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REDLINE VERSION

INTERNATIONAL STANDARD

Calibration of tuneable laser sources

colour inside

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CALIBRATION OF TUNEABLE LASER SOURCES

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 IEC 62522:2014. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

IEC 62522 has been prepared by IEC technical committee 86: Fibre optics. It is an International Standard.

This second edition cancels and replaces the first edition published in 2014. This edition constitutes a technical revision.

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

a) addition of references to IEC 61315;
b) addition of Table 1 and Table 2 on uncertainties;
c) clarification of the reference power meter settings in 6.2.3 and 6.3.2.3.

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

Draft	Report on voting
86/639/FDIS	86/643/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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

- reconfirmed,
- withdrawn, or
- revised.

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INTRODUCTION

Wavelength-division multiplexing (WDM) transmission systems have been deployed in optical trunk lines. ITU-T Recommendations in the G.694 series describe the frequency and wavelength grids for WDM applications. For example, the frequency grid of ITU-T Recommendation G.694.1 supports a variety of channel spacing ranging from 12,5 GHz to 100 GHz and wider. WDM devices, such as arrayed waveguide grating (AWG), thin film filter or grating based multiplexers (MUX), and demultiplexers (DMUX) with narrow channel spacing are incorporated in the WDM transmission systems. When measuring the characteristics of such devices, wavelength tuneable laser sources are commonly used and are required to have well-calibrated performances; wavelength uncertainty, wavelength tuning repeatability, wavelength stability, and output optical power stability are important parameters.

The tuneable laser source (TLS) is generally equipped with the following features:

a) the output wavelength is continuously tuneable in a wavelength range starting at 1 260 nm or higher and ending at less than 1 675 nm (the output should excite only the fundamental LP01 fibre mode);

b) an output port for optical fibre connectors.

The envelope of the spectrum is a single longitudinal mode with a full-width at half-maximum (FWHM) of at most 0,1 nm. Any adjacent modes are at least 20 dB lower than the main spectral mode (for example, a distributed feedback laser diode (DFB-LD), external cavity laser, etc.).

CALIBRATION OF TUNEABLE LASER SOURCES

1 Scope

This document provides a stable and reproducible procedure to calibrate the wavelength and power output of a tuneable laser against reference instrumentation such as optical power meters and optical wavelength meters (including optical frequency meters) that have been previously traceably calibrated.

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 60793-2-50, *Optical fibres – Part 2-50: Product specifications – Sectional specification for class B single-mode fibres*

IEC 60825-1, *Safety of laser products – Part 1: Equipment classification and requirements*

IEC 60825-2, *Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCSs)*

IEC 61315, *Calibration of fibre-optic power meters*

IEC 62129-2, *Calibration of wavelength/optical frequency measurement instruments – Part 2: Michelson interferometer single wavelength meters*

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

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

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

3 Terms, definitions, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

3.1.1
accredited calibration laboratory
calibration laboratory authorized by an appropriate national organization to issue calibration certificates that demonstrates traceability to national standards

3.1.2
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: For more information, see ISO/IEC Guide 99:2007, 3.11.

~~[SOURCE: IEC 60050-300:2001, 311-03-16, modified – minor editorial change, omission of the NOTE]~~

~~[See also ISO/IEC Guide 99:2007, 3.11, modified – 3 NOTES omitted].~~

[SOURCE: IEC 60050-311:2001, 311-03-16, modified – Domain deleted, words "measuring instrument" deleted in the definition, and omission of the Note to entry therein.]

3.1.3
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 standards

Note 1 to entry: The results of a calibration permit either the assignment of measurand values to the indications or the determination of corrections with respect to the indications.

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

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

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

~~[SOURCE: ISO/IEC Guide 99:2007, 2.39, modified – shortened; the two NOTES replaced by 3 new NOTES].~~

3.1.4
calibration conditions
conditions of measurement in which the calibration is performed

3.1.5
calibration at reference conditions
calibration which includes the evaluation of the uncertainty at reference conditions of the light source under calibration

3.1.6
calibration at operating conditions
calibration which includes the evaluation of the uncertainty at operating conditions of the light source under calibration

3.1.7
level of confidence
estimated probability that the true value of a measured parameter lies in the given range

3.1.8
coverage factor
k
factor used to calculate the expanded uncertainty U from the standard uncertainty u

~~**3.1.9**~~
~~**decibels**~~
~~dB, dBm~~
~~sub-multiple of the Bel, B, unit used to express values of optical power on a logarithmic scale~~

~~Note 1 to entry: The power level is always relative to a reference power~~ $\cancel{P_0}$

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

~~where~~ $\cancel{P}$ ~~and~~ $\cancel{P_0}$ ~~are expressed in the same linear units.~~

~~The unit symbol dBm is used to indicate power level relative to 1 mW:~~

$$\cancel{L_{P/1\text{mW}} = 10 \times \log_{10}\left(\frac{P}{1\text{mW}}\right)}$$

~~The linear ratio,~~ $\cancel{R_{\text{lin}}}$~~, of two radiant powers,~~ $\cancel{P_1}$ ~~and~~ $\cancel{P_2}$~~, can alternatively be expressed as an power level difference in decibels (dB):~~

$$\cancel{\Delta L_P = 10 \times \log_{10}(R_{\text{lin}}) = 10 \times \log_{10}\left(\frac{P_1}{P_2}\right) = 10 \times \log_{10}(P_1) - 10 \times \log_{10}(P_2)}$$

~~Similarly, relative uncertainties,~~ $\cancel{U_{\text{lin}}}$~~, or relative deviations, can be alternatively expressed in decibels:~~

$$\cancel{U_{\text{dB}} = \left|10 \times \log_{10}\left|(1 - U_{\text{lin}})\right|\right|}$$

~~Note 2 to entry: For mathematical treatment all measurement results should be expressed in linear units (e.g. watts) and all uncertainties should be expressed in linear form. This is recommended because the accumulation of uncertainties in logarithmic units is mathematically difficult. The final statement of an uncertainty may be either in the linear or in the dB form.~~

~~Note 3 to entry: ISO 80000-3 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 accepted in this standard because it is widely used and accepted by users of fibre optic instrumentation.~~

3.1.9
optical power deviation
D_{P}
difference between the set power of the light source under calibration, P_{TLS}, and the corresponding reference power, P_{meas}, measured by the reference power meter

$$D_{\text{P}} = \frac{P_{\text{TLS}} - P_{\text{meas}}}{P_{\text{meas}}}$$

Note 1 to entry: Power P is expressed in linear units, for example W.

Note 2 to entry: This deviation is relative, it has no unit (it can be expressed in %).

3.1.10
operating conditions
appropriate set of specified ranges of values with influence quantities usually wider than the reference conditions for which the uncertainties of a measuring instrument are specified

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

3.1.11
reference conditions
conditions used for testing the performance of a measuring instrument or for the intercomparison of the measurement results

Note 1 to entry: Reference conditions generally include reference values or reference ranges for the quantities influencing and affecting the measuring instrument.

3.1.12
side-mode suppression ratio
SMSR
peak power ratio between the main mode spectrum and the largest side mode spectrum in a single-mode laser diode such as a DFB-LD

Note 1 to entry: Side-mode suppression ratio is usually expressed in dB.

3.1.13
wavelength
wavelength (in a vacuum) of a light source

3.1.14
wavelength deviation
D_λ
difference between the target wavelength, set on the light source under calibration, λ_{TLS}, and the measured wavelength, λ_{meas}, in nm or µm

$$D_\lambda = \lambda_{TLS} - \lambda_{meas}$$

3.2 Abbreviated terms

APC	angled physical contact
AWG	arrayed waveguide grating
DFB-LD	distributed feedback laser diode
DMUX	demultiplexers
FWHM	full-width ~~/~~ at half-maximum
MUX	multiplexers
O/E	optical-electrical
OSA	optical spectrum analyser
RIN	relative intensity noise
SMSR	side-mode suppression ratio
TLS	tuneable laser source
WDM	wavelength-division multiplexing

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.

There ~~shall~~ 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.

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 calibration equipment which have a significant influence on the calibration results are calibrated.

4.3 Preparation

The environmental conditions shall be commensurate with the level of uncertainty that is required for calibration:

a) calibrations shall be carried out in a clean environment;
b) temperature monitoring and control is required;
c) all laser sources shall be safely operated (according to IEC 60825-1 and IEC 60825-2);
d) the output of the TLS should be examined with an optical spectrum analyser (OSA) having sufficient resolution to resolve the longitudinal mode structure to check for single mode operation.

The recommended temperature is 23 °C, for example, (23 ± 2) °C. Give the calibration equipment ~~a minimum of 2 h~~ enough time prior to testing (2 h is recommended) to reach equilibrium within its environment. Allow the TLS a warm-up period in accordance with the manufacturer's instructions.

4.4 Reference calibration conditions

The reference calibration conditions usually include the following parameters and, if necessary, their tolerance bands: date, temperature, relative humidity, atmospheric pressure, displayed optical power, displayed wavelength, fibre, connector-adapter combination, (spectral) bandwidth and resolution bandwidth (spectral resolution) set. Unless otherwise specified, use a single-mode optical fibre category B1.1 or B1.3 pigtail as ~~prescribed by~~ specified in IEC 60793-2-50, having a length of at least 2 m. It is desirable to perform all the calibration in a situation where back-reflections are negligible. Thus, angled connectors and isolators should be used wherever the situation permits.

Operate the TLS in accordance with the manufacturer's specifications and operating procedures. Where practical, select a range of calibration conditions and parameters that emulate the actual field operating conditions of the TLS under calibration. Choose these parameters to optimize the tuneable laser source's accuracy, as specified by the manufacturer's operating procedures.

Document the conditions as specified in Clause 7.

NOTE The calibration results only apply to the set of calibration conditions used in the calibration process.

5 Wavelength calibration

5.1 Overview

The factors making up the uncertainty in the wavelength of the light source under calibration consist of:

a) the intrinsic uncertainty of the light source under calibration as found in the calibration at reference conditions, including temperature and time dependences for these tight conditions, and;

b) the uncertainties due to dependences on optical power, temperature and time as found in the calibrations at broader operating conditions.

The list of the source of uncertainty is summarized in Table 1.

Table 1 – Source of uncertainty for wavelength calibration

Source of uncertainty	Type of origin	Symbol
Repeatability	Measurement	s_{λ_j}
Temperature	Environment	$u_{\lambda_j,\Delta\Theta}$
Stability	Light source under calibration	$u_{\lambda_j,\Delta t}$
Wavelength resolution	Reference wavelength meter	$u_{\lambda_j,\mathrm{res}}$
Wavelength meter calibration	Reference wavelength meter	$u_{\mathrm{WM}_{\lambda_j}}$
Optical power	Light source under calibration	$u_{\lambda_j,P}$

The wavelength calibration at reference conditions for discrete wavelengths, as described in 5.2, is mandatory. The calibration at operating conditions, described in 5.3, is optional.

5.2 Wavelength calibration at reference conditions

5.2.1 Set-up

Figure 1 shows a system for wavelength calibration. The calibration is performed under the given reference conditions.

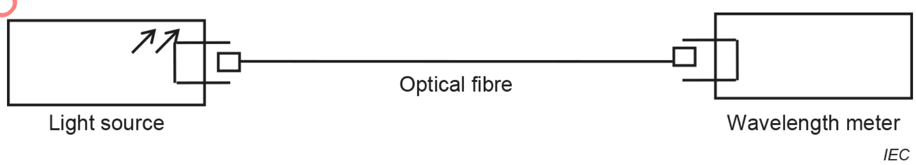

Figure 1 – Measurement set-up for wavelength calibration

5.2.2 Calibration equipment

A wavelength meter shall be used for the calibration. The wavelength meter ~~should~~ shall be calibrated according to IEC 62129-2.

5.2.3 Procedure for wavelength calibration

The calibration procedure is as follows:

a) Regarding the calibration system shown in Figure 1, the set wavelength of the light source is given by $\lambda_{\text{TLS}\ j}$ and the measured values are given by $\lambda_{\text{meas}\ i,j}$. The uncertainty of the wavelength measurement takes into account the tuning repeatability and hysteresis of the TLS. Hysteresis is defined as the deviation resulting from tuning the desired wavelength from both the shorter and the longer wavelengths.

b) It is recommended to repeat the wavelength measurement ~~at least~~ ten (m) times. Ensure that the TLS is tuned to $\lambda_{\text{TLS}\ j}$ prior to each measurement. The target wavelength (j) should be approached in such a way that tuning occurs from both longer and shorter wavelengths.

c) Calculate the average measured wavelength $\bar{\lambda}_{\text{meas}\ j}$:

$$\bar{\lambda}_{\text{meas},\ j} = \frac{1}{m}\sum_{i=1}^{m}\lambda_{\text{meas}\,i,j} \tag{1}$$

where

m is the number of measurements performed.

Each $\lambda_{\text{meas}\ i,j}$ is suggested to be an averaged value from the wavelength meter.

d) Calculate the wavelength deviation D_{λ_j}:

$$D_{\lambda_j} = \lambda_{\text{TLS}\ j} - \bar{\lambda}_{\text{meas}\ j} \tag{2}$$

where $\lambda_{\text{TLS}\ j}$ is the tuned wavelength of the TLS.

d) Calculate the standard deviation for λ_j from the (m) wavelength measurement results $\lambda_{\text{meas}\ i,j}$:

$$s_{\lambda\ j} = \left[\frac{1}{m-1}\sum_{i=1}^{m}\left(\lambda_{\text{meas}\ i,j} - \bar{\lambda}_{\text{meas}\ j}\right)^2\right]^{\frac{1}{2}} \tag{3}$$

e) Calculate the wavelength tuning repeatability S_{rep,λ_j}:

$$S_{\text{rep},\lambda_j} = 2 \times s_{\lambda_j} \tag{4}$$

NOTE A default level of confidence of 95 % is used in Formula (4).

This calibration procedure shall be performed for each calibration wavelength. A minimum of 10 discrete wavelengths or every 10 nm, including the first, the central and the last wavelength of the range, shall be measured.

5.2.4 Dependence on conditions

5.2.4.1 Temperature dependence (optional if known)

5.2.4.1.1 Set-up

Figure 2 shows a calibration system for temperature dependence. This calibration is performed under the reference calibration conditions with the exception of temperature.

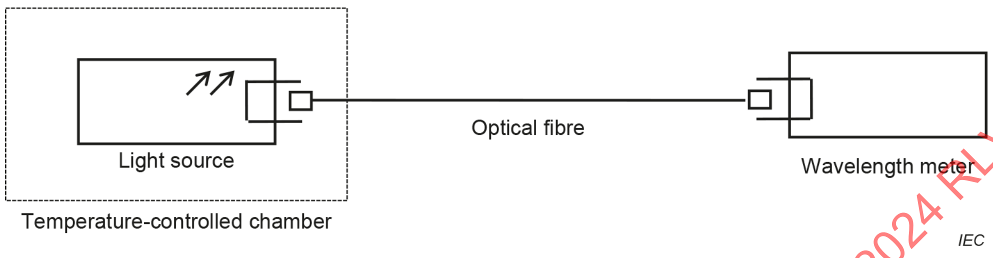

Figure 2 – Measurement set-up for temperature dependence

5.2.4.1.2 Calibration equipment

The calibration equipment is as follows:

a) A wavelength meter capable of detecting wavelength ~~fluctuations at least ten times smaller than the wavelength stability of the TLS~~ deviation of the TLS due to temperature.

b) Temperature-controlled chamber: make sure that the measurement results are immune to the inner temperature distribution.

5.2.4.1.3 Calibration procedure for determining temperature dependence

The calibration procedure is as follows:

a) Regarding the calibration system of Figure 2, measure the nominal wavelength (j) of the TLS at optical power $P_{\text{TLS}j}$ at reference conditions: $\lambda_{j,\text{ref}}$. The wavelength used should possess the maximum response to temperature variations. Otherwise, characterization of several output wavelengths should be performed.

b) Measure the wavelength of the TLS at temperature (i): λ_{j,Θ_i} Wavelength readings corresponding to each temperature setting should be averaged to determine λ_{j,Θ_i}.

c) Calculate the ~~relative~~ wavelength deviation:

$$D_{\lambda_{j,\Theta_i}} = \lambda_{j,\Theta_i} - \lambda_{j,\text{ref}} \tag{5}$$

d) Repeat steps b) and c) with (m) different temperature settings Θ_i ensuring that the instrument is allowed the necessary time to eliminate sufficiently any thermal gradients.

e) Calculate the maximum $\max\left(D_{\lambda_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}$ and minimum $\min\left(D_{\lambda_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}$ wavelength deviations.

f) The standard uncertainty for wavelength temperature dependence $u_{\lambda_{j,\Delta\Theta}}$ at the calibration wavelength (j) using a rectangular distribution model is:

$$u_{\lambda_{j,\Delta\Theta}} = \frac{1}{2\sqrt{3}}\left[\max\left(D_{\lambda_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m} - \min\left(D_{\lambda_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}\right] \tag{6}$$

where

$\Delta\Theta$ is the temperature variation.

It is recommended that a wavelength acquisition be performed with the optical wavelength meter for the duration of this calibration.

5.2.4.2 Wavelength stability

5.2.4.2.1 Set-up

Figure 3 shows a calibration system for wavelength stability. This calibration is performed under the reference calibration conditions with the exception of time.

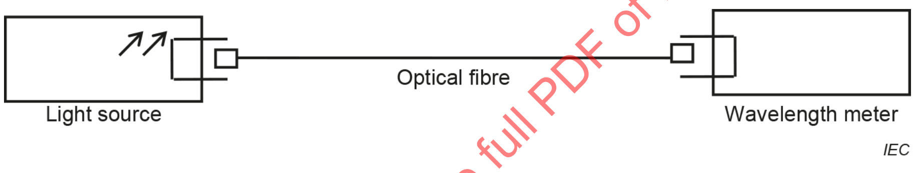

Figure 3 – Measurement set-up for wavelength stability

5.2.4.2.2 Calibration equipment

It is recommended to use a wavelength meter capable of detecting wavelength fluctuations ~~at least ten times smaller than the wavelength stability~~ of the TLS.

5.2.4.2.3 Calibration procedure for wavelength stability

The calibration procedure is as follows:

~~a) Regarding the calibration system in Figure 3, the measurement is performed after the light source is switched on and has been warmed up for some time in accordance with the manufacturer's instructions.~~

a) A ~~specific~~ time period (Δt), for example 10 min, ~~must~~ shall be chosen that is long enough to permit at least 10 wavelength measurements with the reference wavelength meter (in the case of the example, a stability over 10 min will be measured).

b) A continuous wavelength acquisition ~~shall~~ should be performed with wavelength data and time stamp ~~saved to a computer compatible format~~.

c) Ensure to correlate (m) measurements per time period where (m > 10) and conforms exactly to the desired time period (Δt).

d) Calculate the standard deviation of the (m) wavelength measurements corresponding to time period (Δt)

$$u_{\lambda_j,\Delta t} = \left[\frac{1}{m-1}\sum_{i=1}^{m}\left(\lambda_{j,t_i} - \frac{1}{m}\sum_{i=1}^{m}\lambda_{j,t_i}\right)^2\right]^{\frac{1}{2}} \tag{7}$$

e) A minimum of 1 time period is required to evaluate the wavelength stability of the TLS source. In this case, the wavelength stability uncertainty becomes:

$$S_{\text{stab},\lambda_j,\Delta t} = 2 \times u_{\lambda_j,\Delta t} \tag{8}$$

NOTE A default level of confidence of 95 % is used in Formula (8).

The wavelength of the light source should be measured more than ten times (m times) consecutively; at least a few measurements per minute is recommended. The time interval between the repeated measurements should be longer than the response time of the light source. It is preferred to calculate several time periods from the acquisition data using a sliding window and report the maximum value.

