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Optics and photonics — Lasers and laser-related equipment — Test methods for laser beam power, energy and temporal characteristics

Optique et photonique — Lasers et équipements associés aux lasers — Méthodes d'essai de la puissance et de l'énergie des faisceaux lasers et de leurs caractéristiques temporelles

Reference number
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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 11554 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 9, *Electro-optical systems*.

This third edition cancels and replaces the second edition (ISO 11554:2003), which has been technically revised.

For the purposes of this International Standard, the CEN annex regarding fulfilment of European Council Directives has been removed.

Introduction

The measurement of laser power (energy for pulsed lasers) is a common type of measurement performed by laser manufacturers and users. Power (energy) measurements are needed for laser safety classification, stability specifications, maximum laser output specifications, damage avoidance, specific application requirements, etc. This document provides guidance on performing laser power (energy) measurements as applied to stability characterization. The stability criteria are described for various temporal regions (e.g., short-term, medium-term and long-term) and provide methods to quantify these specifications. This International Standard also covers pulse measurements where detector response speed can be critically important when analysing pulse shape or peak power of short pulses. To standardize reporting of power (energy) measurement results, a report template is also included.

This International Standard is a Type B standard as stated in ISO 12100-1.

The provisions of this International standard may be supplemented or modified by a Type C standard.

Note that for machines which are covered by the scope of a Type C standard and which have been designed and built according to the provisions of that standard, the provisions of that Type C standard take precedence over the provisions of this Type B standard.

Optics and photonics — Lasers and laser-related equipment — Test methods for laser beam power, energy and temporal characteristics

1 Scope

This International Standard specifies test methods for determining the power and energy of continuous-wave and pulsed laser beams, as well as their temporal characteristics of pulse shape, pulse duration and pulse repetition rate. Test and evaluation methods are also given for the power stability of cw-lasers, energy stability of pulsed lasers and pulse duration stability.

The test methods given in this International Standard are used for the testing and characterization of lasers.

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 last edition of the referenced document (including any amendments) applies.

ISO 11145:2006, *Optics and optical instruments — Lasers and laser-related equipment — Vocabulary and symbols*

IEC 61040:1990, *Power and energy measuring detectors, instruments and equipment for laser radiation*

International vocabulary of basic and general terms in metrology (VIM). BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML, 2nd ed. 1993

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11145, in the VIM and the following apply.

3.1
relative intensity noise
RIN
$R(f)$
single-sided spectral density of the power fluctuations normalized to the square of the average power as a function of the frequency f

NOTE 1 The relative intensity noise $R(f)$ or RIN as defined above is explicitly spoken of as the “relative intensity noise spectral density”, but usually simply referred to as RIN.

NOTE 2 For further details, see Annex A.

3.2
small signal cut-off frequency
f_c
frequency at which the laser power output modulation drops to half the value obtained at low frequencies when applying small, constant input power modulation and increasing the frequency

4 Symbols and units of measurement

The symbols and units specified in ISO 11145 and in Table 1 are used in this International Standard.

Table 1 — Symbols and units of measurement

Symbol	Unit	Term
f	Hz	Frequency
f_c	Hz	Small signal cut-off frequency
$[f_1, f_2]$	Hz	Frequency range for which the relative intensity noise $R(f)$ is given
k	1	Coverage factor for the determination of uncertainty
m	1	Reading
$\bar{m}$	1	Mean value of readings
P	W	Power averaged over the sampling period
$\bar{P}$	W	Mean power, averaged over the measurement period at the operating conditions specified by the manufacturer
ΔP	1	Relative power fluctuation to a 95 % confidence level for the appropriate sampling period [ΔP (1 µs) and/or ΔP (1 ms) and/or ΔP (0,1 s) and/or ΔP (1 s)]
$\bar{Q}$	J	Mean pulse energy
ΔQ	1	Relative pulse energy fluctuation to a 95 % confidence level
$R(f)$	Hz^{-1} or dB/Hz	Relative intensity noise, RIN
$S(t)$	1	Detector signal
s	1	Measured standard deviation
T	s	Pulse repetition period
t	s	Measurement period
U_{rel}	1	Expanded relative uncertainty corresponding to a 95 % confidence level (coverage factor $k = 2$)
$U_{rel}(C)$	1	Expanded relative uncertainty of calibration corresponding to a 95 % confidence level (coverage factor $k = 2$)
τ_F	s	Fall time of laser pulse
$\Delta\tau_H$	1	Relative pulse duration fluctuation with regard to τ_H to a 95 % confidence level
τ_R	s	Rise time of laser pulse
$\Delta\tau_{10}$	1	Relative pulse duration fluctuation with regard to τ_{10} to a 95 % confidence level

NOTE 1 For further details regarding 95 % confidence level see ISO 2602 [1].

