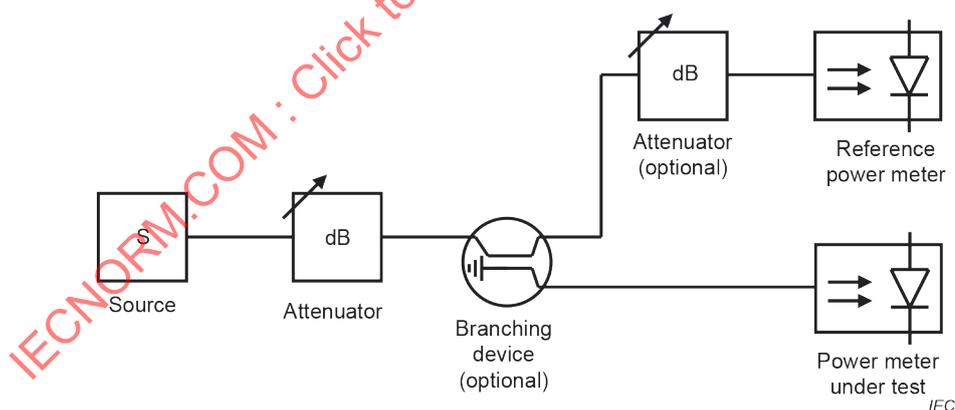

Figure 10 – Measurement setup for *nonlinearity calibration* by comparison

7.3.2   Procedure

(1) Set the desired reference power with the help of the first attenuator.

(2) Measure the *radiant power* with the *reference meter* $P_{\text{ref},0}$ and with the *test meter* $P_{\text{DUT},0}$.

(3) Increase (or decrease) the power with the help of the first attenuator and record the power measured with the *reference* meter $P_{\text{ref},i}$ and with the *test meter* $P_{\text{DUT},i}$.

(4) Calculate the *nonlinearity*:

$$NL_i = 10 \times \log_{10} \frac{P_{DUT,i}}{P_{DUT,0}} - 10 \times \log_{10} \frac{P_{ref,i}}{P_{ref,0}} \quad (dB) \tag{41}$$

(5) Repeat steps (3) to (4) to cover the measurement range.

7.3.3 Uncertainties

Possible sources of measurement uncertainties are given in the following list, which may not be exhaustive. Additional contributions may have to be taken into account, depending on the measurement setup and procedure. The mathematical basis, Annex A, should be used to calculate and state the uncertainties.

a) *nonlinearity* of the linearity standard (usually calibrated by the superposition method);
b) source instability (back-reflections may cause source instability);
c) optical interference (the coherence length of the source should be smaller than the distance between reflection points);
d) polarization dependence of the components;
e) resolution of the *test meter*;
f) stability of the ratio of the beam splitter or the branching device if used;
g) depending on the procedure, the repeatability of the attenuator.

7.4 *Nonlinearity calibration* based on comparison with an attenuator

The simplest but least accurate method to measure the *nonlinearity* is based on varying the power level with a calibrated attenuator. The *traceability chain* (3.34) of the attenuator shall be determined. Care shall be taken in the calculation of the uncertainty since the *calibration* of the attenuator is itself based on the linearity of a calibrated power meter. This method does not require a second power meter; instead, the reference power levels can then be calculated with the known attenuation of the attenuator. The main errors arise from the *nonlinearity* of the variable attenuator, its PDL in the case of single-mode fibres and the source power stability. It is also important to take into account the attenuator's repeatability and wavelength dependence. This method is nevertheless useful when high accuracy is not necessary because it is simple and because the low insertion loss (only the loss of the attenuator) permits measurement at higher power than other methods (up to the maximum input power at which the attenuator remains linear).

7.5 *Calibration* of power meter for high power measurement

Most photoelectric *detectors* become nonlinear above an optical power of about 10 mW. Sensors designed to measure power at higher power usually incorporate an attenuator in front of the *detector*.

Absolute power *calibration* at high power [8] is not available widely. When not possible, it is then necessary to calibrate the *nonlinearity* of the power meter up to high power. In this context, high power is defined as powers greater than 10 mW. It is not straightforward to use the same setup as described in 7.2 to 7.4 since several components may exhibit nonlinear effects. The behaviour at high power of all elements in the *calibration* setup (connectors, attenuators, branching devices, etc.) should be investigated. The superposition method is the preferred method, since it does not rely on a *reference standard*, but note that the use of a long length of fibre in one path of the superposition system is not desirable at high powers due to the possibility of nonlinear effects causing apparent *nonlinearity* of the power meter.

Annex A
(normative)

Mathematical basis for measurement uncertainty calculations

A.1   General

Annex A summarises the form of evaluating, combining and reporting the uncertainty of measurement. It is based on ISO/IEC Guide 98-3. Annex A shall be read in conjunction with ISO/IEC Guide 98-3 for additional information.

This document distinguishes two types of evaluation of uncertainty of measurement. Type A is the method of evaluation of uncertainty by the statistical analysis of a series of measurements on the same measurand. Type B is the method of evaluation of uncertainty based on other knowledge.

A.2   Type A evaluation of uncertainty

Type A evaluation of standard uncertainty can be applied when several independent observations have been made for a quantity under the same conditions of measurement.

For a quantity X estimated from n independent repeated observations X_k, the arithmetic mean is:

$$\overline{X} = \frac{1}{n}\sum_{k=1}^{n} X_k \tag{A.1}$$

This mean is used as the estimate of the quantity, that is $x = \overline{X}$. The experimental standard *deviation* of the observations is given by:

$$s(X) = \left[\frac{1}{n-1}\sum_{k=1}^{n}\left(X_k - \overline{X}\right)^2\right]^{1/2} \tag{A.2}$$

where

$\overline{X}$ is the arithmetic mean of the observed values;

X_k are the measurement samples of a series of measurements;

n is the number of measurements; it is assumed to be large, for example, $n \geq 10$.

The type A standard uncertainty $u_{typeA}(x)$ associated with the estimate x is the experimental standard *deviation* of the mean:

$$u_{typeA}(x) = s(\overline{X}) = \frac{s(X)}{\sqrt{n}} \tag{A.3}$$

A.3 Type B evaluation of uncertainty

Type B evaluation of standard uncertainty is the method of evaluating the uncertainty by means other than the statistical analysis of a series of observations. It is evaluated by scientific judgement based on all available information on the variability of the quantity.

If the estimate x of a quantity X is taken from a manufacturer's specification, *calibration* certificate, handbook, or other source and its quoted uncertainty $U(x)$ is stated to be a multiple k of a standard *deviation*, the standard uncertainty $u(x)$ is simply the quoted value divided by the multiplier.

$$u(x) = U(x) \,/\, k \tag{A.4}$$

If only upper and lower limits $X_{\max}$ and $X_{\min}$ can be estimated for the value of the quantity X, a rectangular probability distribution is assumed.

The standard uncertainty is

$$u\left(x\right) = \frac{\left(\left|X_{\max} - x\right|, \left|X_{\min} - x\right|\right)_{\text{MAX}}}{\sqrt{3}} \tag{A.5}$$

The contribution to the standard uncertainty associated with the output estimate y resulting from the standard uncertainty associated with the input estimate x is

$$u(y) = c \times u(x) \tag{A.6}$$

where

c is the sensitivity coefficient associated with the input estimate x, that is the partial derivative of the model function $y(x)$, evaluated at the input estimate x.

$$c = \frac{\partial y}{\partial x} \tag{A.7}$$

The sensitivity coefficient c describes the extent to which the output estimate y is influenced by variations of the input estimate x. It can be evaluated by Equation (A.7) or by using numerical methods, that is by calculating the change in the output estimate y due to a change in the input estimate x from a model function. Sometimes, it may be more appropriate to find the change in the output estimate y due to the change in x from an experiment.