5.2.5 Uncertainty at reference conditions

The uncertainty for the calibration wavelength (j) at reference conditions is given by:

$$u_{\lambda_j,\text{ref}} = \left(\frac{{s_{\lambda_j}}^2}{m} + {u_{\lambda_j,\Delta\Theta}}^2 + {u_{\lambda_j,\Delta t}}^2 + {u_{\lambda_j,\text{res}}}^2 + {u_{\text{WM}_{\lambda_j}}}^2 \right)^{\frac{1}{2}} \tag{9}$$

where

$u_{\lambda_j,\Delta\Theta}$ and $u_{\lambda_j,\Delta t}$ are evaluated for the reference conditions as defined in 5.2.4;

$u_{\lambda_j,\text{res}}$ is the uncertainty of wavelength resolution defined by $u_{\lambda_j,\text{res}} = d\lambda_j / 2\sqrt{3}$ ($d\lambda_j$ is the wavelength resolution of the wavelength meter);

$u_{\text{WM}_{\lambda_j}}$ is the uncertainty of the wavelength meter at wavelength (j) as described in its certification.

The expanded uncertainty for the calibration wavelength (j) at reference conditions, $U_{\lambda_j,\text{ref}}$, with a coverage factor k is expressed as follows:

$$\cancel{U_{\lambda_{j,ref}} = \pm k u_{\lambda_{j,ref}}}$$

$$U_{\lambda_j,\text{ref}} = k u_{\lambda_j,\text{ref}} \tag{10}$$

where

k corresponds to an appropriate level of confidence as described in Clause A.5.

~~If the wavelength has to be corrected based on the results of the calibration results, the corrections are normally implemented by making software corrections to the instrument, mathematical corrections to the results or hardware adjustments on the instrument. Once the~~

~~adjustments are made, it is advisable to repeat the calibrations to verify that the corrections are correct.~~

Refer to Annex A and Annex C for information on uncertainties.

When adjustments are made to the instrument based on the calibration results, it is advisable to repeat the calibrations after these adjustments to verify the corrections.

5.3 Wavelength calibration at operating conditions

5.3.1 General

Perform the calibration procedure when the light source is used beyond the reference conditions.

The individual factors in wavelength uncertainty at operating conditions consist of following:

a) optical power dependence;

b) temperature dependence;

c) wavelength stability.

5.3.2 Optical power dependence

5.3.2.1 General

Figure 4 shows a calibration system for optical power dependence. This calibration should be performed under the reference calibration conditions with the exception of the optical power. It shall be performed after the optical power calibration (6.2.3).

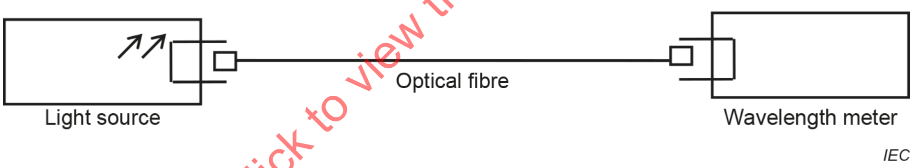

Figure 4 – Measurement set-up for optical power dependence

5.3.2.2 Calibration equipment

~~The calibration equipment is as follows:~~

~~– A wavelength meter capable of detecting wavelength fluctuations at least ten times smaller than the wavelength stability of the TLS.~~

The wavelength meter shall be calibrated according to IEC 62129-2.

5.3.2.3 Calibration procedures for determining power dependence

The calibration procedures are as follows:

a) The wavelength (j) is measured at m optical powers ~~(more than 5)~~ of the light source, $P_{\text{TLS}\,i,j}$ including the upper and lower limits of the specified power range. The interval between these neighbouring levels should be smaller than 10 dB.

b) Regarding the calibration system of Figure 4, the set wavelength of the light source is given by $\lambda_{\text{TLS}\,i,j}$, and the instrument reading of the wavelength meter is given by $\lambda_{P_{i,j}}$.

c) Record the measured wavelength $\lambda_{P_{i,j}}$ for all (m) output power settings $P_{\text{TLS}\,i,j}$ used.

d) Calculate the standard uncertainty of wavelength (j) due to TLS output optical power according to

$$u_{\lambda_{j,P}} = \left[\frac{1}{m-1} \sum_{i=1}^{m} \left(\lambda_{P_{i,j}} - \frac{1}{m} \sum_{i=1}^{m} \lambda_{P_{i,j}} \right)^2 \right]^{\frac{1}{2}} \quad (11)$$

5.3.3 Uncertainty at operating conditions

The uncertainty for the calibration wavelength (j) for any operating conditions is given by

$$u_{\lambda_{j,\mathrm{op}}} = \left(s_{\lambda_j}{}^2 + u_{\lambda_j,P}{}^2 + u_{\lambda_j,\Delta\Theta}{}^2 + u_{\lambda_j,\Delta t}{}^2 + u_{\lambda_j,\mathrm{res}}{}^2 + u_{\mathrm{WM}_{\lambda_j}}{}^2 \right)^{\frac{1}{2}} \quad (12)$$

where

$u_{\lambda_j,P}$, $u_{\lambda_j,\Delta\Theta}$ and $u_{\lambda_j,\Delta t}$ are evaluated for the operating conditions;

$u_{\lambda_j,\mathrm{res}}$ is the uncertainty of wavelength resolution defined by $u_{\lambda_j,\mathrm{res}} = d\lambda_j / 2\sqrt{3}$ ($d\lambda_j$ is wavelength resolution of the wavelength meter);

$u_{\mathrm{WM}_{\lambda_j}}$ is the uncertainty of the wavelength meter at wavelength (j) as described in its certification.

The expanded uncertainty for the calibration wavelength (j) under all operating conditions, $U_{\lambda_{j,op}}$, with a coverage factor k, is expressed as follows:

$$\cancel{U_{\lambda_{j,op}} = \pm k u_{\lambda_{j,op}}}$$

$$U_{\lambda_{j,\mathrm{op}}} = k u_{\lambda_{j,\mathrm{op}}} \quad (13)$$

where

k corresponds to an appropriate level of confidence as described in Clause A.5.

6 Optical power calibration

6.1 Overview

The factors making up the uncertainty in the set optical power of the light source under calibration consists of

a) the intrinsic uncertainty of the light source under calibration as found in the calibration at reference conditions including temperature, time, and connection repeatability/reproducibility dependences for these tight conditions, and

b) the uncertainties due to dependences on wavelength, temperature, time and connection repeatability/reproducibility, as found in the calibrations at broader operating conditions.

The list of the source of uncertainty is summarized in Table 2.

Table 2 – Source of uncertainty for optical power calibration

Source of uncertainty	Type of origin	Symbol
Repeatability	Measurement	s_{DP_j}
Temperature	Environment	$u_{DP_j,\Delta\Theta}$
Stability	Light source under calibration	$u_{DP_j,\Delta t}$
Connection reproducibility	Light source under calibration	$u_{DP_j,\mathrm{con}}$
Optical power resolution	Reference optical power meter	$u_{DP_j,\mathrm{res}}$
Optical power meter calibration	Reference optical power meter	$u_{\mathrm{PM}P_j}$
Wavelength	Light source under calibration	$u_{DP_j,\lambda}$

The optical power calibration at reference conditions as described in 6.2 is mandatory. The calibration at operating conditions described in 6.3 is optional.

6.2 Optical power calibration at reference conditions

6.2.1 Set-up

Figure 5 shows a system for the calibration of the optical power. The calibration is performed under the given reference conditions.

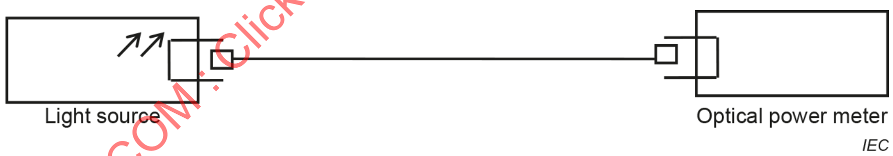

Figure 5 – Measurement set-up for intrinsic optical power calibration

NOTE There ~~may~~ could be problems in calibrating the power of a highly coherent laser source, due to parasitic interference effects arising from reflections from fibre connector end faces and also the optical power meter. The use of angled physical contact (APC) connectors, inline optical isolators and engaging of the laser's coherent control function (if fitted) ~~may~~ can reduce the interference effects to an acceptable level.

The optical power to be calibrated is measured at the end of an optical fibre cable, which ~~may~~ can cause some insertion losses. The calibration condition about the used optical fibre cable such as fibre length, connector type, inline isolator if any, should be reported.

6.2.2 Calibration equipment

~~The calibration equipment is as follows:~~

~~– Optical power meter: This is an optical power meter calibrated with the following standard calibration conditions:~~

~~a) an optical power meter calibrated by an official institution that performs calibration services with a stated uncertainty; or~~

~~b) an optical power meter traceable to such an official institution with a stated uncertainty.~~

The optical power meter shall be calibrated according to IEC 61315.

6.2.3 Procedure for power calibration at reference conditions

The calibration procedure is as follows:

a) Connect the light source and the power meter with the optical fibre ~~to be measured~~.

b) Set the wavelength of the light source and the optical power meter to the required calibration wavelength.

c) Set the output power of the light source to $P_{\text{TLS}j}$. The uncertainty of the power measurement takes into account the setting repeatability and hysteresis of the TLS. Hysteresis is defined as the deviation resulting from setting the desired power from both the lower and the higher powers.

d) Read the measured value of optical power meter.

e) It is recommended to repeat this measurement ~~at least~~ ten (m) times. Ensure that the TLS is set to $P_{\text{TLS}j}$ prior to each measurement. The target power should be approached in such a way that setting occurs from both lower and higher powers.

$$D_{P_{i,j}} = \frac{P_{\text{TLS}\,j} - P_{\text{meas}\,i,j}}{P_{\text{meas}\,i,j}} \tag{14}$$

where

$P_{\text{TLS}j}$ is the set optical power of the TLS.

Each $P_{\text{meas}\,i,j}$ is suggested to be an averaged value from the power meter. Calculate the power deviation D_{P_j}:

$$D_{P_j} = \frac{1}{m}\sum_{i=1}^{m} D_{P_{i,j}} \tag{15}$$

where

m is the number of measurements performed.

f) Calculate the standard deviation for D_{P_j} from the (m) power measurement results $P_{\text{meas}\,i,j}$:

$$s_{D_{P_j}} = \left[\frac{1}{m-1}\sum_{i=1}^{m}(D_{P_{i,j}} - D_{P_j})^2\right]^{\frac{1}{2}} \tag{16}$$

g) Calculate the optical power setting repeatability: $S_{\text{rep},D_{P_j}}$

$$S_{\text{rep},D_{P_j}} = 2 \times s_{D_{P_j}} \tag{17}$$

NOTE A default level of confidence of 95 % is used in Formula (17).

The uncertainty calculations (6.2.3 a) to g)) should be performed for each calibration power.

6.2.4 Dependence on conditions

6.2.4.1 Temperature dependence (optional if known)

6.2.4.1.1 Set-up

Figure 6 shows a calibration system for temperature dependence. This calibration is performed under the reference calibration conditions with the exception of temperature.

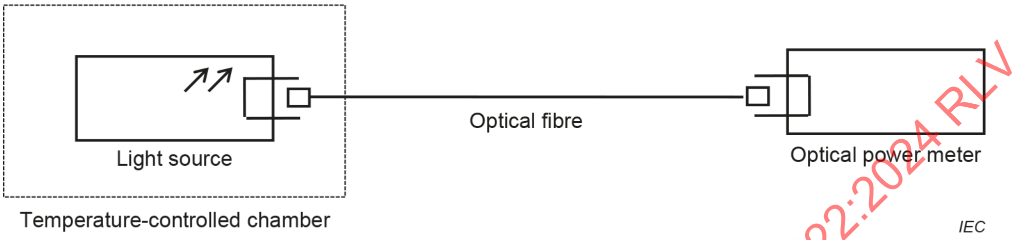

Figure 6 – Measurement set-up for temperature dependence

6.2.4.1.2 Calibration equipment

The calibration equipment is as follows:

~~a) Optical power meter: This is an optical power meter calibrated with the following standard calibration conditions:~~

~~1) an optical power meter calibrated by an official institution that performs calibration services with a stated uncertainty; or~~

~~2) an optical power meter traceable to such an official institution with a stated uncertainty.~~

a) An optical meter capable of detecting optical power deviation of the TLS depending on temperature.

b) Temperature-controlled chamber:

Make sure that the measurement results are immune to the inner temperature distribution.

6.2.4.1.3 Calibration procedure for determining temperature dependence

The calibration procedure is as follows:

a) Regarding the calibration system of Figure 6, measure the nominal optical power of the TLS at wavelength $\lambda_{\mathrm{TLS}\,j}$ at reference conditions $P_{j,\mathrm{ref}}$. The optical power used should possess the maximum response to temperature variations. Otherwise, characterization of several output optical powers will be required.

b) Measure the optical power of the TLS at temperature (i): P_{j,Θ_i}. Optical power readings corresponding to each temperature setting should be averaged to determine P_{j,Θ_i}.

c) Calculate the relative optical power deviation:

$$D_{P_{j,\Theta_i}} = \frac{P_{j,\Theta_i} - P_{j,\mathrm{ref}}}{P_{j,\mathrm{ref}}} \tag{18}$$

d) Repeat steps b) and c) with (m) different temperature settings Θ_i ensuring that the instrument is allowed the necessary time to eliminate sufficiently any thermal gradients.

e) Calculate the maximum $\max\left(D_{P_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}$ and minimum $\min\left(D_{P_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}$ optical power deviations.

f) The standard uncertainty for optical power temperature dependence $u_{P_{j,\Delta\Theta}}$ at the calibration optical power using a rectangular distribution model is:

$$u_{D_{P_{j,\Delta\Theta}}} = \frac{1}{2\sqrt{3}}\left[\max\left(D_{P_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m} - \min\left(D_{P_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}\right] \quad (19)$$

where

$\Delta\Theta$ is the temperature variation.

It is recommended that a optical power acquisition be performed with the optical power meter for the duration of this calibration.

6.2.4.2 Optical power stability

6.2.4.2.1 Set-up

Figure 7 shows a calibration system for optical power stability. This calibration is performed under the reference calibration conditions with the exception of time.

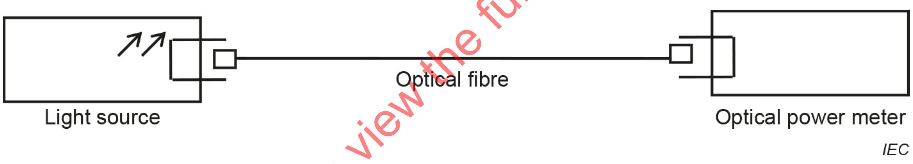

Figure 7 – Measurement set-up for optical power stability

6.2.4.2.2 Calibration equipment

~~– Optical power meter: This is an optical power meter calibrated with the following standard calibration conditions:~~

~~a) an optical power meter calibrated by an official institution that performs calibration services with a stated uncertainty; or~~

~~b) an optical power meter traceable to such an official institution with a stated uncertainty.~~

It is recommended to use an optical power meter capable of detecting optical power fluctuations of the TLS.

6.2.4.2.3 Calibration procedure for optical power stability

The calibration procedure is as follows:

~~a) Regarding the calibration system in Figure 7, the measurement is performed after the light source is switched on and has been warmed up for some time in accordance to the manufacturer's instructions.~~

a) A specific time period (Δt), for example 10 min, shall be chosen that is long enough to permit at least 10 optical power measurements with the reference power meter (in the case of the example, a stability over 10 min will be measured).

b) A continuous optical power acquisition ~~shall~~ should be performed with optical power data and time stamp ~~saved to a computer compatible format~~.

c) Ensure to correlate (m) measurements per time period where (m > 10) and conforms exactly to the desired time period (Δt).

d) Calculate the standard deviation of the (m) measurements corresponding to time period (Δt):

$$u_{D_{P_j,\Delta t}} = \left[\frac{1}{m-1} \sum_{i=1}^{m} \left(P_{j,t_i} - \frac{1}{m} \sum_{i=1}^{m} P_{j,t_i} \right)^2 \right]^{\frac{1}{2}} \Bigg/ \left(\frac{1}{m} \sum_{i=1}^{m} P_{j,t_i} \right) \tag{20}$$

e) A minimum of 1 time period is required to evaluate the optical power stability of the TLS source. In this case, the optical power stability uncertainty becomes:

$$S_{\text{stab},D_{P_j,\Delta t}} = 2 \times u_{D_{P_j,\Delta t}} \tag{21}$$

NOTE A default level of confidence of 95 % is used in Formula (21).

It is preferred to calculate several time periods from the acquisition data using a sliding window and report the maximum value.

The optical power of the light source should be measured more than ten times (m times) consecutively; at least a few measurements per minute is recommended. The time interval between the repeated measurements should be longer than the response time of the light source.

6.2.4.3 Connection repeatability/reproducibility

6.2.4.3.1 Set-up

Figure 8 shows a calibration system for optical power stability. This calibration is performed under the reference calibration conditions.

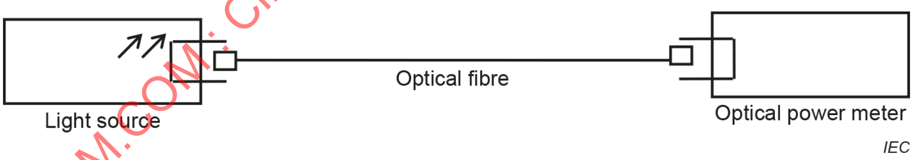

Figure 8 – Measurement set-up for connection repeatability/reproducibility

6.2.4.3.2 Calibration equipment

– ~~Optical power meter: This is an optical power meter calibrated with the following standard calibration conditions~~

  a) ~~an optical power meter calibrated by an official institution that performs calibration services with a stated uncertainty; or~~

  b) ~~an optical power meter traceable to such an official institution with a stated uncertainty.~~

The optical power meter shall be calibrated according to IEC 61315.

6.2.4.3.3 Calibration procedure for connection repeatability/reproducibility

The calibration procedure is as follows:

a) Regarding the calibration system in Figure 8, connect the light source and the power meter with the optical fibre ~~to be measured~~.

b) Read the measured value of optical power meter P_{j,con_i}.

c) Disconnect the optical fibre from the TLS and reconnect the optical fibre to the TLS.

d) Repeat b) and c) for (m) times.

e) Calculate the standard uncertainty of optical power (j) due to TLS connection repeatability/reproducibility according to

$$u_{D_{P_j,\text{con}}} = \left[\frac{1}{m-1} \sum_{i=1}^{m} \left(P_{j,\text{con}_i} - \frac{1}{m} \sum_{i=1}^{m} P_{j,\text{con}_i} \right)^2 \right]^{\frac{1}{2}} \Bigg/ \left(\frac{1}{m} \sum_{i=1}^{m} P_{j,\text{con}_i} \right) \quad (22)$$

6.2.5 Uncertainty at reference conditions

The uncertainty for the calibration optical power at reference conditions is given by:

$$u_{D_{P_j,\text{ref}}} = \left(\frac{{s_{D_{P_j}}}^2}{m} + {u_{D_{P_j,\Delta\Theta}}}^2 + {u_{D_{P_j,\Delta t}}}^2 + {u_{D_{P_j,\text{con}}}}^2 + {u_{D_{P_j,\text{res}}}}^2 + {u_{\text{PM}_{P_j}}}^2 \right)^{\frac{1}{2}} \quad (23)$$

where

$u_{D_{P_j,\Delta\Theta}}$ $u_{D_{P_j,\Delta t}}$ and $u_{D_{P_j,\text{con}}}$ are evaluated for the reference conditions as defined in 6.2.4;

$u_{D_{P_j,\text{res}}}$ is the relative uncertainty of optical power resolution defined by $u_{D_{P_j,\text{res}}} = (dP_{\text{TLS},j} / P_{\text{TLS},j})/2\sqrt{3}$ ($dP_{\text{TLS},j}$ is the optical power resolution of the optical power meter);

$u_{\text{PM}_{P_j}}$ is the relative uncertainty of the power meter at power P_j as described in its certification.

