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Lasers and laser-related equipment — Test methods for laser beam parameters — Beam widths, divergence angle and beam propagation factor

Lasers et équipements associés aux lasers — Méthodes d'essai des paramètres des faisceaux laser — Largeurs du faisceau, angle de divergence et facteur de propagation du faisceau

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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 3.

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.

International Standard ISO 11146 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 9, *Electro-optical systems*.

Annexes A and B form a normative part of this International Standard. Annex C is for information only.

Introduction

Any radially symmetric laser beam requires three parameters for characterization:

a) location of the beam waist z_0;

b) waist diameter $d_{\sigma 0}$; and

c) the far-field divergence angle Θ_σ for the beam under test.

With these three values, one can predict the beam diameter at any plane along the propagation axis. To a first approximation (for divergence angles less than 0,8 rad), the beam propagates as

$$d_\sigma{}^2(z) = d_{\sigma 0}{}^2 + (z - z_0)^2 \cdot \Theta_\sigma{}^2 \tag{1}$$

The beam propagates according to equation (1) provided the second moments of the power (energy) density distribution function are used for the definition of beam widths and divergences. The propagation is described by a beam propagation factor K or a times-diffraction-limit factor M^2 which can be derived from the above basic data. The relationship between K and M^2, respectively, the actual waist diameter $d_{\sigma 0}$ and the divergence angle Θ_σ, is:

$$K = \frac{1}{M^2} = \frac{4\lambda_0}{\pi} \cdot \frac{1}{n \cdot d_{\sigma 0} \cdot \Theta_\sigma} = \frac{4\lambda}{\pi} \cdot \frac{1}{d_{\sigma 0} \cdot \Theta_\sigma} \tag{2}$$

where

K is the beam propagation factor;

M^2 is the times-diffraction-limit factor;

λ_0 is the wavelength in vacuum ;

λ is the wavelength in medium with index of refraction n,

Θ_σ is the divergence angle,

$d_{\sigma 0}$ is the waist diameter,

n is the index of refraction.

NOTE 1 The accuracy of measurement of beam propagation factors is expected to be in the region of 10 %. It is not consistent with divergence angles (full angle according to ISO 11145) above 0,8 rad.

The product

$$n \cdot d_{\sigma 0} \cdot \Theta_\sigma = \frac{4\lambda_0}{K\pi} = \frac{M^2 4\lambda_0}{\pi} \tag{3}$$

describes the propagation of laser beams and is invariant throughout the propagation of the beam as long as aberration-free and non-aperturing optical systems are used.

For non-radially symmetric beams, the values of seven parameters are required for characterization:

— locations of the beam waists z_{0x} and z_{0y}

— waist widths $d_{\sigma 0x}$ and $d_{\sigma 0y}$;

— far-field divergence angles $\Theta_{\sigma x}$ and $\Theta_{\sigma y}$; and

— azimuth angle φ between the x-axis of the beam axes system and the x'-axis of the laboratory system. The x-axis of the beam axes system coincides with the principal axis of the laser beam closest (within ±45°) to the arbitrary x' coordinate.

In analogy to equation (3), the propagation of non-radially symmetric beams, which are however still characterizable using two principal axes orthogonal to each other, can be described independently for the x- and y-axes using K_x and K_y as beam propagation factors, or M_x^2 and M_y^2 as times-diffraction-limit factors, respectively.

NOTE 2 Beams that suffer from general astigmatism (twisted beams) require three additional parameters for their characterization. The propagation in the x-z plane is not necessarily independent of the propagation characteristics in the y-z plane and not necessarily along the propagation path will a generally astigmatic beam exhibit a circular power density distribution. The measurement of generally astigmatic beams is outside the scope of this International Standard.

In this International Standard, the second moments of the power (energy) density distribution function are used for the determination of beam widths. However, there may be problems experienced in the direct measurement of this property in the beams from some laser sources. In this case, other indirect methods of measurement of second moment may be used as long as comparable results are achievable.

