INTERNATIONAL STANDARD

ISO 13695

First edition
2004-06-01

Optics and photonics — Lasers and laser-related equipment — Test methods for the spectral characteristics of lasers

Optique et photonique — Lasers et équipement associé aux lasers — Méthodes d'essai des caractéristiques spectrales des lasers

Reference number
ISO 13695:2004(E)

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 13695 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 9, *Electro-optical systems*.

Introduction

The spectral characteristics of a laser, such as its peak wavelength or spectral linewidth, are important for potential applications. Examples are the specific application requirements of interferometry and lithography. This International Standard gives definitions of key parameters describing the spectral characteristics of a laser, and provides guidance on performing measurements to determine these parameters for common laser types.

The acceptable level of uncertainty in the measurement of wavelength will vary according to the intended application. Therefore, equipment selection and measurement and evaluation procedures are outlined for three accuracy classes. To standardize reporting of spectral characteristics measurement results, a report example is also included.

Optics and photonics — Lasers and laser-related equipment — Test methods for the spectral characteristics of lasers

1 Scope

This International Standard specifies methods by which the spectral characteristics such as wavelength, bandwidth, spectral distribution and wavelength stability of a laser beam can be measured. This International Standard is applicable to both continuous wave (cw) and pulsed laser beams. The dependence of the spectral characteristics of a laser on its operating conditions may also be important.

2 Normative references

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

ISO 11145, *Optics and optical instruments — Lasers and laser-related equipment — Vocabulary and symbols*

ISO 12005, *Lasers and laser-related equipment — Test methods for laser beam parameters — Polarization*

IEC 60747-5-1, *Discrete semiconductor devices and integrated circuits — Part 5-1: Optoelectronic devices — General*

Guide to the expression of uncertainty in measurement (GUM), BIPM 1), IEC, IFCC 2), ISO, IUPAC 3), IUPAP 4), OIML 5), 1993, corrected and reprinted in 1995

International vocabulary of basic and general terms in metrology (VIM). BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, Geneva, ISO

3 Terms and definitions

For the purposes of this document, the terms and definitions given in the VIM, ISO 11145 and IEC 60747-5-1, and the following apply.

3.1
wavelength in vacuum
λ_0
wavelength of an infinite, plane electromagnetic wave propagating in vacuum

NOTE For a wave of frequency f, the wavelength in vacuum is then given by $\lambda_0 = c/f$, where c = 299 792 458 m/s.

1) International Bureau of Weights and Measures (Bureau International des Poids et Measures).

2) International Federation of Clinical Chemistry and Laboratory Medicine.

3) International Union of Pure and Applied Chemistry.

4) International Union of Pure and Applied Physics.

5) International Organization of Legal Metrology (Organization International de Metrologie Legale).

3.2
wavelength in air
λ_{air}
wavelength of radiation propagating in the air and related to the wavelength in vacuum by the relationship:

$$\lambda_{air} = \lambda_0 / n_{air}$$

where n_{air} denotes the refractive index of ambient air (see 6.4)

NOTE The specific properties of the ambient atmosphere, such as humidity, pressure, temperature and composition all influence n_{air}. Therefore it is better to report the wavelength in vacuum, or the wavelength in standard air. These can be calculated from λ_{air} and n_{air} using the equation given in 6.4.

3.3
wavelength in dry air under standard conditions
λ_{std}
wavelength of radiation propagating in dry air (0 % humidity) under standard conditions and related to the wavelength in vacuum λ_0 by the relationship:

$$\lambda_{std} = \lambda_0 / n_{std}$$

where n_{std} denotes the refractive index of air under standard conditions (see 6.4).

NOTE For the purpose of this International Standard, air under standard conditions is as defined in 6.4. Note that various other “standard conditions” have been reported in the literature. It is therefore necessary to quote the conditions in the test report.

3.4
spectral radiant power [energy] distribution
$P_\lambda(\lambda)$, $[Q_\lambda(\lambda)]$
ratio of the radiant power d$P(\lambda)$ [or energy d$Q(\lambda)$ in the case of a pulsed laser] transferred by laser beam in the range of wavelength dλ to that range

$$P_\lambda(\lambda) = \frac{\mathrm{d}P(\lambda)}{\mathrm{d}\lambda} \qquad \left[Q_\lambda(\lambda) = \frac{\mathrm{d}Q(\lambda)}{\mathrm{d}\lambda} \right]$$

NOTE The radiant power (energy) delivered by the laser beam in any bandwidth λ_{low} to λ_{high} is then given by the integral:

$$P = \int_{\lambda_{low}}^{\lambda_{high}} P_\lambda(\lambda)\ \mathrm{d}\lambda \qquad \left[Q = \int_{\lambda_{low}}^{\lambda_{high}} Q_\lambda(\lambda)\ \mathrm{d}\lambda \right]$$

3.5
peak-emission wavelength
λ_p
wavelength at which the spectral radiant power (energy) distribution has its maximum value

See Figure 1.

3.6
weighted average wavelength (first moment)
λ_g
wavelength representing the centre of gravity of the spectral radiant power (energy) distribution, as defined by:

$$\lambda_g = \frac{\int_{\lambda_{min}}^{\lambda_{max}} \lambda \; S(\lambda) \; d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} S(\lambda) \; d\lambda}$$

where $S(\lambda)$ is the spectral radiant power $P_\lambda(\lambda)$ in the case of a cw laser, or the spectral radiant energy distribution $Q_\lambda(\lambda)$ in the case of a pulsed laser

See Figure 1.

NOTE For choosing of the integration limits λ_{min} and λ_{max}, see 6.2.2.

3.7
central wavelength
$\bar{\lambda}$
weighted average of the wavelengths of spectral lines or modes:

$$\bar{\lambda} = \frac{\sum_{i=i_{min}}^{i=i_{max}} I_i \lambda_i}{\sum_{i=i_{min}}^{i=i_{max}} I_i}$$

where

λ_i is the wavelength of the ith spectral line or the ith mode;

I_i is the relative radiant power of the ith spectral line or the ith mode;

i_{min}, i_{max} denote extreme spectral lines or modes below and above λ_p.

NOTE 1 Usually, the summation limits are chosen such that the relative radiant power of spectral lines or modes outside the limits remains less than 1 % of the relative radiant power of the strongest line or mode, located at λ_p.

NOTE 2 This definition is particularly useful in the case of a multi-mode laser.

3.8
average wavelength
λ_{av}
ratio of the light velocity c to the average optical emission frequency f_{av}

$$\lambda_{av} = c/f_{av}$$

NOTE The average optical emission frequency f_{av} can be measured directly, e.g. by the heterodyne measurement method (see 6.6.5).

3.9
RMS spectral radiation bandwidth (second moment)
$\Delta\lambda$
second moment of the spectral radiant power (energy) distribution, as defined by:

$$\Delta\lambda = \sqrt{\frac{\int_{\lambda_{\mathrm{min}}}^{\lambda_{\mathrm{max}}} (\lambda - \lambda_{\mathrm{g}})^2 \; S(\lambda) \; \mathrm{d}\lambda}{\int_{\lambda_{\mathrm{min}}}^{\lambda_{\mathrm{max}}} S(\lambda) \; \mathrm{d}\lambda}}$$

where $S(\lambda)$ is the spectral radiant power $P_\lambda(\lambda)$ in the case of a cw laser, or the spectral radiant energy distribution $Q_\lambda(\lambda)$ in the case of a pulsed laser.