The expanded uncertainty for the calibration power meter at reference conditions $U_{D_{P_j,\text{ref}}}$, with a coverage factor k, is expressed as follows:

$$\cancel{U_{D_{P_j,ref}} = \pm k u_{D_{P_j,ref}}}$$

$$U_{D_{P_j,\text{ref}}} = k u_{D_{P_j,\text{ref}}} \quad (24)$$

where

k corresponds to an appropriate level of confidence as described in Clause A.5.

~~If the optical power needs to be corrected based on the results of the calibration results, the corrections are normally implemented by making software corrections to the instrument, mathematical corrections to the results, or hardware adjustments on the instrument. Once the adjustments are made, it is advisable to repeat the calibrations to verify that the corrections are correct.~~

Refer to Annex A for information on uncertainties.

When adjustments are made to the instrument based on the calibration results, it is advisable to repeat the calibrations after these adjustments to verify the corrections.

6.3 Optical power calibration at operating conditions

6.3.1 General

Perform the calibration procedure when the light source is used beyond the reference conditions.

The individual factors in optical power uncertainty at operating conditions consist of the following:

a) wavelength dependence;
b) temperature dependence;
c) optical power stability;
d) connection repeatability/reproducibility.

6.3.2 Wavelength dependence

6.3.2.1 Set-up

Figure 9 shows a calibration system for wavelength dependence. This calibration should be performed under the reference calibration conditions with the exception of the wavelength. It ~~has to~~ shall be performed after the wavelength calibration (5.2.3).

Figure 9 – Measurement set-up for wavelength dependence

6.3.2.2 Calibration equipment

The calibration equipment is as follows: the optical power meter should be calibrated according to IEC 61315.

~~– Optical power meter: this is an optical power meter calibrated with the following standard calibration conditions:~~

~~a) an optical power meter calibrated by an official institution that performs calibration services with a stated uncertainty; or~~

~~b) an optical power meter traceable to such an official institution with a stated uncertainty.~~

6.3.2.3 Calibration procedure for determining wavelength dependence

The calibration procedure is as follows:

a) The optical power is measured at m wavelengths (more than 5) of the light source, $\lambda_{\text{TLS}\ i,j}$ including the upper and lower limits of the specified wavelength range.
b) Regarding the calibration system of Figure 9, the set optical power of the light source is given by $P_{\text{TLS}\ i,j}$, and the instrument reading of the power meter is given by $P_{\lambda_i,j}$.
c) Set the wavelength of the optical power meter to the required calibration wavelength.

d) Record the measured optical power $P_{\lambda_{i,j}}$ for all (m) wavelength settings $\lambda_{\text{TLS}\,i,j}$ used.

e) Calculate the standard uncertainty of optical power (j) due to TLS output wavelength according to:

$$u_{D_{P_{j,\lambda}}} = \left[\frac{1}{m-1} \sum_{i=1}^{m} \left(P_{\lambda_{i},j} - \frac{1}{m} \sum_{i=1}^{m} P_{\lambda_{i},j} \right)^2 \right]^{\frac{1}{2}} \Bigg/ \left(\frac{1}{m} \sum_{i=1}^{m} P_{\lambda_{i},j} \right) \tag{25}$$

6.3.3 Uncertainty at operating conditions

The uncertainty for the calibration optical power for any operating condition is given by:

$$u_{D_{P_{j,op}}} = \left(s_{D_{P_j}}{}^2 + u_{D_{P_j,\lambda}}{}^2 + u_{D_{P_j,\Delta\Theta}}{}^2 + u_{D_{P_j,\Delta t}}{}^2 + u_{D_{P_j,\text{con}}}{}^2 + u_{D_{P_j,\text{res}}}{}^2 + u_{\text{PM}_{P_j}}{}^2 \right)^{\frac{1}{2}} \tag{26}$$

where

$u_{D_{P_j,\lambda}}$, $u_{D_{P_j,\Delta\Theta}}$, $u_{D_{P_j,\Delta t}}$ and $u_{D_{P_j,\text{con}}}$	are evaluated for the operating conditions;
$u_{D_{P_j,\text{res}}}$	is the relative uncertainty of optical power resolution defined by $u_{D_{P_j,\text{res}}} = (dP_{\text{TLS},j} / P_{\text{TLS},j}) / 2\sqrt{3}$ ($dP_{\text{TLS},j}$ is optical power resolution of the optical power meter);
$u_{PM_{P_j}}$	is the uncertainty of the power meter at optical power P_j as described in its certification.

The expanded uncertainty for the calibration optical power under all operating conditions $U_{D_{P_j,\text{op}}}$, with a coverage factor k, is expressed as follows:

$$\cancel{U_{D_{P_{j,op}}} = \pm k u_{D_{P_{j,op}}}}$$

$$U_{D_{P_j,\text{op}}} = k u_{D_{P_j,\text{op}}} \tag{27}$$

where

k corresponds to an appropriate level of confidence as described in Clause A.5.

7 Documentation

7.1 Calibration data and uncertainty

Calibration certificates claiming to be in compliance with this document shall include the following data and their uncertainties, and the uncertainties shall be stated in the form of estimated confidence intervals by multiplying the relevant standard uncertainty by ~~±~~k:

NOTE 1 Refer to Annex A for information on uncertainty and Clause A.5 for further details on level of confidence and coverage factor.

a) the wavelength deviation, D_{λ_j}, and its uncertainty, $\cancel{\pm} ku_{\lambda_{j,\mathrm{ref}}}$, for example, is in nm, in a vacuum – see the detailed requirements in Clause 5;

b) the optical power deviation, D_{P_j}, and its uncertainty, $\cancel{\pm} ku_{D_{P_{j,\mathrm{ref}}}}$, for example, is in % or dB – see the detailed requirements in Clause 6.

NOTE 2 Other tests can be added to the documentation, refer to Annex B for more information.

7.2 Calibration conditions

The calibration method(s) and the method(s) of obtaining the measurement results shall be stated.

~~Each specification should also be accompanied by a statement of the instrument state(s) and the measurement conditions to which they apply.~~ Calibration conditions shall be reported. The most important parameters are the calibration date, the displayed optical power, the displayed wavelength, the temperature, the humidity and the atmospheric pressure.

NOTE The calibration results only apply to the set of calibration conditions used for the calibration process.

Annex A
(normative)

Mathematical basis for measurement uncertainty calculations

A.1 General

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

This document distinguishes between 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

The 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:

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

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 $u_{\mathrm{typeA}}(x)$ associated with the estimate x is the experimental standard deviation of the mean.

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

A.3 Type B evaluation of uncertainty

The 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 limit 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, and the estimated value is:

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

and the standard uncertainty is:

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

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

$$u(y)=c\times u(x) \tag{A.7}$$

where

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

$$c=\frac{\partial y}{\partial x} \tag{A.8}$$

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 Formula (A.8) 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~~ can be more appropriate to find the change in the output estimate y due to the change of 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:

$$u_c(y) = \sqrt{\sum_{i=1}^{n} u_i^2(y)} \qquad \text{(A.9)}$$

where

i is the current number of individual contribution;

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

n is the number of uncertainties.

NOTE It is acceptable to neglect uncertainty contributions to Formula (A.9) that are smaller than 1/10 of the largest contribution, 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 Formula (A.9). Despite its partially 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:

$$U = k \times u_c(y) \qquad \text{(A.10)}$$

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 (GUM); if these conditions are not met, larger coverage factors are to be used to reach these levels of confidence.

~~Annex B~~
~~(informative)~~

~~Averaged wavelength (or power) deviation over a certain range~~

~~Annex B summarizes how to determine a single mean wavelength (or power) deviation over a certain wavelength (or power) range in wavelength (or power) calibration for convenience in correction.~~

~~Averaging over a range of wavelengths (or powers) should not be done if part of this range has a very different behaviour.~~

~~According to Guide ISO/IEC 98-3 (GUM), a single mean correction $\bar{b}$ can be computed as~~

$$\bar{b} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} b(t)dt \tag{B.1}$$

~~where t_1 and t_2 define the range of interest of the parameter t, and take the best estimate of the measurand $Y(t)$ to be $y'(t) = y(t) + \bar{b}$, where $y(t)$ is the best uncorrected estimate of $Y(t)$. The variance associated with the mean correction $\bar{b}$ over the range of interest is given by~~

$$u^2(\bar{b}) = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2}\left[b(t) - \bar{b}\right]^2 dt \tag{B.2}$$

~~not taking into account the uncertainty of the actual determination of the correction $b(t)$. The mean variance of the correction $b(t)$ due to its actual determination is given by~~

$$\overline{u^2[b(t)]} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} u^2[b(t)]dt \tag{B.3}$$

~~where $u^2[b(t)]$ is the variance of the correction $b(t)$. Similarly, the mean variance of $y(t)$ arising from all sources of uncertainty other than the correction $b(t)$ is obtained from~~

$$\overline{u^2[y(t)]} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} u^2[y(t)]dt \tag{B.4}$$

~~where $u^2[y(t)]$ is the variance of $y(t)$ due to all uncertainty sources other than $b(t)$ The single value of standard uncertainty to be used for all estimates $y'(t) = y(t) + \bar{b}$ of the measurand $Y(t)$ is then the positive square root of~~

$$u_c^2(y') = \overline{u^2[y(t)]} + \overline{u^2[b(t)]} + u^2(\bar{b}) \tag{B.5}$$

~~In wavelength calibration of a tuneable laser source, for example, with assuming that the correction is a constant function, b and t correspond to wavelength deviation D_{λ_j} and~~

~~wavelength setting λ_j, respectively. The single mean wavelength deviation D_λ is given by Equation (B.6) (from Equation (B.1).~~

$$D_\lambda = \frac{1}{n}\sum_{j=1}^{n} D_{\lambda_j} \qquad \text{(B.6)}$$

~~In Equation (B.6) the mean wavelength deviation is calculated using summation over all discreet wavelength settings, instead of integration as shown in Equation (B.1), where n is the number of the wavelength settings.~~

~~The variance of D_λ, $u^2(D_\lambda)$ can be calculated from Equation (B.7) (from Equation (B.2)).~~

$$u^2(D_\lambda) = \frac{1}{n-1}\sum_{j=1}^{n}(D_{\lambda_j} - D_\lambda)^2 \qquad \text{(B.7)}$$

~~In Equation (B.7) summation is also used instead of integration.~~

~~The standard uncertainty of the overall wavelength calibration at reference conditions is given by Equation (B.8) (from Equation (B.5)).~~

$$u_{\lambda ref} = \left[\frac{1}{n}\sum_{j=1}^{n}\left(\frac{s_{\lambda_j}}{m}^2 + u_{\lambda_j,\Delta\Theta}^2 + u_{\lambda_j,\Delta t}^2 + u_{\lambda_j,res}^2 + u_{WM\lambda_j}^2\right) + u^2(D_\lambda)\right]^{\frac{1}{2}} \qquad \text{(B.8)}$$

~~In Equation (B.8) the first term corresponds to $\overline{u^2[b(t)]}$ and the second ~ fifth terms correspond to $u^2[y(t)]$.~~

~~The standard uncertainty of overall wavelength calibration at operating conditions is~~

$$u_{\lambda op} = \left[\frac{1}{n}\sum_{j=1}^{n}\left(s_{\lambda_j}^2 + u_{\lambda_j,P}^2 + u_{\lambda_j,\Delta\Theta}^2 + u_{\lambda_j,\Delta t}^2 + u_{\lambda_j,res}^2 + u_{WM\lambda_j}^2\right) + u^2(D_\lambda)\right]^{\frac{1}{2}} \qquad \text{(B.9)}$$

~~In Equation (B.9) the first term corresponds to $\overline{u^2[b(t)]}$ and the second ~ sixth terms correspond to $u^2[y(t)]$.~~

~~The single mean power deviation can be derived in the same fashion.~~

~~Annex C~~Annex B
(informative)

Other testing

B.1 General

~~Annex C explains the testing methods not applied to the general items or to the precision examinations although they do apply to the performances of tuneable laser sources.~~

Annex B provides some details on other tests which are not mandatory but are related to the performance of tuneable laser sources.

B.2 Wavelength tuning resolution

B.2.1 Set-up

Figure B.1 shows the test set-up for a wavelength tuning resolution test under standard test conditions.

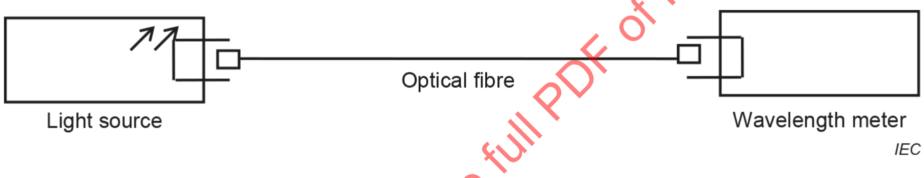

Figure B.1 – Measurement set-up for wavelength resolution

B.2.2 Testing equipment

Testing equipment is as follows:

A wavelength meter which has a better wavelength measurement resolution than the wavelength resolution of test light source should be used.

B.2.3 Testing procedure for determining wavelength resolution

The testing procedure is as follows:

a) Set the wavelength of the test light source to λ_{TLS}. Set the optical output power of the test light source to a suitable value.

b) ~~Inject the optical output of the light source into the wavelength meter.~~ The wavelength for λ_{meas} is measured with the wavelength meter.

c) The wavelength of the light source is set only $qd\lambda$ to the long (or short) wavelength side for λ_{TLS}. Here, $d\lambda$ is the minimum variable width that can be set to λ_{TLS}, and q are integers.

d) Inject the optical output of the light source into the wavelength meter. The wavelength for $\lambda_{\text{meas+1}}$ is measured with the wavelength meter.

e) After the wavelength of the light source is returned to λ_{TLS}, the measurements ~~are~~ should be repeated over ten times (m times).

f) Calculate the wavelength setting resolution $d\lambda_{\text{TLS},j}$ with Formula (B.1).

$$d\lambda_{\text{TLS},j} = \sum_{i=1}^{m} \frac{\left|\lambda_{\text{meas}+1,i} - \lambda_{\text{meas},i}\right|}{m \times q} \tag{B.1}$$

g) Repeat the measurements for a few (j) wavelengths covering the desired wavelength range. Calculate the wavelength setting resolution with Formula (B.2).

$$d\lambda_{\text{TLS}} = \max\left(d\lambda_{TLS,j}\right) \tag{B.2}$$

B.3 Optical power tuning resolution

B.3.1 Set-up

Figure B.2 shows the test set-up for optical power tuning resolution setting tests under standard test conditions.

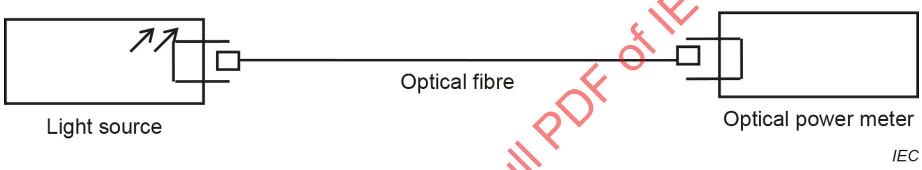

Figure B.2 – Measurement set-up for optical power resolution setting test

B.3.2 Testing equipment

Use an optical power meter with high resolution.

B.3.3 Testing procedure for optical power resolution

Testing procedure is as follows:

a) Set the optical output power of the test light source to P_{TLS}. Set the wavelength of the light source to a suitable value.

b) Inject the optical output into the optical power meter. Measure the optical power P_{meas} with the optical power meter.

c) Only set the minimum variable width dP as a higher (or lower) output power under P_{TLS} settings for optical output power of test light source.

d) ~~Inject the optical output into the optical power meter.~~ Measure the optical power $P_{\text{meas+1}}$ with optical power meter.

e) After the optical output power of test light source is returned to P_{TLS}, the measurements ~~are~~ should be repeated over ten times (m times).

f) Calculate the optical output power setting resolution dP_{TLS} / P_{TLS} with Formula (B.3).

$$\frac{dP_{\text{TLS},j}}{P_{\text{TLS},j}} = \sum_{i=1}^{m} \frac{\left|P_{\text{meas}+1,i} - P_{\text{meas},i}\right|}{m} / \sum_{i=1}^{m} \frac{P_{\text{meas},i}}{m} \tag{B.3}$$

g) Repeat the measurements for a few (j) optical powers covering the desired power range. Calculate the power setting resolutions with Formula (B.4).

$$\frac{dP_{\mathrm{TLS}}}{P_{\mathrm{TLS}}} = \max\left(\frac{dP_{\mathrm{TLS},j}}{P_{\mathrm{TLS},j}}\right) \tag{B.4}$$

B.4 Signal-to-source spontaneous emission ratio

B.4.1 General

Clause B.4 describes how to determine the side-mode suppression ratio (SMSR) of a laser with SSSER that can be measured with an OSA (e.g. SSSER of 60 dB). However, in the case of narrow line width laser sources such as an external cavity laser, the purity of the source can be much higher (around 90 dB) and therefore other methods can be used.

B.4.2 Set-up

Figure B.3 shows the test set-up for a signal-to-source spontaneous emission ratio under standard test conditions.

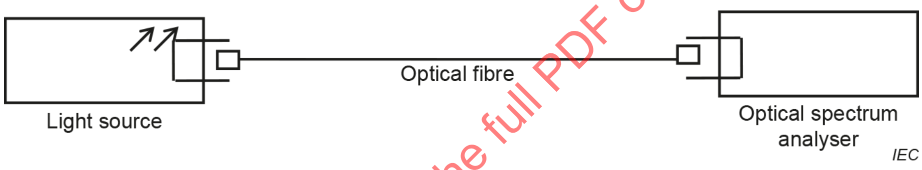

Figure B.3 – Measurement set-up for signal to total source spontaneous emission ratio

B.4.3 Testing equipment

The OSA is used to measure the optical signal power and the spontaneous emission light.

B.4.4 Testing procedure for determining signal-to-source spontaneous emission ratio

The testing procedure is as follows:

a) Set the wavelength of the test light source to λ_{TLS}. Set the optical output power to a suitable value. Usually, the optical power is set to the maximum optical output power defined by the specifications of the test light source.

b) Set the wavelength, the wavelength sweep range, and the resolution bandwidth of an OSA to λ_{TLS}, λ_{span}, and λ_{res} respectively. Usually, λ_{span} is approximately 100 nm, and λ_{res} is approximately 1 nm.

c) Inject the optical output of the light source into the OSA. Measure the optical signal optical power for P_1. Measure the maximum value P_2 of a spontaneous emission optical level in $\lambda_{\mathrm{TLS}} \pm \Delta\lambda$. However, the $\lambda_{\mathrm{TLS}} \pm \Delta\lambda_{\mathrm{exc}}$ range will not be included as the measurement range of the spontaneous emission light (refer to Figure B.4). Usually, $\Delta\lambda$ is approximately 50 nm, $\Delta\lambda_{\mathrm{exc}}$ is approximately 1 nm.

d) Calculate the signal-to-source spontaneous emission ratio with Formula (B.5).

$$\cancel{SSER(dB/nm) = 10\log\frac{P_2 \times 1(nm)/\lambda_{res}}{P_1}(dB/nm)}$$

$$\mathrm{SSER} = -10\log\frac{P_2 \times 1/\lambda_{\mathrm{res}}}{P_1}\ \mathrm{dB/nm} \qquad \text{(B.5)}$$

where

SSER is the signal to source spontaneous emission ratio (dB/nm);

P_1 and P_2 are in mW

λ_{res} is in nm

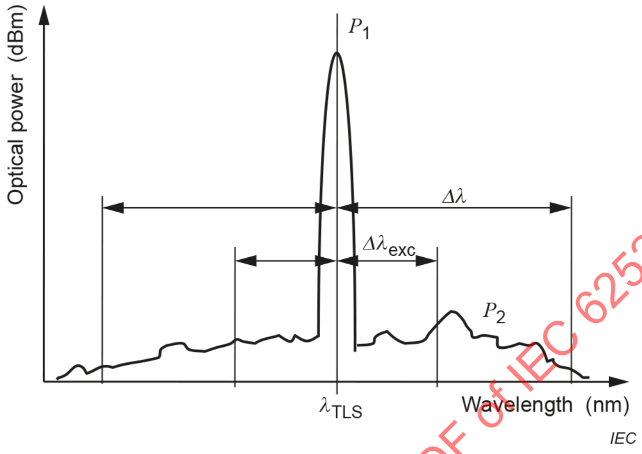

Figure B.4 – Measurement of the signal to spontaneous emission ratio

NOTE ~~1~~ For a TLS with a high SSER, the optical rejection ratio of the OSA can limit the measured value.

