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TECHNICAL SPECIFICATION

Calibration of wavelength/optical frequency measurement instruments –
Part 3: Optical frequency meters using optical frequency combs

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FOREWORD

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Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC/TS 62129-3, which is a technical specification, has been prepared by IEC technical committee 86: Fibre optics.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
86/461/DTS	86/465/RVC

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

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

A list of all parts in the IEC 62129 series, published under the general title *Calibration of wavelength/optical frequency measurement instruments*, can be found on the IEC website.

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

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

It is essential for realizing fibre optic systems that optical channels are defined in the optical frequency domain, not the wavelength domain. One example, the anchor frequency of the ITU-T grid is 193,1 THz, and the channel spacings of the ITU-T grid are 12,5 GHz, 25 GHz, 50 GHz, and 100 GHz [2][1].

ITU-T has also discussed λ-interface systems such as “black link” [3]. “Black link” includes WDM MUX/DEMUX and a transmission fibre, and provides λ-interfaces. Especially in DWDM systems (channel spacing <100 GHz), the uncertainty in specifying optical frequency needs to be minimized.

To implement future telecom systems, it is expected that optical frequency measurements will need to be extremely precise. For example, to achieve the channel spacing of 25 GHz, signal optical frequency uncertainty (Uf_{sig}) and required measurement uncertainty (Uf_{meas}) need to be 2 GHz to 200 MHz ($Uf_{\mathrm{sig}} / f = 10^{-5}$ to 10^{-6}) and 200 MHz to 2 MHz ($Uf_{\mathrm{meas}} / f = 10^{-6}$ to 10^{-8}), respectively. Unfortunately, conventional wavelength meters have measurement uncertainties of 10^{-6} to 10^{-7}. The solution is to use optical frequency measurements since measurement uncertainties can be as small as 10^{-15} to 10^{-16}, which satisfies the above telecom requirement ($Uf_{\mathrm{meas}} / f = 10^{-6}$ to 10^{-8}). Therefore, an optical frequency measurement scheme is necessary for the calibration of future telecom systems.

Optical frequency measurement technology is progressing rapidly. Many fundamental papers have examined the use of equally-spaced “optical frequency comb” lines (spacing of up to 50 GHz) from an optical frequency comb as a “ruler” for optical frequency measurement [4-15]. For example, mode-locked lasers with carrier-envelope phase locked enable ultra-low measurement uncertainties of 10^{-15} to 10^{-16}. Some examples of practical optical frequency combs are shown in Annex B (mode-locked fibre laser + carrier-envelope phase lock, stabilized laser + electro-optical modulator, and stabilized laser + supercontinuum source). Frequency measurements provide more accurate values than interferometric wavelength measurements in air by eliminating the effects of refractive indices. Furthermore, they allow the measurement devices to be significantly smaller than wavelength meters.

1 Numbers between square brackets refer to the Bibliography.

CALIBRATION OF WAVELENGTH/OPTICAL FREQUENCY MEASUREMENT INSTRUMENTS –

Part 3: Optical frequency meters using optical frequency combs

1 Scope

This part of IEC 62129, which is a technical specification, describes the calibration of optical frequency meters. It is applicable to instruments measuring the optical frequency emitted from sources that are typical for the fibre-optic communications industry. It is assumed that the optical radiation will be coupled to the optical frequency meter by a single-mode optical fibre.

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/TR 61931, *Fibre optic – Terminology*

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

ISO/IEC 17025:2005, *General requirements for the competence of testing and calibration laboratories*

3 Terms and definitions

For the purposes of this document, the terms and definitions contained in IEC/TR 61931, as well as the following terms and definitions, apply.