See Figure 1.

NOTE For choosing of the integration limits λ_{min} and λ_{max} see 6.2.2.

3.10
RMS spectral bandwidth
$\Delta\lambda_{\mathrm{rms}}$
rms bandwidth is defined by:

$$\Delta\lambda_{\mathrm{rms}} = \sqrt{\frac{\sum_{i=i_{\mathrm{min}}}^{i=i_{\mathrm{max}}} I_i (\lambda_i - \bar{\lambda})^2}{\sum_{i=i_{\mathrm{min}}}^{i=i_{\mathrm{max}}} I_i}}$$

where

λ_i is the wavelength of the ith spectral line or the ith mode;

I_i is the relative radiant power of the ith spectral line or the ith mode;

$\bar{\lambda}$ is the central wavelength;

i_{min}, i_{max} denote extreme spectral lines or modes below and above λ_{p}

See Figure 1.

NOTE 1 Usually, the summation limits are chosen such that the relative radiant power of spectral lines outside the limits remains less than 1 % of the relative radiant power of the strongest line, located at λ_{p}.

NOTE 2 This definition is particularly useful in the case of a multi-mode laser.

3.11
spectral bandwidth
FWHM
$\Delta\lambda_H$
maximum difference between the wavelengths for which the spectral radiant power (energy) distribution is half of its peak value

See Figure 1.

NOTE Adapted from ISO 11145.

3.12
spectral linewidth
FWHM
$\Delta\lambda_L$
maximum difference between those wavelengths within $\delta\lambda$ for which the spectral radiant power (energy) distribution is half of its peak value found within $\delta\lambda$

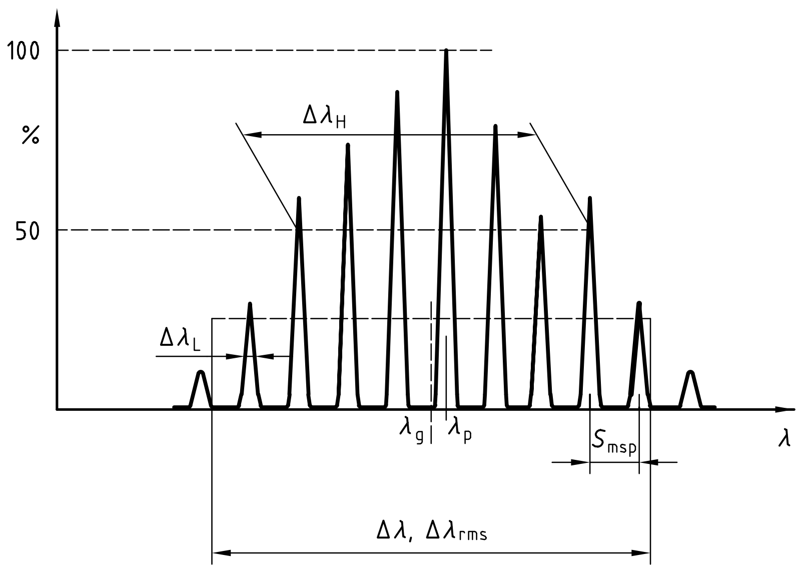
See Figure 1.

cf. **spectral bandwidth** (3.11), $\Delta\lambda_H$

NOTE A spectral linewidth is analogous to a **spectral bandwidth (3.11)**, but is defined for a single (longitudinal) mode or otherwise clearly distinguishable and labelled spectral feature contained within an interval $\delta\lambda$.

3.13
mode spacing
F_{msp} [S_{msp}]
separation of two neighbouring longitudinal modes expressed in frequency (F_{msp}) [wavelength (S_{msp})]

See Figure 1.



Key

λ wavelength

Figure 1 — Spectral characteristics of lasers — Illustration of defined parameters

3.14
number of longitudinal modes
N_m
number of longitudinal modes within a specified bandwidth, usually the rms spectral bandwidth $\Delta\lambda_{rms}$

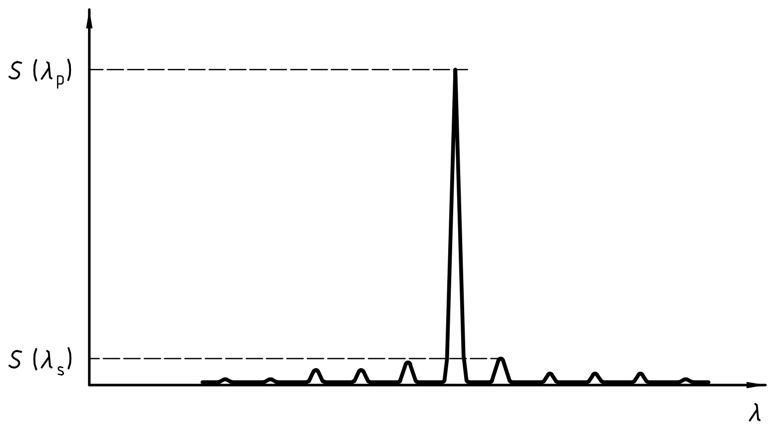
3.15
side-mode suppression ratio
SMS
ratio of the relative radiant power of the most intense mode, I_p, located at λ_p, to the relative radiant power of the second most intense mode, I_s, located at λ_s:

$$SMS = 10 \lg \left(\frac{I_p}{I_s} \right)$$

See Figure 2.

NOTE In practice the SMS can be assumed to be equal to the ratio of the peak values of the spectral distribution for the most intense and second most intense modes:

$$SMS = 10 \lg \left[\frac{S(\lambda_p)}{S(\lambda_s)} \right]$$



Key

λ wavelength

Figure 2 — Side-mode suppression ratio

3.16
pulse repetition rate
f_p
number of laser pulses per second of a repetitively pulsed laser

3.17
temperature dependence of wavelength
$\delta\lambda_T$
wavelength shift per change in temperature T of the laser:

$$\delta\lambda_T = \frac{d\lambda}{dT}$$

3.18
current dependence of wavelength
$\delta\lambda_c$
wavelength shift per change in laser current I

$$\delta\lambda_c = \frac{d\lambda}{dI}$$

3.19
Allan variance for a cw laser
$\sigma_y^2\,(2,\tau)$
two sample variance of frequency fluctuations for an averaging time of τ seconds and is defined by:

$$\sigma_y{}^2(2,\tau) = \left\langle \frac{\left[\bar{y}(k+1) - \bar{y}(k)\right]^2}{2} \right\rangle$$

where

$\langle\ \rangle$ denotes the average over an infinite set of data;

$\bar{y}(k)$ is the kth measurement of $\bar{y}$ in this set of data;

$\bar{y}$ is obtained by averaging $y(t)$ over a time interval τ

NOTE 1 For frequency measurements, the fractional deviation $y(t)$ is given by:

$$y(t) = [\nu(t) - \nu_0]/\nu_0$$

where

$\nu(t)$ is the instantaneous frequency;

ν_0 is the nominal frequency.

The measurement intervals all have the same duration τ and there is no dead time between subsequent measurement intervals. For times $\tau < 100$ s, the data set has to consist of at least 100 data. For larger times τ, the number of data may be reduced but shall be stated in the test report.