A.4 Determining the combined standard uncertainty

The combined standard uncertainty is used to collect a number of individual uncertainties into a single number. The combined standard uncertainty is based on statistical independence of the individual uncertainties; it is calculated by root-sum-squaring all standard uncertainties obtained from type A and type B evaluation:

$$u_{\text{c}}\left(y\right) = \sqrt{\sum_{i=1}^{n} u_i^2\left(y\right)} \tag{A.8}$$

where

i is the current number of individual contributions;

$u_i(y)$ are the standard uncertainty contributions;

n is the number of uncertainties.

NOTE   Uncertainty contributions in this equation that are smaller than 1/10 of the largest contribution are negligible, because squaring them will reduce their significance to 1/100 of the largest contribution.

When the quantities above are to be used as the basis for further uncertainty computations, then the combined standard uncertainty, u_c, can be re-inserted into Equation (A.8). Despite its partial type A origin, u_c should be considered as describing an uncertainty of type B.

A.5   Reporting

In *calibration* reports and technical data sheets, combined standard uncertainties shall be reported in the form of expanded uncertainties, together with the applicable level of confidence. *Correction factors* or *deviations* shall be reported. The expanded uncertainty U is obtained by multiplying the standard uncertainty $u_c(y)$ by a coverage factor k:

$$U = k \times u_c(y) \tag{A.9}$$

For a level of confidence of approximately 95 %, the default level, then $k = 2$. If a level of confidence of approximately 99 % is chosen, then $k = 3$. The above values for k are valid under some conditions (see ISO/IEC Guide 98-3); if these conditions are not met, larger coverage factors are to be used to reach these levels of confidence.

Annex B
(informative)

Linear to dB scale conversion of uncertainties

B.1 Definition of decibel

The decibel is a submultiple of the bel (1 dB = 0,1 B). This unit is used to express values of power level on a logarithmic scale. The power level is always relative to a reference power P_0:

$$L_{P/P_0} = 10 \times \log_{10}\left(\frac{P}{P_0}\right) \text{ (dB)} \tag{B.1}$$

where

P and P_0 are expressed in the same linear units.

B.2 Conversion of relative uncertainties

Similar to the definition in Clause B.1, relative uncertainties, U_{lin}, or relative *deviations*, can be expressed in decibels:

$$U_{\text{dB}} = 10 \times \log_{10}(1 + U_{\%}) \tag{B.2}$$

Reciprocally, U_{lin} can be expressed in % using:

$$U_{\%} = \left[10^{\frac{U_{\text{dB}}}{10}} - 1\right] \times 100 \tag{B.3}$$

For small values of U_{lin}, the first term of the applicable Taylor series can be used. Having:

$$\ln(1+x) = \sum_{n=1}^{\infty} \frac{-1^{n+1}}{n} x^n \text{ and } \log_{10} x = \frac{\ln x}{\ln(10)} \tag{B.4}$$

that leads to:

$$U_{\text{dB}} = \frac{10}{\ln(10)} \sum_{n=1}^{\infty} \frac{-1^{n+1}}{n} U_{\text{lin}}{}^n \approx \frac{10}{\ln(10)} U_{\text{lin}} \tag{B.5}$$

and to two useful expressions:

$$U_{\text{dB}} \approx 4,34 \times U_{\text{lin}} \Leftrightarrow U_{\text{lin}} \approx 0,23 \times U_{\text{dB}} \tag{B.6}$$

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[11]   IEC 60793-1-43:2015, *Optical fibres – Part 1-43: Measurement methods and test procedures – Numerical aperture measurement*

[12]   IEC 60825-1, *Safety of laser products – Part 1: Equipment classification and requirements*

[13]   IEC 60825-2, *Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCS)*

[14]   IEC 61280-4-1, *Fibre-optic communication subsystem test procedures – Part 4-1: Installed cable plant – Multimode attenuation measurement*

[15]   IEC TR 61930, *Fibre optic graphical symbology*

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[2]   This publication has been withdrawn, but for the purpose of this document, it is given as a reference.

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SOMMAIRE

COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

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ÉTALONNAGE DE WATTMÈTRES POUR DISPOSITIFS À FIBRES OPTIQUES

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La Norme internationale IEC 61315 a été établie par le comité d'études 86 de l'IEC: Fibres optiques.

Cette troisième édition annule et remplace la deuxième édition parue en 2005. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

a) mise à jour des termes et définitions;

b) mise à jour du 5.1, y compris le Tableau 1 (nouveau type de source);

c) mise à jour de l'Annexe A;

d) ajout d'une Annexe B sur la conversion en dB.

Le texte de cette Norme internationale est issu des documents suivants:

CDV	Rapport de vote
86/533/CDV	86/540A/RVC

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à l'approbation de cette Norme internationale.

Ce document a été rédigé selon les Directives ISO/IEC, Partie 2.

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INTRODUCTION

Les *wattmètres pour dispositifs à fibres optiques* sont conçus pour mesurer la puissance optique des sources à fibres optiques avec la plus grande exactitude possible. Cette capacité dépend surtout de la qualité du processus d'*étalonnage*. Par opposition à d'autres types d'appareillages de mesure, les *résultats de mesure* des *wattmètres pour dispositifs à fibres optiques* dépendent généralement de nombreuses conditions de mesure. Les conditions de mesure au cours du processus d'*étalonnage* sont appelées *conditions d'étalonnage.* Leur description précise fait donc partie intégrante de l'étalonnage.

Le présent document définit toutes les étapes du processus d'*étalonnage*: établissement des *conditions d'étalonnage*, réalisation de l'*étalonnage*, calcul de l'incertitude et rapport de l'incertitude, des *conditions d'étalonnage* et de la *traçabilité*.

L'*étalonnage* de puissance absolu décrit la façon de déterminer le rapport entre la valeur de la puissance d'entrée et le résultat du wattmètre. Ce rapport est appelé *facteur de correction*. L'incertitude de mesure du *facteur de correction* est composée suivant l'Annexe A à partir des contributions à l'incertitude de l'*appareil de référence*, de l'*appareil de mesure d'essai*, du montage et de la procédure.

Les calculs font l'objet d'interprétations détaillées d'incertitudes individuelles. Il est important de savoir que

a) certaines incertitudes sont des estimations de type B, fondées sur l'expérience,

b) une analyse détaillée de l'incertitude n'est généralement effectuée qu'une seule fois pour chaque type de wattmètre en essai et que tous les *étalonnages* suivants reposent souvent sur cette analyse ponctuelle, en utilisant les contributions de mesure de type A appropriées évaluées au moment de l'*étalonnage*, et

c) certaines incertitudes individuelles sont simplement considérées comme faisant partie d'une liste de contrôle, et auxquelles est associée une valeur réelle qui peut être négligée.

L'Article 5 définit l'*étalonnage* de puissance absolu qui est obligatoire pour les rapports d'*étalonnage* faisant référence au présent document.