NOTE 2 The expanded uncertainty is obtained by multiplying the standard uncertainty by a coverage factor $k = 2$. It is determined according to the *Guide to the Expression of Uncertainty in Measurement* [3]. In general, with this coverage factor, the value of the measurand lies with a probability of approximately 95 % within the interval defined by the expanded uncertainty.

NOTE 3 $R(f)$ expressed in dB/Hz equals 10 lg $R(f)$ with $R(f)$ given in Hz^{-1}.

5 Measurement principles

The laser beam is directed on to the detector surface to produce a signal with amplitude proportional to the power or energy of the laser. The amplitude versus time is measured. Radiation emitted by sources with large divergence angles is collected by an integrating sphere. Beam forming and attenuation devices may be used when appropriate.

The evaluation method depends on the parameter to be determined and is described in Clause 8.

6 Measurement configuration, test equipment and auxiliary devices

6.1 Preparation

6.1.1 Sources with small divergence angles

The laser beam and the optical axis of the measuring system shall be coaxial. Select the diameter (cross-section) of the optical system such that it accommodates the entire cross-section of the laser beam and so that clipping or diffraction loss is smaller than 10 % of the intended measurement uncertainty.

Arrange an optical axis so that it is coaxial with the laser beam to be measured. Suitable optical alignment devices are available for this purpose (e.g., aligning lasers or steering mirrors). Mount the attenuators or beam-forming optics such that the optical axis runs through the geometrical centres. Care should be exercised to avoid systematic errors.

NOTE 1 Reflections, external ambient light, thermal radiation and air currents are all potential sources of errors.

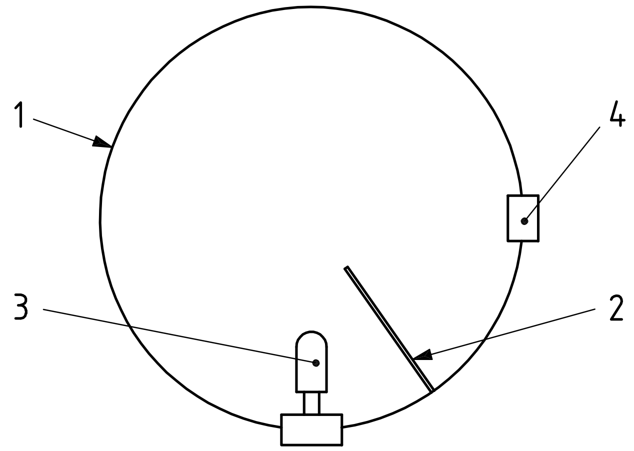
After the initial preparation is completed, make an evaluation to determine if the entire laser beam reaches the detector surface. For this determination, apertures of different diameters can be introduced into the beam path in front of each optical component. Reduce the aperture size until the output signal has been reduced by 5 %. This aperture should have a diameter at least 20 % smaller than the aperture of the optical component. For divergent beams, the aperture should be placed immediately in front of the detector to assure total beam capture.

NOTE 2 Remove these apertures before performing the power (energy) measurements described in Clause 7.

6.1.2 Sources with large divergence angles

The radiation emitted by sources with large divergence angles shall be collected by an integrating sphere. The collected radiation is subjected to multiple reflections from the wall of the integrating sphere; this leads to a uniform irradiance of the surface proportional to the collected flux. A detector located in the wall of the sphere measures this irradiance. An opaque screen shields the detector from the direct radiation of the device being measured. The emitting device is positioned at or near the entrance of the integrating sphere, so that no direct radiation will reach the detector.

Figure 1 shows an integrating sphere measurement configuration for a small emitting source positioned inside the integrating sphere. Large-sized sources should, of course, be positioned outside the sphere but close enough to the input aperture so that all emitted radiation enters the sphere.



Key

1 integrating sphere

2 diffusing opaque screen

3 device being measured

4 detector

Figure 1 — Schematic arrangement for the measurement of highly divergent sources

6.1.3 RIN measurement

The measuring arrangement for determination of the RIN is shown in Figure 2. The beam propagates through the lens, an attenuator or other lossy medium, and falls on the detector. When adjusting the measuring arrangement, feedback of the output power into the laser shall be minimized to avoid measurement errors.

The RIN, $R(f)$ is determined at reference plane A, before any losses. The Poisson component of the RIN is increased at plane B due to losses, and again at plane C due to inefficiency in the detection process.

NOTE For an explanation of the different components of RIN, see Annex A.