~~NOTE 2~~ Record the ratio of signal optical power and the spontaneous emission light as well as the measurement results.

B.5 Side-mode suppression ratio

B.5.1 General

In general, SMSR of a laser source can be measured with an OSA as described in IEC 61280-1-3:~~2010~~2021, 8.8. In the case of narrow line width laser sources such as an external cavity laser, however, the quite close interval between the main and side mode ~~may~~ can cause difficulty to distinguish them with an OSA. Clause A.5 describes how to determine the SMSR of such a narrow line width laser source.

NOTE The testing approach adopted here measures the impact of SMSR on relative intensity noise (RIN), but possibly underestimates the power of the sidemodes when they are not in phase.

B.5.2 Set-up

A special testing system is necessary, although it is performed by the tuneable laser source. For example, Figure B.5 shows the diagram of the test system of the SMSR test under standard test conditions.

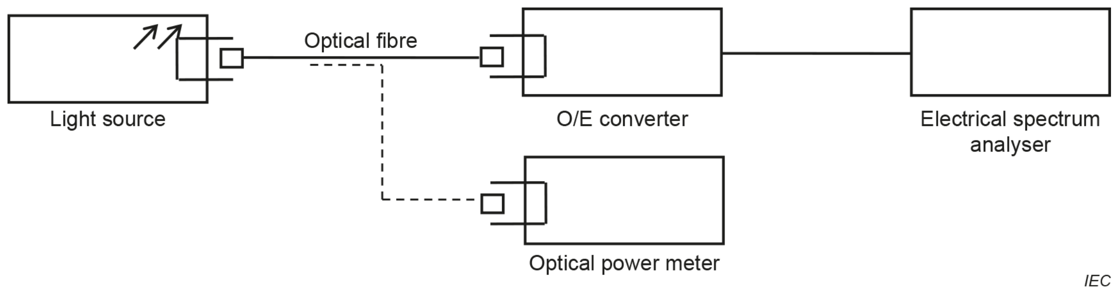

Figure B.5 – Measurement set-up for the side-mode suppression ratio test

B.5.3 Testing equipment

Testing equipment is as follows:

a) O/E (optical-electrical) converter: this is used for heterodyne detection of the intermode beat spectrum between the signal light and the side mode light, converting the optical signal to an electric signal. The frequency band should be several times wider than its mode spacing. The optical-electrical conversion efficiency should be calibrated beforehand.

b) Electrical spectrum analyser: this is used to measure the beat signal level combined with the signal light and the side mode light.

c) Optical power meter: this is used to measure the optical signal power.

B.5.4 Testing procedure for determining the side-mode suppression ratio

The testing procedure is as follows:

a) Set the wavelength of the light source to λ_{TLS}. Set the optical output power to a suitable value.

b) Inject the optical output of the light source into to the O/E converter, and set the largest signal of the displayed beat signals measured by the spectrum analyser to $P_{\text{beat,max}}$ (dBm).

c) Next, inject the optical output of the light source into a optical power meter to measure the signal power. Set this value to P_0 (dBm).

d) Calculate the SMSR (dB) in wavelength λ_{TLS} with Formula (B.6).

$$\cancel{SMSR(dB) = 10\log\frac{P_0}{P_{s,\text{max}}}}$$

$$= 2P_0 - P_{beat,\text{max}} + R(dB) + 10\log(8R_i) - 30$$

$$\text{SMSR} = 10\log\frac{P_0}{P_{\text{s,max}}} = 2P_0 - P_{\text{beat,max}} + R + 10\log(8R_{\text{i}}) - 30 \qquad \text{(B.6)}$$

where

$P_{\text{s,max}}$ is a maximum side mode optical power (dBm);

R is the conversion efficiency of O/E converter (dB);

$$\cancel{R_{dB} = 20\log\frac{R(A/W)}{1(A/W)}}$$

$$R_{\mathrm{dB}} = 20\log\frac{R}{1} \tag{B.7}$$

R_{i} is input impedance of OSA (Ω).

The following explains the measurement principle and Formula (B.6) for the SMSR.

It is assumed that the optical output spectrum of the test light source is composed with the side mode (P_{s}) that is away from ~~$\Delta\omega$~~ $\Delta\Omega$ and the signal light (P_0) – see Figure B.6.

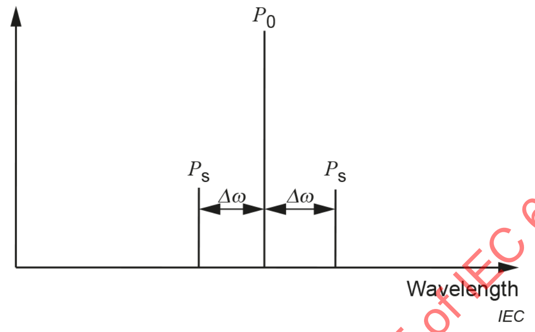

Figure B.6 – Optical spectrum of tuneable laser source

When the signal enters the measurement system shown in Figure B.7, the output current i_{E} of the O/E converter is calculated with Formula (B.8):

$$i_E = R\left\{P_0 + 2P_{\mathrm{s}} + 4\sqrt{P_0 P_{\mathrm{s}}}\cos(\Delta\omega t)\right\} \tag{B.8}$$

where

R is a conversion efficiency of the O/E converter (A/W).

From Formula (B.8) when the beat current emerging from the signal light and the side mode is i_{b}, the beat signal power (electric) P_{b}, which is measured with the spectrum analyser, will be calculated with Formula (B.9) and Formula (B.10).

$$i_{\mathrm{b}} = 4R\sqrt{P_0 P_{\mathrm{s}}}\cos(\Delta\omega t) \tag{B.9}$$

$$P_{\mathrm{b}} = 8R_i P_0 P_{\mathrm{s}} R^2 \tag{B.10}$$

where

R_{i} is the input impedance of the spectrum analyser (Ω).

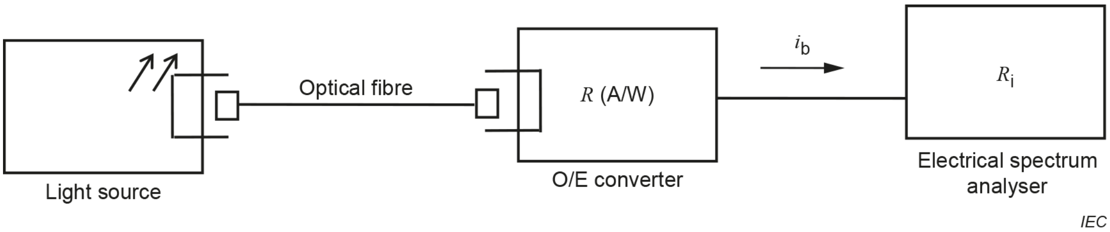

Figure B.7 – Measurement set-up for SMSR

The SMSR, derived from Formula (B.10), is calculated with Formula (B.11):

$$\text{SMSR} = \frac{P_0}{P_s} = 8R_i R^2 \frac{P_0^{\,2}}{P_b} \tag{B.11}$$

If the SMSR is in dB, it will be calculated with Formula (B.12):

$$\begin{aligned} \text{SMSR}_{\text{dB}} &= 10\log\left(8R_i R^2 \frac{P_0^{\,2}}{P_b}\right) \\ &= 2P_{0,\text{dBm}} - P_{b,\text{dBm}} + R_{\text{dB}} + 10\log(8R_i) - 30 \end{aligned} \tag{B.12}$$

where

$$P_{0,\text{dBm}} = 10\log\frac{P_0}{10^{-3}};$$

$$P_{b,\text{dBm}} = 10\log\frac{P_b}{10^{-3}};$$

$$R_{\text{dB}} = 20\log\frac{R}{1}.$$

NOTE The testing approach adopted here is suitable for external cavity lasers only.

Annex C
(informative)

Linear to dB scale conversion of uncertainties

C.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:

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

where

P and P_0 are expressed in the same linear units.

C.2 Conversion of relative uncertainties

Similar to the previous definition, relative uncertainties, U_{lin}, or relative deviations, can be expressed in decibels:

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

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

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

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

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

that leads to:

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

and two useful expressions:

$$U_{\mathrm{dB}} \approx 4{,}34 \times U_{\mathrm{lin}} \Leftrightarrow U_{\mathrm{lin}} \approx 0{,}23 \times U_{\mathrm{dB}} \quad \text{(C.6)}$$

Bibliography

IEC 60027-3, *Letter symbols to be used in electrical technology – Part 3: Logarithmic and related quantities, and their units*

IEC 60050-300~~:2001~~, *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*, available at www.electropedia.org

IEC 60050-731, *International Electrotechnical Vocabulary – Chapter 731: Optical fibre communication*, available at www.electropedia.org

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

IEC 60793-1 (all parts), *Optical fibres – Part 1: Measurement methods and test procedures*

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

IEC 61280-1-3:~~2010~~2021, *Fibre optic communication subsystem test procedures – Part 1-3: General communication subsystems – Measurement of central wavelength ~~and~~, spectral width ~~measurement~~ and additional spectral characteristics*

IEC 61300-3-2, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-2: Examination and measurements – Polarization dependent loss in a single-mode fibre optic device*

~~IEC 61315, *Calibration of fibre-optic power meters*~~

IEC TR 61930, *Fibre optic graphical symbology*

IEC TR 61931, *Fibre optic – Terminology*

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

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

ISO 80000-3, *Quantities and units – Part 3: Space and time*

ITU-T G.694 (all parts), *Spectral grids for WDM applications*

ITU-T G. 694.1, *Spectral grids for WDM applications: DWDM frequency grid*

IEC 62522

Edition 2.0 2024-06

INTERNATIONAL STANDARD

NORME INTERNATIONALE

Calibration of tuneable laser sources

Étalonnage des sources laser accordables

IEC 62522:2024-06(en-fr)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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CALIBRATION OF TUNEABLE LASER SOURCES

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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IEC 62522 has been prepared by IEC technical committee 86: Fibre optics. It is an International Standard.

This second edition cancels and replaces the first edition published in 2014. This edition constitutes a technical revision.

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

a) addition of references to IEC 61315;
b) addition of Table 1 and Table 2 on uncertainties;
c) clarification of the reference power meter settings in 6.2.3 and 6.3.2.3.

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

Draft	Report on voting
86/639/FDIS	86/643/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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

- reconfirmed,
- withdrawn, or
- revised.

INTRODUCTION

Wavelength-division multiplexing (WDM) transmission systems have been deployed in optical trunk lines. ITU-T Recommendations in the G.694 series describe the frequency and wavelength grids for WDM applications. For example, the frequency grid of ITU-T Recommendation G.694.1 supports a variety of channel spacing ranging from 12,5 GHz to 100 GHz and wider. WDM devices, such as arrayed waveguide grating (AWG), thin film filter or grating based multiplexers (MUX), and demultiplexers (DMUX) with narrow channel spacing are incorporated in the WDM transmission systems. When measuring the characteristics of such devices, wavelength tuneable laser sources are commonly used and are required to have well-calibrated performances; wavelength uncertainty, wavelength tuning repeatability, wavelength stability, and output optical power stability are important parameters.

The tuneable laser source (TLS) is generally equipped with the following features:

a) the output wavelength is continuously tuneable in a wavelength range starting at 1 260 nm or higher and ending at less than 1 675 nm (the output should excite only the fundamental LP01 fibre mode);

b) an output port for optical fibre connectors.

The envelope of the spectrum is a single longitudinal mode with a full-width at half-maximum (FWHM) of at most 0,1 nm. Any adjacent modes are at least 20 dB lower than the main spectral mode (for example, a distributed feedback laser diode (DFB-LD), external cavity laser, etc.).

CALIBRATION OF TUNEABLE LASER SOURCES

1 Scope

This document provides a stable and reproducible procedure to calibrate the wavelength and power output of a tuneable laser against reference instrumentation such as optical power meters and optical wavelength meters (including optical frequency meters) that have been previously traceably calibrated.

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 60793-2-50, *Optical fibres – Part 2-50: Product specifications – Sectional specification for class B single-mode fibres*

IEC 60825-1, *Safety of laser products – Part 1: Equipment classification and requirements*

IEC 60825-2, *Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCSs)*

IEC 61315, *Calibration of fibre-optic power meters*

IEC 62129-2, *Calibration of wavelength/optical frequency measurement instruments – Part 2: Michelson interferometer single wavelength meters*

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

3 Terms, definitions, and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

3.1.1
accredited calibration laboratory
calibration laboratory authorized by an appropriate national organization to issue calibration certificates that demonstrates traceability to national standards

3.1.2
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: For more information, see ISO/IEC Guide 99:2007, 3.11.

[SOURCE: IEC 60050-311:2001, 311-03-16, modified – Domain deleted, words "measuring instrument" deleted in the definition, and omission of the Note to entry therein.]

3.1.3
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 standards

Note 1 to entry: The results of a calibration permit either the assignment of measurand values to the indications or the determination of corrections with respect to the indications.

Note 2 to entry: A calibration can also determine other metrological properties such as the effects of influence quantities.

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

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

3.1.4
calibration conditions
conditions of measurement in which the calibration is performed

3.1.5
calibration at reference conditions
calibration which includes the evaluation of the uncertainty at reference conditions of the light source under calibration

3.1.6
calibration at operating conditions
calibration which includes the evaluation of the uncertainty at operating conditions of the light source under calibration

3.1.7
level of confidence
estimated probability that the true value of a measured parameter lies in the given range

3.1.8
coverage factor
k
factor used to calculate the expanded uncertainty U from the standard uncertainty u

3.1.9
optical power deviation
D_P
difference between the set power of the light source under calibration, P_{TLS}, and the corresponding reference power, P_{meas}, measured by the reference power meter

$$D_P = \frac{P_{TLS} - P_{meas}}{P_{meas}}$$

Note 1 to entry: Power P is expressed in linear units, for example W.

Note 2 to entry: This deviation is relative, it has no unit (it can be expressed in %).

3.1.10
operating conditions
appropriate set of specified ranges of values with influence quantities usually wider than the reference conditions for which the uncertainties of a measuring instrument are specified

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

3.1.11
reference conditions
conditions used for testing the performance of a measuring instrument or for the intercomparison of the measurement results

Note 1 to entry: Reference conditions generally include reference values or reference ranges for the quantities influencing and affecting the measuring instrument.

3.1.12
side-mode suppression ratio
SMSR
peak power ratio between the main mode spectrum and the largest side mode spectrum in a single-mode laser diode such as a DFB-LD

Note 1 to entry: Side-mode suppression ratio is usually expressed in dB.

3.1.13
wavelength
wavelength (in a vacuum) of a light source

3.1.14
wavelength deviation
D_λ
difference between the target wavelength, set on the light source under calibration, λ_{TLS}, and the measured wavelength, λ_{meas}, in nm or µm

$$D_\lambda = \lambda_{TLS} - \lambda_{meas}$$

3.2 Abbreviated terms

APC	angled physical contact
AWG	arrayed waveguide grating
DFB-LD	distributed feedback laser diode
DMUX	demultiplexers
FWHM	full-width at half-maximum
MUX	multiplexers
O/E	optical-electrical
OSA	optical spectrum analyser
RIN	relative intensity noise
SMSR	side-mode suppression ratio
TLS	tuneable laser source
WDM	wavelength-division multiplexing

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.

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.

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 calibration equipment which have a significant influence on the calibration results are calibrated.

4.3 Preparation

The environmental conditions shall be commensurate with the level of uncertainty that is required for calibration:

a) calibrations shall be carried out in a clean environment;
b) temperature monitoring and control is required;
c) all laser sources shall be safely operated (according to IEC 60825-1 and IEC 60825-2);
d) the output of the TLS should be examined with an optical spectrum analyser (OSA) having sufficient resolution to resolve the longitudinal mode structure to check for single mode operation.

The recommended temperature is 23 °C, for example, (23 ± 2) °C. Give the calibration equipment enough time prior to testing (2 h is recommended) to reach equilibrium within its environment. Allow the TLS a warm-up period in accordance with the manufacturer's instructions.

4.4 Reference calibration conditions

The reference calibration conditions usually include the following parameters and, if necessary, their tolerance bands: date, temperature, relative humidity, atmospheric pressure, displayed optical power, displayed wavelength, fibre, connector-adapter combination, (spectral) bandwidth and resolution bandwidth (spectral resolution) set. Unless otherwise specified, use a single-mode optical fibre category B1.1 or B1.3 pigtail as specified in IEC 60793-2-50, having a length of at least 2 m. It is desirable to perform all the calibration in a situation where back-reflections are negligible. Thus, angled connectors and isolators should be used wherever the situation permits.

Operate the TLS in accordance with the manufacturer's specifications and operating procedures. Where practical, select a range of calibration conditions and parameters that emulate the actual field operating conditions of the TLS under calibration. Choose these parameters to optimize the tuneable laser source's accuracy, as specified by the manufacturer's operating procedures.

Document the conditions as specified in Clause 7.

NOTE The calibration results only apply to the set of calibration conditions used in the calibration process.

5 Wavelength calibration

5.1 Overview

The factors making up the uncertainty in the wavelength of the light source under calibration consist of:

a) the intrinsic uncertainty of the light source under calibration as found in the calibration at reference conditions, including temperature and time dependences for these tight conditions, and;

b) the uncertainties due to dependences on optical power, temperature and time as found in the calibrations at broader operating conditions.

The list of the source of uncertainty is summarized in Table 1.

Table 1 – Source of uncertainty for wavelength calibration

Source of uncertainty	Type of origin	Symbol
Repeatability	Measurement	s_{λ_j}
Temperature	Environment	$u_{\lambda_j,\Delta\Theta}$
Stability	Light source under calibration	$u_{\lambda_j,\Delta t}$
Wavelength resolution	Reference wavelength meter	$u_{\lambda_j,\text{res}}$
Wavelength meter calibration	Reference wavelength meter	$u_{\text{WM}_{\lambda_j}}$
Optical power	Light source under calibration	$u_{\lambda_j,P}$

The wavelength calibration at reference conditions for discrete wavelengths, as described in 5.2, is mandatory. The calibration at operating conditions, described in 5.3, is optional.

5.2 Wavelength calibration at reference conditions

5.2.1 Set-up

Figure 1 shows a system for wavelength calibration. The calibration is performed under the given reference conditions.

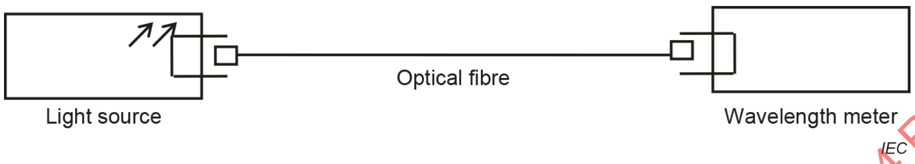

Figure 1 – Measurement set-up for wavelength calibration

5.2.2 Calibration equipment

A wavelength meter shall be used for the calibration. The wavelength meter shall be calibrated according to IEC 62129-2.