NOTE 2 $\bar{y}$ may be derived from heterodyne measurements where a frequency difference $\Delta\nu$ is integrated over an interval τ and normalized to the oscillation frequency ν_0.

NOTE 3 Since $y = \Delta\nu/\nu = -\Delta\lambda/\lambda$, $\sigma_y^2\,(2,\tau)$ is at the same time a measure of the frequency stability and of the wavelength stability.

NOTE 4 For further details see reference [1] in the Bibliography.

3.20
instrumental response function
$R(\lambda,\lambda_0)$
response, i.e. the output signal, of the instrument at the wavelength setting λ to a monochromatic input of wavelength λ_0

NOTE Usually, over the wavelength range of the instrument, $R(\lambda,\lambda_0)$ is nearly independent of the input wavelength λ_0, and the second argument is omitted. For a properly adjusted instrument, the first moment of the instrumental response function $R(\lambda,\lambda_0)$, as defined by:

$$\lambda_g = \frac{\int_{\lambda_{min}}^{\lambda_{max}} \lambda\ R(\lambda,\lambda_0)\ d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} R(\lambda,\lambda_0)\ d\lambda}$$

should be equal to the input wavelength: $\lambda_g = \lambda_0$.

3.21
instrumental effective spectral bandwidth
$\Delta\lambda_{ins}(\lambda_0)$
second moment of the instrumental response function $R(\lambda,\lambda_0)$, as defined by:

$$\Delta\lambda_{ins}(\lambda_0) = \sqrt{\frac{\int_{\lambda_{min}}^{\lambda_{max}} (\lambda-\lambda_g)^2 \ R(\lambda,\lambda_0) \ d\lambda}{\int_{\lambda_{min}}^{\lambda_{max}} R(\lambda,\lambda_0) \ d\lambda}}$$

NOTE If, as usually assumed, $R(\lambda,\lambda_0)$ and therefore $\Delta\lambda_{ins}(\lambda_0)$ are approximately independent of the input wavelength λ_0, the effective bandwidth $\Delta\lambda_{ins}$ is used without argument.

4 Symbols and abbreviated terms

Symbol	Unit	Term
F_{msp}	Hz	mode spacing in the frequency domain
f_p	Hz	pulse repetition rate
N_m		number of longitudinal modes
n_{air}		refractive index of ambient air
n_{std}		refractive index of dry air under standard conditions
P_λ	W/m	spectral radiant power distribution
Q_λ	W·s/m	spectral radiant energy distribution
$R(\lambda,\lambda_0)$	1/m	instrumental response function
S_{msp}	m	mode spacing in the wavelength domain
$S(\lambda)$		spectral radiant power $P_\lambda(\lambda)$ in the case of a cw laser or the spectral radiant energy distribution $Q_\lambda(\lambda)$ in the case of a pulsed laser
SMS	dB	side-mode suppression ratio
U_x		expanded standard uncertainty for measurand x
$\delta\lambda_T$	m/K	temperature dependence of wavelength
$\delta\lambda_c$	m/A	current dependence of wavelength
λ	m	wavelength
λ_0	m	wavelength in vacuum
λ_{air}	m	wavelength in air
λ_{av}	m	average wavelength
λ_g	m	weighted average wavelength (first moment)
λ_p	m	peak-emission wavelength
λ_{std}	m	wavelength in dry air under standard conditions
$\bar{\lambda}$	m	central wavelength
$\Delta\lambda$	m	rms spectral radiation bandwidth (second moment)
$\Delta\lambda_H$	m	spectral bandwidth (FWHM)
$\Delta\lambda_{ins}$	m	instrumental effective spectral bandwidth
$\Delta\lambda_L$	m	spectral linewidth (FWHM)
$\Delta\lambda_{meas}$	m	measured spectral radiation bandwidth (second moment)
$\Delta\lambda_{rms}$	m	rms spectral bandwidth
ν	Hz	frequency of the wave
ν_{FSR}	Hz	free spectral range (FSR) of the Fabry-Perot (FP) interferometer
$\sigma_Y{}^2(2,\tau)$		Allan variance characterizing the wavelength stability of a cw laser
τ_H	s	pulse duration

5 Traceability

All measurement results shall be traceable to the SI Units. For example, the wavelength shall be traceable to the meter by one of the methods recommended by the International Committee for Weights and Measures (CIPM).

NOTE For the meter, this is most commonly achieved by using a reference wavelength recommended by the CIPM, for details see reference [2] in the Bibliography.

6 Measurement of wavelength and bandwidth

6.1 General

6.1.1 Preparations

Depending on the spectral characteristics, the intended use of the laser and on the required level of uncertainty U_λ or U_ν (as defined in GUM) in the measurement of wavelength (or frequency) of the laser, $U_\lambda/\lambda = U_\nu/\nu$, different parameters need to be tested, see 6.2.

In the case of a laser with unknown characteristics, an operational test should be performed in order to select well-adapted instrumentation and the best choice of parameters to be measured.

It is assumed in this International Standard that the spectral characteristics of the laser beam are the same throughout the spatial power (energy) distribution in the beam. If this is not the case, spatially resolved measurements could be achieved by means of limiting apertures.

As a guideline, three testing levels are proposed, see 6.2.

6.1.2 Common laser types

The choice of parameters most suitable for characterizing the spectral characteristics of a laser depend on the type of laser. Common types of laser are:

a) broad-bandwidth lasers, for example pulsed lasers, or multi-mode lasers showing significant and fast mode fluctuations;

b) multi-mode lasers with a stable mode-structure over the time-scale of interest;

c) single frequency lasers.

For these three types of lasers, the use of the following parameters is recommended:

— for a broad-bandwidth laser:

  the weighted average wavelength (first moment) λ_g, rms spectral radiation bandwidth (second moment) $\Delta\lambda$ or spectral bandwidth (FWHM) $\Delta\lambda_H$; the dependence of the wavelength $\delta\lambda_T$ and/or $\delta\lambda_c$, on the operating parameters, temperature and/or injection current;

— for a multi-mode laser:

  the central wavelength $\bar{\lambda}$, the root mean square spectral bandwidth $\Delta\lambda_{rms}$, the mode spacing F_{msp} (frequency domain) or S_{msp} (wavelength domain), the number of longitudinal modes within a specified bandwidth N_m; the dependence of the wavelength, $\delta\lambda_T$ and/or $\delta\lambda_c$, on the operating parameters, temperature and/or injection current;

— for a single frequency laser:

the peak wavelength λ_p or average wavelength λ_{av} and the spectral linewidth $\Delta\lambda_L$ and side mode suppression SMS; the dependence of the wavelength, $\delta\lambda_T$ and/or $\delta\lambda_c$, on the operating parameters, temperature and/or injection current, the Allan variance $\sigma_y{}^2(2,\tau)$ as a measure of wavelength stability.

6.2 Types of measurements

6.2.1 General

The spectral characteristics of the lasers are assumed to be stable during the duration of the measurements, though this may need evaluation through subsequent stability and drift tests (see Clause 7).

6.2.2 Low accuracy measurements

These measurements are useful at a typical uncertainty of $U_\lambda/\lambda = U_\nu/\nu > 10^{-4}$. This applies to broad bandwidth lasers, e.g. pulsed lasers or multi-mode cw lasers or measurements involving an instrument of low resolution.