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

3.2
calibration
set of operations that establish, under specified conditions, the relationship between the values of quantities indicated by a measuring instrument and the corresponding values realized by measurement standards

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

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

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

[SOURCE: ISO/IEC Guide 99:2007, 2.39, modified] [16]

3.3
national (measurement) standard
measurement standard recognized by a national decision to serve, in a country, as the basis for assigning values to other measurement standards of the quantity concerned

[SOURCE: ISO/IEC Guide 99:2007, 5.3 modified]

3.4
national standards laboratory
laboratory which maintains the national measurement standard

3.5
reference standard
measurement standard, generally having the highest metrological quality available at a given location or in a given organization, from which measurements made there are derived

[SOURCE: ISO/IEC Guide 99:2007, 5.6 modified]

3.6
traceability
property of the result of a measurement or the value of a measurement standard whereby it can be related to stated references, usually national or international measurement standards, through an unbroken chain of comparisons all having stated uncertainties

[SOURCE: ISO/IEC Guide 99:2007, 2.41 modified]

3.7
traceability chain
unbroken chain of comparison

[SOURCE: ISO/IEC Guide 99:2007, 2.42 modified]

3.8
working standard
measurement standard that is used routinely to calibrate or check measuring instruments

Note 1 to entry: A working standard is usually calibrated against a reference standard.

[SOURCE: ISO/IEC Guide 99:2007, 5.7 modified]

4 Calibration test requirements

4.1 Preparation

The following recommendations apply.

The calibration laboratory should satisfy requirements of 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.

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

a) the environment shall be clean;
b) temperature monitoring and control is required;
c) all laser sources shall be safely operated (refer to IEC 60825-1).

Perform all tests at an ambient room temperature of 23 °C ± 3 °C with a relative humidity of (50 ± 20) % unless otherwise specified. Give the test equipment a minimum of 2 h prior to testing to reach equilibrium with its environment. Allow the optical frequency meter a warm-up period in accordance with the manufacturer’s instructions.

4.2 Reference test conditions

The reference test conditions usually include the following parameters and, if necessary, their tolerance bands: date, temperature, relative humidity, displayed power level, displayed optical frequency, fibre, connector-adapter combination, (spectral) bandwidth and resolution bandwidth (spectral resolution) set. Unless otherwise specified, use a single-mode optical fibre input pigtail as prescribed by IEC 60793-2-50, having a length of at least 2 m.

Operate the optical frequency meter in accordance with the manufacturer’s specifications and operating procedures. Where practical, select a range of test conditions and parameters which emulate the actual field operating conditions of the optical frequency meter under test. Choose these parameters so as to optimize the optical frequency meter’s uncertainties, as specified by the manufacturer’s operating procedures.

Because of the potential for hazardous radiation, be sure to establish and maintain conditions of laser safety. Refer to IEC 60825-1 and IEC 60825-2.

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

4.3 Traceability

4.3.1 General

The requirements of ISO/IEC 17025 should be met.

Make sure that any test equipment which has a significant influence on the calibration results is calibrated in an unbroken chain to the appropriate national standard or natural physical constant. Upon request, specify this test equipment and its calibration chain(s). The recalibration period(s) shall be defined and documented.

Figure 1 shows an example of a traceability chain using the frequency comb. It consists of a national standard, transfer standard, and working standard. The traceability chain can provide optical frequency standards suitable for the telecom region.

4.3.2 National standard

The national standard of optical frequency (or wavelength) can be realized by using the combination of UTC(k) (universal time, coordinated) and an optical frequency comb, for example, described in 5.1. The optical frequency comb generates an optical frequency comb with fixed, uniform spacing.

By using the optical frequency measurement technique shown in 5.1, uncertainty can be held to the standard frequency limited by the time base (up to 10^{-15}) throughout the whole span of the comb.

4.3.3 Transfer standard

A stabilized laser can be utilized as the transfer standard which is generally utilized between an accredited calibration laboratory and a calibration laboratory of company.

4.3.4 Working standard

The working standard is composed of a stabilized laser, and an optical frequency comb in each calibration laboratory. As the optical frequency comb, mode-locked lasers, electro-optical modulators or supercontinuum sources shown in Annex B can be used as they offer low uncertainty down to 10^{-9}.

