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Calibration of tuneable laser sources

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National foreword

This British Standard is the UK implementation of EN 62522:2014. It is identical to IEC 62522:2014.

The UK participation in its preparation was entrusted to Technical Committee GEL/86, Fibre optics.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Calibration of tuneable laser sources (IEC 62522:2014)

Étalonnage des sources laser accordables
(CEI 62522:2014)

Kalibrierung von abstimmbaren Laserquellen
(IEC 62522:2014)

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
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Foreword

The text of document 86/443/CDV, future edition 1 of IEC 62522, prepared by IEC TC 86 "Fibre optics" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62522:2014.

The following dates are fixed:

– latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2014-10-18
– latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2017-03-21

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Endorsement notice

The text of the International Standard IEC 62522:2014 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60027-3	NOTE	Harmonised as EN 60027-3.
IEC 60359	NOTE	Harmonised as EN 60359.
IEC 60793-1 (Series)	NOTE	Harmonised in EN 60793-1 (Series)
IEC 60793-2 (Series)	NOTE	Harmonised in EN 60793-2 (Series)
IEC 61280-1-3:2010	NOTE	Harmonised as EN 61280-1-3:2010.
IEC 61300-3-2	NOTE	Harmonised as EN 61300-3-2
IEC 61315	NOTE	Harmonised as EN 61315

Annex ZA
(normative)
Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE 1 When an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu

Publication	Year	Title	EN/HD	Year
IEC 60793-2-50	-	Optical fibres -- Part 2-50: Product specifications - Sectional specification for class B single-mode fibres	EN 60793-2-50	-
IEC 60825-1	-	Safety of laser products -- Part 1: Equipment classification and requirements	EN 60825-1	-
IEC 60825-2	-	Safety of laser products -- Part 2: Safety of optical fibre communication systems (OFCS)	EN 60825-2	-
IEC 62129-2	-	Calibration of wavelength/optical frequency measurement instruments -- Part 2: Michelson interferometer single wavelength meters	EN 62129-2	-
ISO/IEC 17025	-	General requirements for the competence of testing and calibration laboratories	EN ISO/IEC 17025	-
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)	-	-

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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 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 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 International Standard 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, in whole or in part, are normatively referenced in this document and are indispensable for its application. 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 (OFCS)*

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 abbreviations

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

3.1 Terms and definitions

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

[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].

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 also determine other metrological properties such as the effects of influence quantities.

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

[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

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 P_0

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

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

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

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

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

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

Similarly, relative uncertainties, U_{lin}, or relative deviations, can be alternatively expressed in decibels:

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

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.

3.1.10
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

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

3.1.11
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.

3.1.12
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.

3.1.13
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.

3.1.14
wavelength

wavelength (in a vacuum) of a light source

3.1.15
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

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

3.2 Abbreviations

APC	Angled physical contact
DFB-LD	Distributed feedback laser diode
FWHM	Full-width/half-maximum
OSA	Optical spectrum analyser
SMSR	Side-mode suppression ration
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.

There shall 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.

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 (refer to IEC 60825-1 and IEC 60825-2);

d) the output of the tuneable laser source should be examined with an optical spectrum analyser (OSA) to check for single mode operation.

The recommended temperature is 23 °C (for example, 23 °C ± 2 °C). Give the calibration equipment a minimum of 2 h prior to testing to reach equilibrium within its environment. Allow the tuneable laser source a warm-up period in accordance to 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 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 tuneable laser source 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 tuneable laser source under calibration. Choose these parameters so as 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 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.

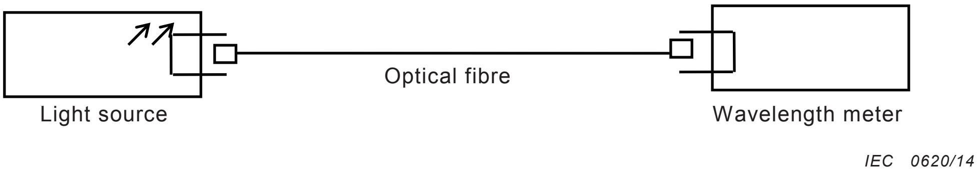


Figure 1 – Measurement set-up for wavelength calibration

5.2.2 Calibration equipment

A wavelength meter shall be used for the calibration. The wavelength meter should be calibrated using 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 $\lambda_{\mathrm{TLS}\ j}$ and the measured values are given by $\lambda_{meas\ i,j}$. The uncertainty of the wavelength measurement takes into account the tuning repeatability and hysteresis of the tuneable laser source (TLS). Hysteresis is defined as the deviation resulting from tuning the desired wavelength from both the shorter and the longer wavelengths.