For these measurements, the individual modes need not be resolved and the weighted average wavelength, λ_g, and the rms radiation bandwidth, $\Delta\lambda$, should be determined. The wavelength stability should be assessed as a function of the operating parameters, i.e. $\delta\lambda_T$ and/or $\delta\lambda_c$ should be measured.

For the determination of the weighted average wavelength, the integration limits λ_{min} and λ_{max} are usually chosen such that outside of this interval the spectral distribution remains smaller than 1 % of its maximum value. In case other integration limits are used, these shall be reported in the test report.

There may be cases where the spectral distribution takes values not much smaller than 1 % of its maximum value over a very wide range of wavelengths, e.g. for a narrow peak superimposed on a broad background. In such a case, a considerable fraction of the total power may be found outside the integration limits. In addition, for very narrow distributions the instrumental resolution may affect the measured maximum value of $S(\lambda)$ at λ_p, which in turn affects the integration limits. Care should be taken to ensure that the calculated value of λ_g is not significantly influenced by this.

6.2.3 Medium accuracy measurements

These measurements are useful at a typical uncertainty $U_\lambda/\lambda = U_\nu/\nu$ in the order of 10^{-4} to 10^{-5}. This applies to narrow bandwidth pulsed lasers or cw multi-mode lasers.

For these measurements, the individual modes are usually resolved and the mode spacing F_{msp} (frequency domain) or S_{msp} (wavelength domain), the number of longitudinal modes within a specified bandwidth N_m and the side-mode suppression SMS can be assessed. The central wavelength $\bar{\lambda}$, the rms spectral bandwidth $\Delta\lambda_{rms}$ should be determined. The wavelength stability as a function of the operating parameters, i.e. $\delta\lambda_T$ and/or $\delta\lambda_c$, should be measured.

6.2.4 High accuracy measurements

These measurements are useful at a typical uncertainty of $U_\lambda/\lambda = U_\nu/\nu < 10^{-5}$. This applies to single mode lasers, or narrow bandwidth pulsed lasers.

For these measurements, possible side modes have to be identified and if applicable, the side-mode suppression SMS has to be determined.

The peak wavelength λ_p or average wavelength λ_{av} and the spectral linewidth $\Delta\lambda_L$, the dependence on operating conditions $\delta\lambda_T$ and/or $\delta\lambda_c$ should be determined and, as a measure of the wavelength stability, the Allan variance $\sigma_y^2\,(2,\tau)$ should be measured.

6.3 Equipment selection

The proper equipment shall be chosen according to the required accuracy and the type of the laser. As an example, a high resolution grating spectrometer may be capable of a practical resolving power $R = \lambda/\Delta\lambda_{ins}$ on the order of 10^5 to 10^6.

In the case of a pulsed laser, interferometers can only be used if the pulse duration, τ_H, is large compared to the inverse bandwidth of the instrument. For a Fabry-Perot interferometer with a free spectral range ν_{FSR} and a finesse F, the minimum pulse duration is F/ν_{FSR}. For a two-wave interferometer with maximum path difference L, the minimum pulse duration is L/c, where c is the speed of light.

The wavelength accuracy required may often be low. There may, however, be a requirement for high accuracy in the measurement of the amplitude of the spectral power distribution, for example to determine spectral flatness, ripple, etc. in the case of broad bandwidth sources.

Any optical component to be used to couple the laser beam to the measurement system (lenses, mirrors, optical fibres, etc.) should be either spectrally insensitive, or spectrally characterized, within the range of measurement. Their possible sensitivity to the state of polarization of the laser beam should be wavelength independent, or characterized by for instance, proper wavelength-dependent Mueller matrices (see ISO 12005). The polarization-dependent spectral response of the measurement system shall be taken into account. Devices such as grating monochromators are known to have a polarization-dependent transmission curve. The same can be true for detectors or for other components of the measurement system.

For narrow bandwidth laser beams the transmission can often be considered as flat, independent of the polarization state.

As many types of lasers are susceptible to optical feedback, any reflections of laser light back to the laser, e.g. from optical windows, filters or lenses should be avoided by, for example, tilting the elements or by the use of optical isolators.

6.4 Measurements in air

If λ_{air} is measured, the measurement results depend on environmental conditions such as temperature, atmospheric pressure and humidity, as these influence the refractive index of air. Also, the refractive index varies with the wavelength itself (dispersion). If a laser with known wavelength is used as a reference, the influence of the refractive index partially cancels, and only the smaller effect of dispersion (and its dependence on the environmental conditions) needs to be taken into account.

The calculation of the refractive index starts with the dispersion formula of dry air. Under standard conditions, at a temperature of 15 °C, a pressure of 101 325 Pa, a CO_2 volume fraction of 450×10^{-6} [450 ppm [6)]] and 0 % humidity, the refractive index of air may be calculated using an updated Edlén-Equation (see reference [3] in the Bibliography):

$$(n_{std} - 1) \times 10^8 = 8\,342{,}54 + \frac{2\,406\,147}{130 - (1\,000\,\text{nm}/\lambda)^2} + \frac{15\,998}{38{,}9 - (1\,000\,\text{nm}/\lambda)^2}$$

NOTE 1 The above formula is accurate to about one part in 10^7 for 300 nm $< \lambda <$ 1 700 nm. Within the visible range, significantly higher accuracy is achieved with this formula.

NOTE 2 n_{std}(633 nm) = 1,000 276 5, n_{std}(532 nm) = 1,000 278 2, n_{std}(1 530 nm) = 1,000 273 3.

— If the accepted level of uncertainty in the measurement of wavelength (or frequency) of the laser, $U_\lambda/\lambda_m = U_\nu / \nu_m$ is larger than 10^{-4}, the atmospheric conditions need not be taken into account explicitly.

6) The use of ppm is deprecated.

— If the accepted level of uncertainty in the measurement of wavelength (or frequency) of the $U_\lambda/\lambda_m = U_v / \nu_m$ is less than or equal to 10^{-4}, measurement results shall be corrected by the following formula (see reference [3] in the Bibliography):

$$(n_{air} - 1) = (n_{std} - 1) \times \frac{1{,}040\,632\,2 \times 10^{-5} p}{1 + 0{,}003\,661\,0 \times T} \times (1+\varepsilon) \times (1+x) - f \times \left[3{,}734\,5 - 0{,}040\,1 \times (1\,000\,\mathrm{nm}/\lambda)^2\right] \times 10^{-10}$$

where

n_{air} is the refractive index in air;

n_{std} is the refractive index in dry air under standard conditions, see above, at the measurement wavelength;

T is the temperature, in °C;

f is the partial pressure of water vapour, in Pa;

p is the total atmospheric pressure, in Pa;

and the correction terms are defined as follows:

$1 + \varepsilon$ is the higher order, p and T, correction term, and $1 + \varepsilon = 1 + 10^{-8} \times p \times (0{,}601 - 0{,}009\,72 \times T)$;

$1 + x$ is a term taking into account deviations of CO_2 volume fraction, φ_{CO_2}, from 450×10^{-6} [450 ppm], and $1 + x = 1 + 0{,}54 \times (\varphi_{CO_2} - 0{,}000\,45)$.

Both correction terms may be taken to be equal to 1, if the accepted level of uncertainty in the wavelength, U_λ/λ_m, is larger than 10^{-6}.

φ_{CO_2} is the CO_2 volume fraction, in air.