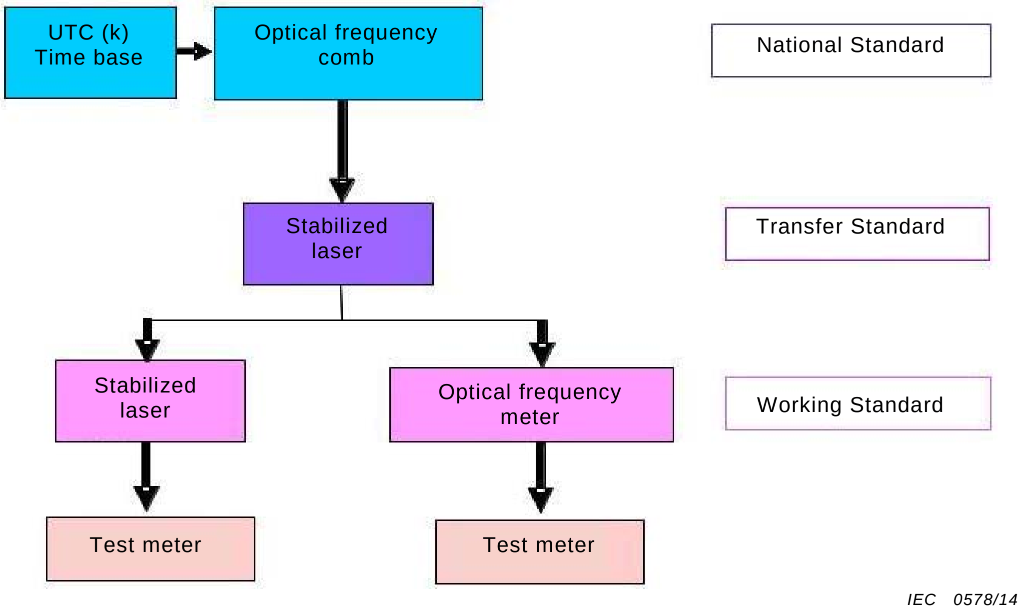


Figure 1 – Traceability chain using optical frequency measurement scheme

5 Optical frequency calibration

5.1 General

For optical frequency measurement, equally-spaced “frequency comb” lines (spacing of up to 50 GHz) from an optical frequency comb are utilized as a “ruler” for optical frequency measurement [4 – 15]. Optical frequency measurements provide more accurate calibration than interferometric wavelength measurements in air by eliminating the effects of refractive indices.

Some examples of practical optical frequency comb are shown in Clause 5.

Figure 2 is the schematic configuration of an optical frequency measurement technique that uses optical frequency combs. *f* (comb spacing) comb spacing

f (beat) beat frequency

f (*N*) optical frequency of

f (CEO) carrier envelope offset frequency

Figure 3 shows the optical spectrum of the laser and the optical frequency comb. The optical frequency comb generates an optical frequency comb with uniform spacing (*f* (comb spacing)) which is equal to the electrical clock frequency driving the optical frequency comb. *f*(comb spacing) is also equal to the pulse repetition rate. Thus, the uncertainty of comb spacing based on that of the electrical clock. The comb spacing generally lies between 100 MHz and 25 GHz. In this case, the stabilized laser (*f*(stabilized laser)) output is combined with the optical frequency comb, and then these two lights are input to an optical-electrical (O/E) converter. The beat frequency (*f* (beat)) between the two lights is taken as the output of the O/E converter. Optical frequency (*f*(stabilized laser)) of the stabilized laser can be calculated by the following equation (see *f* (comb spacing) comb spacing *f* (beat) beat frequency

f (*N*) optical frequency of

f (CEO) carrier envelope offset frequency

Figure 3):

$$f(\text{stabilized laser}) = f(N) \pm f(\text{beat}) \tag{1}$$

Here, $f(N)$ is the optical frequency of the N-th mode of optical frequency comb, and is the summation of f(comb spacing) and the carrier envelope offset frequency f(CEO), as shown in the following equation

$$f(N) = N \times f(\text{comb spacing}) + f(\text{CEO}) \tag{2}$$

Here, N is the large integer, and can be obtained by wavelength meter. The sign before the beat frequency (+ or –) can be deduced by changing f(stabilized laser) slightly. f(CEO) is related to the pulse-to-pulse phase shift, $\Delta\phi$, between the peak of electrical field and the peak of envelope [5].