5.2.3 Procedure for wavelength calibration

The calibration procedure is as follows:

a) Regarding the calibration system shown in Figure 1, the set wavelength of the light source is given by $\lambda_{\text{TLS}\,j}$ and the measured values are given by $\lambda_{\text{meas}\,i,j}$. The uncertainty of the wavelength measurement takes into account the tuning repeatability and hysteresis of the TLS. Hysteresis is defined as the deviation resulting from tuning the desired wavelength from both the shorter and the longer wavelengths.

b) It is recommended to repeat the wavelength measurement ten (m) times. Ensure that the TLS is tuned to $\lambda_{\text{TLS}\,j}$ prior to each measurement. The target wavelength (j) should be approached in such a way that tuning occurs from both longer and shorter wavelengths.

c) Calculate the average measured wavelength $\bar{\lambda}_{\text{meas}\,j}$:

$$\bar{\lambda}_{\text{meas},\,j} = \frac{1}{m}\sum_{i=1}^{m}\lambda_{\text{meas}\,i,j} \tag{1}$$

where

m is the number of measurements performed.

Each $\lambda_{\text{meas}\,i,j}$ is suggested to be an averaged value from the wavelength meter.

d) Calculate the wavelength deviation D_{λ_j}:

$$D_{\lambda_j} = \lambda_{\text{TLS}\,j} - \bar{\lambda}_{\text{meas}\,j} \tag{2}$$

where $\lambda_{\text{TLS}\,j}$ is the tuned wavelength of the TLS.

e) Calculate the standard deviation for λ_j from the (m) wavelength measurement results $\lambda_{\text{meas}\,i,j}$:

$$s_{\lambda_j} = \left[\frac{1}{m-1} \sum_{i=1}^{m} \left(\lambda_{\text{meas}\,i,j} - \bar{\lambda}_{\text{meas}\,j} \right)^2 \right]^{\frac{1}{2}} \tag{3}$$

f) Calculate the wavelength tuning repeatability S_{rep,λ_j}:

$$S_{\text{rep},\lambda_j} = 2 \times s_{\lambda_j} \tag{4}$$

NOTE A default level of confidence of 95 % is used in Formula (4).

This calibration procedure shall be performed for each calibration wavelength. A minimum of 10 discrete wavelengths or every 10 nm, including the first, the central and the last wavelength of the range, shall be measured.

5.2.4 Dependence on conditions

5.2.4.1 Temperature dependence (optional if known)

5.2.4.1.1 Set-up

Figure 2 shows a calibration system for temperature dependence. This calibration is performed under the reference calibration conditions with the exception of temperature.

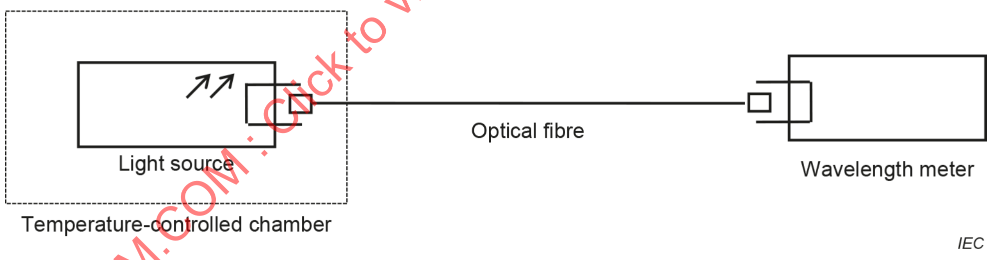

Figure 2 – Measurement set-up for temperature dependence

5.2.4.1.2 Calibration equipment

The calibration equipment is as follows:

a) A wavelength meter capable of detecting wavelength deviation of the TLS due to temperature.

b) Temperature-controlled chamber: make sure that the measurement results are immune to the inner temperature distribution.

5.2.4.1.3 Calibration procedure for determining temperature dependence

The calibration procedure is as follows:

a) Regarding the calibration system of Figure 2, measure the nominal wavelength (j) of the TLS at optical power $P_{\text{TLS}j}$ at reference conditions: $\lambda_{j,\text{ref}}$. The wavelength used should possess the maximum response to temperature variations. Otherwise, characterization of several output wavelengths should be performed.

b) Measure the wavelength of the TLS at temperature (i): λ_{j,Θ_i} Wavelength readings corresponding to each temperature setting should be averaged to determine λ_{j,Θ_i} .

c) Calculate the wavelength deviation:

$$D_{\lambda_{j,\Theta_i}} = \lambda_{j,\Theta_i} - \lambda_{j,\mathrm{ref}} \tag{5}$$

d) Repeat steps b) and c) with (m) different temperature settings Θ_i ensuring that the instrument is allowed the necessary time to eliminate sufficiently any thermal gradients.

e) Calculate the maximum $\max\left(D_{\lambda_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}$ and minimum $\min\left(D_{\lambda_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}$ wavelength deviations.

f) The standard uncertainty for wavelength temperature dependence $u_{\lambda_{j,\Delta\Theta}}$ at the calibration wavelength (j) using a rectangular distribution model is:

$$u_{\lambda_{j,\Delta\Theta}} = \frac{1}{2\sqrt{3}}\left[\max\left(D_{\lambda_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m} - \min\left(D_{\lambda_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}\right] \tag{6}$$

where

$\Delta\Theta$ is the temperature variation.

It is recommended that a wavelength acquisition be performed with the optical wavelength meter for the duration of this calibration.

5.2.4.2 Wavelength stability

5.2.4.2.1 Set-up

Figure 3 shows a calibration system for wavelength stability. This calibration is performed under the reference calibration conditions with the exception of time.

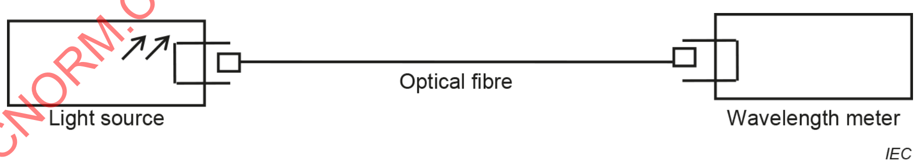

Figure 3 – Measurement set-up for wavelength stability

5.2.4.2.2 Calibration equipment

It is recommended to use a wavelength meter capable of detecting wavelength fluctuations of the TLS.

5.2.4.2.3 Calibration procedure for wavelength stability

The calibration procedure is as follows:

a) A time period (Δt), for example 10 min, shall be chosen that is long enough to permit at least 10 wavelength measurements with the reference wavelength meter (in the case of the example, a stability over 10 min will be measured).

b) A continuous wavelength acquisition should be performed with wavelength data and time stamp.

c) Ensure to correlate (m) measurements per time period where (m > 10) and conforms exactly to the desired time period (Δt).

d) Calculate the standard deviation of the (m) wavelength measurements corresponding to time period (Δt)

$$u_{\lambda_j,\Delta t} = \left[\frac{1}{m-1} \sum_{i=1}^{m} \left(\lambda_{j,t_i} - \frac{1}{m} \sum_{i=1}^{m} \lambda_{j,t_i} \right)^2 \right]^{\frac{1}{2}} \tag{7}$$

e) A minimum of 1 time period is required to evaluate the wavelength stability of the TLS source. In this case, the wavelength stability uncertainty becomes:

$$S_{\text{stab},\lambda_j,\Delta t} = 2 \times u_{\lambda_j,\Delta t} \tag{8}$$

NOTE A default level of confidence of 95 % is used in Formula (8).

The wavelength of the light source should be measured more than ten times (m times) consecutively; at least a few measurements per minute is recommended. The time interval between the repeated measurements should be longer than the response time of the light source. It is preferred to calculate several time periods from the acquisition data using a sliding window and report the maximum value.

5.2.5 Uncertainty at reference conditions

The uncertainty for the calibration wavelength (j) at reference conditions is given by:

$$u_{\lambda_j,\text{ref}} = \left(\frac{s_{\lambda_j}^{\ 2}}{m} + u_{\lambda_j,\Delta\Theta}^{\ 2} + u_{\lambda_j,\Delta t}^{\ 2} + u_{\lambda_j,\text{res}}^{\ 2} + u_{\text{WM}_{\lambda_j}}^{\ 2} \right)^{\frac{1}{2}} \tag{9}$$

where

$u_{\lambda_j,\Delta\Theta}$ and $u_{\lambda_j,\Delta t}$	are evaluated for the reference conditions as defined in 5.2.4;
$u_{\lambda_j,\text{res}}$	is the uncertainty of wavelength resolution defined by $u_{\lambda_j,\text{res}} = d\lambda_j / 2\sqrt{3}$ ($d\lambda_j$ is the wavelength resolution of the wavelength meter);
$u_{\text{WM}_{\lambda_j}}$	is the uncertainty of the wavelength meter at wavelength (j) as described in its certification.

The expanded uncertainty for the calibration wavelength (j) at reference conditions, $U_{\lambda_{j,\mathrm{ref}}}$, with a coverage factor k is expressed as follows:

$$U_{\lambda_{j,\mathrm{ref}}} = k u_{\lambda_{j,\mathrm{ref}}} \tag{10}$$

where

k corresponds to an appropriate level of confidence as described in Clause A.5.

Refer to Annex A and Annex C for information on uncertainties.

When adjustments are made to the instrument based on the calibration results, it is advisable to repeat the calibrations after these adjustments to verify the corrections.

5.3 Wavelength calibration at operating conditions

5.3.1 General

Perform the calibration procedure when the light source is used beyond the reference conditions.

The individual factors in wavelength uncertainty at operating conditions consist of following:

a) optical power dependence;
b) temperature dependence;
c) wavelength stability.

5.3.2 Optical power dependence

5.3.2.1 General

Figure 4 shows a calibration system for optical power dependence. This calibration should be performed under the reference calibration conditions with the exception of the optical power. It shall be performed after the optical power calibration (6.2.3).

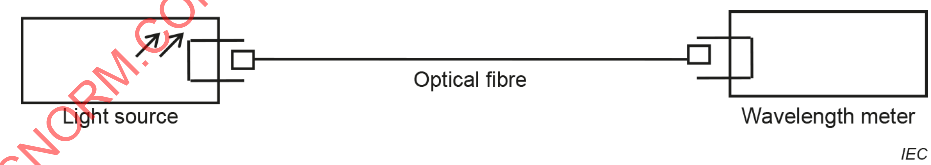

Figure 4 – Measurement set-up for optical power dependence

5.3.2.2 Calibration equipment

The wavelength meter shall be calibrated according to IEC 62129-2.

5.3.2.3 Calibration procedures for determining power dependence

The calibration procedures are as follows:

a) The wavelength (j) is measured at m optical powers of the light source, $P_{\text{TLS}\,i,j}$ including the upper and lower limits of the specified power range. The interval between these neighbouring levels should be smaller than 10 dB.

b) Regarding the calibration system of Figure 4, the set wavelength of the light source is given by $\lambda_{\text{TLS}\,i,j}$, and the instrument reading of the wavelength meter is given by $\lambda_{P_{i,j}}$.

c) Record the measured wavelength $\lambda_{P_{i,j}}$ for all (m) output power settings $P_{\text{TLS}\,i,j}$ used.

d) Calculate the standard uncertainty of wavelength (j) due to TLS output optical power according to

$$u_{\lambda_{j,P}} = \left[\frac{1}{m-1}\sum_{i=1}^{m}(\lambda_{P_{i,j}} - \frac{1}{m}\sum_{i=1}^{m}\lambda_{P_{i,j}})^2\right]^{\frac{1}{2}} \tag{11}$$

5.3.3 Uncertainty at operating conditions

The uncertainty for the calibration wavelength (j) for any operating conditions is given by

$$u_{\lambda_{j,\text{op}}} = \left(s_{\lambda_j}{}^2 + u_{\lambda_j,P}{}^2 + u_{\lambda_j,\Delta\Theta}{}^2 + u_{\lambda_j,\Delta t}{}^2 + u_{\lambda_j,\text{res}}{}^2 + u_{\text{WM}_{\lambda_j}}{}^2\right)^{\frac{1}{2}} \tag{12}$$

where

$u_{\lambda_j,P}$, $u_{\lambda_j,\Delta\Theta}$ and $u_{\lambda_j,\Delta t}$ are evaluated for the operating conditions;

$u_{\lambda_j,\text{res}}$ is the uncertainty of wavelength resolution defined by $u_{\lambda_j,\text{res}} = d\lambda_j / 2\sqrt{3}$ ($d\lambda_j$ is wavelength resolution of the wavelength meter);

$u_{\text{WM}_{\lambda_j}}$ is the uncertainty of the wavelength meter at wavelength (j) as described in its certification.

The expanded uncertainty for the calibration wavelength (j) under all operating conditions, $U_{\lambda_{j,op}}$, with a coverage factor k, is expressed as follows:

$$U_{\lambda_{j,\text{op}}} = k u_{\lambda_{j,\text{op}}} \tag{13}$$

where

k corresponds to an appropriate level of confidence as described in Clause A.5.

6 Optical power calibration

6.1 Overview

The factors making up the uncertainty in the set optical power of the light source under calibration consists of

a) the intrinsic uncertainty of the light source under calibration as found in the calibration at reference conditions including temperature, time, and connection repeatability/reproducibility dependences for these tight conditions, and

b) the uncertainties due to dependences on wavelength, temperature, time and connection repeatability/reproducibility, as found in the calibrations at broader operating conditions.

The list of the source of uncertainty is summarized in Table 2.

Table 2 – Source of uncertainty for optical power calibration

Source of uncertainty	Type of origin	Symbol
Repeatability	Measurement	s_{DP_j}
Temperature	Environment	$u_{DP_j,\Delta\Theta}$
Stability	Light source under calibration	$u_{DP_j,\Delta t}$
Connection reproducibility	Light source under calibration	$u_{DP_j,\mathrm{con}}$
Optical power resolution	Reference optical power meter	$u_{DP_j,\mathrm{res}}$
Optical power meter calibration	Reference optical power meter	$u_{\mathrm{PM}P_j}$
Wavelength	Light source under calibration	$u_{DP_j,\lambda}$

The optical power calibration at reference conditions as described in 6.2 is mandatory. The calibration at operating conditions described in 6.3 is optional.

6.2 Optical power calibration at reference conditions

6.2.1 Set-up

Figure 5 shows a system for the calibration of the optical power. The calibration is performed under the given reference conditions.

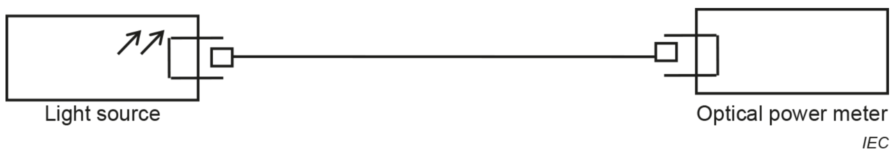

Figure 5 – Measurement set-up for intrinsic optical power calibration

NOTE There could be problems in calibrating the power of a highly coherent laser source, due to parasitic interference effects arising from reflections from fibre connector end faces and also the optical power meter. The use of angled physical contact (APC) connectors, inline optical isolators and engaging of the laser's coherent control function (if fitted) can reduce the interference effects to an acceptable level.

The optical power to be calibrated is measured at the end of an optical fibre cable, which can cause some insertion losses. The calibration condition about the used optical fibre cable such as fibre length, connector type, inline isolator if any, should be reported.

6.2.2 Calibration equipment

The optical power meter shall be calibrated according to IEC 61315.

6.2.3 Procedure for power calibration at reference conditions

The calibration procedure is as follows:

a) Connect the light source and the power meter with the optical fibre.

b) Set the wavelength of the light source and the optical power meter to the required calibration wavelength.

c) Set the output power of the light source to $P_{\mathrm{TLS}j}$. The uncertainty of the power measurement takes into account the setting repeatability and hysteresis of the TLS. Hysteresis is defined as the deviation resulting from setting the desired power from both the lower and the higher powers.

d) Read the measured value of optical power meter.

e) It is recommended to repeat this measurement ten (m) times. Ensure that the TLS is set to $P_{\mathrm{TLS}j}$ prior to each measurement. The target power should be approached in such a way that setting occurs from both lower and higher powers.

$$D_{P_{i,j}} = \frac{P_{\mathrm{TLS}\,j} - P_{\mathrm{meas}\,i,j}}{P_{\mathrm{meas}\,i,j}} \tag{14}$$

where

$P_{\mathrm{TLS}j}$ is the set optical power of the TLS.

Each $P_{\mathrm{meas}\,i,j}$ is suggested to be an averaged value from the power meter. Calculate the power deviation D_{P_j}.

$$D_{P_j} = \frac{1}{m}\sum_{i=1}^{m} D_{P_{i,j}} \tag{15}$$

where

m is the number of measurements performed.

f) Calculate the standard deviation for D_{P_j} from the (m) power measurement results $P_{\mathrm{meas}\,i,j}$:

$$s_{D_{P_j}} = \left[\frac{1}{m-1}\sum_{i=1}^{m}(D_{P_{i,j}} - D_{P_j})^2\right]^{\frac{1}{2}} \tag{16}$$

g) Calculate the optical power setting repeatability: $S_{\mathrm{rep},D_{P_j}}$

$$S_{\mathrm{rep},D_{P_j}} = 2 \times s_{D_{P_j}} \tag{17}$$

NOTE A default level of confidence of 95 % is used in Formula (17).

The uncertainty calculations (6.2.3 a) to g)) should be performed for each calibration power.

6.2.4 Dependence on conditions

6.2.4.1 Temperature dependence (optional if known)

6.2.4.1.1 Set-up

Figure 6 shows a calibration system for temperature dependence. This calibration is performed under the reference calibration conditions with the exception of temperature.

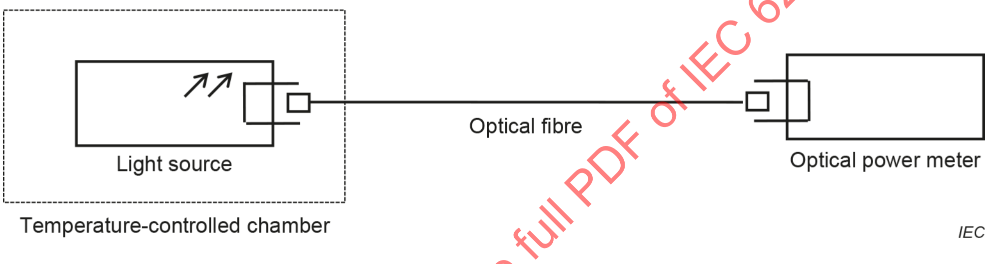

Figure 6 – Measurement set-up for temperature dependence

6.2.4.1.2 Calibration equipment

The calibration equipment is as follows:

a) An optical meter capable of detecting optical power deviation of the TLS depending on temperature.
b) Temperature-controlled chamber:
   Make sure that the measurement results are immune to the inner temperature distribution.

6.2.4.1.3 Calibration procedure for determining temperature dependence

The calibration procedure is as follows:

a) Regarding the calibration system of Figure 6, measure the nominal optical power of the TLS at wavelength $\lambda_{\mathrm{TLS}\,j}$ at reference conditions $P_{j,\mathrm{ref}}$. The optical power used should possess the maximum response to temperature variations. Otherwise, characterization of several output optical powers will be required.
b) Measure the optical power of the TLS at temperature (i): P_{j,Θ_i}. Optical power readings corresponding to each temperature setting should be averaged to determine P_{j,Θ_i}.
c) Calculate the relative optical power deviation:

$$D_{P_{j,\Theta_i}} = \frac{P_{j,\Theta_i} - P_{j,\mathrm{ref}}}{P_{j,\mathrm{ref}}} \tag{18}$$

d) Repeat steps b) and c) with (m) different temperature settings Θ_i ensuring that the instrument is allowed the necessary time to eliminate sufficiently any thermal gradients.

e) Calculate the maximum $\max\left(D_{P_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}$ and minimum $\min\left(D_{P_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}$ optical power deviations.

f) The standard uncertainty for optical power temperature dependence $u_{P_{j,\Delta\Theta}}$ at the calibration optical power using a rectangular distribution model is:

$$u_{D_{P_{j,\Delta\Theta}}} = \frac{1}{2\sqrt{3}}\left[\max\left(D_{P_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m} - \min\left(D_{P_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}\right] \quad (19)$$

where

$\Delta\Theta$ is the temperature variation.