NOTE 3 The refractive index n_{air} is changed by approximately 1×10^{-7} by each of the following changes in the environmental conditions: temperature: $\Delta T = 0{,}1$ °C, pressure: $\Delta p = 30$ Pa (or 0,3 mbar), CO_2-content: $\Delta\varphi_{CO_2} = 600 \times 10^{-6}$ [600 ppm], humidity: $\Delta f = 250$ Pa.

NOTE 4 The above equations assume normal composition of the atmosphere. Enclosed apparatus may contain vapours of oils or solvents changing the refractive index by 1×10^{-7} or more. Particularly in the near infrared, the wings of infrared absorption lines of water vapour, CO_2 or other gases may need to be taken into account.

Further details may be found in Annex A.

If the accepted level of uncertainty in the measurement of wavelength (or frequency) of the laser, $U_\lambda/\lambda_m = U_v / \nu_m$, is smaller than 10^{-7}, wavelength measurements shall be performed in vacuum or by frequency measurements by heterodyne methods.

6.5 Measurements at low resolution

6.5.1 Principle

For unknown sources, a preliminary low-resolution measurement of the weighted average wavelength and spectral radiation bandwidth shall be done in order to determine the required instrumentation.

For this test a grating monochromator of moderate size (focal length of the order of 30 cm) is appropriate. A single instrument may be used for all kinds of laser devices, but the choice of some components and accessories shall be made according to the spectral domain of the laser radiation.

The aspects of the choice of the instrument and the accessories are given in the informative Annex B.

6.5.2 Measurement procedure

The laser beam to be measured, or a fraction of this beam extracted from an appropriate beamsplitter, shall be directed onto the input of the instrument e.g. the entrance slit of the monochromator. The aperture ratio of the instrument should be matched to the beam by means of an appropriate optical system. This usually requires focusing of the laser beam. It should be remembered that the instrument, e.g. the lips of the entrance slit, can be damaged if too high a power density is used, and attenuators can be used if necessary.

The value of the effective spectral bandwidth of the instrument, $\Delta\lambda_{\mathrm{ins}}$, shall be checked using, as a reference, the beam of a narrow-linewidth laser adjusted to form a beam following approximately the same geometry. For this test a narrow-linewidth laser can be any laser device known to provide a beam of spectral bandwidth and of wavelength drift fluctuation at least 10 times smaller than the required value for $\Delta\lambda_{\mathrm{ins}}$ (see 6.5.3). In many cases, a 633 nm free-running He-Ne laser will be adequate.

If the instrument is scanned over the wavelength range of interest, the step size should be adapted to the required resolution. The time constant of the recorder has to be much smaller than the time it takes to scan through the halfwidth of the line. For example, a factor of ten between both times still leads to a shift of a tenth of the linewidth.

The dynamic range of the detector shall be large enough so that intensity measurements cover at least 2 decades.

6.5.3 Analysis

The above procedure for measurements should allow the observation of the apparent spectral radiant power (energy) distribution $P_\lambda(\lambda)$, or $Q_\lambda(\lambda)$, respectively. If necessary, correct for the spectral sensitivity of the instrument, the detector and the optics.

a) Apply any corrections to the wavelength scale and calculate the first moment of the measured spectral radiant power (energy) distribution, i.e. the weighted average wavelength λ_{g} of the spectral radiant power (energy) distribution.

   For the determination of the weighted average wavelength, the integration limits λ_{min} and λ_{max} are usually chosen such that outside of this interval the spectral distribution remains smaller than 1 % of its maximum value. In case other integration limits are used, these shall be reported in the test report.

   There may be cases where the spectral distribution takes values not much smaller than 1 % of its maximum value over a very wide range of wavelengths, e.g. for a narrow peak superimposed on a broad background. In such a case, a considerable fraction of the total power may be found outside the integration limits. In addition, for very narrow distributions the instrumental resolution may affect the measured maximum value of $S(\lambda)$ at λ_{p}, which in turn affects the integration limits. Care should be taken to ensure that the calculated value of λ_{g} is not significantly influenced by this.

b) Calculate the second moment of the measured spectral radiant power (energy) distribution, $\Delta\lambda_{\mathrm{meas}}$ (see 3.9).

c) Record the results in the test report data sheet.

d) Compare the second moment, $\Delta\lambda_{\mathrm{meas}}$, to the instrumental bandwidth $\Delta\lambda_{\mathrm{ins}}$.

   — If the second moment is found larger than 10 times the instrumental bandwidth, no further measurement is needed and $\Delta\lambda = \Delta\lambda_{\mathrm{meas}}$.

   — If $\Delta\lambda_{\mathrm{meas}}$ is found between 2 and 10 times the instrumental bandwidth $\Delta\lambda_{\mathrm{ins}}$, specify in the test report the corrected spectral width, calculated as $\Delta\lambda = \sqrt{(\Delta\lambda_{\mathrm{meas}})^2 - (\Delta\lambda_{\mathrm{ins}})^2}$ or obtained by a deconvolution procedure.

— If the second moment is found smaller than 2 times the instrumental bandwidth, a higher resolving power instrument shall be selected to further determine the spectral characteristics of the laser beam.

6.6 Measurement at higher resolution

6.6.1 General

All the measurements for evaluation of the spectral characteristics of a laser with uncertainty $U_\lambda/\lambda = U_\nu/\nu < 10^{-5}$ should be performed in a mechanically and thermally stable environment.

6.6.2 Preliminary test

For unknown sources a preliminary low-resolution measurement of the weighted average wavelength, spectral radiation bandwidth shall be done in order to determine the required instrumentation.

The choice of the equipment necessary to further characterize the source depends on the following properties:

a) The expected oscillation modes.

b) The cw or pulsed character of the laser: in the latter case the pulse duration, τ_H, shall be considered.

c) The spectral characteristics to be measured: wavelength, or spectral radiant power (energy) distribution.

6.6.3 Measurement with a grating spectrometer

In this regime a high resolving power grating will be preferred in most cases, since it is adequate for the measurement of both the wavelength and the spectral bandwidths. If a grating spectrometer is used, the procedure is the same as in 6.5.2.

6.6.4 Measurement with an interferometer

A Fizeau interferometer (optical wedge), or preferentially a set of Fizeau interferometers, is a valuable tool to measure the wavelength with high accuracy. Appropriate combination of the wedge angles and of the base lengths of the several interferometers in a multi-stage arrangement allows the achievement of a relative accuracy of 10^{-8} in the measurement of a wavelength. The Fizeau interferometer can be used for both cw and pulsed laser beams.

If only the spectral radiant power (energy) distribution is to be determined, a scanning or solid Fabry-Perot (FP) interferometer can be used (see Annex C). There is, however, a limitation to the use of this kind of instrument in the case of pulsed lasers. The pulse duration, τ_H, has to be longer than the product of finesse F and cavity round-trip time t, which is given by:

$$t = 2nD/c$$

where

n is the refractive index of the optical medium;

D the distance between the two FP mirrors.

In the case of very short laser pulses, a grating spectrometer is more suitable.

A scanning Fabry-Perot interferometer will be preferred for the measurement of the spectral radiant power of a cw laser; a solid Fabry-Perot interferometer will be preferred for the measurement of the spectral energy distribution of a pulsed laser. In either case, the optical path length between the mirrors (nD) and/or the finesse F should be large enough so that the instrumental resolution $\Delta\lambda_{ins}$ of the interferometer is at least

10 times smaller than the bandwidth of the spectral distribution. The free spectral range, $\nu_{FSR} = c/2nD$, of the instrument should be bigger than the bandwidth of the spectral distribution by a factor of 10.