$$f(\text{CEO}) = (\Delta\phi/2\pi)\, f(\text{comb spacing}) \tag{3}$$

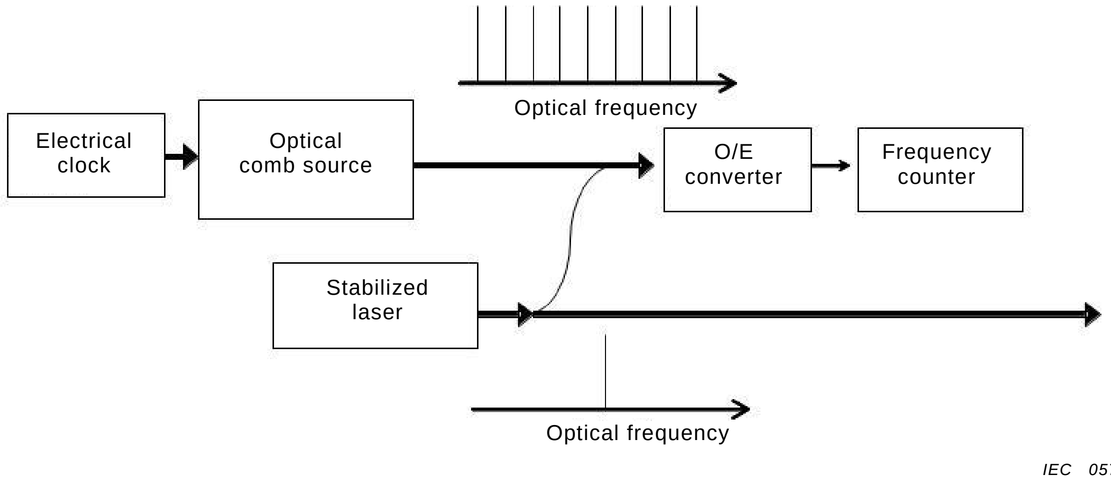
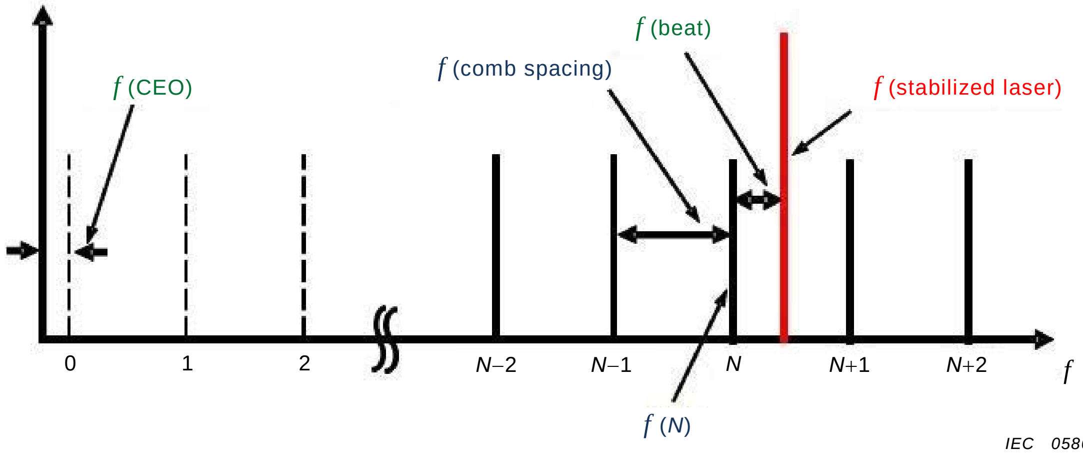


Figure 2 – Schematic configuration of optical frequency measurement technique that uses optical comb



Key

f optical frequency

f (stabilized laser) stabilized laser frequency

f (comb spacing)	comb spacing
f (beat)	beat frequency
f (*N*)	optical frequency of
f (CEO)	carrier envelope offset frequency