It is recommended that a optical power acquisition be performed with the optical power meter for the duration of this calibration.

6.2.4.2 Optical power stability

6.2.4.2.1 Set-up

Figure 7 shows a calibration system for optical power stability. This calibration is performed under the reference calibration conditions with the exception of time.

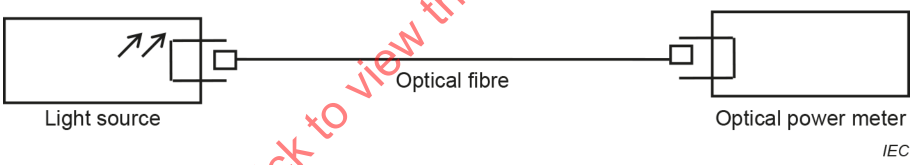

Figure 7 – Measurement set-up for optical power stability

6.2.4.2.2 Calibration equipment

It is recommended to use an optical power meter capable of detecting optical power fluctuations of the TLS.

6.2.4.2.3 Calibration procedure for optical power stability

The calibration procedure is as follows:

a) A specific time period (Δt), for example 10 min, shall be chosen that is long enough to permit at least 10 optical power measurements with the reference power meter (in the case of the example, a stability over 10 min will be measured).

b) A continuous optical power acquisition should be performed with optical power data and time stamp.

c) Ensure to correlate (m) measurements per time period where $(m > 10)$ and conforms exactly to the desired time period (Δt).

d) Calculate the standard deviation of the (m) measurements corresponding to time period (Δt):

$$u_{D_{P_j,\Delta t}} = \left[\frac{1}{m-1} \sum_{i=1}^{m} \left(P_{j,t_i} - \frac{1}{m} \sum_{i=1}^{m} P_{j,t_i} \right)^2 \right]^{\frac{1}{2}} \Bigg/ \left(\frac{1}{m} \sum_{i=1}^{m} P_{j,t_i} \right) \quad (20)$$

e) A minimum of 1 time period is required to evaluate the optical power stability of the TLS source. In this case, the optical power stability uncertainty becomes:

$$S_{\text{stab},D_{P_j,\Delta t}} = 2 \times u_{D_{P_j,\Delta t}} \quad (21)$$

NOTE A default level of confidence of 95 % is used in Formula (21).

It is preferred to calculate several time periods from the acquisition data using a sliding window and report the maximum value.

The optical power of the light source should be measured more than ten times (m times) consecutively; at least a few measurements per minute is recommended. The time interval between the repeated measurements should be longer than the response time of the light source.

6.2.4.3 Connection repeatability/reproducibility

6.2.4.3.1 Set-up

Figure 8 shows a calibration system for optical power stability. This calibration is performed under the reference calibration conditions.

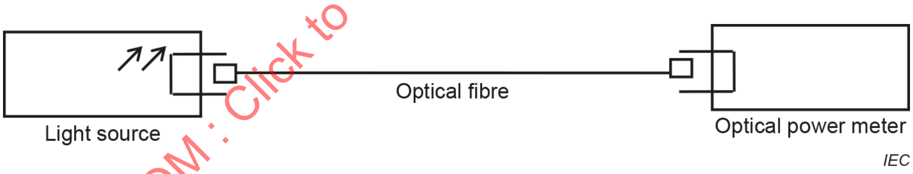

Figure 8 – Measurement set-up for connection repeatability/reproducibility

6.2.4.3.2 Calibration equipment

The optical power meter shall be calibrated according to IEC 61315.

6.2.4.3.3 Calibration procedure for connection repeatability/reproducibility

The calibration procedure is as follows:

a) Regarding the calibration system in Figure 8, connect the light source and the power meter with the optical fibre.

b) Read the measured value of optical power meter P_{j,con_i}.

c) Disconnect the optical fibre from the TLS and reconnect the optical fibre to the TLS.

d) Repeat b) and c) for (m) times.

e) Calculate the standard uncertainty of optical power (j) due to TLS connection repeatability/reproducibility according to

$$u_{D_{P_j,\mathrm{con}}} = \left[\frac{1}{m-1} \sum_{i=1}^{m} \left(P_{j,\mathrm{con}_i} - \frac{1}{m} \sum_{i=1}^{m} P_{j,\mathrm{con}_i} \right)^2 \right]^{\frac{1}{2}} \Bigg/ \left(\frac{1}{m} \sum_{i=1}^{m} P_{j,\mathrm{con}_i} \right) \tag{22}$$

6.2.5 Uncertainty at reference conditions

The uncertainty for the calibration optical power at reference conditions is given by:

$$u_{D_{P_j,\mathrm{ref}}} = \left(\frac{{s_{D_{P_j}}}^2}{m} + {u_{D_{P_j,\Delta\Theta}}}^2 + {u_{D_{P_j,\Delta t}}}^2 + {u_{D_{P_j,\mathrm{con}}}}^2 + {u_{D_{P_j,\mathrm{res}}}}^2 + {u_{\mathrm{PM}_{P_j}}}^2 \right)^{\frac{1}{2}} \tag{23}$$

where

$u_{D_{P_j,\Delta\Theta}}$ $u_{D_{P_j,\Delta t}}$ and $u_{D_{P_j,\mathrm{con}}}$ are evaluated for the reference conditions as defined in 6.2.4;

$u_{D_{P_j,\mathrm{res}}}$ is the relative uncertainty of optical power resolution defined by $u_{D_{P_j,\mathrm{res}}} = (dP_{\mathrm{TLS},j} / P_{\mathrm{TLS},j}) / 2\sqrt{3}$ ($dP_{\mathrm{TLS},j}$ is the optical power resolution of the optical power meter);

$u_{\mathrm{PM}_{P_j}}$ is the relative uncertainty of the power meter at power P_j as described in its certification.

The expanded uncertainty for the calibration power meter at reference conditions $U_{D_{P_j,\mathrm{ref}}}$, with a coverage factor k, is expressed as follows:

$$U_{D_{P_j,\mathrm{ref}}} = k u_{D_{P_j,\mathrm{ref}}} \tag{24}$$

where

k corresponds to an appropriate level of confidence as described in Clause A.5.

Refer to Annex A for information on uncertainties.

When adjustments are made to the instrument based on the calibration results, it is advisable to repeat the calibrations after these adjustments to verify the corrections.

6.3 Optical power calibration at operating conditions

6.3.1 General

Perform the calibration procedure when the light source is used beyond the reference conditions.

The individual factors in optical power uncertainty at operating conditions consist of the following:

a) wavelength dependence;
b) temperature dependence;
c) optical power stability;
d) connection repeatability/reproducibility.

6.3.2 Wavelength dependence

6.3.2.1 Set-up

Figure 9 shows a calibration system for wavelength dependence. This calibration should be performed under the reference calibration conditions with the exception of the wavelength. It shall be performed after the wavelength calibration (5.2.3).

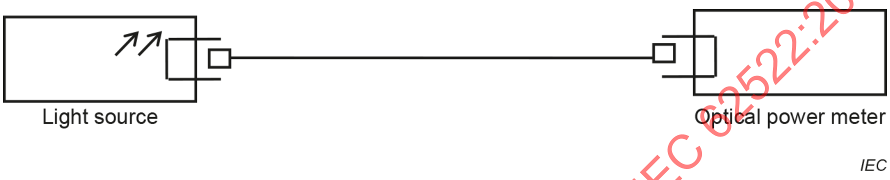

Figure 9 – Measurement set-up for wavelength dependence

6.3.2.2 Calibration equipment

The calibration equipment is as follows: the optical power meter should be calibrated according to IEC 61315.

6.3.2.3 Calibration procedure for determining wavelength dependence

The calibration procedure is as follows:

a) The optical power is measured at m wavelengths (more than 5) of the light source, $\lambda_{\mathrm{TLS}\,i,j}$ including the upper and lower limits of the specified wavelength range.
b) Regarding the calibration system of Figure 9, the set optical power of the light source is given by $P_{\mathrm{TLS}\,i,j}$, and the instrument reading of the power meter is given by $P_{\lambda_i,j}$.
c) Set the wavelength of the optical power meter to the required calibration wavelength.
d) Record the measured optical power $P_{\lambda_{i,j}}$ for all (m) wavelength settings $\lambda_{\mathrm{TLS}\,i,j}$ used.
e) Calculate the standard uncertainty of optical power (j) due to TLS output wavelength according to:

$$u_{D_{P_{j,\lambda}}} = \left[\frac{1}{m-1} \sum_{i=1}^{m} \left(P_{\lambda\,i,j} - \frac{1}{m} \sum_{i=1}^{m} P_{\lambda\,i,j} \right)^2 \right]^{\frac{1}{2}} \Bigg/ \left(\frac{1}{m} \sum_{i=1}^{m} P_{\lambda\,i,j} \right) \tag{25}$$

6.3.3 Uncertainty at operating conditions

The uncertainty for the calibration optical power for any operating condition is given by:

$$u_{D_{P_{j,op}}} = \left(s_{D_{P_j}}{}^2 + u_{D_{P_j,\lambda}}{}^2 + u_{D_{P_j,\Delta\Theta}}{}^2 + u_{D_{P_j,\Delta t}}{}^2 + u_{D_{P_j,\mathrm{con}}}{}^2 + u_{D_{P_j,\mathrm{res}}}{}^2 + u_{\mathrm{PM}_{P_j}}{}^2 \right)^{\frac{1}{2}} \tag{26}$$

where

$u_{D_{P_j,\lambda}}$, $u_{D_{P_j,\Delta\Theta}}$, $u_{D_{P_j,\Delta t}}$ and $u_{D_{P_j,\mathrm{con}}}$ are evaluated for the operating conditions;

$u_{D_{P_j,\mathrm{res}}}$ is the relative uncertainty of optical power resolution defined by $u_{D_{P_j,\mathrm{res}}} = (dP_{\mathrm{TLS},j} / P_{\mathrm{TLS},j}) / 2\sqrt{3}$ ($dP_{\mathrm{TLS},j}$ is optical power resolution of the optical power meter);

$u_{PM_{P_j}}$ is the uncertainty of the power meter at optical power P_j as described in its certification.

The expanded uncertainty for the calibration optical power under all operating conditions $U_{D_{P_{j,\mathrm{op}}}}$, with a coverage factor k, is expressed as follows:

$$U_{D_{P_{j,\mathrm{op}}}} = k u_{D_{P_{j,\mathrm{op}}}} \tag{27}$$

where

k corresponds to an appropriate level of confidence as described in Clause A.5.

7 Documentation

7.1 Calibration data and uncertainty

Calibration certificates claiming to be in compliance with this document shall include the following data and their uncertainties, and the uncertainties shall be stated in the form of estimated confidence intervals by multiplying the relevant standard uncertainty by k:

NOTE 1 Refer to Annex A for information on uncertainty and Clause A.5 for further details on level of confidence and coverage factor.

a) the wavelength deviation, D_{λ_j}, and its uncertainty, $ku_{\lambda_{j,\mathrm{ref}}}$, for example, is in nm, in a vacuum – see the detailed requirements in Clause 5;

b) the optical power deviation, D_{P_j}, and its uncertainty, $ku_{D_{P_{j,\mathrm{ref}}}}$, for example, is in % or dB – see the detailed requirements in Clause 6.

NOTE 2 Other tests can be added to the documentation, refer to Annex B for more information.

7.2 Calibration conditions

The calibration method(s) and the method(s) of obtaining the measurement results shall be stated.

Calibration conditions shall be reported. The most important parameters are the calibration date, the displayed optical power, the displayed wavelength, the temperature, the humidity and the atmospheric pressure.

NOTE The calibration results only apply to the set of calibration conditions used for the calibration process.

Annex A
(normative)

Mathematical basis for measurement uncertainty calculations

A.1 General

Annex A summarizes 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 between 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

The 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:

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

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

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

where

$\bar{X}$ 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.

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

A.3 Type B evaluation of uncertainty

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

$$u(y)=c\times u(x) \tag{A.7}$$

where

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

$$c=\frac{\partial y}{\partial x} \tag{A.8}$$

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 Formula (A.8) 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 can be more appropriate to find the change in the output estimate y due to the change of 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:

$$u_c(y) = \sqrt{\sum_{i=1}^{n} u_i^2(y)} \tag{A.9}$$

where

i is the current number of individual contribution;

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

n is the number of uncertainties.

NOTE It is acceptable to neglect uncertainty contributions to Formula (A.9) that are smaller than 1/10 of the largest contribution, 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 Formula (A.9). Despite its partially 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:

$$U = k \times u_c(y) \tag{A.10}$$

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 (GUM); if these conditions are not met, larger coverage factors are to be used to reach these levels of confidence.

Annex B
(informative)

Other testing

B.1 General

Annex B provides some details on other tests which are not mandatory but are related to the performance of tuneable laser sources.

B.2 Wavelength tuning resolution

B.2.1 Set-up

Figure B.1 shows the test set-up for a wavelength tuning resolution test under standard test conditions.

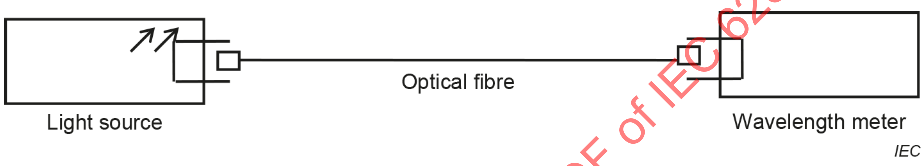

Figure B.1 – Measurement set-up for wavelength resolution

B.2.2 Testing equipment

Testing equipment is as follows:

A wavelength meter which has a better wavelength measurement resolution than the wavelength resolution of test light source should be used.

B.2.3 Testing procedure for determining wavelength resolution

The testing procedure is as follows:

a) Set the wavelength of the test light source to λ_{TLS}. Set the optical output power of the test light source to a suitable value.

b) The wavelength for λ_{meas} is measured with the wavelength meter.

c) The wavelength of the light source is set only $qd\lambda$ to the long (or short) wavelength side for λ_{TLS}. Here, $d\lambda$ is the minimum variable width that can be set to λ_{TLS}, and q are integers.

d) Inject the optical output of the light source into the wavelength meter. The wavelength for $\lambda_{\text{meas+1}}$ is measured with the wavelength meter.

e) After the wavelength of the light source is returned to λ_{TLS}, the measurements should be repeated over ten times (m times).

f) Calculate the wavelength setting resolution $d\lambda_{\text{TLS},j}$ with Formula (B.1).

$$d\lambda_{\text{TLS},j} = \sum_{i=1}^{m} \frac{\left|\lambda_{\text{meas+1},i} - \lambda_{\text{meas},i}\right|}{m \times q} \tag{B.1}$$

g) Repeat the measurements for a few (j) wavelengths covering the desired wavelength range. Calculate the wavelength setting resolution with Formula (B.2).

$$d\lambda_{\mathrm{TLS}} = \max\left(d\lambda_{TLS,j}\right) \tag{B.2}$$

B.3 Optical power tuning resolution

B.3.1 Set-up

Figure B.2 shows the test set-up for optical power tuning resolution setting tests under standard test conditions.

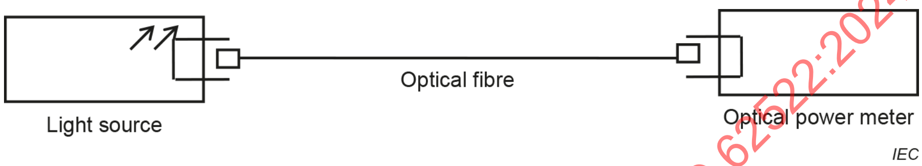

Figure B.2 – Measurement set-up for optical power resolution setting test

B.3.2 Testing equipment

Use an optical power meter with high resolution.

B.3.3 Testing procedure for optical power resolution

Testing procedure is as follows:

a) Set the optical output power of the test light source to P_{TLS}. Set the wavelength of the light source to a suitable value.

b) Inject the optical output into the optical power meter. Measure the optical power P_{meas} with the optical power meter.

c) Only set the minimum variable width dP as a higher (or lower) output power under P_{TLS} settings for optical output power of test light source.

d) Measure the optical power $P_{\mathrm{meas+1}}$ with optical power meter.

e) After the optical output power of test light source is returned to P_{TLS}, the measurements should be repeated over ten times (m times).

f) Calculate the optical output power setting resolution dP_{TLS} / P_{TLS} with Formula (B.3).

$$\frac{dP_{\mathrm{TLS},j}}{P_{\mathrm{TLS},j}} = \sum_{i=1}^{m} \frac{\left|P_{\mathrm{meas+1},i} - P_{\mathrm{meas},i}\right|}{m} \Big/ \sum_{i=1}^{m} \frac{P_{\mathrm{meas},i}}{m} \tag{B.3}$$

g) Repeat the measurements for a few (j) optical powers covering the desired power range. Calculate the power setting resolutions with Formula (B.4).

$$\frac{dP_{\mathrm{TLS}}}{P_{\mathrm{TLS}}} = \max\left(\frac{dP_{\mathrm{TLS},j}}{P_{\mathrm{TLS},j}}\right) \tag{B.4}$$

B.4 Signal-to-source spontaneous emission ratio

B.4.1 General

Clause B.4 describes how to determine the side-mode suppression ratio (SMSR) of a laser with SSSER that can be measured with an OSA (e.g. SSSER of 60 dB). However, in the case of narrow line width laser sources such as an external cavity laser, the purity of the source can be much higher (around 90 dB) and therefore other methods can be used.

B.4.2 Set-up

Figure B.3 shows the test set-up for a signal-to-source spontaneous emission ratio under standard test conditions.

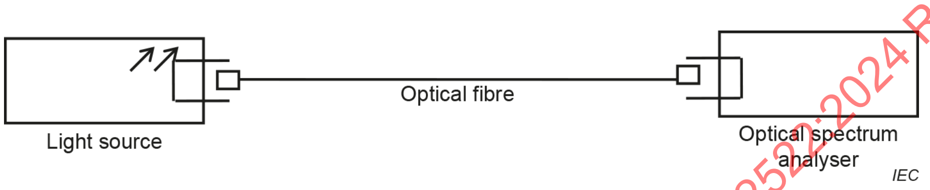

Figure B.3 – Measurement set-up for signal to total source spontaneous emission ratio

B.4.3 Testing equipment

The OSA is used to measure the optical signal power and the spontaneous emission light.