To measure RIN, an electrical splitter sends the dc detector signal produced by a test laser to a meter while the ac electrical noise is amplified and then displayed on an electrical spectrum analyser. RIN depends on numerous quantities, the primary ones being:

— frequency;

— output power;

— temperature;

— modulation frequency;

— time delay and magnitude of optical feedback;

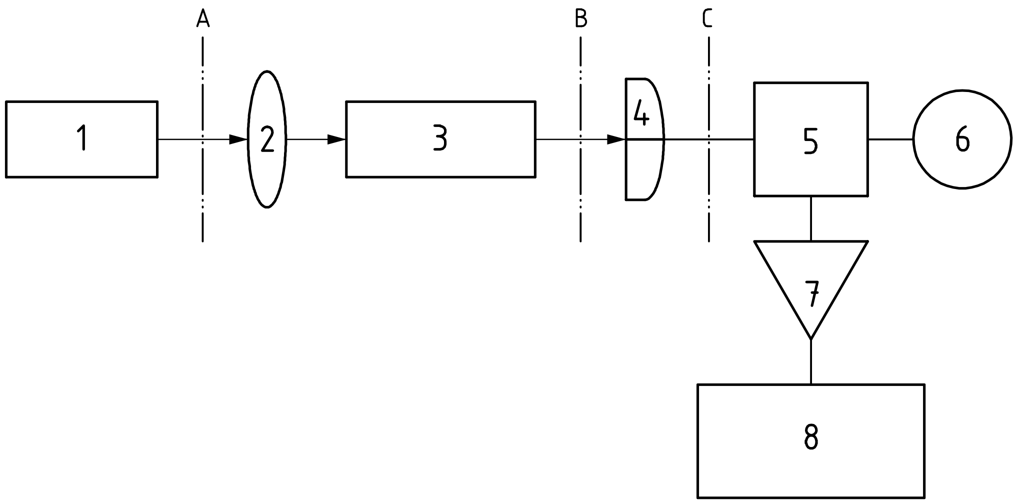
— mode-suppression ratio;

— relaxation oscillation frequency.

Consequently, variations or changes in these quantities should be minimized during the measurement process.

6.1.4 Measurement of small signal cut-off frequency

For determination of the small signal cut-off frequency, f_c, of lasers, the laser is modulated as described in 7.9 and the ac output power measured. Figure 3 shows the basic measurement arrangement for the case of diode lasers. When adjusting the measuring arrangement, feedback of the output power into the laser shall be minimized to avoid measurement errors.



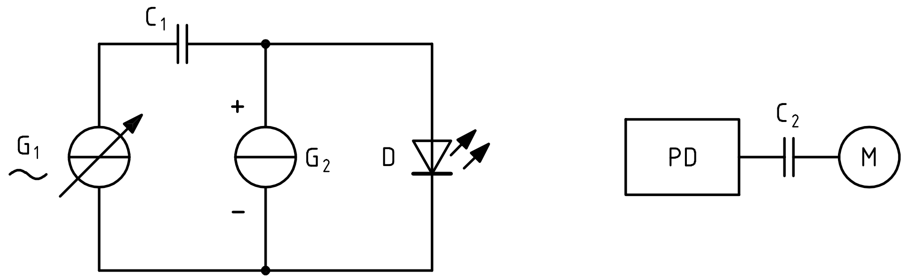
Key

1 laser
2 lens
3 attenuator or other lossy medium
4 detector
5 electrical splitter
6 meter
7 pre-amplifier
8 electrical spectrum analyser

A reference plane that defines RIN
B Poisson RIN increases due to losses
C detector adds shot-noise RIN

NOTE See reference [4].

Figure 2 — Measurement arrangement for RIN determination



Key

D device being measured
PD detector (e.g. photodetector)
M measuring instrument for ac output power
G_1 adjustable frequency ac generator
G_2 dc generator
C_1, C_2 coupling capacitors

Figure 3 — Measurement arrangement for determination of the small signal cut-off frequency of diode lasers

6.2 Control of environmental impacts

Take suitable precautions, such as vibration mechanical and acoustical isolation of the test set-up, shielding from extraneous radiation, temperature stabilization of the laboratory and choice of low-noise amplifiers, in order to ensure that the contribution to the total error is less than 10 % of the intended uncertainty. Check by performing background measurements such as described in Clause 7, but with the laser beam blocked from the detector (e.g. by a beam stop in the laser resonator or close to the laser output). The value for the standard deviation (laser beam blocked) obtained by an evaluation as described in Clause 8 shall be smaller than one tenth of the value obtained from a measurement with the laser beam reaching the detector.

6.3 Detectors

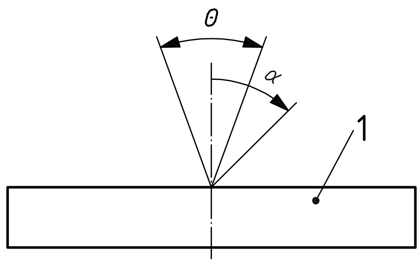
The radiation detector shall be in accordance with IEC 61040:1990, in particular with Clauses 3 and 4. Furthermore, the following points shall be noted:

a) Calibrated power (energy) meter:

— any wavelength dependency, non-linearity or non-uniformity of the detector or the electronic device shall be minimized or corrected by use of a calibration procedure;

— the direct measurement, i.e. using a planar-surface detector without an integrating sphere, can only be used when it has been determined that the sensitivity of the detector is uniform and independent on incident angles, α, to within at least the divergence angle, Θ, of the incident beam (see Figure 4) and the entire beam reaches the sensitive surface of the detector; for measuring beams with large divergence, an integrating sphere detector should be used to assure collection of all the emitted radiation [see 6.3, b)];

— detectors used for all quantitative measurements shall be calibrated with traceability back to relevant national standards.



