

# INTERNATIONAL STANDARD

## NORME INTERNATIONALE



**Calibration of fibre-optic power meters**

**Étalonnage de wattmètres pour dispositifs à fibres optiques**



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**Calibration of fibre-optic power meters**

**Étalonnage de wattmètres pour dispositifs à fibres optiques**

INTERNATIONAL  
ELECTROTECHNICAL  
COMMISSION

COMMISSION  
ELECTROTECHNIQUE  
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## CALIBRATION OF FIBRE-OPTIC POWER METERS

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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:

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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 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

$\lambda_c$   
power-weighted mean wavelength of a light source in vacuum

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

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

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

$$\lambda_c = \frac{\sum_i P_i \lambda_i}{\sum_i P_i} \quad (2)$$

where

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

$\lambda_i$  is the vacuum wavelength of the  $i^{\text{th}}$  discrete line;

$P_i$  is the power of the  $i^{\text{th}}$  discrete line, for example, in W;

$P_{\text{total}}$  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)  $P_{\text{DUT}}$  and the reference power  $P_{\text{ref}}$ :

$$D = \frac{P_{\text{DUT}} - P_{\text{ref}}}{P_{\text{ref}}} \quad (3)$$

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*  $\partial P$  incident on an element of the reference plane by the incremental area  $\partial A$  of that element:

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

[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 results* 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*<sub>0</sub>:

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

If expressed in decibels, the *nonlinearity* is:

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

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:

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

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]<sup>1</sup>

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:

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

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

### 3.29

#### spectral responsivity

#### responsivity

$R$

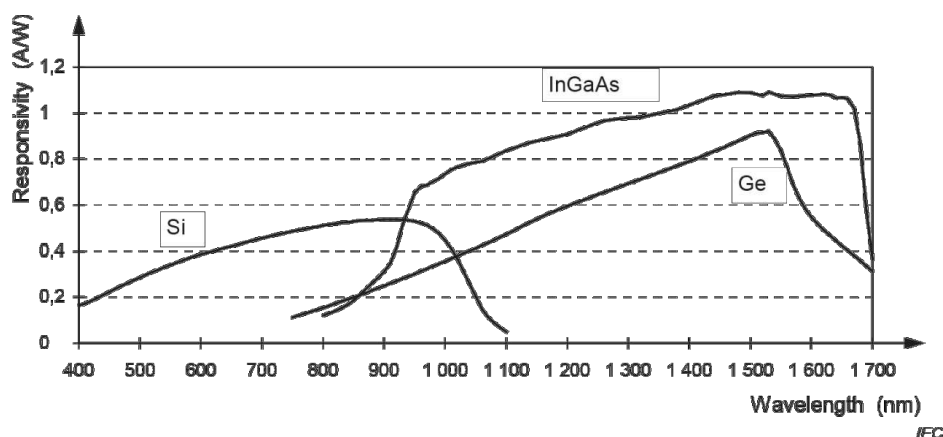
quotient of the *detector* output current  $I$  by the incident monochromatic optical power  $P$ :

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

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.

<sup>1</sup> 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):

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

$$P_{\text{total}} = \sum_i P_i \quad (11)$$

where

$\lambda_c$  is the *centroidal wavelength* (3.5) of the laser diode, in nm;

$P_{\text{total}}$  is the total power, in W;

$P_i$  is the power of  $i^{\text{th}}$  longitudinal mode, in W;

$\lambda_i$  is the vacuum wavelength of  $i^{\text{th}}$  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.