Figure 3 – Optical spectra of lasers and optical frequency combs

5.2 Establishing the calibration conditions

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

a) the date of calibration,

b) the ambient temperature, with uncertainty, for example 23 °C ± 3 °C. The temperature may need to be monitored continuously to ensure that it remains within the prescribed limits,

c) the ambient relative humidity, for example 30 % – 70 %. The ambient relative humidity may need to be monitored continuously to ensure that it remains within the prescribed limits. A relative humidity below the condensation point is assumed by default,

d) the input optical power (that has to fall within the allowable specification for the instruments),

e) details of the reference material or its identification number. Examples have been taken for a gas absorption cell:

   1) gas and isotope, e.g. $^{13}C_2H_2$,

   2) path length, e.g. 15 cm,

   3) pressure within the vessel, e.g. 1 000 Pa,

   4) transition, e.g. R(21),

f) if a transition locked source is used, then the quality of the lock shall be continuously monitored during the measurements; a lock indicator can be sufficient.

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

5.3 Calibration procedure

5.3.1 General

The main steps of the calibration procedure are as follows:

a) establish and record the appropriate measurement conditions (see 5.2). Switch on all instrumentation and wait for enough time to stabilize;

b) set up the reference source;

c) set up the instrument state of the test optical frequency meter according to the instruction manual. Select appropriate units;

d) record the instrument states of the optical frequency meter.

5.3.2 Measurement configuration

For calibration laboratories, a stabilized laser (a transfer standard in Figure 1) can be utilized as a reference source.

Figure 4 shows the configuration using the reference source. The temperature of the environment is monitored.

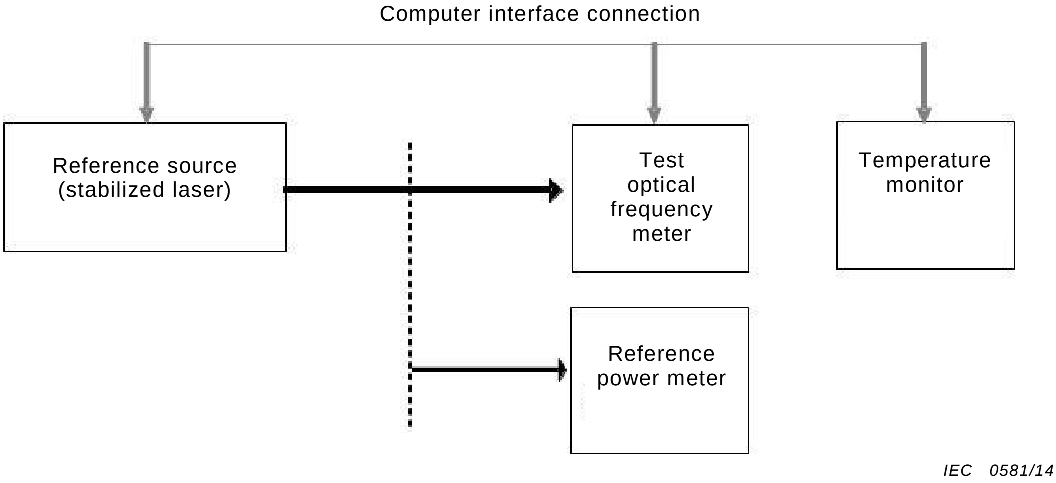


Figure 4 – Optical frequency meter measurement using a reference source

Figure 5 shows the configuration using a reference optical frequency meter as a working standard in Figure 1. The temperature of the environment is monitored.

It is necessary that the measurements are performed simultaneously on both the reference and the test optical frequency meters.