Key

1 planar detector

Θ divergence angle of the beam

α maximum acceptance angle

Figure 4 — Planar detector — Illustration of angles

b) Calibrated integrating sphere:

— the area of the sphere openings shall be small compared to the overall surface area of the sphere;

— the inner surface of the sphere and screen shall have a uniform diffusing coating with a high reflectance ($\rho > 0,9$);

— the total losses through the sphere ports shall be less than 5 %;

— if the device being measured is mounted inside the sphere, the sphere surface shall be large compared to the device surface, the screen and the apertures;

— the sphere and detector assembly shall be calibrated with traceability back to relevant national standards.

c) Time resolving detector:

— it shall be confirmed, from manufacturer’s data or by measurement, that the output quantity of the detector (e.g. the voltage) is linearly dependent on the input quantity (laser power); any wavelength dependency, non-linearity or non-uniformity of the detector and any associated electronic devices shall be minimized or corrected by use of a calibration procedure;

— the electrical frequency bandwidth of the detector, including the bandwidth of all associated electronics, shall correctly reproduce the temporal laser pulse shape.

When measuring pulse shape characteristics (e.g. peak power, pulse width, etc.), the rise time and the fall time of the detector (including the amplifier and other associated electronics) being used shall be less than one tenth of the rise time and the fall time of the pulses to be measured, respectively.

When measuring small signal cut-off frequency, the detector shall have a frequency response greater than $3f_c$.

Care shall be taken to ascertain the damage thresholds (for irradiance, radiant exposure, power and energy) of the detector surface and all optical elements located between the laser and the detector (e.g. polarizer, attenuator) to ensure they are not exceeded by the incident laser beam.

6.4 Beam-forming optics

If the cross-section of the beam is greater than the detector area, a suitable optical system shall be used to image the area of the cross-section of the laser beam on to the detector surface.

Optics shall be selected appropriate to the wavelength of the laser radiation being measured. Absorption/reflection/clipping/diffraction losses shall be measured and accounted for in all measurements. The laser radiation polarization state shall be accounted for if polarization-dependent reflections are present.

6.5 Optical attenuators

When necessary, an attenuator can be used to reduce the laser power density at the surface of the detector.

Optical attenuators shall be used when the output laser power or power density exceeds either the detector's working (linear) range or its damage threshold. Any wavelength dependency, polarization dependency, angular dependency, non-linearity or spatial non-uniformity of the optical attenuator shall be minimized or corrected by use of a calibration procedure.

7 Measurements

7.1 General

If not otherwise stated, carry out all measurements 10 times, with intervening background measurements.

Before beginning the measurement the laser shall be warmed up according to the manufacturer's specifications in order to achieve thermal equilibrium. Carry out the measurements at the operating conditions specified by the laser manufacturer for the type of laser that is being evaluated.

7.2 Power of cw lasers

Measure the power using a calibrated power meter and, if required, using a calibrated attenuator.

7.3 Power stability of cw lasers

For the determination of short-term stability, the measurement period is 1 ms. The beam is sampled every 1 µs. The time constant of the detecting system shall be less than or equal to 1/3 µs.

For the determination of medium-short-term stability, the measurement period is 1 s. The beam is sampled every 1 ms. The time constant of the detecting system shall be less than or equal to 1/3 ms.

For the determination of the medium-term stability, the measuring period is 1 min. The beam is sampled every 1/10 s. The time constant of the detecting system shall be less than or equal to 1/30 s. Synchronization with the laser’s electrical power supply shall be avoided.

For the determination of the long-term stability, the measuring period is 1 h. The beam is sampled every 1 s. The time constant of the detecting system shall be less than or equal to 1/3 s.

Record maximum and minimum readings.

For characterizing the high frequency noise, measure the RIN as described in 6.1.3.

7.4 Pulse energy of pulsed lasers

Measure the energy of a single pulse with a calibrated energy meter and, if required, with a calibrated attenuator.

7.5 Energy stability of pulsed lasers

Carry out the measurement described in 7.4 for 100, if possible, successive pulses. In case this is not possible, 100 pulses which do not succeed each other may also be used. State in the test report the procedure used.

Record maximum and minimum readings.

7.6 Temporal pulse shape, pulse duration, rise time, fall time and peak power

Measure the temporal pulse shape with a detector as described in 6.3. For the determination of peak power, if the pulse detector cannot directly measure absolute power (e.g. is uncalibrated or too small to collect the entire beam), then measure the pulse energy at the same time in accordance with 7.4.