In annex A, three alternative methods for beam width measurement and their correlation with the method used in this International Standard are described. These methods are:

- Variable aperture method
- Moving knife-edge method
- Moving slit method

The problem of the dependence of the measuring result on the truncation limits of the integration has been investigated and evaluated by an international round robin carried out in 1997. The results of this round robin testing were taken into consideration in this document.

Lasers and laser-related equipment — Test methods for laser beam parameters — Beam widths, divergence angle and beam propagation factor

1 Scope

This International Standard specifies methods for measuring beam widths (diameter), divergence angles and beam propagation factors of laser beams.

These methods may not apply to highly diffractive beams such as those produced by unstable resonators or passing through hard-edged apertures.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 11145:1994, *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*.

3 Terms and definitions

For the purposes of this International Standard, the terms and definitions given in ISO 11145 and IEC 61040, and the following apply:

3.1
energy density
$H(x,y)$
that part of the beam energy which impinges on the area δA at the location x, y divided by the area δA

3.2
power density
$E(x,y)$
that part of the beam power which impinges on the area δA at the location x, y divided by the area δA

3.3
beam waist locations
z_0, z_{0x}, z_{0y}
positions where beam widths reach their minimum values along the axis of propagation

See Figure 1.

NOTE The locations are expressed as the distances to the beam waists (inside or outside the resonator) from a reference plane defined by the manufacturer e.g. the front of the laser enclosure.

3.4
beam diameter
d_σ

$$d_\sigma(z) = 2\sqrt{2}\,\sigma(z) \tag{4}$$

where the second moment of the power density distribution function $E(x, y, z)$ of the beam at the location z is given by

$$\sigma^2(z) = \frac{\iint r^2 E(r,z) r \mathrm{d}r \mathrm{d}\varphi}{\iint E(r,z) r \mathrm{d}r \mathrm{d}\varphi} \tag{5}$$

where r is the distance to the centroid $(\bar{x}, \bar{y})$

and where the first moments give the coordinates of the centroid, i. e.

$$\bar{x} = \frac{\iint x E(x, y, z) \mathrm{d}x \mathrm{d}y}{\iint E(x, y, z) \mathrm{d}x \mathrm{d}y} \tag{6}$$

$$\bar{y} = \frac{\iint y E(x, y, z) \mathrm{d}x \mathrm{d}y}{\iint E(x, y, z) \mathrm{d}x \mathrm{d}y} \tag{7}$$

NOTE 1 In principle, integration is carried out over the whole x-y plane. In practice, the integration is performed over an area such that at least 99 % of the beam power (energy) is captured. Refer to practical limits in 6.4.

NOTE 2 The power density E is replaced by the energy density H for pulsed lasers.

NOTE 3 This definition differs from that given in ISO 11145:1994, for the reason that only beam propagation factors based on beam widths and divergence angles derived from the second moments of the power (energy) density distribution function allow calculation of the beam propagation. Other definitions of beam widths and divergence angles may be helpful for other applications, but must be shown to be equivalent to the second-order moment definition to be used for calculating the correct beam propagation.

3.5
beam widths
$d_{\sigma x}$; $d_{\sigma y}$

$$d_{\sigma x}(z) = 4\sigma_x(z) \tag{8}$$

$$d_{\sigma y}(z) = 4\sigma_y(z) \tag{9}$$

where the second moments of the power density distribution function $E(x, y, z)$ of the beam at the location z are given by

$$\sigma_x^2(z) = \frac{\iint (x-\bar{x})^2\, E(x,y,z) \mathrm{d}x \mathrm{d}y}{\iint E(x,y,z) \mathrm{d}x \mathrm{d}y} \tag{10}$$

$$\sigma_y^2(z) = \frac{\iint (y-\bar{y})^2\, E(x,y,z) \mathrm{d}x \mathrm{d}y}{\iint E(x,y,z) \mathrm{d}x \mathrm{d}y} \tag{11}$$

where $(x-\bar{x})$ and $(y-\bar{y})$ are the distances to the centroid $(\bar{x}, \bar{y})$

and where the first moments give the coordinates of the centroid, i. e.