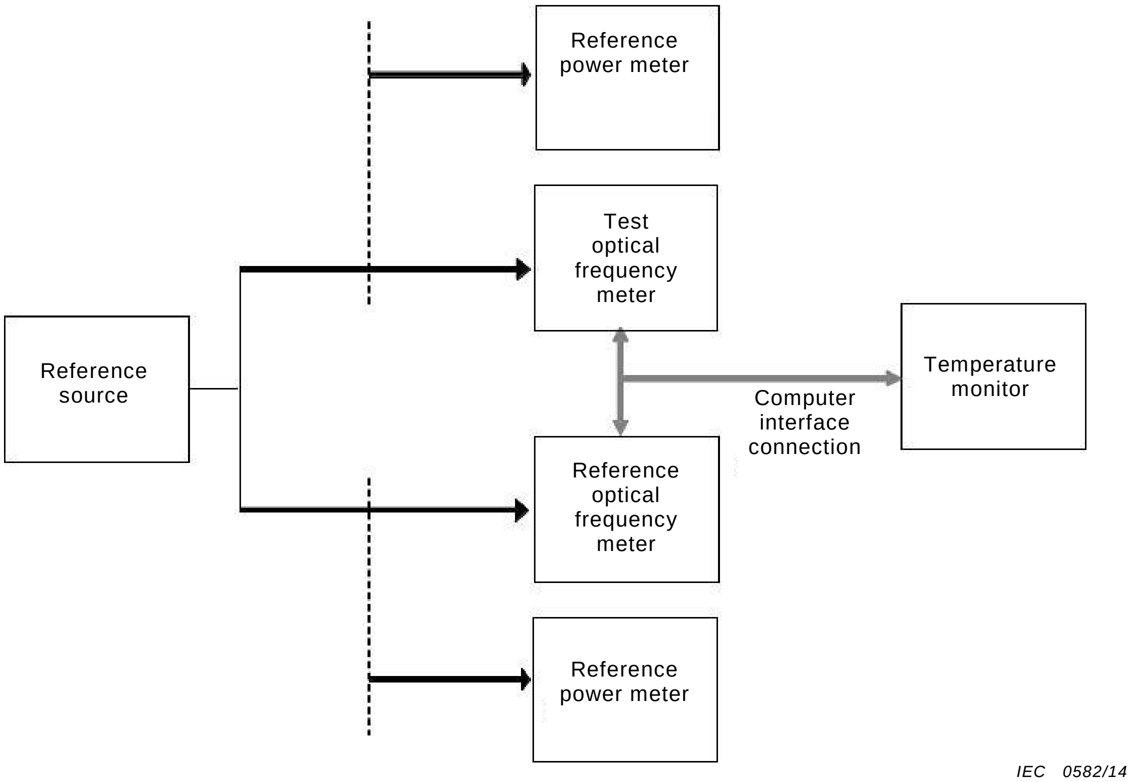


Figure 5 – Optical frequency meter measurement using a reference optical frequency meter

5.3.3 Detailed procedure

Typically, 50 samples (n) are taken per measurement.

The measurement process is as follows:

a) allow the equipment to reach equilibrium;

b) configure the data acquisition software;

c) ensure that the optical source is locked and is operating correctly;

d) run the data acquisition software.

The correction factor is determined from the difference between the reference optical frequency and the mean values from each measurement:

$$CF = fref - \frac{1}{n}\sum_{i=1}^{n} ftest_i \tag{4}$$

where $fref$ is the reference optical frequency and $ftest$ is the optical frequency measured by the test optical frequency meter.

5.4 Calibration uncertainty

Note that the following list may not be complete. Additional contributions may have to be taken into account, depending on the measurement setup and procedure. The mathematical basis, Annex A, should be used to calculate and state the uncertainty.

a) Source uncertainty (how well the source is stabilized to the natural standard).

b) Standard deviation of measurement samples.

5.5 Reporting the results

The results of each calibration should be reported as required by ISO/IEC 17025. Calibration certificates referring to this standard shall at least include the following information:

a) all calibration conditions of the calibration process as described in 5.2;

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

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

d) the calibration uncertainty in the form of an expanded uncertainty as described in 5.3 and Annex A;

e) the instrument state of the test meter during the calibration;

f) evidence that the measurements are traceable (see 5.10.4.1c) of ISO/IEC 17025:2005).

Annex A
(normative)

Mathematical basis

A.1 General

This annex summarizes the form of evaluating, combining and reporting the uncertainty of measurement. It is based on ISO/IEC 98-3, *Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995).* It does not replace the need to consult this guide for more advice.