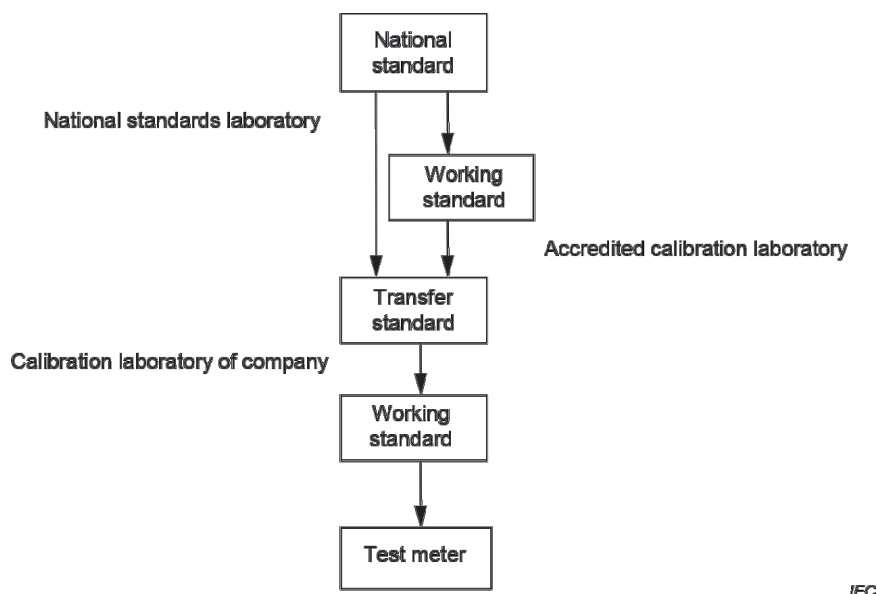


Figure 2 – Example of a *traceability chain*

### 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  $\geq 3$  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  $\leq 10$  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        | $P \approx 10 \mu\text{W}$             | $P \approx 10 \text{ nW}$ to $0,3 \mu\text{W}$ (MMF)<br>$P \approx 2 \text{ nW}$ (SMF) |
| Laser diode                      | $P \approx 10 \mu\text{W}$ to a few mW | $P \approx 10 \mu\text{W}$ to a few mW (SMF and MMF)                                   |
| Supercontinuum laser with filter | $P \approx 1 \mu\text{W}$ to a few mW  | $P \approx 1 \mu\text{W}$ to $700 \mu\text{W}$ (SMF and MMF)                           |

| Radiation source                                                                          | Open-beam calibration | Fibre beam calibration |
|-------------------------------------------------------------------------------------------|-----------------------|------------------------|
| <b>Key</b><br>MMF: multimode fibre (usually graded-index fibre)<br>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.

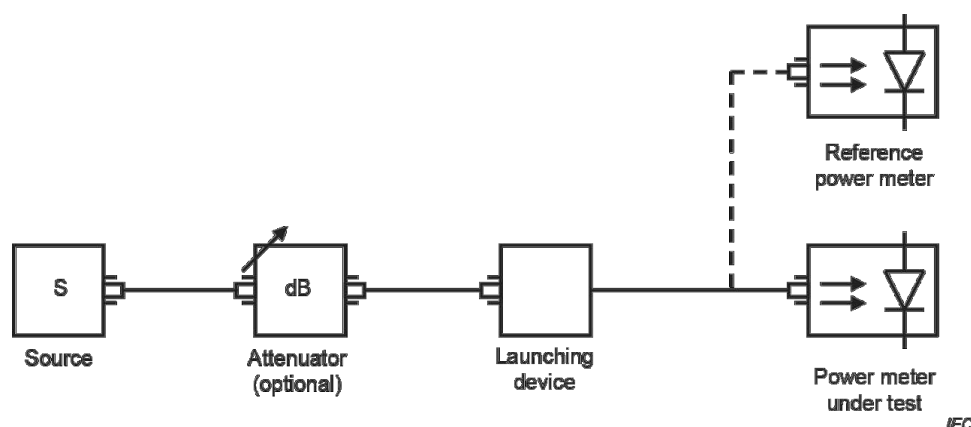


Figure 3 – Measurement setup for sequential, fibre-based calibration

## 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  $23\text{ °C} \pm 1\text{ °C}$ ;
- 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, indefinite 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*  $P_{\text{std},1}$ . Multiply the *measurement result* by the *correction factor* of the *reference meter*  $CF_{\text{std}}$  reported in its *calibration* certificate if it has not been adjusted. Multiply by the *correction factor*  $CF_{\text{change}}$  calculated in 5.4.4 if necessary. Record the *measurement result*,  $P_{\text{ref},1} = P_{\text{std},1} \times CF_{\text{std}} \times CF_{\text{change}}$ .
- (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*:

$$CF_{\text{comparison},1} = \frac{P_{\text{ref},1}}{P_{\text{DUT},1}} \quad (12)$$

- (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*,  $CF_{\text{DUT}}$  from the individual *correction factors*:

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

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

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

In later use of the *test meter*, the *measurement results* shall be multiplied with  $CF_{\text{DUT}}$ . 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*  $CF_{\text{DUT}}$ . Calculate the combined standard uncertainty from:

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

where

- $u_{\text{setup}}$  is the uncertainty due to the setup (5.4.2);
- $u_{\text{ref}}$  is the uncertainty of the *reference meter* (5.4.3);
- $u_{\text{DUT}}$  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:

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

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.