$$\bar{x} = \frac{\iint x E(x,y,z)\mathrm{d}x\mathrm{d}y}{\iint E(x,y,z)\mathrm{d}x\mathrm{d}y} \quad (12)$$

$$\bar{y} = \frac{\iint y E(x,y,z)\mathrm{d}x\mathrm{d}y}{\iint E(x,y,z)\mathrm{d}x\mathrm{d}y} \quad (13)$$

NOTE 1 In principle, integration is carried out over the whole x-y plane. In practice, the integration is performed over an area such that at least 99 % of the beam power (energy) is captured. Refer to practical limits in 6.4.

NOTE 2 The power density E is replaced by the energy density H for pulsed lasers.

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3.6
times-diffraction-limit factor
M^2
measure of how close the beam parameter product is to the diffraction limit of a perfect Gaussian beam

$$M^2 = \frac{\pi}{\lambda} \cdot \frac{d_{\sigma 0}\,\Theta_\sigma}{4} \quad (14)$$

4 Coordinate systems

4.1 General

The x, y and z axes define the orthogonal space directions in the beam axes system. The x and y axes are transverse to the beam and define the transverse plane. The beam propagates along the z axis. The origin of the z axis is in a reference xy plane defined by the manufacturer, e.g. the front of the laser enclosure.

For elliptical beams, the principal planes of propagation, defined as xz and yz, are the planes containing the major and the minor axes, respectively, of the ellipse. See figure 1.

If the principle planes of propagation do not coincide with the $x'z$ and $y'z$ planes of the laboratory system x', y', z, then one of two equivalent procedures can be chosen:

4.2 Description in the beam axis system

If the azimuth of the beam axis system relative to the laboratory system is known, then the beam parameters can be measured directly in the beam axis system and the azimuth angle recorded with those measurements.

4.3 Description in the laboratory system

If the principal axes of the beam are not known, they can be determined by measuring the two second moments $\sigma_{x'}{}^2$, $\sigma_{y'}{}^2$ and the mixed moment $\sigma_{x'y'}{}^2$ of the beam distribution in the laboratory system. It is then possible to calculate the second moments in the beam axis system **and** the azimuth angle φ between the two systems.

The mixed moment is given by

$$\sigma_{x'y'}{}^2(z) = \frac{\iint (x'-\overline{x'})(y'-\overline{y'})E(x',y',z)\mathrm{d}x'\mathrm{d}y'}{\iint E(x',y',z)\mathrm{d}x'\mathrm{d}y'} \quad (15)$$