7.7 Pulse duration stability

Measure the duration of 100 pulses as described in 7.6.

Record maximum and minimum readings.

7.8 Pulse repetition rate

A frequency counter may be used to measure the pulse repetition rate from the detector output signal. Care must be exercised in the triggering method selected to avoid false or double triggering of the counter. This is of particular concern when the laser pulse contains more than one peak. An oscilloscope or transient recorder may be used to view the power versus time waveform output from the detector.

Alternatively, a measurement of the time between two successive pulses from the detector output will yield the pulse repetition period T. The pulse repetition rate, f_p, is evaluated as the reciprocal of the pulse repetition period T.

$$f_p = 1/T \tag{1}$$

7.9 Small signal cut-off frequency

Operate the laser at its specified output power. Modulate the laser using generator G_1 (see Figure 3) at a low frequency (less than f_c/100) and measure the ac output power with measuring instrument M. Increase the modulation frequency keeping the modulation level constant so that the output power indicated by the measuring instrument M drops to half of its low frequency value.

This frequency is the small signal cut-off frequency f_c.

8 Evaluation

8.1 General

The standard deviation, s, from n readings m_i is calculated according to

$$s = \sqrt{\frac{\sum_{i=1}^{n}\left(m_i - \bar{m}\right)^2}{n-1}} \tag{2}$$

where mean value

$$\bar{m} = \frac{\sum_{i=1}^{n} m_i}{n} \tag{3}$$

The standard deviation of the mean value, $s_{\bar{m}}$, is calculated according to

$$s_{\bar{m}} = \sqrt{\frac{\sum_{i=1}^{n}\left(m_i - \bar{m}\right)^2}{n(n-1)}} \tag{4}$$

The expanded relative uncertainty, $U_{\text{rel}}(\bar{m})$, of the mean value $\bar{m}$ has to be determined from the standard deviation, $s_{\bar{m}}$, of the mean value and the expanded relative uncertainty of the calibration factor, $U_{\text{rel}}(C)$, using

$$U_{\text{rel}}(\bar{m}) = \sqrt{\frac{4{s_{\bar{m}}}^2}{\bar{m}^2} + \left[U_{\text{rel}}(C)\right]^2} \tag{5}$$

where

$$U_{\text{rel}}(C) = \sqrt{\sum_{i=1}^{n}\left[U_{\text{rel}}(C_i)\right]^2} \tag{6}$$

$U_{\text{rel}}(C_i)$ represents the expanded relative uncertainties of the calibration factors for the different components of the measurement system, e.g. detector, attenuator, electronic measurement equipment. The expanded relative uncertainties, U_{rel}, are determined to a 95 % confidence level (coverage factor $k = 2$).

NOTE For further details regarding 95 % confidence level, see ISO 2602 [1].

8.2 Power of cw lasers

The power, $\bar{P}$, to be determined is the mean value of at least 10 single measurements taken in accordance with 7.2. This is required to estimate the variability of the measurement.

Calculate the expanded relative uncertainty, $U_{\text{rel}}(\bar{P})$, using the standard deviation, $s_{\bar{P}}$, of the mean value and the expanded relative uncertainty of the calibration factor $U_{\text{rel}}(C)$:

$$U_{\text{rel}}(\bar{P}) = \sqrt{\frac{4 s_{\bar{P}}^2}{\bar{P}^2} + \left[U_{\text{rel}}(C)\right]^2} \quad (7)$$

8.3 Power stability of cw lasers

Calculate the mean value of the power, $\bar{P}$, and the respective standard deviation, s, for the appropriate stability time domain (short-term, medium-short-term, medium-term and long-term) according to the specifications given in 7.3.

Power stability is given as the relative power fluctuation, ΔP, in the corresponding stability time domain calculated from Equation (8):

$$\Delta P = \frac{2s}{\bar{P}} \quad (8)$$

To determine the RIN, $R(f)$, in the electrical domain, the noise power per unit frequency bandwidth, $P_{\text{E}}(f)$, measured with an electrical spectrum analyser is weighted with the frequency dependent calibration function $C(f)$ for the detection system, and is divided by electrical dc power P. If system losses are accounted for, the RIN is

$$R(f) = \frac{P_{\text{E}}(f)}{P \cdot C(f)} \quad (9)$$

where $P_{\text{E}}(f)$ is the noise after subtracting the thermal noise floor.

8.4 Pulse energy of pulsed lasers

Calculate the pulse energy, $\bar{Q}$, as the mean value of 10 single measurements taken in accordance with 7.4.