B.4.4 Testing procedure for determining signal-to-source spontaneous emission ratio

The testing procedure is as follows:

a) Set the wavelength of the test light source to λ_{TLS}. Set the optical output power to a suitable value. Usually, the optical power is set to the maximum optical output power defined by the specifications of the test light source.

b) Set the wavelength, the wavelength sweep range, and the resolution bandwidth of an OSA to λ_{TLS}, λ_{span}, and λ_{res} respectively. Usually, λ_{span} is approximately 100 nm, and λ_{res} is approximately 1 nm.

c) Inject the optical output of the light source into the OSA. Measure the optical signal optical power for P_1. Measure the maximum value P_2 of a spontaneous emission optical level in $\lambda_{\mathrm{TLS}} \pm \Delta\lambda$. However, the $\lambda_{\mathrm{TLS}} \pm \Delta\lambda_{\mathrm{exc}}$ range will not be included as the measurement range of the spontaneous emission light (refer to Figure B.4). Usually, $\Delta\lambda$ is approximately 50 nm, $\Delta\lambda_{\mathrm{exc}}$ is approximately 1 nm.

d) Calculate the signal-to-source spontaneous emission ratio with Formula (B.5).

$$\mathrm{SSER} = -10\log\frac{P_2 \times 1/\lambda_{\mathrm{res}}}{P_1}\ \mathrm{dB/nm} \qquad \text{(B.5)}$$

where

SSER	is the signal to source spontaneous emission ratio (dB/nm);
P_1 and P_2	are in mW
λ_{res}	is in nm

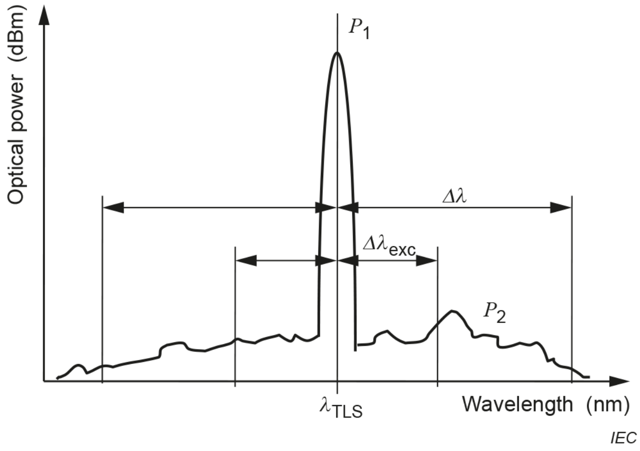

Figure B.4 – Measurement of the signal to spontaneous emission ratio

NOTE For a TLS with a high SSER, the optical rejection ratio of the OSA can limit the measured value.

Record the ratio of signal optical power and the spontaneous emission light as well as the measurement results.

B.5 Side-mode suppression ratio

B.5.1 General

In general, SMSR of a laser source can be measured with an OSA as described in IEC 61280-1-3:2021, 8.8. In the case of narrow line width laser sources such as an external cavity laser, however, the quite close interval between the main and side mode can cause difficulty to distinguish them with an OSA. Clause A.5 describes how to determine the SMSR of such a narrow line width laser source.

NOTE The testing approach adopted here measures the impact of SMSR on relative intensity noise (RIN), but possibly underestimates the power of the sidemodes when they are not in phase.

B.5.2 Set-up

A special testing system is necessary, although it is performed by the tuneable laser source. For example, Figure B.5 shows the diagram of the test system of the SMSR test under standard test conditions.

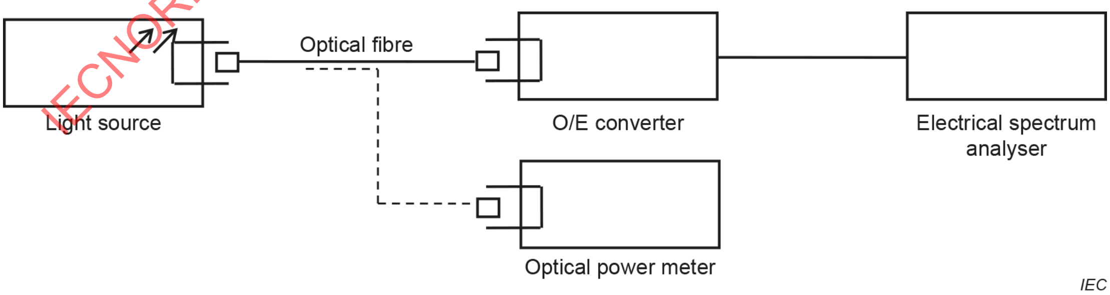

Figure B.5 – Measurement set-up for the side-mode suppression ratio test

B.5.3 Testing equipment

Testing equipment is as follows:

a) O/E (optical-electrical) converter: this is used for heterodyne detection of the intermode beat spectrum between the signal light and the side mode light, converting the optical signal to an electric signal. The frequency band should be several times wider than its mode spacing. The optical-electrical conversion efficiency should be calibrated beforehand.

b) Electrical spectrum analyser: this is used to measure the beat signal level combined with the signal light and the side mode light.

c) Optical power meter: this is used to measure the optical signal power.

B.5.4 Testing procedure for determining the side-mode suppression ratio

The testing procedure is as follows:

a) Set the wavelength of the light source to λ_{TLS}. Set the optical output power to a suitable value.

b) Inject the optical output of the light source into to the O/E converter, and set the largest signal of the displayed beat signals measured by the spectrum analyser to $P_{\mathrm{beat,max}}$ (dBm).

c) Next, inject the optical output of the light source into a optical power meter to measure the signal power. Set this value to P_0 (dBm).

d) Calculate the SMSR (dB) in wavelength λ_{TLS} with Formula (B.6).

$$\begin{aligned} \mathrm{SMSR} &= 10\log\frac{P_0}{P_{\mathrm{s,max}}} \\ &= 2P_0 - P_{\mathrm{beat,max}} + R + 10\log(8R_{\mathrm{i}}) - 30 \end{aligned} \tag{B.6}$$

where

$P_{\mathrm{s,max}}$ is a maximum side mode optical power (dBm);

R is the conversion efficiency of O/E converter (dB);

$$R_{\mathrm{dB}} = 20\log\frac{R}{1} \tag{B.7}$$

R_{i} is input impedance of OSA (Ω).

The following explains the measurement principle and Formula (B.6) for the SMSR.

It is assumed that the optical output spectrum of the test light source is composed with the side mode (P_{s}) that is away from ΔΩ and the signal light (P_0) – see Figure B.6.

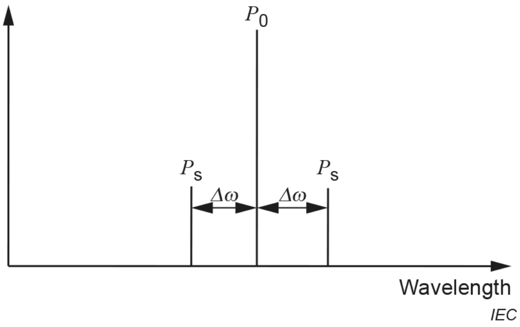

Figure B.6 – Optical spectrum of tuneable laser source

When the signal enters the measurement system shown in Figure B.7, the output current i_E of the O/E converter is calculated with Formula (B.8):

$$i_E = R\left\{P_0 + 2P_s + 4\sqrt{P_0 P_s}\cos(\Delta\omega t)\right\} \tag{B.8}$$

where

R is a conversion efficiency of the O/E converter (A/W).

From Formula (B.8) when the beat current emerging from the signal light and the side mode is i_b, the beat signal power (electric) P_b, which is measured with the spectrum analyser, will be calculated with Formula (B.9) and Formula (B.10).

$$i_b = 4R\sqrt{P_0 P_s}\cos(\Delta\omega t) \tag{B.9}$$

$$P_b = 8R_i P_0 P_s R^2 \tag{B.10}$$

where

R_i is the input impedance of the spectrum analyser (Ω).

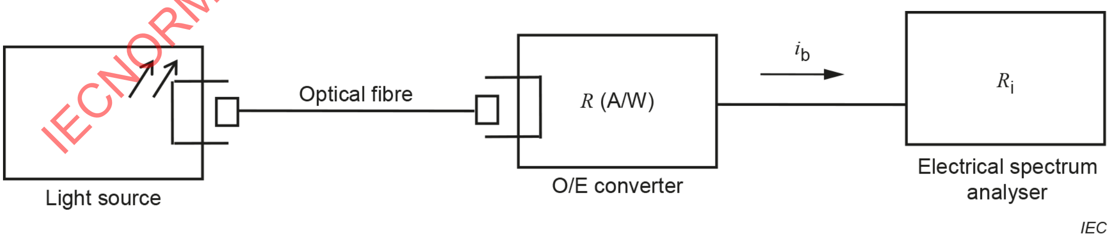

Figure B.7 – Measurement set-up for SMSR

The SMSR, derived from Formula (B.10), is calculated with Formula (B.11):

$$\text{SMSR} = \frac{P_0}{P_s} = 8R_i R^2 \frac{P_0^{\,2}}{P_b} \tag{B.11}$$

If the SMSR is in dB, it will be calculated with Formula (B.12):

$$\begin{aligned}\mathrm{SMSR_{dB}} &= 10\log\left(8R_i R^2 \frac{P_0^{\,2}}{P_\mathrm{b}}\right)\\ &= 2P_{0,\mathrm{dBm}} - P_{\mathrm{b,dBm}} + R_{\mathrm{dB}} + 10\log(8R_i) - 30\end{aligned} \tag{B.12}$$

where

$$P_{0,\mathrm{dBm}} = 10\log\frac{P_0}{10^{-3}};$$

$$P_{\mathrm{b,dBm}} = 10\log\frac{P_\mathrm{b}}{10^{-3}};$$

$$R_{\mathrm{dB}} = 20\log\frac{R}{1}.$$

NOTE The testing approach adopted here is suitable for external cavity lasers only.

Annex C
(informative)

Linear to dB scale conversion of uncertainties

C.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:

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

where

P and P_0 are expressed in the same linear units.

C.2 Conversion of relative uncertainties

Similar to the previous definition, relative uncertainties, U_{lin}, or relative deviations, can be expressed in decibels:

$$U_{\text{dB}} = 10 \times \log_{10}\left(1 + U_{\%}\right) \tag{C.2}$$

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

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

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

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

that leads to:

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

and two useful expressions:

$$U_{\mathrm{dB}} \approx 4{,}34 \times U_{\mathrm{lin}} \Leftrightarrow U_{\mathrm{lin}} \approx 0{,}23 \times U_{\mathrm{dB}} \qquad \text{(C.6)}$$

Bibliography

IEC 60027-3, *Letter symbols to be used in electrical technology – Part 3: Logarithmic and related quantities, and their units*

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*, available at www.electropedia.org

IEC 60050-731, *International Electrotechnical Vocabulary – Chapter 731: Optical fibre communication*, available at www.electropedia.org

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

IEC 60793-1 (all parts), *Optical fibres – Part 1: Measurement methods and test procedures*

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

IEC 61280-1-3:2021, *Fibre optic communication subsystem test procedures – Part 1-3: General communication subsystems – Measurement of central wavelength, spectral width and additional spectral characteristics*

IEC 61300-3-2, *Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 3-2: Examination and measurements – Polarization dependent loss in a single-mode fibre optic device*

IEC TR 61930, *Fibre optic graphical symbology*

IEC TR 61931, *Fibre optic – Terminology*

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

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

ISO 80000-3, *Quantities and units – Part 3: Space and time*

ITU-T G.694 (all parts), *Spectral grids for WDM applications*

ITU-T G. 694.1, *Spectral grids for WDM applications: DWDM frequency grid*

SOMMAIRE

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L'IEC 62522 a été établie par le comité d'études 86 de l'IEC: Fibres optiques. Il s'agit d'une Norme internationale.

Cette deuxième édition annule et remplace la première édition parue en 2014. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

a) ajout de références à l'IEC 61315;
b) ajout du Tableau 1 et du Tableau 2 sur les incertitudes;
c) clarification des paramètres du wattmètre de référence en 6.2.3 et 6.3.2.3.

Le texte de cette Norme internationale est issu des documents suivants:

Projet	Rapport de vote
86/639/FDIS	86/643/RVD

Le rapport de vote indiqué dans le tableau ci-dessus donne toute information sur le vote ayant abouti à son approbation.

La langue employée pour l'élaboration de cette Norme internationale est l'anglais.

Le présent document a été rédigé selon les Directives ISO/IEC, Partie 2, il a été développé selon les Directives ISO/IEC, Partie 1 et les Directives ISO/IEC, Supplément IEC, disponibles sous www.iec.ch/members_experts/refdocs. Les principaux types de documents développés par l'IEC sont décrits plus en détail sous www.iec.ch/publications.

Le comité a décidé que le contenu de ce document ne sera pas modifié avant la date de stabilité indiquée sur le site Web de l'IEC sous webstore.iec.ch dans les données relatives au document recherché. À cette date, le document sera

- reconduit,
- supprimé, ou
- révisé.

INTRODUCTION

Les systèmes de transmission par multiplexage par répartition en longueur d'onde (MRL) sont déployés dans les lignes optiques principales. Les recommandations UIT-T de la série G.694 décrivent des grilles de fréquences et de longueurs d'onde pour des applications MRL. Par exemple, la grille de fréquence de la recommandation UIT-T G.694.1 prend en charge un certain nombre d'espacements entre les canaux sur une plage allant de 12,5 GHz à 100 GHz et sur une plage plus large dispositifs MRL, tels qu'un réseau de guide d'onde (AWG, Arrayed Waveguide Grating), des multiplexeurs (MUX) et des démultiplexeurs (DMUX) basés sur un filtre à couche mince ou sur des réseaux, avec un espacement étroit entre les canaux, sont intégrés dans les systèmes de transmission MRL. Lors de la mesure des caractéristiques de tels dispositifs, des sources laser accordables en longueur d'onde sont utilisées la plupart du temps et sont nécessaires pour obtenir des performances bien étalonnées. L'incertitude sur les longueurs d'onde, la répétabilité du caractère accordable des longueurs d'onde, la stabilité de la longueur d'onde et la stabilité de la puissance optique de sortie sont des paramètres importants.

Une source laser accordable (TLS, Tuneable Laser Source) présente généralement les fonctionnalités suivantes:

a) la longueur d'onde de sortie est accordable de manière continue dans une plage de longueurs d'onde comprise entre 1 260 nm ou plus et 1 675 nm ou moins (il convient que la sortie n'excite que le mode fondamental LP01 de la fibre);
b) un port de sortie pour connecteurs de fibres optiques.

L'enveloppe du spectre représente un mode longitudinal unique avec une largeur à mi-hauteur (FWHM, Full-Width at Half-Maximum) de 0,1 nm au plus. Tout mode adjacent est inférieur d'au moins 20 dB par rapport au mode spectral principal (par exemple, une diode laser à rétroaction répartie [DFB-LD, Distributed Feedback Laser Diode], un laser à cavité externe, etc.).

ÉTALONNAGE DES SOURCES LASER ACCORDABLES

1 Domaine d'application

Le présent document fournit une procédure fiable et reproductible pour étalonner la longueur d'onde et la puissance de sortie d'un laser accordable en fonction des instruments de référence tels que des wattmètres optiques et des appareils de mesure de longueur d'onde optique (y compris des fréquencemètres optiques) dont la traçabilité a été préalablement étalonnée.

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 60793-2-50, *Fibres optiques — Partie 2-50: Spécifications de produits — Spécification intermédiaire pour les fibres unimodales de classe B*

IEC 60825-1, *Sécurité des appareils à laser — Partie 1: Classification des matériels et exigences*

IEC 60825-2, *Sécurité des appareils à laser — Partie 2: Sécurité des systèmes de télécommunication par fibres optiques (STFO)*

IEC 61315, *Étalonnage de wattmètres pour dispositifs à fibres optiques*

IEC 62129-2, *Étalonnage des appareils de mesure de longueur d'onde/appareil de mesure de la fréquence optique — Partie 2: Appareils de mesure de longueur d'onde unique à interféromètre de Michelson*

ISO/IEC Guide 98-3:2008, *Incertitude de mesure — Partie 3: Guide pour l'expression de l'incertitude de mesure (GUM:1995)*

3 Termes, définitions et abréviations

3.1 Termes et définitions

Pour les besoins du présent document, les termes et définitions 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 https://www.electropedia.org/
- ISO Online browsing platform: disponible à l'adresse https://www.iso.org/obp

3.1.1
laboratoire d'étalonnage accrédité
laboratoire d'étalonnage autorisé par l'organisation nationale compétente à publier des certificats d'étalonnage qui démontrent la traçabilité aux étalons nationaux

3.1.2
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: Pour plus d'informations, voir l'ISO/IEC Guide 99:2007, 3.11.

[SOURCE: IEC 60050-311:2001, 311-03-16, modifié — Le domaine a été supprimé, le terme "appareil de mesure" a été supprimé de la définition et la Note à l'article correspondante a été omise.]

3.1.3
étalonnage
ensemble des opérations qui, dans des conditions spécifiées, établissent une relation entre les valeurs des grandeurs indiquées par un appareil de mesure et les valeurs correspondantes fournies par des étalons

Note 1 à l'article: Le résultat d'un étalonnage permet soit l'affectation des valeurs d'un mesurande 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 certificat d'étalonnage ou rapport d'étalonnage.

Note 4 à l'article: Voir également l'ISO/IEC Guide 99:2007, 2.39.

3.1.4
conditions d'étalonnage
conditions de mesure dans lesquelles l'étalonnage est réalisé

3.1.5
étalonnage dans les conditions de référence
étalonnage qui inclut l'évaluation de l'incertitude dans les conditions de référence de la source de rayonnement lumineux à étalonner

3.1.6
étalonnage dans les conditions de fonctionnement
étalonnage qui inclut l'évaluation de l'incertitude dans les conditions de fonctionnement de la source de rayonnement lumineux à étalonner

3.1.7
niveau de confiance
estimation de la probabilité que la valeur réelle d'un paramètre mesuré se trouve dans la plage donnée

3.1.8
facteur d'élargissement
k
facteur utilisé pour calculer l'incertitude élargie U à partir de l'incertitude-type u

3.1.9
écart de puissance optique
D_P
différence entre la puissance définie de la source de rayonnement lumineux à étalonner, P_{TLS}, et la puissance de référence correspondante, P_{meas}, mesurée par le wattmètre de référence

$$D_P = \frac{P_{TLS} - P_{meas}}{P_{meas}}$$

Note 1 à l'article: La puissance P est exprimée en unités linéaires, par exemple W.

Note 2 à l'article: L'écart est relatif, il n'a pas d'unité (il peut être exprimé en %).

3.1.10
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 appareil de mesure sont spécifiées

Note 1 à l'article: Les conditions de fonctionnement et l'incertitude dans les conditions de fonctionnement sont généralement spécifiées par le fabricant à l'intention de l'utilisateur.

3.1.11
conditions de référence
conditions utilisées pour les essais de performance d'un appareil de mesure ou pour la comparaison entre les résultats des mesures

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'appareil de mesure.

3.1.12
taux de suppression des modes latéraux
SMSR
rapport de la puissance de crête entre le spectre du mode principal et le spectre du mode latéral le plus large, ceci dans une diode laser unimodale telle qu'une diode laser DFB-LD

Note 1 à l'article: Le taux de suppression des modes latéraux est généralement exprimé en dB.

3.1.13
longueur d'onde
longueur d'onde (dans le vide) d'une source de rayonnement lumineux

3.1.14
écart en longueur d'onde
D_λ
différence entre la longueur d'onde cible, définie sur la source de rayonnement lumineux à étalonner, λ_{TLS}, et la longueur d'onde mesurée, λ_{meas}, en nm ou en µm

$$D_\lambda = \lambda_{TLS} - \lambda_{meas}$$

3.2 Abréviations

APC	angled physical contact (contact physique à angles)
AWG	arrayed waveguide grating (réseau sélectif planaire)
DFB-LD	distributed feedback laser diode (diode laser à rétroaction répartie)
DMUX	démultiplexeurs
FWHM	full-width at half-maximum (largeur à mi-hauteur)
MUX	multiplexeurs
O/E	optique-électrique
OSA	optical spectrum analyser (analyseur de spectre optique)
RIN	relative intensity noise (intensité relative de bruit)
SMSR	side-mode suppression ratio (taux de suppression des modes latéraux)
TLS	tuneable laser source (source laser accordable)
MRL	multiplexage par répartition en longueur d'onde

4 Préparation pour l'étalonnage

4.1 Organisation

Il convient que le laboratoire d'étalonnage s'assure que des exigences d'étalonnage appropriées sont respectées.

NOTE Des recommandations relatives aux bonnes pratiques d'étalonnage peuvent être consultées dans l'ISO/IEC 17025.