b) Repeat the wavelength measurement $\lambda_{meas\ i,j}$ at least 10 times. Ensure that the TLS is tuned to $\lambda_{\mathrm{TLS}\ j}$ 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: $\overline{\lambda}_{meas\ j}$

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

where m is the number of measurements performed. Each $\lambda_{meas\ i,j}$ is suggested to be an averaged value from the wavelength meter. Calculate the wavelength deviation: D_{λ_j}

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

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

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

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

e) Calculate the wavelength tuning repeatability: $S_{\mathrm{rep},\lambda_j}$

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

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.

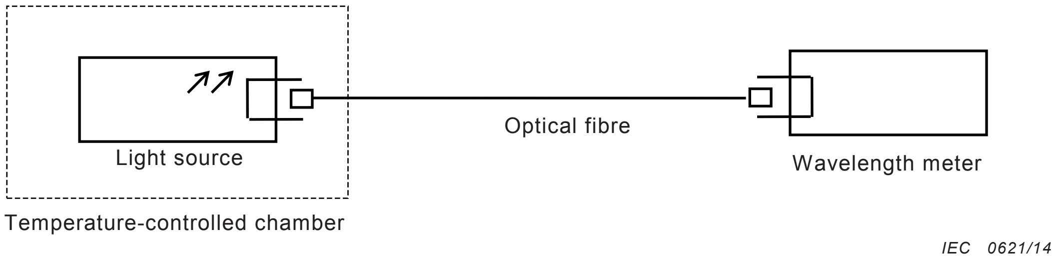


Figure 2 – Measurement set-up for temperature dependence

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.

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 $P_{\mathrm{TLS}j}$ at reference conditions: $\lambda_{j,\mathrm{ref}}$. 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:

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

d) Repeat steps 2 and 3 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.

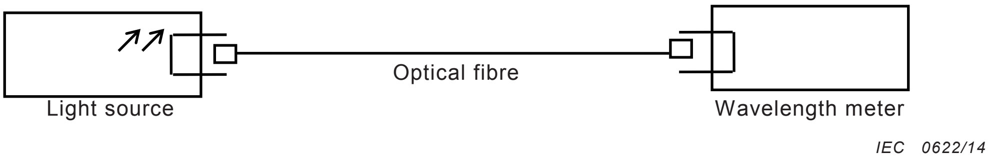


Figure 3 – Measurement set-up for wavelength stability

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.

b) A specific time period (Δt), for example 10 min, must 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).

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

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

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

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

f) 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

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

The wavelength of the light source should be measured more than 10 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

$$u_{\lambda_{j,ref}} = \left(\frac{s_{\lambda_j}{}^2}{m} + u_{\lambda_j,\Delta\Theta}{}^2 + u_{\lambda_j,\Delta t}{}^2 + u_{\lambda_j,res}{}^2 + u_{WM_{\lambda_j}}{}^2 \right)^{\frac{1}{2}} \quad (9)$$

where $u_{\lambda_j,\Delta\Theta}$ and $u_{\lambda_j,\Delta t}$ are evaluated for the reference conditions as defined in 5.2.4, $u_{\lambda_j,res}$ is the uncertainty of wavelength resolution defined by $u_{\lambda_j,res} = d\lambda_{\text{j}}/2\sqrt{3}$ ($d\lambda_{\text{j}}$ is wavelength resolution of the wavelength meter) and $u_{WM_{\lambda_j}}$ 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: $U_{\lambda_{j,ref}}$ with a coverage factor k is expressed as follows:

$$U_{\lambda_{j,ref}} = \pm k u_{\lambda_{j,ref}} \quad (10)$$

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.

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).