L'Article 6 décrit l'évaluation de l'incertitude de mesure d'un wattmètre étalonné fonctionnant dans les *conditions de référence* ou dans les *conditions de fonctionnement*. Elle dépend de l'incertitude d'*étalonnage* du wattmètre calculée en 5.4, des conditions et de sa dépendance par rapport à ces conditions. Elle est généralement effectuée par des fabricants, afin d'établir des spécifications, et n'est pas obligatoire pour les rapports faisant référence au présent document. L'un de ces facteurs de dépendance, la *non-linéarité*, est déterminé dans un *étalonnage* séparé (Article 7).

ÉTALONNAGE DE WATTMÈTRES POUR DISPOSITIFS À FIBRES OPTIQUES

1   Domaine d'application

Le présent document s'applique aux appareils qui mesurent la *puissance rayonnante* émise par des sources typiques pour l'industrie des communications par fibres optiques. Ces sources comprennent les diodes laser, les diodes émettant de la lumière (LED) et les sources fibrées. Le rayonnement divergent ainsi que le rayonnement collimaté sont couverts par le présent document. Ce dernier définit l'*étalonnage* des wattmètres à effectuer par des laboratoires d'*étalonnage* ou par des fabricants de wattmètres.

2   Références normatives

Les documents suivants sont cités dans le texte de sorte qu'ils constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60793-2, *Fibres optiques – Partie 2: Spécifications de produits – Généralités*

IEC TR 61931:1998, *Fibres optiques – Terminologie*

ISO/IEC 98-3 Guide:2008*, Incertitude de mesure – Partie 3: Guide pour l'expression de l'incertitude de mesure (GUM:1995)*

3   Termes et définitions

Pour les besoins du présent document, les termes et définitions donnés dans l'IEC TR 61931, ainsi que les suivants s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse http://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse http://www.iso.org/obp

3.1
laboratoire d'étalonnage accrédité
laboratoire d'*étalonnage* autorisé par l'organisation nationale compétente à publier des certificats d'*étalonnage* avec une incertitude minimale spécifiée, qui démontrent la *traçabilité aux étalons nationaux* (3.14)

3.2
ajustage
ensemble des opérations réalisées sur un appareil pour qu'il fournisse des indications données correspondant à des valeurs données du mesurande

Note 1 à l'article: Lorsque l'appareil est conçu pour donner une indication égale à zéro correspondant à une valeur égale à zéro du mesurande, l'ensemble des opérations est appelé réglage de zéro.

Note 2 à l'article: Voir l'ISO/IEC Guide 99:2007, 3.11, pour de plus amples informations.

[SOURCE: IEC 60050-311:2001, 311-03-16, modifiée – Les mots "d'un appareil de mesure" ont été supprimés du terme, et la Note 2 à l'article a été ajoutée.]

3.3
étalonnage
ensemble des opérations qui établissent, dans des conditions spécifiées, la relation entre les valeurs des grandeurs indiquées par un instrument de mesure et les valeurs correspondantes réalisées par les étalons de mesure

Note 1 à l'article: Le résultat d'un *étalonnage* permet soit l'affectation des valeurs des mesurandes aux indications, soit la détermination de corrections par rapport aux indications.

Note 2 à l'article: Un *étalonnage* peut également déterminer d'autres propriétés métrologiques, telles que l'effet des grandeurs d'influence.

Note 3 à l'article: Le résultat d'un *étalonnage* peut être enregistré dans un document, appelé parfois certificat d'*étalonnage* ou rapport d'*étalonnage*.

Note 4 à l'article: Voir aussi l'ISO/IEC Guide 99:2007, 2.39.

3.4
conditions d'étalonnage
conditions de mesure dans lesquelles l'*étalonnage* est réalisé

3.5
longueur d'onde centrale
λ_c
longueur d'onde moyenne pondérée en puissance d'une source de lumière dans le vide

Note 1 à l'article: Pour un spectre continu, la *longueur d'onde centrale* est définie par:

$$\lambda_c = \frac{\int p(\lambda)\lambda d\lambda}{P_{totale}} \tag{1}$$

Pour un spectre constitué de modes discrets, la *longueur d'onde centrale* est définie par:

$$\lambda_c = \frac{\sum_i P_i \lambda_i}{\sum_i P_i} \tag{2}$$

où

$p(\lambda)$ est la densité spectrale de puissance de la source, par exemple en W/nm;

λ_i est la longueur d'onde dans le vide du $i^{\text{ème}}$ mode discret

P_i est la puissance du $i^{\text{ème}}$ mode discret, par exemple, en W;

P_{totale} est la puissance totale, par exemple, en W.

Note 2 à l'article: Les intégrales et sommations ci-dessus s'étendent en théorie sur l'ensemble du spectre de la source de lumière. Cependant, il est généralement suffisant de réaliser l'intégrale ou la sommation sur le spectre sur lequel la densité spectrale $p(\lambda)$ ou la puissance P_i est supérieure à 0,1 % de la densité spectrale maximale $p(\lambda)$ ou de la puissance P_i.

3.6
facteur de correction
CF
facteur numérique par lequel le résultat brut d'un mesurage est multiplié pour compenser une erreur systématique

Note 1 à l'article: Le symbole "*CF*" est dérivé du terme anglais développé correspondant "correction factor".

3.7
détecteur
élément du wattmètre qui convertit la *puissance rayonnante* optique en une grandeur mesurable, normalement électrique

Note 1 à l'article: Dans le présent document, le *détecteur* est considéré comme étant connecté au *port d'entrée optique* par un chemin optique.

Note 2 à l'article: Voir l'ISO/IEC Guide 99:2007, 3.9, pour de plus amples informations.

3.8
écart
D
différence relative entre la puissance mesurée par l'*appareil de mesure d'essai* (3.32) P_{DUT} et la puissance de référence P_{ref}:

$$D = \frac{P_{\text{DUT}} - P_{\text{ref}}}{P_{\text{ref}}} \tag{3}$$

Note 1 à l'article: Le symbole "*D*" est dérivé du terme anglais développé correspondant "deviation".

3.9
excitation
<fibre> description de la répartition de la puissance optique entre les modes dans la fibre

Note 1 à l'article: Dans le cas des fibres multimodales, l'*excitation* de la fibre est décrite par

a) le *diamètre du spot* (3.31) à la surface de l'extrémité de la fibre, et

b) l'*ouverture numérique* (3.17) du rayonnement émis par la fibre.

Par hypothèse, les fibres unimodales sont généralement excitées uniquement par un mode (le mode fondamental).

3.10
mode de l'appareil
ensemble de paramètres qui peuvent être choisis sur un appareil

Note 1 à l'article: Les paramètres typiques du *mode de l'appareil* sont la plage de puissance optique, le réglage de longueur d'onde, l'unité de mesure de l'affichage et la sortie qui permet d'obtenir le *résultat de mesure* (par exemple affichage, bus d'interface, sortie analogique).

3.11
éclairement énergétique
quotient de la *puissance rayonnante* différentielle ∂P incidente sur un élément du plan de référence par la surface différentielle ∂A de cet élément:

$$E = \frac{\partial P}{\partial A} \quad \left(\text{W/m}^2\right) \tag{4}$$

Note 1 à l'article: Voir l'IEC TR 61931:1998, 2.1.15, pour de plus amples informations.