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

A.2 Type A evaluation of uncertainty

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

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

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:

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

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, i.e. 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

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

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

Annex B
(informative)

References of optical frequency comb source

B.1 Method A (mode-locked fibre laser + carrier-envelope phase lock)

Figure B.1 shows an optical comb system combining a mode-locked laser and nonlinear optical effects [4 – 13]. The mode-locked laser is driven by an electrical clock (frequency: *f*(clock)). The optical pulse train from a mode-locked laser is input to a nonlinear material (fibre, etc.) and spectral broadening can exceed an octave. By comparing the optical frequencies of the octave-broadened comb with that of the second harmonic, one can stabilize and measure the frequency offset (*f*(CEO)). The frequencies *f*(CEO) and *f*(comb spacing) are locked to the electrical clock, thus yielding a very stable optical comb without the use of an external stabilized laser. The uncertainty of the optical comb is determined by that of the electrical clock so very small values can be expected. A titanium-doped sapphire (Ti:S) laser or a fibre laser can be used as the mode-locked laser. These optical frequency comb systems can be extended to any IR wavelength region (1 µm to 2 µm).

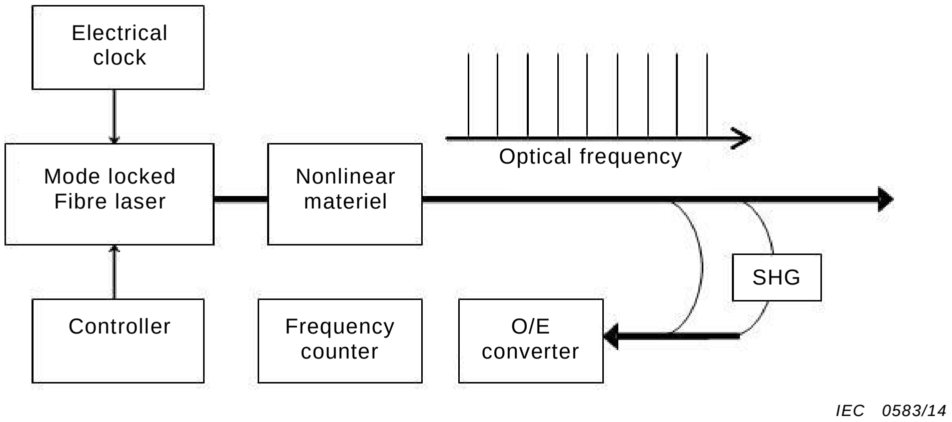


Figure B.1 – Mode-locked laser + nonlinear optical effect

B.2 Method B (stabilized laser + electro-optical modulator)

Figure B.2 shows an electro-optical modulator type comb source with a stabilized laser. The stabilized laser output is amplified and then input into the electro-optical modulator which is driven by an electrical clock. This method has been reported to offer 5 THz bandwidth optical comb generation with 6,25 GHz spacing [14].

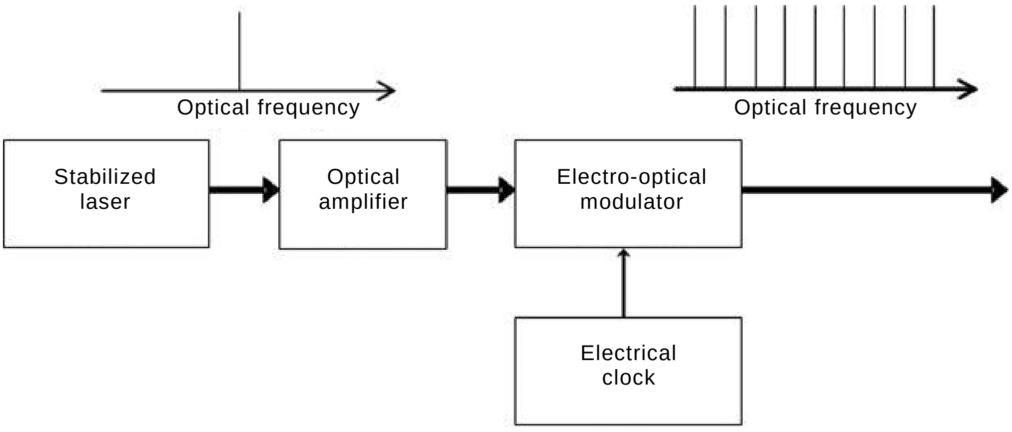


Figure B.2 – Electro-optical modulator type comb source

B.3 Method C (stabilized laser + supercontinuum source)