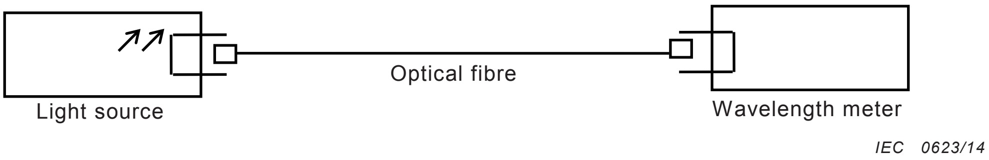


Figure 4 – Measurement set-up for optical power dependence

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.

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, $P_{TLS\ i,j}$ 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 $\lambda_{TLS\ i,j}$, 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 $P_{TLS\ i,j}$ 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

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

where $u_{\lambda_j,P}$, $u_{\lambda_j,\Delta\Theta}$ and $u_{\lambda_j,\Delta t}$ are evaluated for the operating conditions, $u_{\lambda_j,res}$ is the uncertainty of wavelength resolution defined by $u_{\lambda_j,res} = d\lambda_j / 2\sqrt{3}$ ($d\lambda_\mathrm{j}$ is wavelength resolution of the wavelength meter) and $u_{WM\lambda_j}$ 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:

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

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 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.

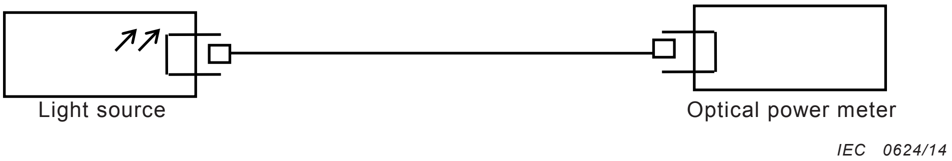


Figure 5 – Measurement set-up for intrinsic optical power calibration

NOTE 1 There may 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 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 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 uncertainty of the reference power meter is already known and is described in its certification.

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 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 tuneable laser source (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) Repeat this measurement at least ten 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.

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

where $P_{\mathrm{TLS}\,j}$ is the set optical power of the TLS. Each $P_{meas\;i,j}$ 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: $P_{meas\;i,j}$

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

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

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

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.

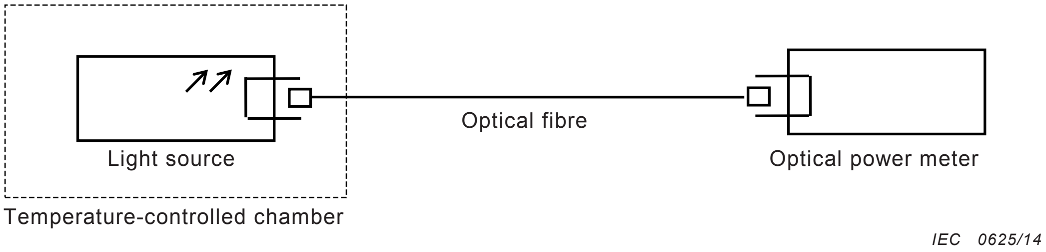


Figure 6 – Measurement set-up for temperature dependence

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.

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 $\lambda_{\mathrm{TL}S\,j}$ at reference conditions: $P_{j,ref}$. 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:

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

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

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

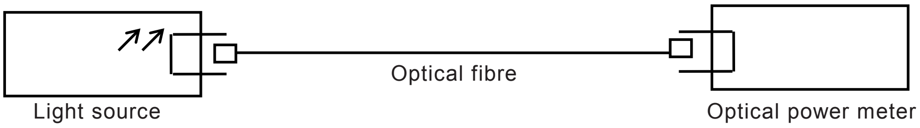
where $\Delta\Theta$ is the temperature variation.

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.



IEC 0626/14

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.

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.

b) 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).

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

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

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

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

f) 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

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

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 10 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.

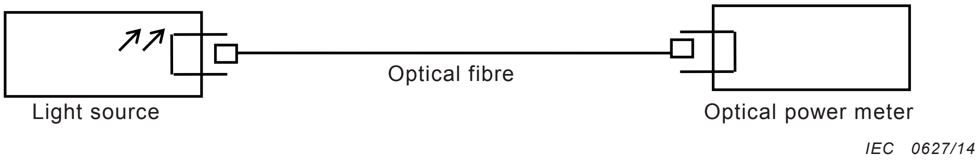


Figure 8 – Measurement set-up for connection repeatability/reproducibility

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.