A scanning interferometer requires an input beam that is matched to the device, e.g. for a plane-mirror Fabry-Perot interferometer, a collimated beam has to be used. A focussing lens at the output images all rays that leave the interferometer to a detector. The intensity profile at the detector obtained by scanning the mirror spacing represents the spectral distribution of the laser. A linear frequency scale is determined by the repeated occurrence of the spectral distribution of every free spectral range. The instrument resolution depends on the reflectivity of the mirrors and the collimation of the input radiation.

A solid interferometer requires a collimated input beam if the mirrors are aligned with a slight wedge (Fizeau interferometer) or a diverging input beam if the mirrors are parallel (Fabry-Perot interferometer). Both types can be used for spectral analysis and wavelength measurement of cw or pulsed laser sources. The Fizeau interferometer produces a pattern of straight-line fringes; the Fabry-Perot interferometer produces circular fringes in the image plane. A CCD camera or linear CCD photodiode array (centered on the circular fringes) can be used to record the image. The spectral distribution of the source is determined by comparison with the fringe spacing or the free spectral range ($\nu_{FSR} = c/2nD$) of the interferometer. For the Fizeau fringes this relationship is linear but for the Fabry-Perot fringes there is a square root dependence of the circular fringe diameters. The choice of the mirror spacing and the size of the camera pixels shall be matched to the resolution required for the measurement.

With either a scanning interferometer or a solid interferometer, the wavelength of the source is determined by comparing the fringe spacing and the fringe positions of the input laser with that of a known reference laser.

A Michelson interferometer is an effective tool for the measurement of the peak emission wavelength, λ_p, mainly for cw lasers. Although the resolving power of a Michelson interferometer is inversely proportional to the moving distance of a movable mirror, the wavelength resolution can be improved by means of fringe dividing technology in the data treatment.

For wavelength measurements, both the collimated beam of the laser to be tested and the beam from a reference laser of known wavelength shall be aligned into the interferometer to allow the wavefronts travelling in the two arms of the instrument to interfere. The wavelength is measured using a fringe counting method whereby the fringes of the reference and test lasers are observed simultaneously while the movable mirror is scanned, and the wavelength of the laser under test, λ_t, is calculated using the following equation:

$$\lambda_t = \lambda_r \frac{N_r}{N_t}$$

where

λ_r is the wavelength of the reference laser;

N_r the number of fringes at the reference wavelength;

N_t is the number of fringes at the wavelength of the test laser.

The resolution of the measurement increases with the number of fringes that have been counted, i.e. with the displacement of the movable mirror.

In order to obtain the spectral distribution of a laser beam using a Michelson interferometer, it is necessary to record a full interferogram (transmitted intensity in the interference zone as a function of the mirror displacement), and to perform a Fourier transform. Caution is necessary in the choices of the baseline, the sampling frequency and the computer code. For a proper treatment refer to the documentation of the manufacturer.

The use of a Mach-Zehnder interferometer is analogous to the case of a Michelson interferometer.

With interferometers, special care should be taken to make sure that the measurement is not influenced by residual side-modes that overlap with the measured line because of the periodic transmission function of the instrument.

6.6.5 Measurement with photoelectric mixing methods

A self-delayed homodyne method is a useful tool for measurement of spectral bandwidths of lasers emitting in the wavelength range between visible and mid-infrared. For the measurement of $\Delta\lambda_L$ of a test laser, the laser beam is coupled into an optical fibre which is then divided into two lines in order to introduce a time delay between the optical paths. The two beams in their fibre lines are mixed with one another after their exit to produce a self-beat note. The spectral bandwidth is determined from the self-beat note with an RF-spectrum analyser. The resolving power of this method is inversely proportional to the optical fibre length for an optical delay line.

A heterodyne method is a powerful tool to determine the relevant quantities of the spectral characteristics of a cw or pulsed laser. Unlike the homodyne method, a second laser is needed here as a reference radiation source, and care needs to be exercised which of the two lasers has the dominant bandwidth, the resolving power and accuracy of the wavelength measurement being only dependent on the quality of the reference radiation source.

For the measurement of the spectral distribution in the optical frequency domain of a laser to be tested, a collimated beam of the test laser is mixed with a reference laser beam to produce a beat note. The spectral distribution in the optical frequency domain and the frequency difference are determined from the beat note profile with an RF-spectrum analyzer. The average beat frequency may also be determined by counting the beat note with an electronic counter. The wavelength in vacuum of the test laser converts from the beat note frequency in accordance with a following equation:

$$\lambda_{\mathrm{vac}} = \frac{c}{\nu_{\mathrm{r}} \pm \delta\nu}$$

where

c is the speed of light, $c = 299\,792\,458$ m/s;

ν_{r} is the oscillation frequency of the reference laser;

$\delta\nu$ is the frequency of the beat note.

6.6.6 Analysis for medium accuracy $U_\lambda/\lambda = U_\nu/\nu$ in the range 10^{-5} to 10^{-4}

The above procedure for measurements should allow the recovery of the apparent spectral radiant power (energy) distribution $P_\lambda(\lambda)$, or $Q_\lambda(\lambda)$, respectively.

a) Calculate the side-mode suppression ratio SMS as defined in 3.15.

b) Calculate the central wavelength $\bar{\lambda}$ and the rms spectral bandwidth $\Delta\lambda_{\mathrm{rms}}$ as defined in 3.7 and 3.10.

c) Determine the number of longitudinal modes, N_{m}, as defined in 3.14.

d) Determine the mode spacing, S_{msp}, as defined in 3.13.

e) Record the results in the test report data sheet.

f) Compare the measured spectral linewidth, $\Delta\lambda_{\mathrm{meas}}$, to the instrumental bandwidth, $\Delta\lambda_{\mathrm{ins}}$.

If a correction of the instrumental bandwidth is necessary, use the same procedure as 6.5.3 d).

6.6.7 Analysis for high accuracy $U_\lambda/\lambda = U_\nu/\nu < 10^{-5}$

The above procedure for measurements should allow the recovery of the apparent spectral radiant power (energy) distribution $P_\lambda(\lambda)$, or $Q_\lambda(\lambda)$, respectively.

a) Calculate the side-mode suppression ratio SMS as defined in 3.15,

— if the SMS is less than or equal to 20 dB, use the analysis for medium accuracy;

— if the SMS is larger than 20 dB, proceed with b).

b) Determine the peak-emission wavelength, λ_p, and the spectral linewidth, $\Delta\lambda_\mathrm{L}$, as defined in 3.5 and 3.12.

c) Record the results in the test report data sheet.

d) Compare the mode spectral bandwidth of the dominant mode to the instrumental effective spectral bandwidth, $\Delta\lambda_\mathrm{ins}$.

e) If a correction of the instrumental effective spectral bandwidth is necessary, use the same procedure as 6.5.3 d).