Calculate the expanded relative uncertainty, $U_{\text{rel}}(\bar{Q})$, using the standard deviation, $s_{\bar{Q}}$, of the mean value and the expanded relative uncertainty of the calibration factor $U_{\text{rel}}(C)$:

$$U_{\text{rel}}(\bar{Q}) = \sqrt{\frac{4 s_{\bar{Q}}^2}{\bar{Q}^2} + \left[U_{\text{rel}}(C)\right]^2} \quad (10)$$

8.5 Energy stability of pulsed lasers

Calculate the mean value of the pulse energy, $\bar{Q}$, and the standard deviation, s, from the readings Q_i taken according to the specifications given in 7.5.

Pulse energy stability is given as the relative pulse energy fluctuation ΔQ:

$$\Delta Q = \frac{2s}{\bar{Q}} \quad (11)$$

8.6 Temporal pulse shape, pulse duration, rise time, fall time and peak power

The following parameters can be obtained from the time profiles of the laser power (see Figure 5):

— the pulse duration, τ_{H}, which is the maximum time interval between two points in time at which the power attains half of the peak power ($P_{\text{pk}}/2$);

— the 10 % pulse duration, τ_{10}, which is the maximum time interval between two points in time at which the power attains 1/10 of the peak power (0,1 P_{pk}).

If the laser pulse consists of a high-power pulse of narrow width at the beginning and of a low-power pulse of long duration at the latter part of the laser pulse (e.g. TEA laser, see Figure 6), it is necessary to specify both times.

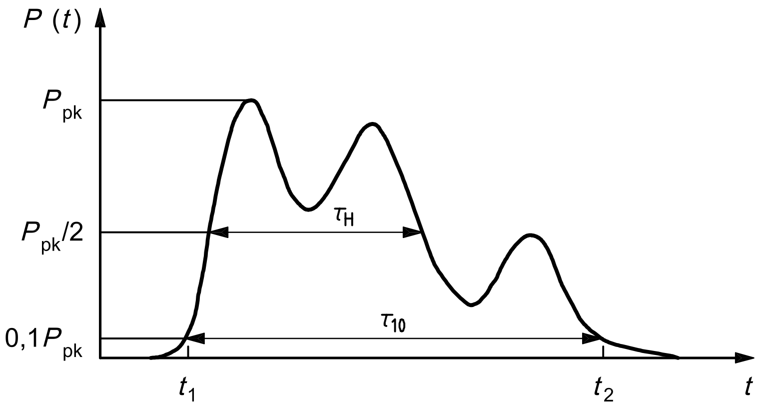


Figure 5 — Example of the variation of radiation power of a laser pulse with time

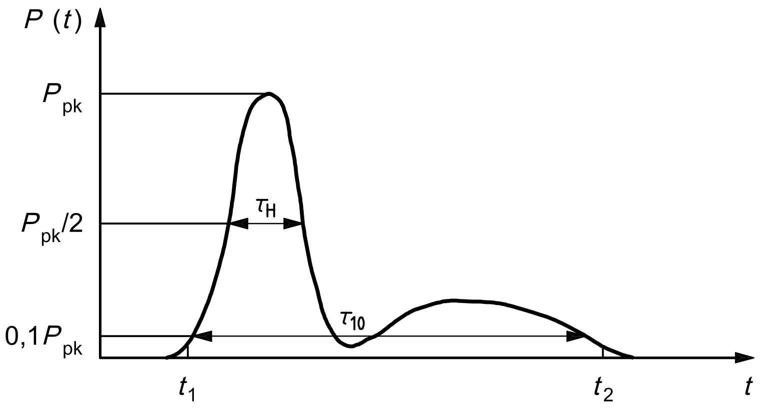


Figure 6 — Example of the variation of radiation power of the pulse of a TEA laser with time

— The rise time, τ_R, i.e. the time interval between two points of time at which the laser power attains 10 % (0,1 P_{pk}) and 90 % (0,9 P_{pk}) of the peak power (see Figure 7).

— The fall time τ_F, i.e. the time interval between two points of time at which the laser power falls from 90 % (0,9 P_{pk}) to 10 % (0,1 P_{pk}) of the peak power.

For pulses with more than one 90 % point, or more than one 10 % point, rise time, fall time or pulse duration might not be defined unambiguously. In that case the temporal pulse shape shall be given.

— The temporal pulse shape, i.e. laser power $P(t)$ as a function of time, represented by the detector electrical output signal $S(t)$; when using a pulse energy detector as described in 7.6 to determine Q, in conjunction with an uncalibrated detector to measure the pulse shape, the quantitative pulse shape is given by

$$P(t) = \frac{S(t)Q}{\int_{t_1}^{t_2} S(t)\mathrm{d}t} \qquad (12)$$

where the limits of integration t_1 and t_2 are determined by t_1, $t_2 = t$ [where $S(t) \leqslant 0{,}1\, S_{max}$] (see Figure 5); the pulse energy Q is measured and evaluated according to the provisions of 7.4 and 8.4.