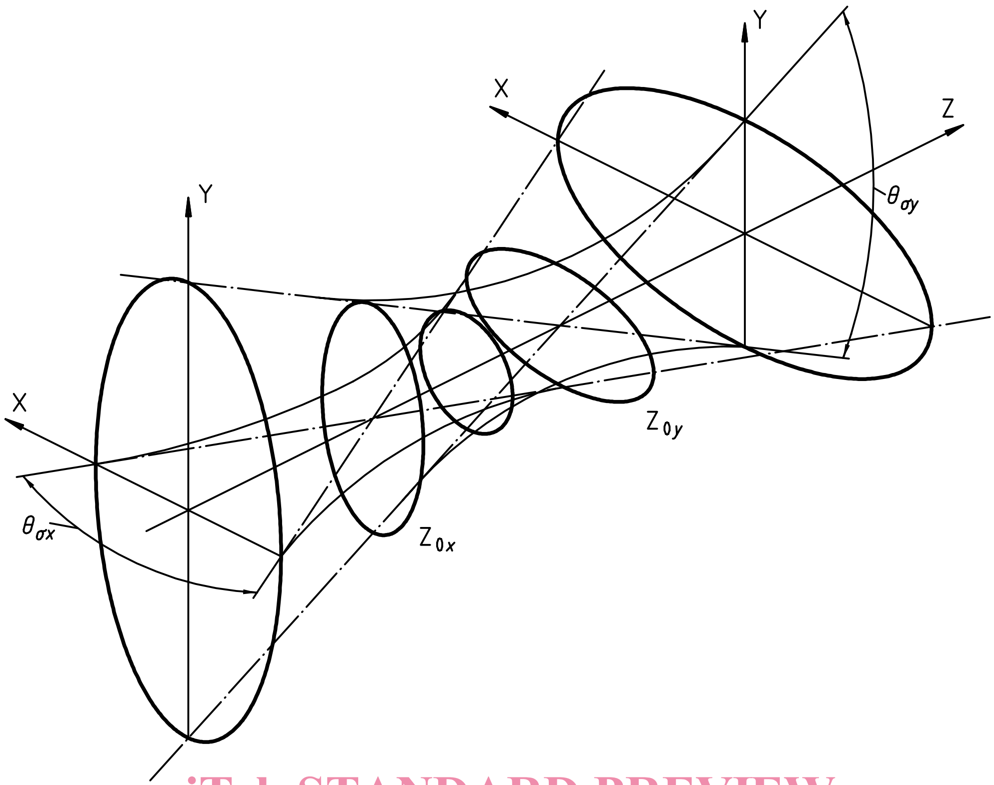

Figure 1 — Coordinates in the beam axis system

5 Test principles

5.1 Beam widths and beam diameter

For the determination of beam widths or diameter at location z, the power (energy) density distribution function of the laser beam shall be determined in the $x'y'$ plane at the location z. Additionally, the azimuth angle φ shall be determined.

From the measured cross-sectional distribution function, the first spatial moments $\bar{x},\bar{y}$ containing the beam axis are determined. In a second step, the second moments σ_x^2, σ_y^2 or σ^2 as well as the beam widths $d_{\sigma x}$, $d_{\sigma y}$ or the beam diameter d_σ are calculated. See equations (4) to (7) and (8) to (13), respectively.

5.2 Divergence angles

The determination of the divergence angles follows from measurements of the beam widths or the beam diameter:

First, the laser beam shall be transformed by an aberration-free focusing element. The beam diameter $d_{\sigma f}$ is then measured one focal length f away from the rear principal plane of the focusing element. The divergence angle of the laser beam before the focusing element is determined using the relationship

$$\Theta_\sigma = \frac{d_{\sigma f}}{f} \qquad (16)$$

For non-radially symmetric beams, the divergence angles $\theta_{\sigma x}$ or $\theta_{\sigma y}$ in the xz or yz planes are determined by using the beam widths instead of the beam diameter.

5.3 Beam propagation factor and times-diffraction-limit factor, respectively

For the determination of the beam propagation factors K_x, K_y or K and the times-diffraction-limit factors M_x^2, M_y^2 or M^2, respectively, it is necessary to determine the waist widths $d_{\sigma 0x}$, $d_{\sigma 0y}$ or the waist diameter $d_{\sigma 0}$ and the related beam divergence angles $\theta_{\sigma x}$, $\theta_{\sigma y}$ or θ_{σ}.

5.4 Beam waist location, combined measurement of beam widths, beam divergence angle and beam propagation factor or times-diffraction-limit factor

For determination of the waist location the beam widths, data along the propagation axis shall be fit to a hyperbola as discussed in clause 9.

The other beam parameters can also be determined by this method.

6 Measurement arrangement and test equipment

6.1 General

The test is based on the measurement of the cross-sectional power (energy) density distribution function of the entire laser beam.

6.2 Preparation

The optical axis of the measuring system should be coaxial with the laser beam to be measured. Suitable optical alignment devices are available for this purpose (e.g. aligning lasers or steering mirrors).

The aperture of the optical system shall accommodate the entire cross-section of the laser beam. Clipping shall be smaller than 1 % of the total beam power or energy.