3.12
résultat de mesure
y
sortie (affichée ou électrique) d'un wattmètre (ou étalon), après exécution de toutes les actions indiquées dans les instructions de fonctionnement, par exemple préchauffage, réglage de zéro et correction de la longueur d'onde

Note 1 à l'article: Le *résultat de mesure* est exprimé en watts (W). Pour les besoins de l'incertitude, il convient de convertir en watts les *résultats de mesure* exprimés dans d'autres unités, par exemple en volts. Il convient aussi de convertir les *résultats de mesure* exprimés en décibels (dB) en watts, car le cumul de l'incertitude totale repose sur les *résultats de mesure* exprimés en watts. Voir l'Annexe B.

3.13
étendue de mesure
ensemble des valeurs du mesurande pour lesquelles l'erreur d'un instrument de mesure est définie comme étant comprise dans des limites spécifiées

Note 1 à l'article: Dans le présent document, l'*étendue de mesure* est la plage de la *puissance rayonnante* (partie de *plage de fonctionnement*), pour laquelle l'incertitude aux *conditions de fonctionnement* est spécifiée. Dans ce contexte, il convient d'éviter le terme "dynamique".

Note 2 à l'article: Voir l'ISO/IEC Guide 99:2007, 4.7, pour de plus amples informations.

3.14
étalon national
étalon reconnu par une décision nationale pour servir, dans un pays, de base pour attribuer des valeurs à d'autres étalons de la grandeur concernée

Note 1 à l'article: Voir l'ISO/IEC Guide 99:2007, 5.3, pour de plus amples informations.

3.15
laboratoire d'étalon national
laboratoire qui conserve l'*étalon national* (3.14)

3.16
non-linéarité
NL
différence relative entre la *réponse* (3.28) à une puissance P donnée et la *réponse* à une puissance de référence P_0:

$$nl_{P/P_0} = \frac{r(P)}{r(P_0)} - 1 \qquad (5)$$

Si elle est exprimée en décibels, la *non-linéarité* est:

$$NL_{P/P_0} = 10 \times \log_{10} \frac{r(P)}{r(P_0)} \text{ (dB)} \qquad (6)$$

Note 1 à l'article: La *non-linéarité* est égale à zéro à la puissance de référence.

Note 2 à l'article: Le terme "*non-linéarité* locale" est utilisé pour la différence relative entre les *réponses* à deux niveaux de puissance différents (séparés par 3,01 dB) obtenues au cours de l'*étalonnage* de la *non-linéarité*. Le terme "*non-linéarité* globale" est utilisé pour le résultat de la somme des *non-linéarités* locales (en dB); il est identique à la *non-linéarité* définie ici.

3.17
ouverture numérique
description de la divergence du faisceau d'une source optique

Note 1 à l'article: Dans le présent document, l'*ouverture numérique* est le sinus (linéaire) du demi-angle auquel l'*éclairement énergétique* correspond à 5 % de l'*éclairement énergétique* maximal.

Note 1 à l'article: Adapte de la définition de l'*ouverture numérique* pour les fibres multimodales à gradient d'indice donnée à l'IEC 60793-1-43:2015, Article 3; dans le présent document, la définition sert à décrire la divergence de tous les faisceaux divergents.

3.18
conditions de fonctionnement
ensemble approprié de plages spécifiées de valeurs des grandeurs d'influence généralement supérieures aux *conditions de référence* pour lesquelles les incertitudes d'un instrument de mesure sont spécifiées

Note 1 à l'article: Les *conditions de fonctionnement* et l'incertitude aux *conditions de fonctionnement* sont généralement spécifiées par le fabricant à l'intention de l'utilisateur.

3.19
plage de fonctionnement
plage spécifiée de valeurs d'un des ensembles des *conditions de fonctionnement* (3.18)

3.20
port d'entrée optique
entrée physique du wattmètre (ou étalon) à laquelle la *puissance rayonnante* doit être appliquée ou à laquelle l'extrémité de la fibre optique doit être connectée

Note 1 à l'article: Un chemin optique (chemin de rayons avec ou sans éléments optiques tels que lentilles, diaphragmes, guides de lumière, etc.) est réputé connecter le *port d'entrée optique* avec le *détecteur* du wattmètre.

3.21
plan de référence optique
plan sur ou près du *port d'entrée optique* (3.20) qui sert à définir le diamètre du *diamètre du spot* (3.31)

Note 1 à l'article: Par hypothèse, le *plan de référence optique* est généralement perpendiculaire à la propagation du faisceau, et il convient de le décrire à l'aide de dimensions mécaniques appropriées se rapportant au *port d'entrée optique* du wattmètre.

3.22
réponse dépendant de la polarisation
PDR
variation de la *réponse* d'un wattmètre en fonction de tous les états possibles de polarisation de la lumière d'entrée:

$$PDR = 10 \times \log_{10}\left(\frac{r_{max}}{r_{min}}\right) \text{ (dB)} \tag{7}$$

où

r_{max} et r_{min} sont les *réponses* maximale et minimale (3.28) enregistrées sur tous les états de polarisation

Note 1 à l'article: La *réponse dépendant de la polarisation* est exprimée en décibels.

Note 2 à l'article: L'abréviation "PDR" est dérivée du terme anglais développé correspondant "polarization dependent response".

3.23
wattmètre pour dispositifs à fibres optiques
appareil pouvant mesurer la *puissance rayonnante* des sources à couplage de fibres telles que les lasers et les LED, typiques pour l'industrie des communications par fibres optiques

Note 1 à l'article: Le rayonnement peut être divergent ou collimaté. Par hypothèse, le rayonnement est défini comme étant incident sur le *plan de référence optique* dans les conditions spécifiées.

Note 2 à l'article: Un wattmètre peut comporter soit un appareil unique, soit un appareil principal et une tête de détection séparée. Dans le cas d'une tête de détection séparée, la tête peut être étalonnée sans l'appareil principal. Toutefois, si des systèmes électroniques analogiques sont utilisés dans l'appareil principal, la tête de détection doit être étalonnée avec l'appareil principal.

Note 3 à l'article: Un *wattmètre pour dispositifs à fibres optiques* peut en général mesurer la valeur moyenne temporelle d'une puissance optique modulée. Une incertitude plus importante peut être observée qui dépend du cycle de service et de la puissance de crête de la puissance optique modulée.

3.24
puissance rayonnante
P

puissance émise, transférée ou reçue sous la forme de rayonnement optique [1][1]

Note 1 à l'article: La *puissance rayonnante* est exprimée en watts.

3.25
conditions de référence
conditions d'utilisation exigées pour les essais de performance d'un instrument de mesure ou pour la comparaison entre les résultats des mesurages

Note 1 à l'article: Les *conditions de référence* comprennent généralement les valeurs de référence ou les plages de référence pour les grandeurs d'influence affectant l'instrument de mesure.

3.26
appareil de référence
étalon qui est utilisé comme référence pour l'*étalonnage* (3.3) d'un *appareil de mesure d'essai* (3.32)

3.27
étalon de référence
étalon, en général de la plus haute qualité métrologique disponible à un emplacement donné ou dans un organisme donné, dont les mesurages qui y sont effectués sont dérivés

Note 1 à l'article: Voir l'ISO/IEC Guide 99:2007, 5.6, pour de plus amples informations.

3.28
réponse
r

résultat de mesure d'un wattmètre, *y*, divisé par la *puissance rayonnante* sur le *plan de référence optique* du wattmètre *P*, à une condition de mesure donnée:

$$r = \frac{y}{P} \ \text{(W/W, sans dimension)} \tag{8}$$

Note 1 à l'article: Un wattmètre idéal indique une *réponse* de 1 pour toutes les *conditions de fonctionnement*.