7 Measurement of wavelength stability

7.1 Dependence of the wavelength on operating conditions

The wavelength stability is an essential characteristic for many lasers in the whole wavelength range. Most lasers will exhibit some dependence of their emission wavelength on operating conditions, which should be characterized. An oscillation wavelength depends mainly on mechanical distortion or vibration, on the temperature and in the case of a diode laser on the injection current of the laser device. The temperature dependence is quoted as wavelength change per unit temperature, measured in a range where no mode jumps occur. In the case of diode lasers, the current dependence is quoted as wavelength change per unit injection current of the diode laser with otherwise unchanged measurement conditions. The measurement procedure is the same as described in 6.5 and 6.6 and the dependence of the measured wavelength (peak-emission wavelength λ_p, weighted average wavelength λ_g, central wavelength $\bar{\lambda}$ depending on the type of laser) on the operating parameters has to be determined.

Since the oscillation wavelength of a diode laser depends mainly on the temperature and the forward current of the laser device, for a diode laser a temperature and a current dependence have to be determined. For other laser devices usually only the temperature dependence needs to be determined.

7.2 Wavelength stability of a single frequency laser

Given nominally constant operating conditions, the wavelength or frequency stability over time of a laser may be of interest. For a single frequency laser, the (in)stability of the laser frequency may be described by the Allan variance. This two-sample variance has to be determined from a time series of the optical laser frequency (usually measured by the heterodyne methods) measured with an integration time, τ, i.e. the gate time of frequency counter with no dead time between successive measurements. From the time series a two-sample variance $\sigma_y^2(2,\tau)$ is determined for the evaluation of a single frequency laser. Integration times should be chosen according to the information required on medium- (1 ms to 100 ms) or long- (> 1 s) term stability.

The Allan variance $\sigma_y^2(2,\tau)$ is calculated as specified in 3.19.

8 Test report

The test report shall contain the following information.

a) General information:

1) reference to this International Standard (ISO 13695:2004);

2) date of test;

3) name and address of test organization;

4) name of individual performing the test.

b) Information concerning the tested laser:

1) laser type;

2) manufacturer;

3) manufacturer's model designation;

4) serial number.

c) Test conditions:

1) laser wavelength(s) at which tested;

2) temperature in kelvins (diode laser cooling fluid) (only applicable for diode lasers);

3) operating mode (cw or pulsed);

4) laser parameter settings:

— output power or energy;

— current or energy input;

— pulse energy;

— pulse duration;

— pulse repetition rate;

5) mode structure (if known);

6) state of polarization;

7) environmental conditions:

— room temperature;

— humidity;

— atmospheric pressure.

d) Information concerning testing:

1) measuring instrument:

— effective spectral bandwidth $\Delta\lambda_{ins}$;

— wavelength repeatability or calibration accuracy;

2) measuring time (number of pulses in the case of a pulsed laser).

e) Results and the most suitable parameters characterizing the tested laser type:

1) state whether wavelengths in vacuum λ_0, wavelengths in air λ_{air} or standard wavelengths (wavelength in dry air under standard conditions) λ_{std} are reported below.

2) unless a wavelength in vacuum was measured directly, characterize the environmental conditions to suitable accuracy, allowing the accurate determination of the refractive index during the measurement, and for λ_{std}, explicitly state the standard conditions used;

3) if available, include a graphical representation of the spectral density $P_\lambda(\lambda)$ or $Q_\lambda(\lambda)$;

4)	peak-emission wavelength	λ_p;
5)	central wavelength	$\bar{\lambda}$;
6)	weighted average wavelength	λ_g;
7)	spectral linewidth	$\Delta\lambda_L$;
8)	rms spectral bandwidth	$\Delta\lambda_{rms}$;
9)	spectral radiation bandwidth (second moment)	$\Delta\lambda$;
10)	side-mode suppression ratio	SMS;
11)	temperature dependence	$\delta\lambda_T$;
12)	current dependence (if applicable)	$\delta\lambda_c$;
13)	radiant power/energy of pulse (if applicable)	P, Q;
14)	Allan variance (two-sample variance)	$\sigma_y{}^2(2,\tau)$.

f) Remark(s) (optional).

Annex A
(informative)

Refractive index of air

A.1 Determination of partial pressure of water vapour

For the transformation of relative humidity and dew-point temperatures to water-vapour pressure, the equation for the saturation pressure of water, p_{sv}, expressed in pascals, may be used (see reference [4] in the Bibliography):

$$p_{sv} = F_p \times \exp(\mathrm{A}T^2 + \mathrm{B}T + \mathrm{C} + \mathrm{D}T^{-1})$$

where

F_p is the conversion factor signal to 1 Pa (F_p = 1 Pa);

A $= 1{,}237\ 884\ 7 \times 10^{-5}\ \mathrm{K}^{-2}$;

B $= -\ 1{,}912\ 131\ 6 \times 10^{-2}\ \mathrm{K}^{-1}$;

C $= 33{,}937\ 110\ 47$;

D $= -\ 6{,}343\ 164\ 5 \times 10^{3}\ \mathrm{K}$;

T is the absolute temperature in kelvins.

EXAMPLE For water vapour at 20 °C, a total atmospheric pressure, $p = 101\ 325$ Pa, and a relative humidity of 50 %, the partial pressure of water vapour is given by

$$f = p_{sv}(20\ °\mathrm{C}) \times 50\ \% = 1\ 169{,}25\ \mathrm{Pa}$$

A.2 High accuracy calculation of the refractive index over a wide range of wavelengths and atmospheric conditions

Where measurements are carried out routinely and/or a programmable computer is available, the equations developed by Ciddor [5] may be useful. They were developed to apply over the whole visible and near infrared wavelength range and a very wide range of atmospheric conditions, that is 0 % to 100 % relative humidity, sub-zero temperatures. Standard conditions defined are identical to those used here.

A.3 Alternative standard conditions

For historical reasons, the standard conditions were chosen as described in 6.4. However, most modern laboratories maintain temperatures of around 20 °C, and the reference temperature for length measurements of material standards is fixed at 20 °C. Defining new standard conditions, in particular a temperature of 20 °C, (see reference [4] in the Bibliography) alternative equations for the determination of the refractive index as a function of wavelength, temperature, pressure, humidity and CO_2 content have been derived. These equations are very accurate within the visible range and reduce the corrections that need to be applied when working with air near these standard conditions, for example in a laboratory with well-controlled atmosphere and temperature very close to 20 °C.

Annex B
(informative)

Criteria for the choice of a grating monochromator and its accessories — Calibration

B.1 Introduction

B.1.1 General

The capabilities of a grating monochromator are directly related to the diffraction characteristics and size of its grating, to the dimensions of the instrument relative to the size of the grating, and to the spectral range of interest.

The instruments equipped with gratings diffracting by reflection are considered here.

The grating formula is applicable:

$$\sin\alpha_1 + \sin \alpha_2 = k\,N\,\lambda$$

where

k is the diffraction order;

N is the number of grooves per unit length;

λ is the wavelength in the same length unit.

In most cases, the incidence angle α_1 is very close to the diffraction angle $\alpha_2 \approx \alpha_1 = \alpha$. Thus

$$2\sin\alpha = k\,N\,\lambda$$

B.1.2 Theoretical resolving power

The theoretical resolving power using the kth diffraction order is:

$$R_{\text{t}k} = k \quad L_{\text{e}}$$

where L_{e} is the effectively used size (orthogonal to the grooves).