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

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

6.2.5 Uncertainty at reference conditions

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

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

where $u_{D_{P_j,\Delta\Theta}}$ $u_{D_{P_j,\Delta t}}$ and $u_{D_{P_j,con}}$ are evaluated for the reference conditions as defined in 6.2.4, $u_{D_{P_j,res}}$ is the relative uncertainty of optical power resolution defined by $u_{D_{P_j,res}} = (dP_{TLS,j} / P_{TLS,j})/2\sqrt{3}$ ($dP_{TLS,j}$ is optical power resolution of the optical power meter) and $u_{PM_{P_j}}$ is the 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: $U_{D_{P_j,ref}}$ with a coverage factor k is expressed as follows:

$$U_{D_{P_{j,ref}}} = \pm k u_{D_{P_{j,ref}}} \tag{24}$$

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.

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 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 be performed after the wavelength calibration (5.2.3).

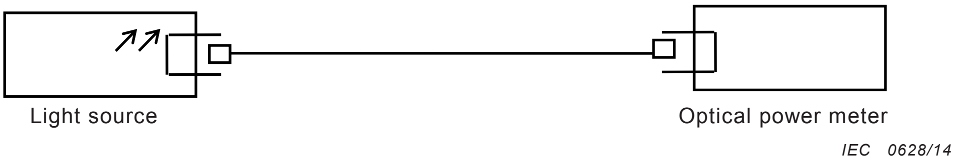


Figure 9 – Measurement set-up for wavelength dependence

6.3.2.2 Calibration equipment

The calibration equipment is as follows:

- 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, $\lambda_{TLS\ i,j}$ 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 $P_{TLS\,i,j}$, and the instrument reading of the power meter is given by $P_{\lambda_i,j}$.

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

d) 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

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

where $u_{D_{P_j,\lambda}}$, $u_{D_{P_j,\Delta\Theta}}$, $u_{D_{P_j,\Delta t}}$ and $u_{D_{P_j,con}}$ are evaluated for the operating conditions, $u_{D_{P_j,res}}$ is the relative uncertainty of optical power resolution defined by $u_{DP_{j},res} = (dP_{TLS,j} / P_{TLS,j})/2\sqrt{3}$ ($dP_{TLS,j}$ is optical power resolution of the optical power meter) and $u_{PM_{P_j}}$ 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: $U_{D_{P_j,op}}$ with a coverage factor k is expressed as follows:

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

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 standard 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:

a) the wavelength deviation, D_{λ_j}, and its uncertainty, $\pm k u_{\lambda_{j,ref}}$, 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, $\pm k u_{D_{P_{j,ref}}}$, for example, is in % or dB – see the detailed requirements in Clause 6.

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. The most important parameters are: the calibration date, displayed optical power, displayed wavelength, temperature, humidity, atmospheric pressure.

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

Annex A
(normative)

Mathematical basis

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.

This standard 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

$$\overline{X} = \frac{1}{n}\sum_{k=1}^{n} X_\mathrm{k} \qquad \text{(A.1)}$$

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

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

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

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

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, the estimated value is

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

and the standard uncertainty is

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

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, that is the partial derivative of the model function $y(x)$, evaluated at the input estimate x.

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

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 Equation (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 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:

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

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 this equation 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 Equation (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)

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

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

where $u^2\left[b(t)\right]$ 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

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

where $u^2\left[y(t)\right]$ 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

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

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).

$$D_{\lambda} = \frac{1}{n}\sum_{j=1}^{n} D_{\lambda_j} \tag{B.6}$$

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)):

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

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)).

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

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

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

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
(informative)

Other testing

C.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.