3.29
sensibilité spectrale
sensibilité
R

quotient du courant de sortie du *détecteur I* par la puissance optique monochromatique incidente *P*:

$$R = \frac{I}{P} \ \text{(A/W)} \tag{9}$$

Note 1 à l'article: La *sensibilité* dépend des conditions (longueur d'onde, température, etc.). Voir Figure 1.

Note 2 à l'article: Le symbole "*R*" est dérivé du terme anglais développé correspondant "responsivity".

_____

1   Les chiffres entre crochets se réfèrent à la Bibliographie.
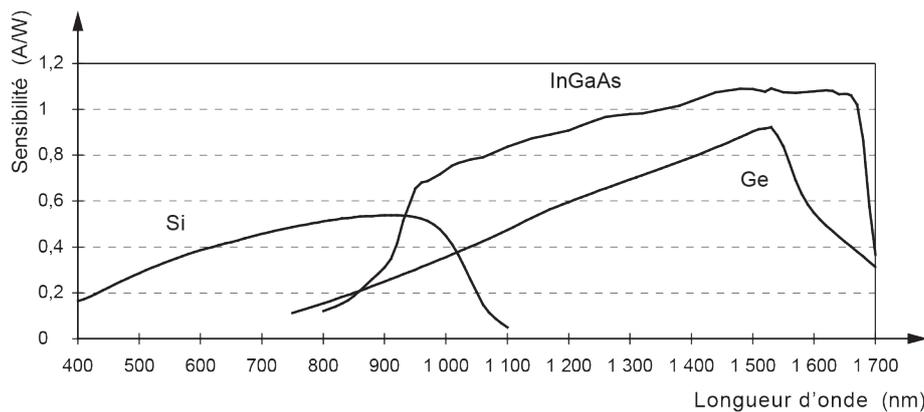
Légende

Si   silicium

Ge   germanium

InGaAs   arséniure de gallium-indium

Figure 1 – *Sensibilité spectrale* typique des *détecteurs* photoélectriques

3.30
largeur de bande spectrale
B
largeur à mi-hauteur (LMH) du spectre de la source

Note 1 à l'article: Si la source est une diode laser avec un spectre présentant différents modes longitudinaux, alors la *largeur de bande spectrale* LMH *B* est la *largeur de bande spectrale* efficace, multipliée par 2,35 (la source étant réputée comporter une enveloppe gaussienne):

$$B = 2,35 \sqrt{\frac{1}{P_{\text{totale}}} \sum_i P_i \left(\lambda_i - \lambda_{\text{c}}\right)^2} \tag{10}$$

$$P_{\text{totale}} = \sum_i P_i \tag{11}$$

où

λ_{c} est la *longueur d'onde centrale* (3.5) de la diode laser, en nm;

P_{totale} est la puissance totale, en W;

P_i est la puissance du $i^{\text{ème}}$ mode longitudinal, en W;

λ_i est la longueur d'onde dans le vide du $i^{\text{ème}}$ mode longitudinal, en nm.

Note 2 à l'article: Si la source émet uniquement à une longueur d'onde (spectre à une raie), il peut suffire de définir une limite supérieure, par exemple *largeur de bande spectrale* < 1 nm.

Note 3 à l'article: Il est généralement suffisant de réaliser l'intégrale ou la sommation sur le spectre sur lequel la puissance est supérieure à 0,1 % de la puissance maximale.

Note 4 à l'article: Le symbole "*B*" est dérivé du terme anglais développé correspondant "bandwidth".

3.31
diamètre du spot
diamètre de la surface éclairée sur le *plan de référence optique*, défini par le cercle (meilleure approximation) auquel l'*éclairement énergétique* (3.11) est tombé à 5 % de l'*éclairement énergétique* de crête

Note 1 à l'article: Le rapport de 5 % a été adopté pour des raisons de compatibilité avec la définition de l'*ouverture numérique*. D'autres rapports sont souvent utilisés pour décrire les faisceaux laser, par exemple $1/e^2$ ou $1/e$. Dans ce cas, cela doit être établi avec la valeur du *diamètre du spot*.

3.32
appareil de mesure d'essai
wattmètre pour dispositifs à fibres optiques (3.23) (ou étalon) à étalonner, par comparaison avec l'*appareil de référence* (3.26)

3.33
traçabilité
propriété du résultat d'un mesurage ou d'un étalon tel qu'il puisse être relié à des références déterminées, généralement des *étalons nationaux* ou internationaux, par l'intermédiaire d'une chaîne ininterrompue de comparaisons, ayant toutes des incertitudes déterminées

Note 1 à l'article: Voir l'ISO/IEC Guide 99:2007, 2.41, pour de plus amples informations.

3.34
chaîne de traçabilité
chaîne ininterrompue de comparaisons (voir Figure 2)

Note 1 à l'article: Voir l'ISO/IEC Guide 99:2007, 2.42, pour de plus amples informations.
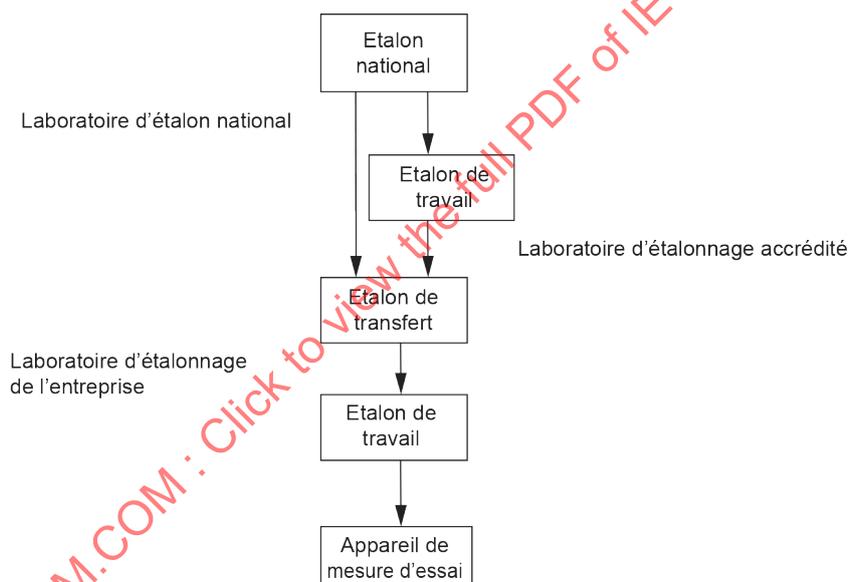
Figure 2 – Exemple d'une *chaîne de traçabilité*

3.35
étalon de travail
étalon qui est utilisé couramment pour étalonner ou contrôler des instruments de mesure

Note 1 à l'article: Un *étalon de travail* est habituellement étalonné par rapport à un *étalon de référence* (3.27).

Note 2 à l'article: Voir l'ISO/IEC Guide 99:2007, 5.7, pour de plus amples informations.

3.36
erreur à zéro
résultat de mesure d'un wattmètre sans *éclairement* du *port d'entrée optique*

Note 1 à l'article: Voir l'ISO/IEC Guide 99:2007, 4.28, pour de plus amples informations.

4 Préparation pour l'*étalonnage*

4.1 Organisation

Le laboratoire d'*étalonnage* doit s'assurer que les exigences appropriées en matière d'*étalonnage* sont suivies.