B.1.3 Practical resolving power

The practical resolving power depends not only on the grating, but also on the mechanical and optical characteristics of the instrument, as well as on the spectral range. The degradation of the resolving power relative to the theoretical value is described globally by a quality factor, F_{q}:

$$F_{\text{q}} = F_{\text{q}1}\,F_{\text{q}2}$$

so that the practical resolving power is

$$R_{\text{p}k} = F_{\text{q}1}\,F_{\text{q}2}\,k\,RT_1$$

in the kth order.

The sensitivity to optical aberrations depends on the value of the aperture number of the monochromator, defined as L_f/L_e, if L_f is the focal length of the collimating optics. The corresponding typical values of the quality factor F_{q1} are:

$F_{q1} = 1$ if $L_f/L_e > 10$

$F_{q1} = 0{,}7$ if $4 < L_f/L_e < 10$

$F_{q1} = 0{,}5$ if $L_f/L_e < 4$

The sensitivity to the surface defects of the optical elements depends on the spectral range. The corresponding typical values of the quality factor F_{q2} are:

$F_{q2} = 0{,}9$ if $\lambda > 0{,}7$ µm

$F_{q2} = 0{,}5$ if $0{,}4$ µm $< \lambda < 0{,}7$ µm

$F_{q2} = 0{,}33$ if $\lambda < 0{,}4$ µm

The expression of the resolving power given above assumes that the width of the entrance slit and that of the exit slit (or the size of the detector pixel if a CCD array is used) can be made as small as the size imposed by the diffraction limit $(\lambda L_f)/(L_e \cos\alpha)$. It may be difficult to achieve this in the short wavelength region. Also the CCD array will sometimes be advantageously used after a magnifier optical system to increase the size of the monochromatic image. The practical effects of these considerations may be included in the quality factor F_{q2}.

B.1.4 Holographic grating monochromator

The luminous efficiency of holographic gratings is approximately constant (about 30 % to 50 %) in the unique diffraction order $k = 1$. Then the spectral range of a monochromator equipped with a holographic grating will be limited only by the mechanically allowed rotations of the mount, α_{min} and α_{max}. Correspondingly:

$$\lambda_{min} < \lambda < \lambda_{max}$$

where

$N \lambda_{min} = 2 \sin\alpha_{min}$ and

$N \lambda_{max} = 2 \sin\alpha_{max}$

B.1.5 Blazed grating monochromator

The blaze angle of ruled gratings is connected to the inclination of the groove pattern relative to the plane of the substrate. The blaze angle α_B corresponds to the incidence angle giving the maximum efficiency for diffraction in the first order. It is associated to a wavelength, defined as the blaze wavelength λ_B, for which efficiency is the maximum in the normal operation of the monochromator.

$$2 \sin\alpha_B = N \lambda_B$$

Manufacturers give the variation of the efficiency versus wavelength, typically:

$S = 0{,}5$ for $\lambda = 2/3\lambda_B$ and $\lambda = 3/2\lambda_B$

$S = 0{,}9$ for $\lambda = \lambda_B$

Furthermore a blazed grating can be used in higher diffraction orders. The efficiency curve versus angle is unchanged, so that optimal efficiency is found around the wavelength λ_B/k.

The practical resolving power becomes: $R_{pk} = k\, F_q\, RT_1 = k\, F_q\, N\, L_e$.

Practical spectral limits also exist for ruled grating monochromators, but they depend on the choice of the diffraction order, through:

$k\,N\,\lambda_{\text{min}} = 2\,\sin\alpha_{\text{min}}$ and $k\,N\,\lambda_{\text{max}} = 2\,\sin\alpha_{\text{max}}$

B.2 Choice of the monochromator

The quality of the spectral information on the laser beam to be tested depends on the characteristics of the monochromator selected for that testing. Among the questions to be addressed are:

— Which accuracy is needed on the values of wavelengths?

— Which resolving power is needed to specify the spectral bandwidth?

The uncertainty on the values of wavelengths should take into account the absolute accuracy in the readings of the wavelength counter or display, in addition to the uncertainty on positioning.

This last accuracy is, in general, of the order of 1/6 of the effective bandwidth $\Delta\lambda_\alpha$ resulting from the practical resolving power (see B.1.3).

The absolute accuracy in the readings depends on the mechanical quality of the instrument; it should be calibrated (see B.3).

B.3 Calibration of the monochromator

The calibration operations are an integral part of the measurement method, and should be included in the test report data sheet.

They have to be made periodically according to the monochromator manufacturer's instructions. They provide actual values of the effective spectral bandwidth $\Delta\lambda_\alpha$ (or quality factor F_q), and of the reading accuracy.

Annex C
(informative)

Criteria for the choice of a Fabry-Perot interferometer

A Fabry-Perot (FP) interferometer is a valid tool for the measurement of the spectral distribution of a cw or pulsed laser. A scanning Fabry-Perot interferometer or a solid Fabry-Perot etalon are both suitable for lasers of good spectral purity. A scanning Fabry-Perot interferometer may be used in the case of lasers of high spectral purity.

The main characteristic of an FP interferometer is its free spectral range, σ_{FSR}, as given in wavenumbers (cm^{-1}) by

$$\sigma_{FSR} = 1/(2nD)$$

where

n is the refractive index of the optical medium;

D is the distance, in centimetres, between the two high reflectivity mirrors.

In principle, the spectral characteristics are analysed by an FP in the wavenumber space $\sigma = 1/\lambda$. The conversion to the wavelength space should be done using:

$$P_\sigma(\sigma) = \lambda^2 \ P_\lambda(\lambda) \quad \text{or} \quad Q_\sigma(\sigma) = \lambda^2 \ Q_\lambda(\lambda)$$

in particular for most practical cases $\Delta\lambda = \lambda^2 \Delta\sigma$

The second characteristic of an FP interferometer is its finesse, F, as resulting from the reflectivity, R, of the FP mirrors, through:

$$F = \pi \frac{\sqrt{R}}{1 - R}$$

The intrinsic width of an FP cavity resonance is then $\delta\sigma = (\sigma_{FSR})/F$, and the resolving power of the interferometer is given by

$$\frac{\sigma}{\delta\sigma} = \frac{2nD}{\lambda} \frac{\pi\sqrt{R}}{(1 - R)}$$

The σ_{FSR} and the finesse should be chosen to enable an adequate analysis of the spectral distribution, so that the expected bandwidth in the wavenumber space, $\Delta\sigma$, satisfies:

$$\sigma_{FSR} > 3\,\Delta\sigma \quad \text{and} \quad \Delta\sigma > 10\,(\sigma_{FSR})/F$$

The fulfilment of these conditions requires high finesse instruments.

Wavenumber scanning of the cavity resonance can be achieved either by progressive admission of dry air or of a neutral gas in the cavity (scanning of the refractive index n) or by sweeping the relative distance D between two mirrors, e.g. by piezo-electric transducer or by angle.

Bibliography

[1] BARNES, J.A., *et al*. Characterization of frequency stability. *IEEE Transaction of Instrumentation and Measurement*, **IM-20** (2), March 1971

[2] QUINN, T.J., International Report: Practical realization of the definition of the meter (1997). *Metrologia*, , 1999, **36**, pp. 211-244

[3] BIRCH and DOWNS. *Metrologia*, 1994, **31**, pp. 315-316

[4] BÖNSCH and POTULSKI. *Metrologia*, 1998, **35**, pp. 133-139

[5] CIDDOR. *Appl. Optics*, 1996, **35** (9), pp. 1566-1573

ICS 31.260; 37.020

Price based on 25 pages