— The peak power P_{pk} of the pulse is calculated as follows:

$$P_{pk} = \frac{S_{max}\, Q}{\int_{t_1}^{t_2} S(t)\mathrm{d}t} \qquad (13)$$

where S_{max} represents the peak value of the detector signal $S(t)$.

NOTE If pulse energy measurement is not needed (i.e. the detector being used for pulse shape determination has a responsivity calibrated in terms of absolute power), then both $P(t)$ and P_{pk} can be determined directly from $S(t)$.

Calculate the mean values of τ_H, τ_{10}, τ_R, τ_F, and P_{pk} as well as the corresponding expanded relative uncertainties $U_{rel}(\bar{\tau}_H)$, $U_{rel}(\bar{\tau}_{10})$, $U_{rel}(\bar{\tau}_R)$, $U_{rel}(\bar{\tau}_F)$ and $U_{rel}(\bar{P}_{pk})$ using the corresponding standard deviations, $s_{\bar{m}}$, of the mean values as well as the expanded relative uncertainties of the corresponding calibration factors, $U_{rel}(C)$, as described in 8.1.

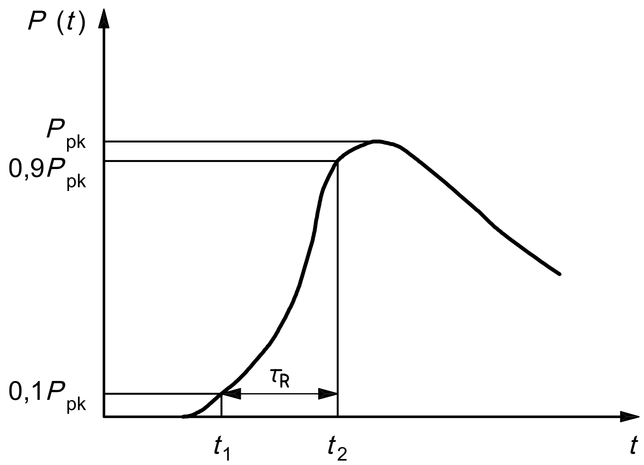


Figure 7 — Example of rise time measurement

8.7 Pulse duration stability

Calculate the relative pulse duration fluctuation $\Delta\tau_H$ (or $\Delta\tau_{10}$) from the mean value $\bar{\tau}_H$ (or $\bar{\tau}_{10}$) and the standard deviation s_H (or s_{10}) of the 100 values determined according to 7.7:

$$\Delta\tau_H = \frac{2s_H}{\bar{\tau}_H} \quad \text{or} \quad \Delta\tau_{10} = \frac{2s_{10}}{\bar{\tau}_{10}} \tag{14}$$

8.8 Pulse repetition rate

Calculate the pulse repetition rate as the mean value of the results of measurements taken according to 7.8.

Calculate the expanded relative uncertainty, $U_{rel}(\bar{f}_p)$, using the standard deviation, $s_{\bar{f}_p}$, of the mean value and the expanded relative uncertainty of the calibration factor $U_{rel}(C_T)$ of the time base or the frequency counter:

$$U_{rel}(\bar{f}_p) = \sqrt{\frac{4 s_{\bar{f}_p}^{\;2}}{\bar{f}_p^{\;2}} + \left[U_{rel}(C_T)\right]^2} \tag{15}$$

8.9 Small signal cut-off frequency

Calculate the small signal cut-off frequency as the mean value of the results of measurements taken according to 7.9.

9 Test Report

The following information shall be included in the test report.

a) General information:

1) test has been performed according to ISO 11554:2006;

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) tested;

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

3) operating mode (cw/pulsed);

4) laser parameter settings:

— output power or energy,

— current or energy input,

— pulse energy,

— pulse duration,

— pulse repetition rate;

5) mode structure;

6) polarization;

7) environmental conditions.

d) Information concerning testing and evaluation:

1) test method used;

2) detector and sampling system:

— response time of the detector system,

— trigger delay of sampling (for pulsed lasers only),

— measuring time interval (for pulsed lasers only);

3) beam forming optics and attenuating method:

— type of attenuator,

— type of beam splitter,

— type of focusing element;

4) other optical components and devices used for the test (polarizer, monochromator, etc.);

5) other relevant parameters or characteristics of the test to be chosen (aperture setting, reference plane, reference axis, laboratory system).

e) Test results:

1) for measurements according to 7.2:

— power, $\overline{P}$,

— expanded relative uncertainty, $U_{\text{rel}}(\overline{P})$, of the measurement,

2) for measurements according to 7.3:

— relative power fluctuation, ΔP, for the appropriate sampling period [ΔP (1 µs) and/or ΔP (1 ms) and/or ΔP (0,1 s) and/or ΔP (1 s)],

— maximum and minimum readings of the power during test,

— RIN, $R(f)$ at frequency f or in frequency interval [f_1, f_2];

3) for measurements according to 7.4:

— pulse energy, $\bar{Q}$,

— expanded relative uncertainty, $U_{rel}(\bar{Q})$, of the measurement;