C.2 Wavelength resolution

C.2.1 Set-up

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

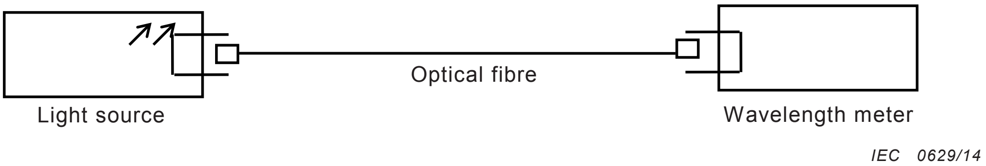


Figure C.1 – Measurement set-up for wavelength resolution

C.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.

C.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 λ_{meas+1} is measured with the wavelength meter.

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

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

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

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

$$d\lambda_{TLS} = \max(d\lambda_{TLS,j}) \tag{C.2}$$

C.3 Optical power resolution

C.3.1 Set-up

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

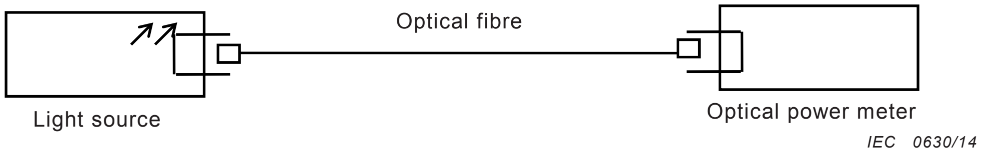


Figure C.2 – Measurement set-up for optical power resolution setting test

C.3.2 Testing equipment

Use an optical power meter with high resolution.

C.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_{meas+1} with optical power meter.

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

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

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

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

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

C.4 Signal to source spontaneous emission ratio

C.4.1 Set-up

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

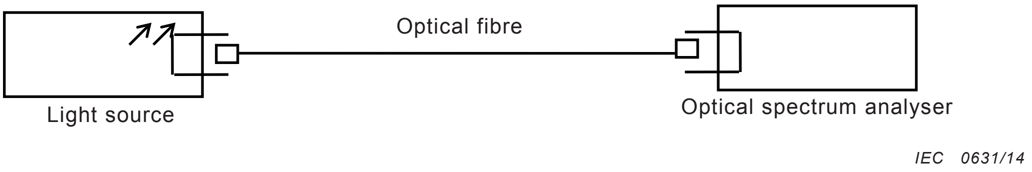


Figure C.3 – Measurement set-up for signal to total source spontaneous emission ratio

C.4.2 Testing equipment

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

C.4.3 Testing procedure for determining signal to source spontaneous emission ratio

The testing procedure is as follows:

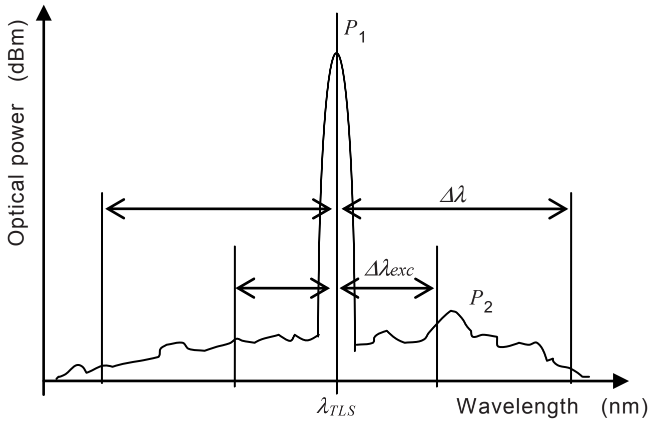
a) Set the wavelength of the test light source to λ_{TLS}. Set the optical output power to a suitable value. Usually, the optical power is set to the maximum optical output power defined by the specifications of the test light source.

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

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

d) Calculate the SSER (signal to source spontaneous emission ratio) with Equation (C.5).

$$SSER(dB/nm) = -10\log\frac{P_2 \times 1(nm)/\lambda_{res}}{P_1}(dB/nm) \tag{C.5}$$



IEC 0632/14

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

NOTE 1 For a TLS with a high SSER, the optical rejection ratio of the optical spectrum analyser 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.