NOTE   Les conseils sur les bonnes pratiques en matière d'*étalonnage* sont disponibles dans l'ISO/IEC 17025 [18].

Il convient d'établir une procédure de mesure détaillée pour chaque type d'*étalonnage* effectué, donnant des instructions de fonctionnement étape par étape et l'appareillage à utiliser.

4.2 *Traçabilité*

Le laboratoire d'*étalonnage* doit s'assurer que les exigences appropriées sont suivies.

NOTE   Les conseils sur les bonnes pratiques en matière d'*étalonnage* sont disponibles dans l'ISO/IEC 17025 [18].

Tous les étalons utilisés dans le processus d'*étalonnage* doivent être étalonnés selon un programme détaillé présentant la *traçabilité* avec les *laboratoires d'étalons nationaux* ou des *laboratoires d'étalonnage accrédités*. Il est recommandé de conserver plus d'un étalon à chaque niveau de la hiérarchie, de telle sorte que les qualités de fonctionnement de l'étalon puissent être vérifiées par comparaison au même niveau. Vérifier l'*étalonnage* de tout autre matériel d'essai ayant une influence significative sur les résultats d'*étalonnage*. Sur demande, définir ce matériel d'essai et sa ou ses *chaînes de traçabilité*. La ou les périodes de ré*étalonnage* doivent être définies et documentées.

4.3 Recommandations pour les mesurages et les *étalonnages*

4.3 fournit des recommandations d'ordre général pour tous les mesurages et *étalonnages* des wattmètres optiques et pour dispositifs à fibres optiques.

Il convient d'effectuer l'*étalonnage* dans une pièce à température régulée si des *détecteurs* sans régulation de température sont utilisés. La température recommandée est de 23 °C. Le contrôle de l'humidité peut être nécessaire si des *détecteurs* optiques sensibles à l'humidité sont utilisés, ou si la condensation des composants est possible. Une variation de l'humidité du laboratoire peut modifier l'absorption de l'air et par conséquent modifier la puissance. Cet effet est relativement important entre 1 360 nm et 1 410 nm, en particulier lorsqu'un *étalonnage* à faisceau en espace libre, de type séquentiel, est utilisé et que l'humidité varie entre les étapes. Dans le cas d'*étalonnages* de type parallèle avec des trajets de faisceaux en espace libre de longueurs approximativement identiques, les *résultats de mesure* de l'*appareil de référence* et de l'*appareil de mesure d'essai* varient environ au même moment, avec un effet négligeable sur le résultat de l'*étalonnage*.

Il convient de maintenir le laboratoire propre. Il convient de toujours nettoyer les connecteurs et les *ports d'entrée optique* avant mesurage. Il convient de vérifier la qualité et la propreté du connecteur en face du *détecteur*. Il convient de déplacer toutes les fibres aussi peu que possible pendant les mesurages; elles peuvent être fixées au banc d'essai si nécessaire. Il convient de déplacer les capteurs vers la fibre plutôt que la fibre vers le capteur.

Il convient de caractériser la source optique utilisée pour l'*excitation* du wattmètre pour la *longueur d'onde centrale* et la *largeur de bande spectrale*. Il convient que la *largeur de bande spectrale* soit suffisamment étroite afin d'éviter l'intégration sur une plage étendue de longueurs d'onde. Les moyens permettant de garantir la stabilité de la source, par exemple à l'aide d'un contrôle de puissance indépendant, peuvent être recommandés.

Les diodes laser sont sensibles aux rétroréflexions. Pour améliorer la stabilité, il est recommandé d'utiliser un affaiblisseur optique ou un isolateur optique entre la diode laser et l'*appareil de mesure d'essai.* En raison de leurs largeurs de bandes spectrales réduites, la

combinaison de diodes laser et de fibres multimodales peut également générer des motifs de tachetures sur le *plan de référence optique*, ce qui a pour résultat d'accroître l'incertitude de mesure.

Les connecteurs de fibre et les adaptateurs sont susceptibles d'engendrer des erreurs dans le *résultat de mesure* [2], en raison des réflexions multiples entre le *port d'entrée optique* (ou le *détecteur*) et la combinaison connecteur-adaptateur (comme partie de la source). Par conséquent, les connecteurs et les adaptateurs à faible réflectivité sont recommandés pour l'*étalonnage*. À défaut, un *facteur de correction* et une incertitude plus importante peuvent devoir être pris en compte.

Il est recommandé d'utiliser des a*ppareils de référence* avec des diamètres de *détecteur* de ≥ 3 mm, car ils peuvent être éclairés facilement avec un faisceau en espace libre et sont moins sujets à la contamination (impuretés et poussière). Il convient de réduire le plus possible les réflexions de surface de l'*appareil de référence*. Si la source émet un faisceau divergent, l'utilisation d'un *appareil de référence* à sphère intégrante peut alors être recommandée. Il est aussi possible d'utiliser des appareils à *détecteurs* "plats" et une correction mathématique, fondée sur la multiplication de la répartition du champ lointain émis par la dépendance angulaire mesurée du *détecteur* de l'*appareil de référence* et l'intégration sur la plage des angles de champ lointain.

Il convient d'envisager un contrôle de température des *détecteurs* pour les *étalonnages* extrêmement précis, car les *détecteurs* présentent d'importantes dépendances par rapport à la température sur certaines plages de longueurs d'onde.

4.4 Recommandations aux utilisateurs

Il est recommandé que l'utilisateur du wattmètre conserve au moins un wattmètre de référence, qui lui permette de comparer les appareils pour confirmation. Ces comparaisons sont particulièrement importantes avant et après l'envoi de l'appareil en ré*étalonnage*, car elles permettent à l'utilisateur de déterminer si son échelle a changé ou non, par exemple en raison du transport, lorsque l'appareil revient. Les changements d'échelle dus à l'*ajustage* (3.2) (voir l'IEC 60050-311:2001, 311-03-16, et le Guide ISO/IEC 99:2007, 4.30) sont consignés sur le certificat d'*étalonnage*.

Une comparaison régulière des *facteurs de correction* (3.6), ou des *écarts* (3.8) permet à l'utilisateur de faire ressortir un vieillissement excessif et peut-être d'ajuster les intervalles de ré*étalonnage*.

5 *Étalonnage* de puissance absolu

5.1 Méthodes d'*étalonnage*

L'*étalonnage* d'un wattmètre s'effectue généralement en exposant à la fois l'appareil en essai et un wattmètre étalonné dont l'incertitude est connue (*appareil de référence*) à un rayonnement optique, et en transférant le *résultat de mesure* de l'*appareil de référence* (3.26) à l'*appareil de mesure d'essai* (3.32).

La *largeur de bande spectrale* admissible (3.30) dépend de la *sensibilité spectrale* (3.29) de l'*appareil de mesure d'essai*: plus forte est sa dépendance par rapport à la longueur d'onde, plus étroite est la *largeur de bande spectrale*. Les largeurs de bandes habituelles sont ≤ 10 nm, ce qui exclut la possibilité d'étalonner avec des LED de plus grande largeur de bande. Par conséquent, des combinaisons de sources "blanches" et de filtres de largeur de bande étroite (par exemple monochromateurs), des diodes lasers ou des combinaisons de lasers supercontinuum avec filtres passe-bandes ajustables sont utilisées pour les *étalonnages* des *wattmètres pour dispositifs à fibres optiques*.