The attenuators or beam-forming optics shall be mounted such that the optical axis runs through the geometrical centres. Care should be taken to avoid systematic errors. Reflections, interference effects, external ambient light, thermal radiation or air draughts are all potential sources of error.

After the initial preparation is complete, an evaluation to determine if the entire laser beam reaches the detector surface shall be made. For testing this, apertures of different widths can be introduced into the beam path in front of each optical component. The aperture which reduces the output signal by 5 % should have a diameter less than 0,8 times the aperture of the optical component.

6.3 Control of environment

Suitable measures such as mechanical and acoustical isolation of the test set-up, shielding from extraneous radiation, temperature stabilization of the laboratory, choice of low-noise amplifiers shall be taken to ensure that the contribution to the total probable error of the parameter to be measured is low.

Care should be taken to ensure that the atmospheric environment in high-power laser beam paths does not contain gases or vapours that can absorb the laser radiation and cause thermal distortion in the beam to be assessed.

6.4 Detector system

Measurement of the cross-sectional power (energy) density distribution function requires the use of a power (energy) meter with high spatial resolution and high signal-to-noise-ratio.

The accuracy of the measurement is directly related to the spatial resolution of the detector system and its signal-to-noise ratio. The latter is important for laser beams with low power (energy) densities at larger diameters (e.g. for diffracted parts of the laser beams).

In practice, noise in the wings of the density distribution function [either $E(x,y,z)$ or $H(x,y,z)$] may readily dominate the second moment integral. Thus it is usually necessary to subtract a background map (the detector response with the beam blocked) from the signal map in determining the experimental distribution function.

NOTE For example, consider calculating the second moment of a Gaussian beam at diameter $2w$. Truncating the integration at r/w = 1,9 clips off only 0,5 % of the value of the second moment. Assuming a 0,8 % peak-to-peak amplitude noise to simulate the real experimental profile, truncation within these limits is required to be reasonably assured of a ± 5 % uncertainty in the measured second moment.

The smallest spatial structures which are to be resolved should be sampled more than twice (sampling theorem). Therefore the detector resolution necessary for the measurement is directly correlated to the structures of the beam to be measured.

The provisions of IEC 61040:1990 apply to the radiation detector system; clauses 3 and 4 are particularly important. Furthermore, the following points should be noted.

— It shall be confirmed, from manufacturers' data or by measurement, that the output quantity of the detector system (e.g. the voltage) is linearly dependent on the input quantity (laser power). 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.

— Care shall be taken to ascertain the damage thresholds of the detector surface so that they are not exceeded by the laser beam.

— When using a scanning device for determining the power density distribution function, care shall be taken to ensure that the laser output is spatially and temporally stable during the whole scanning period.

— When measuring pulsed laser beams, the trigger time delay of sampling as well as the measuring time interval play an important role because the beam parameters may change during the pulse. Therefore it is necessary to specify these parameters in the test report.

6.5 Beam-forming optics and optical attenuators

If the beam cross-sectional area is greater than the detector area, a suitable optical system shall be used to reduce the beam cross-sectional area on the detector surface. The change in magnification shall be taken into account during the evaluation procedure.

Optics shall be selected appropriate to wavelength.

An attenuator may be required to reduce the laser power density at the surface of the detector.

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

None of the optical elements used shall significantly influence the relative power (energy) density distribution.

6.6 Focusing system

The focusing system for the divergence angle measurement shall conform with the requirements relating to the beam-forming optics given in 6.5. The total error contributed by the focusing system shall be less than 1 % of the beam width.

7 Beam widths and beam diameter measurement

7.1 Test procedure

Before the measurements are started, the laser shall warm up for at least 1 h (unless otherwise stated by the manufacturer) to achieve thermal equilibrium. The measurements shall be carried out at the operating conditions specified by the laser manufacturer for the type of laser being evaluated.

Repeat at least five times the measurement of the cross-sectional power (energy) density distribution function at each location z at which the beam widths are determined.