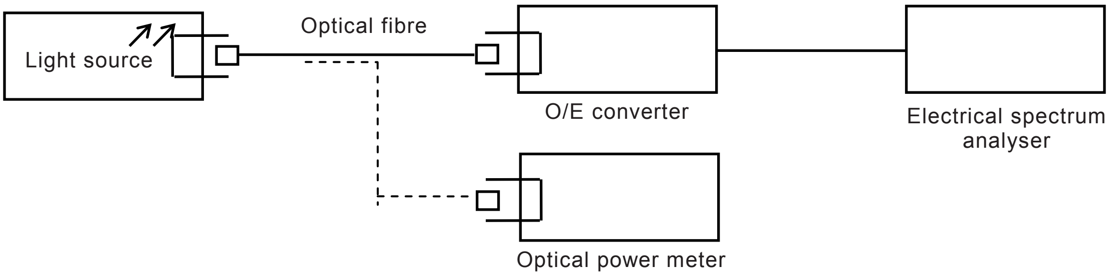
C.5 Side mode suppression ratio

C.5.1 General

In general, side mode suppression ratio of a laser source can be measured with an optical spectrum analyser as described in 8.8 of IEC 61280-1-3:2010. 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 cause difficulty to distinguish them with an optical spectrum analyser. This clause describes how to determine the side mode suppression ratio of such a narrow line width laser source.

C.5.2 Set-up

This needs a special testing system although it is performed by the tuneable laser source. For example, Figure C.5 shows the diagram of the test system of the side mode suppression ratio test under standard test conditions.



IEC 0633/14

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

C.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 optic-electric 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.

C.5.4 Testing procedure

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 $P_{beat,\max}$ (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 side mode suppression ratio SMSR in wavelength λ_{TLS} with Equation (C.6).

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

where

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

R is the conversion efficiency of O/E converter;

$$R_{dB} = 20\log\frac{R(A/W)}{1(A/W)} \tag{C.7}$$

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

The following explains the measurement principle and the Formula (C.6) for the side mode suppression ratio.

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 $\Delta\omega$ and the signal light (P_0) – see Figure C.6.

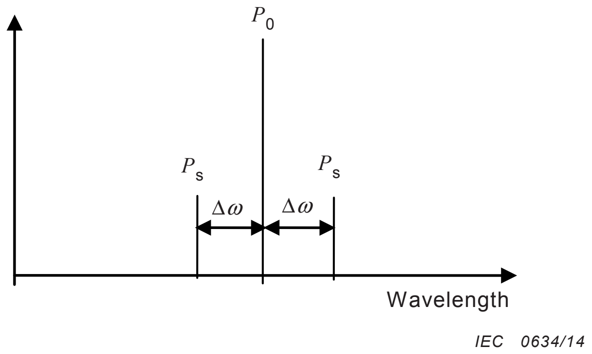


Figure C.6 – Optical spectrum of tuneable laser source

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

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

where

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

From Equation (C.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 Equations (C.9) and (C.10).

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

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

where

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

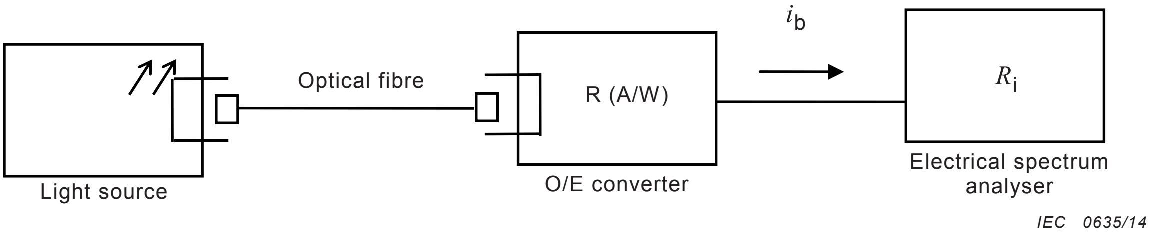


Figure C.7 – Measurement set-up for SMSR

The side mode suppression ratio SMSR, derived from Equation (C.10), is calculated with Equation (C.11):

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

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

$$SMSR_{dB} = 10\log\left(8R_i R^2 \frac{{P_0}^2}{P_b}\right)$$

$$= 2P_{0,dBm} - P_{b,dBm} + R_{dB} + 10\log(8R_i) - 30 \qquad \text{(C.12)}$$

where

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

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

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

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

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