Six méthodes plus fréquentes d'*étalonnage* (voir Tableau 1) peuvent être déterminées selon le type de source et de géométrie du faisceau d'*excitation*:

Tableau 1 – Méthodes d'*étalonnage* et puissance typique correspondante

Source de rayonnement	*Étalonnage* à faisceau en espace libre	*Étalonnage* à faisceau issu d'une fibre
"Blanche" avec filtre	$P \approx 10\ \mu W$	$P \approx 10\ nW$ à $0,3\ \mu W$ (MMF) $P \approx 2\ nW$ (SMF)
Diode laser	$P \approx 10\ \mu W$ à quelques mW	$P \approx 10\ \mu W$ à quelques mW (SMF et MMF)
Laser supercontinuum avec filtre	$P \approx 1\ \mu W$ à quelques mW	$P \approx 1\ \mu W$ à $700\ \mu W$ (SMF et MMF)
Key		
MMF (multimode fibre): fibre multimodale (généralement fibre à gradient d'indice)		
SMF (single-mode fibre): fibre unimodale		

Pour les *wattmètres pour dispositifs à fibres optiques*, un *étalonnage* à faisceau issu d'une fibre est recommandé. Pour un *étalonnage* à faisceau en espace libre, il convient de corriger les résultats d'*étalonnage* en utilisant une série de résultats d'*étalonnage* par laser à faisceau issu d'une fibre obtenus à quelques longueurs d'onde.

La méthode de mesure séquentielle et la méthode de mesure parallèle peuvent être déterminées. Lorsque l'*appareil de référence* et l'*appareil de mesure d'essai* sont exposés séquentiellement à la source, il convient alors de maintenir la puissance rayonnée aussi constante que possible, par exemple par une stabilisation appropriée. Dans le cas de l'*étalonnage* de type parallèle, un séparateur de faisceau ou un dispositif de couplage permet de générer deux faisceaux qui excitent simultanément l'*appareil de référence* et l'*appareil de mesure d'essai*. Dans ce cas, le rapport du séparateur de faisceau ou du dispositif de couplage doit être déterminé de la manière la plus exacte possible et sa stabilité doit être étudiée.

À titre d'exemple, la Figure 3 représente un montage de mesure pour un *étalonnage* séquentiel utilisant le faisceau issu d'une fibre. Un appareil d'injection, pour suppression des modes de gaine et création d'une *excitation* modale appropriée, est compris dans le montage.
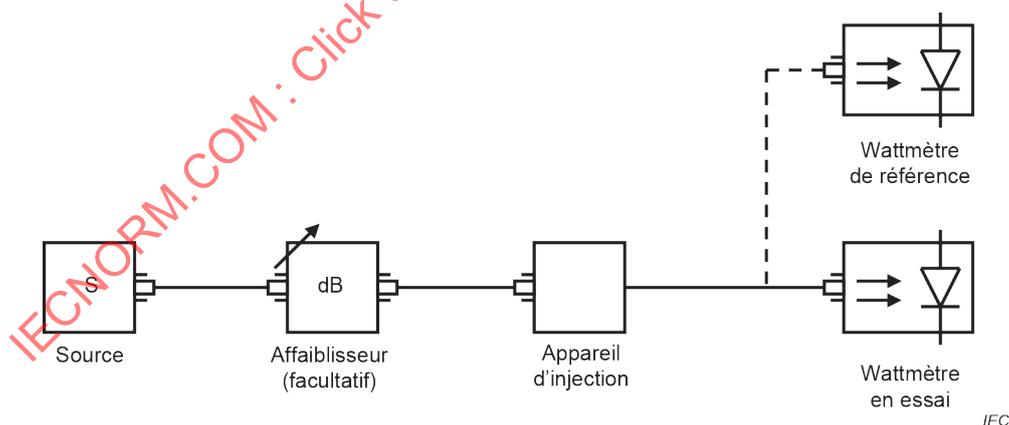

Figure 3 – Montage de mesure pour un *étalonnage* séquentiel, utilisant le faisceau issu d'une fibre

5.2   Établissement des conditions d'*étalonnage*

Les *conditions d'étalonnage* (3.4) sont les conditions de mesure au cours du processus d'*étalonnage*. L'établissement et le maintien des *conditions d'étalonnage* constituent une partie importante de l'*étalonnage* (3.3), car toute modification de ces conditions peut entraîner des *résultats de mesure* erronés. Il convient que les *conditions d'étalonnage* représentent une approximation fidèle des *conditions de fonctionnement* prévues (3.18). Cela garantit une incertitude (supplémentaire) dans l'environnement de fonctionnement aussi faible que possible.

Il convient de définir les *conditions d'étalonnage* sous la forme de valeurs nominales avec des incertitudes le cas échéant. Afin de satisfaire aux exigences du présent document, les *conditions d'étalonnage* doivent comprendre au minimum les éléments suivants:

a) la date d'*étalonnage*;

b) la température ambiante avec une incertitude, par exemple 23 °C ± 1 °C.

c) l'humidité relative ambiante, si elle a une influence; sinon, par hypothèse, une humidité relative en deçà du point de condensation est prise en compte.

d) la *puissance rayonnante* nominale sur le *plan de référence optique* (3.21);

e) la géométrie du faisceau:

1) un faisceau en espace libre (par exemple collimaté), décrit par le *diamètre du spot* (3.31) sur le *plan de référence optique*, l'*ouverture numérique* du faisceau (3.17) et la distribution de l'*éclairement énergétique* (3.11) dans le faisceau; les distributions de l'*éclairement énergétique* typiques sont: uniforme, gaussienne, voire irrégulière (avec des tachetures);

2) le type de fibre et, le cas échéant, son degré d'*excitation* (par exemple dans des modèles de flux inscrit définis dans l'IEC 61280-4-1 en cas d'utilisation d'une fibre multimodale A1a ou A1b);

f) la combinaison connecteur-adaptateur: type de connecteur, polissage et adaptateur comme partie de la source d'*excitation* (le cas échéant);

g) la *longueur d'onde centrale* (3.5) de la source d'*excitation*;

h) la *largeur de bande spectrale* (3.30) de la source d'*excitation*;

i) l'état de polarisation: "lumière non polarisée" ou "lumière polarisée, état non défini". Si ce dernier est choisi, l'incertitude due à la *réponse dépendant de la polarisation* (3.22) doit être prise en compte en 5.4.3 et 5.4.5.

Les conditions citées ci-dessus peuvent ne pas être exhaustives. Il peut y avoir d'autres paramètres qui ont une influence significative sur l'incertitude d'*étalonnage* et, par conséquent, ils doivent aussi être mentionnés.

Dans le cas d'un *étalonnage* avec un faisceau en espace libre, il convient d'éclairer le *plan de référence optique* du wattmètre (3.21) au centre avec un diamètre de faisceau inférieur à la surface active du *plan de référence optique*.

Dans le cas d'un *étalonnage* avec une fibre, une fibre unimodale ou multimodale peut être utilisée. Une fibre unimodale peut être avantageuse en raison de ses caractéristiques de faisceau reproductibles, mais peut ne pas être disponible pour toutes les longueurs d'onde. Si une fibre multimodale est utilisée, une *excitation* comprise entre 85 % et 95 % (condition légèrement sous-remplie) est préférable, car elle peut être plus facilement reproduite (les modèles de flux inscrit définis dans l'IEC 61280-4-1 constituent un bon exemple de cet état). Un appareil d'injection peut être nécessaire pour créer l'*excitation* appropriée. Noter que les fibres multimodales émettent des faisceaux aux distributions irrégulières (motifs de tachetures), lorsqu'elles sont pilotées par une diode laser. Ceci entraîne une plus grande incertitude d'*étalonnage*.