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

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:

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

### 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*,  $u_{\text{change}}$ , 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-adaptor 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  $\delta y_{\text{ref}}$ , the standard uncertainty is (see ISO/IEC Guide 98-3:2008, F.2.2.1):

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

- 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:

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

where  $u_{\text{change}}$  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.

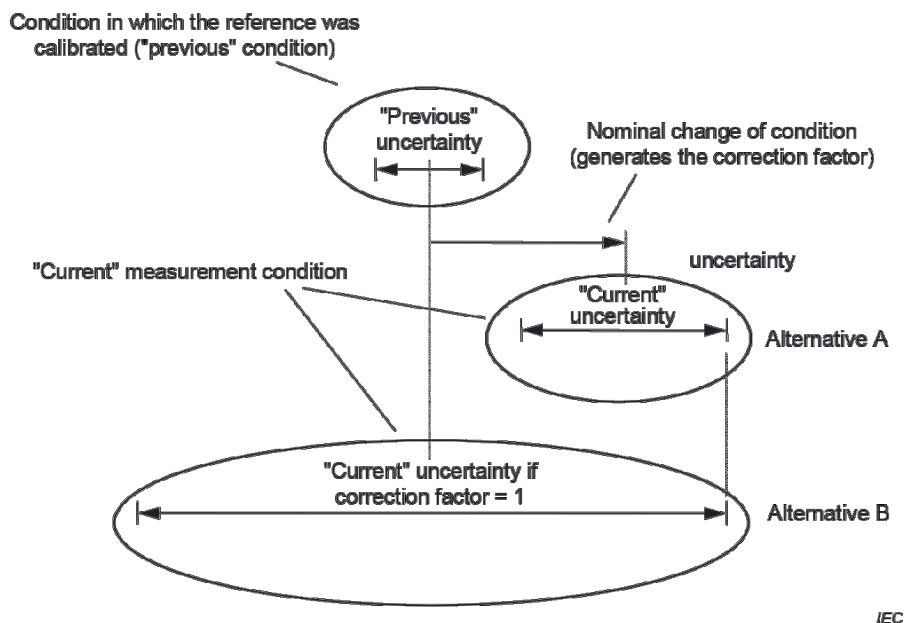


Figure 4 – Change of conditions and uncertainty

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  $CF_{\text{change}} = 1$ ) and taking larger uncertainties into account to embrace the worst-case conditions.

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

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

or 
$$CF_{\text{change}} = 1 - \Delta r \quad (22)$$

where

- $r_{\text{previous}}$  is the *response* of the reference with *excitation* at the conditions at which it was calibrated;
- $r_{\text{current}}$  is the *response* of the reference with *excitation* at the current *calibration conditions*;
- $\Delta r$  is the relative change of *response*  $\Delta r = (r_{\text{current}} - r_{\text{previous}}) / r_{\text{current}}$ .

Calculate the (cumulative) *reference meter's change-related correction factor* by accumulating the partial *correction factors*,  $CF_{\text{change},i}$ , 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*:

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

The relative change of *response*  $\Delta r_i$  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  $\Delta x_i$ , and the *reference meter's* nominal relative dependence on this quantity:

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

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:

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

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:

$$CF_{\text{change}} = \prod_{i=1}^n CF_{\text{change},i} \quad (26)$$

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

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

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  $c_\Theta$  of the *reference meter* (for example in %/°C).

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

#### 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:

$$CF_{\text{change},NL} = 10^{\frac{-NL}{10}} \quad (29)$$

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  $c_\lambda$ .

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

#### 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-adaptor 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  $\delta y_{\text{DUT}}$ , the standard uncertainty is (see ISO/IEC Guide 98-3:2008, F.2.2.1):

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

- 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:

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

## 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:

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

where

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

$u_{\text{DUT}}$  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*:

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

where