Figure B.3 shows a supercontinuum (SC) type comb source with a stabilized laser. The SC source consists of a pump pulse source, an optical amplifier and a nonlinear material (optical fibre etc.). The pump pulse source is driven by an electrical clock (frequency: *f*(clock)). The pump pulse source generates an optical pulse train with a repetition rate of *f*(clock). The pump pulse train is amplified and input to the nonlinear material for SC generation. SC is a spectral broadening phenomenon and is realized when nonlinear materials, such as optical fibres, are pumped by short optical pulses. It occurs due to the combined effects of self-phase modulation, cross-phase modulation, parametric, four-wave mixing and Raman scattering. A superbroadened bandwidth of more than 200 nm (25 THz) with the spacing range from several GHz to several 10 GHz at 1,5 μm has been reported. The comb spacing of supercontinuum light also equals the electrical clock frequency *f*(clock). The optical comb frequencies are determined by measuring the beat frequency between the optical comb and the stabilized laser, and the uncertainty of 1 MHz has been realized for 25 GHz spacing in the telecom bands [15].

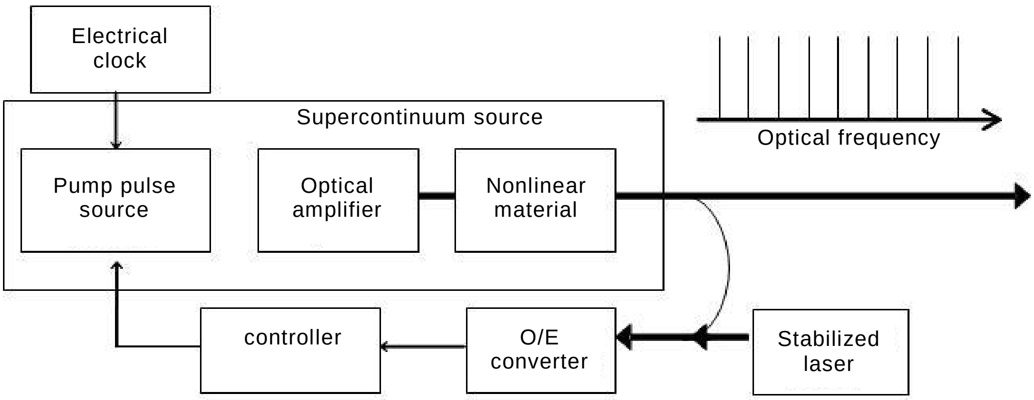


Figure B.3 – Supercontinuum source

Annex C
(informative)

Frequency-dependence of uncertainty

The uncertainty arising from electrical clocks in Clauses B.1 to B.3 will affect the mode spacing in a way that varies with comb mode number.

From Equation (1)

$$f(\text{tuneable laser}) = f(\text{stabilized laser}) + N \times f(\text{comb spacing}) \pm f(\text{beat})$$

Therefore the uncertainty in the comb spacing multiplies up by N, which varies depending on the frequency of the tuneable laser under test.

For example, when the uncertainty arising from electrical clocks is less than 10^{-8} and the measurement frequency range is 5 THz, the great uncertainty of less than 50 kHz can be realized at whole measurement frequency range. However, if the uncertainty of electrical clocks degrades to 10^{-6}, the measurement uncertainty in the frequency of 25 GHz away from the stabilized laser will be 25 kHz, whereas at a 5 THz separation it will be 5 MHz. In this case, due to the frequency-dependence, the measurement uncertainty at some frequency range may not satisfy the required uncertainty (200 MHz to 2 MHz) for telecom systems.

When the uncertainty of electrical clocks is not clear, it is recommended to test the device with a minimum of two reference frequencies, one close to the frequency of the stabilized laser and the second reference at a widely separated frequency. From these results, frequency-dependence of uncertainty can be calculated.

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