Il convient d'utiliser une combinaison connecteur-adaptateur uniquement si le wattmètre est étalonné avec une fibre, et non pas avec un faisceau en espace libre. Il est recommandé d'utiliser une combinaison de connecteur et d'adaptateur ayant des réflexions suffisamment faibles vers le wattmètre.

5.3 Procédure d'*étalonnage*

(1) Établir et enregistrer les *conditions d'étalonnage* appropriées (5.2). Mettre tous les appareils sous tension et attendre suffisamment de temps pour qu'ils se stabilisent.

(2) Régler le *mode* (3.10) de l'*appareil de référence* et de l'*appareil de mesure* selon le manuel d'utilisation. Définir la longueur d'onde de tous les appareils sur la longueur d'onde de la

source. Sélectionner les plages de puissance appropriées. Enregistrer les modes d'appareil des deux wattmètres. Régler le zéro des deux appareils, le cas échéant.

(3) Mesurer la puissance optique avec l'*appareil de référence* $P_{\text{std},1}$. Multiplier le *résultat de mesure* par le *facteur de correction* de l'*appareil de référence* CF_{std} indiqué dans son certificat d'*étalonnage*, s'il n'a pas été ajusté. Multiplier par le *facteur de correction* $CF_{\text{variation}}$ calculé en 5.4.4 si nécessaire. Enregistrer le *résultat de mesure*, $P_{\text{ref},1} = P_{\text{std},1} \times CF_{\text{std}} \times CF_{\text{variation}}$.

(4) Mesurer la puissance optique avec l'*appareil de mesure d'essai*. Appliquer les corrections nécessaires, comme le proposent les instructions de fonctionnement. Enregistrer le *résultat de mesure*, $P_{\text{DUT},1}$.

(5) Calculer le premier d'une série de *facteurs de correction*:

$$CF_{\text{comparaison},1} = \frac{P_{\text{ref},1}}{P_{\text{DUT},1}}\qquad(12)$$

(6) Répéter les étapes (3) à (5) plusieurs fois dans le but d'obtenir plusieurs *facteurs de correction*, $CF_{\text{comparaison},1}$ à $CF_{\text{comparaison},n}$.

(7) Calculer et enregistrer le *facteur de correction* moyen, CF_{DUT} à partir des *facteurs de correction* individuels:

$$CF_{\text{DUT}} = \frac{1}{n} \times \sum_{i=1}^{n} CF_{\text{comparaison},i}\qquad(13)$$

Lorsque cela est souhaité, l'*écart D* peut être calculé à partir du *facteur de correction*:

$$D = \frac{1}{CF_{\text{DUT}}} - 1\qquad(14)$$

Dans une utilisation ultérieure de l'*appareil de mesure d'essai*, les *résultats de mesure* doivent être multipliés par CF_{DUT}. En variante, un *ajustage* (3.2) de l'*appareil de mesure d'essai* peut être effectué, de telle sorte que le *facteur de correction* soit modifié à 1. Dans ce cas, il convient de répéter la comparaison pour vérification.

5.4 Incertitude d'*étalonnage*

5.4.1 Généralités

L'incertitude d'*étalonnage* est l'incertitude de mesure du *facteur de correction* CF_{DUT}. Calculer l'incertitude type composée à partir de:

$$u\left(CF_{\text{DUT}}\right) = \sqrt{u_{\text{montage}}^2 + u_{\text{ref}}^2 + u_{\text{DUT}}^2}\qquad(15)$$

où

u_{montage} is the incertitude due au montage (5.4.2);

u_{ref} is the incertitude de l'*appareil de référence* (5.4.3);

u_{DUT} is the incertitude due à l'*appareil de mesure d'essai* (5.4.5).

L'Équation (15) n'est valable que si les grandeurs d'entrée sont indépendantes ou non corrélées. Si certaines grandeurs d'entrée sont corrélées de façon significative, tenir compte de la corrélation. Voir l'ISO/IEC Guide 98-3 pour de plus amples informations.

Calculer ensuite l'incertitude élargie à partir de:

$$U\left(CF_{\mathsf{DUT}}\right) = k \times u\left(CF_{\mathsf{DUT}}\right) \tag{16}$$

où

k est le facteur d'élargissement.

Voir l'Annexe A pour de plus amples informations.

5.4.2   Incertitude due au montage

Les incertitudes suivantes peuvent provenir du montage.

a) Incertitude due à l'instabilité de puissance de la source. Outre la variation intrinsèque de puissance de sortie par rapport au temps, une source laser peut réagir avec une puissance instable aux variations des rétroréflexions et aux variations de l'état de polarisation de la lumière rétroréfléchie.

b) Incertitude due au rapport du séparateur de faisceau ou du dispositif de couplage (pour la méthode parallèle), par exemple en raison de leur dépendance par rapport à la polarisation.

c) En fonction du montage et de la méthode, d'autres incertitudes peuvent devoir être prises en compte.

L'instabilité de puissance de la source, du rapport du séparateur de faisceau ou du dispositif de couplage (pour la méthode parallèle) provoque une diffusion dans le mesurage du *facteur de correction*. L'incertitude due à ces instabilités peut être calculée à partir de l'*écart* type expérimental des *facteurs de correction* $CF_{\mathsf{comparaison,1}}$ à $CF_{\mathsf{comparaison,n}}$ mesuré au cours de l'*étalonnage* (Équation (12)). Il convient que le nombre de comparaisons soit grand, afin de réduire cette incertitude. Voir l'Annexe A pour de plus amples informations sur l'évaluation de l'incertitude de type A.

$$u_{\mathsf{montage,typeA}} = \frac{s\left(CF_{\mathsf{comparaison}}\right)}{\sqrt{n}} \tag{17}$$

où

$s(CF_{\mathsf{comparaison}})$ est l'*écart* type expérimental des *facteurs de correction*;

n est le nombre de cycles de mesure au cours du processus d'*étalonnage*.

Cette incertitude peut également être calculée à partir d'un *écart* type évalué une fois à partir des mesurages et utilisé pour tous les *étalonnages* ou à partir d'une évaluation de type B. Il convient par conséquent que l'instabilité ne varie pas trop d'un *étalonnage* à l'autre et qu'elle ne dépende pas de l'*appareil de mesure d'essai*. Le nombre n dans l'Équation (17) représente toujours le nombre de cycles de mesure au cours du processus d'*étalonnage* actuel.

Cette incertitude évaluée de type A est également influencée par la répétabilité de la connexion, en utilisant une méthode de mesure séquentielle ou par de légères modifications dans les conditions de mesure au cours du processus d'*étalonnage*. Elle peut (partiellement) prendre en compte certaines des incertitudes dues à l'*appareil de référence* (5.4.3) ou à l'*appareil de mesure d'essai* (5.4.5). Il convient de ne pas prendre en compte deux fois les composantes de l'incertitude, mais également de ne pas les oublier.

Calculer l'incertitude due au montage en combinant toutes les incertitudes partielles décrites en 5.4.2:

$$u_{\mathsf{montage}} = \sqrt{\sum_{i=1}^{m} u_{\mathsf{montage,i}}^2} \tag{18}$$