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

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CONTENTS

FOREWORD 3
INTRODUCTION 5
1 Scope 6
2 Normative references 6
3 Terms and definitions 6
4 Calibration test requirements 7
4.1 Preparation 7
4.2 Reference test conditions 8
4.3 Traceability 8
4.3.1 General 8
4.3.2 National standard 8
4.3.3 Transfer standard 9
4.3.4 Working standard 9
5 Optical frequency calibration 9
5.1 General 9
5.2 Establishing the calibration conditions 11
5.3 Calibration procedure 11
5.3.1 General 11
5.3.2 Measurement configuration 11
5.3.3 Detailed procedure 13
5.4 Calibration uncertainty 13
5.5 Reporting the results 13
Annex A (normative) Mathematical basis 14
A.1 General 14
A.2 Type A evaluation of uncertainty 14
A.3 Type B evaluation of uncertainty 15
A.4 Determining the combined standard uncertainty 15
A.5 Reporting 16
Annex B (informative) References of optical frequency comb source 17
B.1 Method A (mode-locked fibre laser + carrier-envelope phase lock) 17
B.2 Method B (stabilized laser + electro-optical modulator) 17
B.3 Method C (stabilized laser + supercontinuum source) 18
Annex C (informative) Frequency-dependence of uncertainty 19
Bibliography 20

Figure 1 – Traceability chain using optical frequency measurement scheme 9
Figure 2 – Schematic configuration of optical frequency measurement technique that uses optical comb 10
Figure 3 – Optical spectra of lasers and optical frequency combs 11
Figure 4 – Optical frequency meter measurement using a reference source 12
Figure 5 – Optical frequency meter measurement using a reference optical frequency meter 12
Figure B.1 – Mode-locked laser + nonlinear optical effect 17
Figure B.2 – Electro-optical modulator type comb source 18
Figure B.3 – Supercontinuum source 18

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CALIBRATION OF WAVELENGTH/OPTICAL FREQUENCY MEASUREMENT INSTRUMENTS –

Part 3: Optical frequency meters using optical frequency combs

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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 ($Uf_{sig} / f = 10^{-5}$ to 10^{-6}) and 200 MHz to 2 MHz ($Uf_{meas} / f = 10^{-6}$ 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 ($Uf_{meas} / f = 10^{-6}$ 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}.

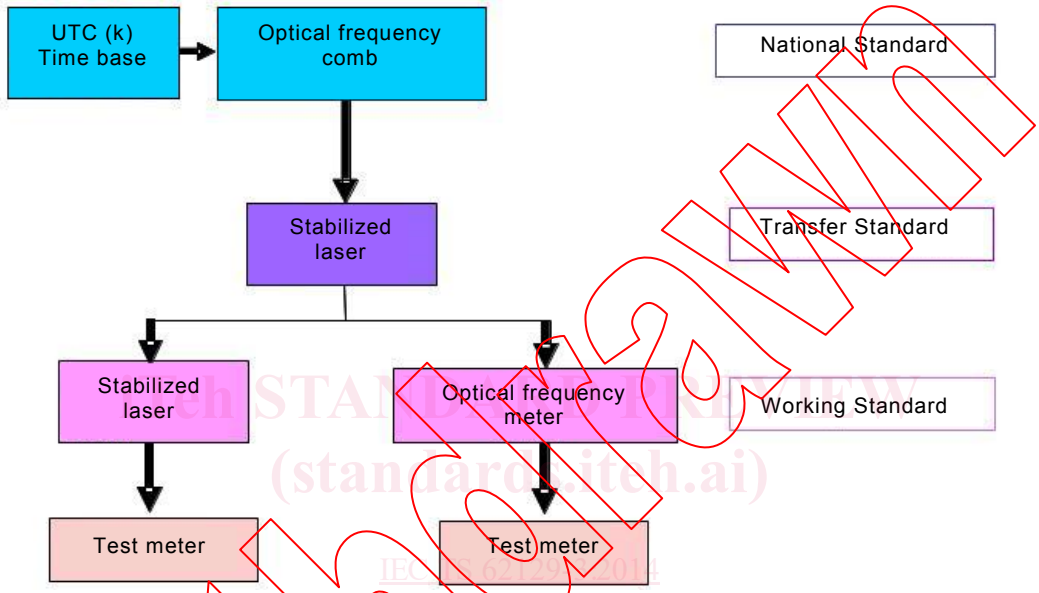

Figure 1 – Traceability chain using optical frequency measurement scheme

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