Il convient qu'une procédure de mesure documentée soit établie pour chaque type d'étalonnage effectué, donnant des instructions de fonctionnement étape par étape et l'appareillage à utiliser.

4.2 Traçabilité

Il convient que le laboratoire d'étalonnage s'assure que des exigences appropriées sont respectées.

NOTE Des recommandations relatives aux bonnes pratiques d'étalonnage peuvent être consultées dans l'ISO/IEC 17025.

Tous les étalons utilisés dans le processus d'étalonnage doivent être étalonnés conformément à un programme documenté avec une traçabilité reconnue par les laboratoires d'étalons nationaux ou par les laboratoires d'étalonnage accrédités.

Il est conseillé de conserver plus d'un étalon à chaque niveau de la hiérarchie, de telle sorte que les performances de l'étalon puissent être vérifiées par comparaison au même niveau. S'assurer que tout autre appareil d'étalonnage ayant une influence significative sur les résultats d'étalonnage est étalonné.

4.3 Préparation

Les conditions d'environnement doivent être compatibles avec le niveau d'incertitude exigé pour l'étalonnage:

a) les étalonnages doivent être réalisés dans un environnement propre;
b) le contrôle et la commande de la température sont exigés;
c) toutes les sources laser doivent fonctionner en toute sécurité (conformément à l'IEC 60825-1 et à l'IEC 60825-2);
d) il convient d'examiner la sortie de la TLS avec un analyseur de spectre optique (OSA, Optical Spectrum Analyser) ayant une résolution suffisante pour résoudre la structure en mode longitudinal dans le but de vérifier le fonctionnement en unimodal.

La température recommandée est de 23 °C, par exemple (23 ± 2) °C. Laisser aux appareils d'étalonnage suffisamment de temps avant l'essai (un temps de 2 h est recommandé) pour atteindre l'équilibre dans leur environnement. Faire subir à la TLS un temps de mise en température conforme aux instructions du fabricant.

4.4 Conditions d'étalonnage de référence

Les conditions d'étalonnage de référence incluent généralement les paramètres suivants et, si nécessaire, leurs bandes de tolérance: date, température, humidité relative, pression atmosphérique, puissance optique affichée, longueur d'onde affichée, fibre, combinaison connecteur-raccord, largeur de bande (spectrale) et largeur de bande de résolution (résolution spectrale) définies. Sauf spécification contraire, utiliser une fibre amorce pour fibre optique unimodale de catégorie B1.1 ou B1.3 comme spécifié dans l'IEC 60793-2-50, ayant une longueur d'au moins 2 m. Il est souhaitable d'effectuer tout l'étalonnage dans une situation où les rétroréflexions sont négligeables. Ainsi, il convient d'utiliser des isolateurs et des connecteurs à angles chaque fois que la situation le permet.

Utiliser la TLS conformément aux spécifications et aux modes opératoires du fabricant. Lorsque cela est possible, sélectionner un ensemble de conditions et de paramètres d'étalonnage de manière à simuler les conditions de fonctionnement réelles de la TLS à étalonner. Sélectionner ces paramètres afin d'optimiser la précision de la TLS, comme indiqué dans les modes opératoires du fabricant.

Documenter les conditions comme spécifié à l'Article 7.

NOTE Les résultats d'étalonnage ne sont valables que pour l'ensemble des conditions d'étalonnage utilisées dans le processus d'étalonnage.

5 Étalonnage de la longueur d'onde

5.1 Présentation

Les facteurs à l'origine de l'incertitude sur la longueur d'onde de la source de rayonnement lumineux à étalonner sont les suivants:

a) l'incertitude intrinsèque de la source de rayonnement lumineux à étalonner dans les conditions de référence, qui inclut les dépendances à la température et à la durée pour ces conditions strictes;
b) les incertitudes dues aux dépendances à la puissance optique, la température et la durée telles que dans les étalonnages dans des conditions de fonctionnement élargies.

La liste de la source d'incertitude est résumée dans le Tableau 1.

Tableau 1 – Source d'incertitude pour l'étalonnage de la longueur d'onde

Source d'incertitude	Type d'origine	Symbole
Répétabilité	Mesure	s_{λ_j}
Température	Environnement	$u_{\lambda_j,\Delta\Theta}$
Stabilité	Source de rayonnement lumineux à étalonner	$u_{\lambda_j,\Delta t}$
Résolution de longueur d'onde	Appareil de mesure de la longueur d'onde de référence	$u_{\lambda_j,\mathrm{res}}$
Étalonnage de l'appareil de mesure de la longueur d'onde	Appareil de mesure de la longueur d'onde de référence	$u_{\mathrm{WM}_{\lambda_j}}$
Puissance optique	Source de rayonnement lumineux à étalonner	$u_{\lambda_j,P}$

L'étalonnage de la longueur d'onde dans les conditions de référence, pour des longueurs d'onde discrètes, décrit en 5.2, est obligatoire. L'étalonnage dans les conditions de fonctionnement, décrit en 5.3, est facultatif.

5.2 Étalonnage de la longueur d'onde dans des conditions de référence

5.2.1 Montage

La Figure 1 représente un système d'étalonnage de la longueur d'onde. L'étalonnage est réalisé dans les conditions de référence données.

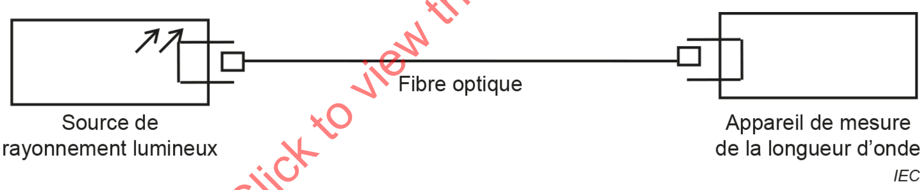

Figure 1 – Montage de mesure de l'étalonnage de la longueur d'onde

5.2.2 Équipement d'étalonnage

Un appareil de mesure de la longueur d'onde doit être utilisé pour l'étalonnage. L'appareil de mesure de la longueur d'onde doit être étalonné selon l'IEC 62129-2.

5.2.3 Procédure d'étalonnage de la longueur d'onde

La procédure d'étalonnage est la suivante:

a) en utilisant le système d'étalonnage représenté sur la Figure 1, la longueur d'onde définie de la source de rayonnement lumineux est donnée par $\lambda_{\mathrm{TLS}\ j}$, et les valeurs mesurées sont données par $\lambda_{\mathrm{meas}\ i,j}$. L'incertitude de la mesure de la longueur d'onde tient compte de la répétabilité de l'ajustage et de l'hystérésis de la TLS. L'hystérésis est définie comme l'écart résultant de l'ajustage de la longueur d'onde souhaitée à partir à la fois de la longueur d'onde plus petite et de la longueur d'onde plus grande;

b) il est recommandé de répéter la mesure de la longueur d'onde dix ((m)) fois. S'assurer que la TLS est accordée sur $\lambda_{\mathrm{TLS}\ j}$ avant chaque mesure. Il convient que la longueur d'onde cible (j) soit approchée d'une manière telle que l'accord se fait à la fois depuis la longueur d'onde plus petite et depuis la longueur d'onde plus grande;

c) calculer la longueur d'onde mesurée moyenne $\bar{\lambda}_{\text{meas } j}$:

$$\bar{\lambda}_{\text{meas}, j} = \frac{1}{m}\sum_{i=1}^{m}\lambda_{\text{meas} i,j} \tag{1}$$

où

m est le nombre de mesures réalisées

il est pris pour hypothèse que chaque $\lambda_{\text{meas } i,j}$ est une valeur moyenne de l'appareil de mesure de la longueur d'onde;

d) calculer l'écart en longueur d'onde D_{λ_j} :

$$D_{\lambda_j} = \lambda_{\text{TLS } j} - \bar{\lambda}_{\text{meas } j} \tag{2}$$

où $\lambda_{\text{TLS } j}$ est la longueur d'onde accordée de la TLS;

e) calculer l'écart-type pour λ_j à partir des (m) résultats de mesure de la longueur d'onde $\lambda_{\text{meas } i,j}$:

$$s_{\lambda_j} = \left[\frac{1}{m-1}\sum_{i=1}^{m}\left(\lambda_{\text{meas } i,j} - \bar{\lambda}_{\text{meas } j}\right)^2\right]^{\frac{1}{2}} \tag{3}$$

f) calculer la répétabilité de l'accord de la longueur d'onde S_{rep,λ_j} :

$$S_{\text{rep},\lambda_j} = 2 \times s_{\lambda_j} \tag{4}$$

NOTE Un niveau de confiance par défaut de 95 % est utilisé dans la Formule (4).

Cette procédure d'étalonnage doit être réalisée pour chaque longueur d'onde d'étalonnage. Un minimum de 10 longueurs d'onde discrètes, ou tous les 10 nm, y compris la première longueur d'onde, la longueur d'onde centrale et la dernière longueur d'onde de la plage doivent être mesurées.

5.2.4 Dépendance par rapport aux conditions

5.2.4.1 Dépendance par rapport à la température (facultative, si connue)

5.2.4.1.1 Montage

La Figure 2 représente un système d'étalonnage concernant la dépendance par rapport à la température. Cet étalonnage est réalisé dans les conditions d'étalonnage de référence à l'exception de la température.

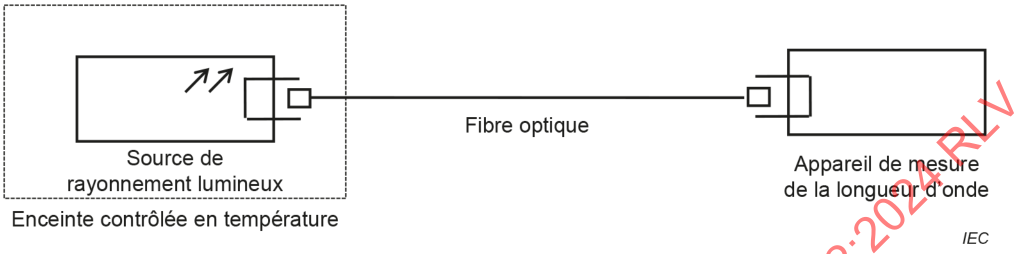

Figure 2 – Montage de mesure de la dépendance par rapport à la température

5.2.4.1.2 Équipement d'étalonnage

L'équipement d'étalonnage est le suivant:

a) un appareil de mesure de la longueur d'onde capable de détecter l'écart en longueur d'onde de la TLS en raison de la température;
b) enceinte contrôlée en température: s'assurer que les résultats de mesure ne sont pas affectés par la répartition de la température interne.

5.2.4.1.3 Procédure d'étalonnage concernant la détermination de la dépendance par rapport à la température

La procédure d'étalonnage est la suivante:

a) en utilisant le système d'étalonnage de la Figure 2, mesurer la longueur d'onde nominale (j) de la TLS à la puissance optique $P_{\mathrm{TLS}j}$ dans les conditions de référence: $\lambda_{j,\mathrm{ref}}$. Il convient que la longueur d'onde utilisée possède la réponse maximale aux variations de température. Sinon, il convient de caractériser plusieurs longueurs d'onde de sortie;
b) mesurer la longueur d'onde de la TLS à la température (i): λ_{j,Θ_i} Il convient de prendre la moyenne des longueurs d'onde lues correspondant à chaque réglage de température pour déterminer λ_{j,Θ_i} ;
c) calculer l'écart en longueur d'onde:

$$D_{\lambda_{j,\Theta_i}} = \lambda_{j,\Theta_i} - \lambda_{j,\mathrm{ref}} \quad (5)$$

d) répéter les étapes b) et c) avec (m) différents réglages de température Θ_i en s'assurant que l'appareil dispose du temps nécessaire pour s'affranchir suffisamment de tout gradient thermique;

e) calculer les écarts de longueur d'onde maximal $\max\left(D_{\lambda_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}$ et minimal $\min\left(D_{\lambda_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}$;

f) l'incertitude-type concernant la dépendance de la longueur d'onde par rapport à la température $u_{\lambda_{j,\Delta\Theta}}$, à la longueur d'onde d'étalonnage (j), en utilisant un modèle de distribution rectangulaire est:

$$u_{\lambda_{j,\Delta\Theta}} = \frac{1}{2\sqrt{3}}\left[\max\left(D_{\lambda_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m} - \min\left(D_{\lambda_{j,\Theta_i}}\right)\Big|_{i=1}^{i=m}\right] \tag{6}$$

où

$\Delta\Theta$ est la variation de température.

Il est recommandé de procéder à une acquisition de longueur d'onde avec l'appareil de mesure de la longueur d'onde optique pour la durée de cet étalonnage.

5.2.4.2 Stabilité de la longueur d'onde

5.2.4.2.1 Montage

La Figure 3 représente un système d'étalonnage de la stabilité de la longueur d'onde. Cet étalonnage est réalisé dans les conditions d'étalonnage de référence à l'exception du temps.

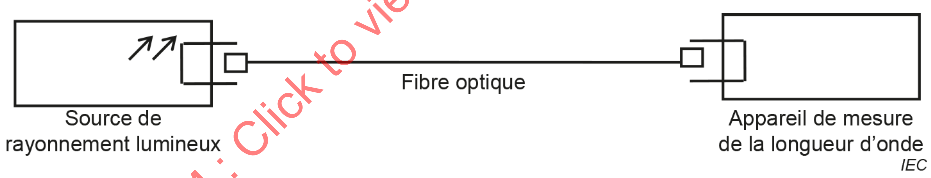

Figure 3 – Montage de mesure de la stabilité de la longueur d'onde

5.2.4.2.2 Équipement d'étalonnage

Il est recommandé d'utiliser un appareil de mesure de la longueur d'onde capable de détecter les fluctuations de longueur d'onde de la TLS.

5.2.4.2.3 Procédure d'étalonnage concernant la stabilité de la longueur d'onde

La procédure d'étalonnage est la suivante:

a) une période (Δt) assez longue, par exemple 10 min, doit être choisie pour permettre de procéder à au moins 10 mesures de la longueur d'onde avec l'appareil de mesure de la longueur d'onde de référence (dans le cas de l'exemple, la stabilité est mesurée sur 10 min);

b) il convient d'effectuer une acquisition continue de la longueur d'onde qui inclut les données de longueur d'onde et d'horodatage;

c) s'assurer de corréler les (m) mesures par période, avec (m > 10) et exactement conforme à la période souhaitée (Δt);

d) calculer l'écart-type pour les (m) mesures de la longueur d'onde correspondant à la période (Δt);

$$u_{\lambda_j,\Delta t}=\left[\frac{1}{m-1}\sum_{i=1}^{m}(\lambda_{j,t_i}-\frac{1}{m}\sum_{i=1}^{m}\lambda_{j,t_i})^2\right]^{\frac{1}{2}} \quad (7)$$

e) au minimum, 1 période est exigée pour évaluer la stabilité de la longueur d'onde de la TLS. Dans ce cas, l'incertitude sur la stabilité de la longueur d'onde devient:

$$S_{\text{stab},\lambda_j,\Delta t}=2\times u_{\lambda_j,\Delta t} \quad (8)$$

NOTE Un niveau de confiance par défaut de 95 % est utilisé dans la Formule (8).

Il convient de mesurer la longueur d'onde de la source de rayonnement lumineux plus de dix fois (m fois) consécutivement. Il est recommandé d'effectuer au moins quelques mesures par minute. Il convient que l'intervalle de temps entre les mesures répétées soit plus long que le temps de réponse de la source de rayonnement lumineux. Il est préférable de calculer plusieurs périodes à partir des données d'acquisition en utilisant une fenêtre glissante et la valeur maximale est consignée.

5.2.5 Incertitude dans les conditions de référence

L'incertitude sur la longueur d'onde d'étalonnage (j) dans les conditions de référence est donnée par:

$$u_{\lambda_j,\text{ref}}=\left(\frac{s_{\lambda_j}^{2}}{m}+u_{\lambda_j,\Delta\Theta}^{2}+u_{\lambda_j,\Delta t}^{2}+u_{\lambda_j,\text{res}}^{2}+u_{\text{WM}_{\lambda_j}}^{2}\right)^{\frac{1}{2}} \quad (9)$$

où

$u_{\lambda_j,\Delta\Theta}$ et $u_{\lambda_j,\Delta t}$ sont évalués pour les conditions de référence telles qu'elles sont définies en 5.2.4;

$u_{\lambda_j,\text{res}}$ est l'incertitude sur la résolution de la longueur d'onde définie par $u_{\lambda_j,\text{res}}=d\lambda_{\text{j}}/2\sqrt{3}$ ($d\lambda_j$ est la résolution de longueur d'onde de l'appareil de mesure de la longueur d'onde);

$u_{\text{WM}_{\lambda_j}}$ est l'incertitude de l'appareil de mesure de la longueur d'onde à la longueur d'onde (j) telle qu'elle est décrite dans sa certification;

l'incertitude élargie sur la longueur d'onde d'étalonnage (j) dans les conditions de référence, $U_{\lambda_{j,\text{ref}}}$, avec un facteur d'élargissement k est exprimée comme suit:

$$U_{\lambda_{j,\text{ref}}}=k u_{\lambda_{j,\text{ref}}} \quad (10)$$

où

k correspond à un niveau de confiance approprié comme cela est décrit à l'Article A.5.

Voir l'Annexe A et l'Annexe C pour plus d'informations sur les incertitudes.

Lorsque les réglages sont effectués sur l'appareil d'après les résultats d'étalonnage, il est recommandé de répéter les étalonnages après ces réglages pour vérifier les corrections.

5.3 Étalonnage de la longueur d'onde dans les conditions de fonctionnement

5.3.1 Généralités

Effectuer la procédure d'étalonnage quand la source de rayonnement lumineux est utilisée au-delà des conditions de référence.

Les différents facteurs de l'incertitude sur la longueur d'onde dans les conditions de fonctionnement sont les suivants:

a) dépendance par rapport à la puissance optique;
b) dépendance par rapport à la température;
c) stabilité de la longueur d'onde.

5.3.2 Dépendance par rapport à la puissance optique

5.3.2.1 Généralités

La Figure 4 représente un système d'étalonnage concernant la dépendance par rapport à la puissance optique. Il convient de procéder à cet étalonnage dans les conditions d'étalonnage de référence à l'exception de la puissance optique. Il doit être réalisé après l'étalonnage de la puissance optique (6.2.3).

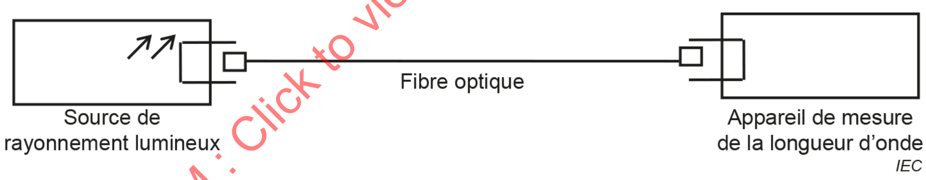

Figure 4 – Montage de mesure de la dépendance par rapport à la puissance optique

5.3.2.2 Équipement d'étalonnage

L'appareil de mesure de la longueur d'onde doit être étalonné selon l'IEC 62129-2.

5.3.2.3 Procédures d'étalonnage concernant la détermination de la dépendance par rapport à la puissance

Les procédures d'étalonnage sont les suivantes:

a) la longueur d'onde (j) est mesurée à m puissances optiques de la source de rayonnement lumineux, $P_{\text{TLS}\,i,j}$, y compris les limites supérieures et inférieures de la plage de puissances spécifiée. Il convient que l'intervalle entre ces niveaux voisins soit inférieur à 10 dB;
b) en utilisant le système d'étalonnage représenté sur la Figure 4, la longueur d'onde définie de la source de rayonnement lumineux est donnée par $\lambda_{\text{TLS}\,i,j}$, et les valeurs de l'appareil de mesure de la longueur d'onde sont données par $\lambda_{P_{i,j}}$;