4) for measurements according to 7.5:

— relative pulse energy fluctuation, ΔQ,

— selection procedure if pulses were chosen which do not succeed each other,

— maximum and minimum readings of the energy during test;

5) for measurements according to 7.6:

— pulse duration, $\bar{\tau}_H$,

— 10 % pulse duration, $\bar{\tau}_{10}$,

— rise time, $\bar{\tau}_R$,

— fall time, $\bar{\tau}_F$,

— plot of a typical temporal pulse shape, $P(t)$, (i.e. time profile of the laser pulse),

— peak power, $\bar{P}_{pk}$, of the pulse;

— corresponding expanded relative uncertainties, U_{rel}, of the mean values

6) for measurements according to 7.7:

— relative pulse duration fluctuation, $\Delta\tau$, ($\Delta\tau_H$ and/or $\Delta\tau_{10}$),

— maximum and minimum readings of pulse duration during test;

7) for measurements according to 7.8:

— pulse repetition rate, $\bar{f}_p$,

— expanded relative uncertainty, $U_{rel}(\bar{f}_p)$, of the measurement;

8) for measurements according to 7.9:

— small signal cut-off frequency $\bar{f}_c$.

Annex A
(informative)

Relative intensity noise (RIN)

In the time domain, the optical power $P(t)$ can be written as $P(t) = P_0 + \Delta P(t)$, where $P_0 = \langle P \rangle$ is the averaged power and $\Delta P(t)$ describes the power fluctuations.

In the frequency domain the relative intensity noise, $R(f)$, is the single sided spectral density of the power fluctuations normalized to $P_0{}^2$:

$$R(f) = \frac{S_{\Delta P}(f)}{P_0{}^2} \tag{A.1}$$

where $S_{\Delta P}(f) = \lim_{T\to\infty} \frac{4\pi \left| V_T(f) \right|^2}{T}$ with $V_T(f) = \int_{-T/2}^{T/2} \Delta P(t) e^{-2\pi i f t} \mathrm{d}t$

Alternatively, $R(f)$ can be calculated from the auto-correlation function

$$C_{\Delta P}(\tau) = \left\langle \Delta P(t) \Delta P(t+\tau) \right\rangle \tag{A.2}$$

since it can be shown (Wiener-Khintchine theorem, see reference [5]), that the Fourier transform of $C_{\Delta \mathrm{P}}(\tau)$ is the spectral density function $S_{\Delta P}(f)$:

$$S_{\Delta P}(f) = 4 \int_0^\infty C_{\Delta P}(\tau) e^{-2\pi i f \tau} \mathrm{d}\tau \tag{A.3}$$

The signal-to-noise ratio SNR of a system with bandwidth $[f_\mathrm{L}, f_\mathrm{H}]$ is the inverse of the RIN integrated over all spectral components of the power fluctuations within the system bandwidth

$$\mathrm{SNR} = \frac{P_0{}^2}{\left\langle \Delta P(t)^2 \right\rangle} = \left[\int_{f_\mathrm{L}}^{f_\mathrm{H}} R(f) \mathrm{d}f \right]^{-1} \tag{A.4}$$

Since the electrical power, P_E, is proportional to the current, i squared, and hence to the optical power P_opt squared,

$$P_\mathrm{E} \propto i^2 \propto P_\mathrm{opt}^2 \tag{A.5}$$

this definition is consistent with the definition of the electrical SNR which is the ratio of the (electrical) powers $P_\mathrm{signal}/P_\mathrm{noise} = P_\mathrm{AC}/P_\mathrm{DC}$.

There are two contributions to laser noise: Poisson and excess noise.

Poisson RIN is directly related to the quantum nature of coherent radiation

$$R(f)\mathrm{d}f = \frac{2}{n_t} \mathrm{d}f \tag{A.6}$$

with $n_t = \mathrm{d}n/\mathrm{d}t$ being the number of photons of radiation frequency, ν, per unit time.

Applying the relation

$$n_t = \frac{P_0}{h\nu} \quad \text{(A.7)}$$

where h is Planck's constant, it follows that

$$R(f)\mathrm{d}f = \frac{2h\nu}{P_0}\mathrm{d}f \quad \text{(A.8)}$$

This is the minimum relative intensity noise achievable with classical (laser) radiation, often called standard quantum limit.

Excess RIN describes the deviation from Poisson RIN and is usually positive (e.g. due to spontaneous emission). An exception is squeezed radiation with excess RIN < 0 but increased phase noise.

Since Poisson RIN is related to the photon number, it is inversely proportional to the efficiency, η, of the transmission and detection system, while the excess RIN remains unchanged. In addition, there could be noise from other sources such as shot noise or the power-independent Johnson noise (thermal noise) from detectors. This affects the Poisson noise and excess noise in different ways, which has to be taken into account when calculating the RIN of the laser.

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