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Lasers and laser-related equipment — Test methods for laser beam widths, divergence angles and beam propagation ratios —

Part 2:
General astigmatic beams

Lasers et équipements associés aux lasers — Méthodes d'essai des largeurs du faisceau, angles de divergence et des facteurs de limite de diffraction —

Partie 2: Faisceaux astigmatiques généraux

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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.

ISO 11146-2 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 9, *Electro-optical systems.*

ISO 11146 consists of the following parts, under the general title *Lasers and laser-related equipment — Test methods for laser beam widths, divergence angles and beam propagation ratios*:

— *Part 1: Stigmatic and simple astigmatic beams*

— *Part 2: General astigmatic beams*

— *Part 3: Intrinsic and geometrical laser beam classification, propagation, and details of test methods* (Technical Report)

Introduction

The propagation properties of laser beams can be characterized by ten independent parameters when applying the method of second order moments (see ISO/TR 11146-3). Most laser beams need few parameters for a complete description due to their higher symmetry. Lasers emit beams which are stigmatic or simple astigmatic due to their resonator design.

Part 1 of ISO 11146 describes the measurement methods for stigmatic and simple astigmatic beams while this part of ISO 11146 deals with the measurement procedures for general astigmatic beams. This part of ISO 11146 is applicable to beams of unknown type. Beam characterization, based on the method of second order moments as described in Part 1 and this part of ISO 11146, is only valid within the paraxial approximation.

The theoretical description of beam characterization and propagation as well as the classification of laser beams is given in ISO/TR 11146-3, which is an informative Technical Report. The procedures for background subtraction and offset correction are also given in ISO/TR 11146-3.

In ISO 11146, the second order moments of the power (energy) density distribution function are used for the determination of beam widths. If problems are experienced in the direct measurements of these quantities, other indirect methods of measurement of second order moments may be used as long as comparable results are achievable.

In ISO/TR 11146-3, three alternative methods for beam width measurement and their correlation with the method used in this part of ISO 11146 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 area was investigated and evaluated by an international interlaboratory experiment carried out in 1997. The results of this interlaboratory testing were taken into consideration in this document.

The International Organization for Standardization (ISO) draws attention to the fact that it is claimed that compliance with this document may involve the use of a patent concerning the determination of beam characteristics by measuring along the beam caustic of the transformed beam produced by a lens as described in 5.3 and 5.4.

ISO takes no position concerning the evidence, validity and scope of this patent right.

The holder of this patent right (U.S. No. 5,267,012) has assured ISO that he is willing to negotiate licences under reasonable and non-discriminatory terms and conditions with applicants throughout the world. In this respect, the statement of the holder of this patent right is registered with the ISO. Information may be obtained from:

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

Lasers and laser-related equipment — Test methods for laser beam widths, divergence angles and beam propagation ratios —

Part 2: General astigmatic beams

1 Scope

This part of ISO 11146 specifies methods for measuring beam widths (diameter), divergence angles and beam propagation ratios of laser beams. This part of ISO 11146 is applicable to general astigmatic beams or unknown types of beams. For stigmatic and simple astigmatic beams, ISO 11146-1 is applicable.

Within this part of ISO 11146, the description of laser beams is accomplished by means of the second order moments of the Wigner distribution rather than physical quantities such as beam widths and divergence angles. However these physical quantities are closely related to the second order moments of the Wigner distribution. In ISO/TR 11146-3, formulae are given to calculate all relevant physical quantities from the measured second order moments.

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 11146-1:2005, *Lasers and laser-related equipment — Test methods for laser beam widths, divergence angles and beam propagation ratios — Part 1: Stigmatic and simple astigmatic beams*

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11145, ISO 11146-1, IEC 61040 and the following apply.

NOTE The x–, y– and z-axes in the following definitions refer to the laboratory system (as described in Clause 4). Here and throughout this document the term “power density distribution” refers to continuous wave sources. It might be replaced by “energy density distribution” in case of pulsed sources.

3.1
generalized beam diameter
d_g
measure of the extent of the power density distribution of a beam in a cross-section at an axial location z, derived from the centred second order moments by

$$d_{\mathrm{g}} = 2\sqrt{2}\sqrt{\left\langle x^2 \right\rangle + \left\langle y^2 \right\rangle} \quad (1)$$

NOTE This definition is similar to the beam diameter defined in ISO 11145 or ISO 11146-1. But in this context the definition is not restricted to circular power density distributions.

3.2
generalized beam waist location
$z_{0,\mathrm{g}}$
position where the generalized beam diameter reaches its minimum value along the axis of propagation

3.3
generalized Rayleigh length
$z_{\mathrm{R,g}}$
distance along the beam axis from the generalized beam waist where the generalized beam diameter is a factor of $\sqrt{2}$ larger than the generalized beam waist diameter

3.4
Wigner distribution
phase space distribution representing a laser beam in a transverse plane at location z

NOTE The Wigner distribution is a function of two spatial and two angular coordinates, giving the amount of beam power propagating through the point (x,y) in the direction (Θ_x, Θ_y).

3.5
spatial first order moments of the Wigner distribution
$\langle x \rangle, \langle y \rangle$

subset of the first order moments, which can be directly obtained from measured power density distribution by

$$\langle x \rangle (z) = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x,y,z)\, x \;\mathrm{d}x\;\mathrm{d}y}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x,y,z)\,\mathrm{d}x\;\mathrm{d}y} \quad (2)$$

and

$$\langle y \rangle (z) = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x,y,z)\, y \;\mathrm{d}x\;\mathrm{d}y}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x,y,z)\,\mathrm{d}x\;\mathrm{d}y} \quad (3)$$

where $E(x,y,z)$ is the power density distribution at the specific plane z = constant.

3.6
second order moments of the Wigner distribution
$\left\langle x^2 \right\rangle, \left\langle y^2 \right\rangle, \left\langle xy \right\rangle, \left\langle \Theta_x^2 \right\rangle, \left\langle \Theta_y^2 \right\rangle, \left\langle \Theta_x \Theta_y \right\rangle, \left\langle x\Theta_x \right\rangle, \left\langle x\Theta_y \right\rangle, \left\langle y\Theta_x \right\rangle, \left\langle y\Theta_y \right\rangle$

ten second order moments of the Wigner distribution of the beam at location z

NOTE 1 The ten second order moments contain information on the following physical beam properties: beam size and orientation, divergence angles and their orientation, radii of curvature of the phase paraboloid and their orientation and the twist parameter. Details on these relations are given in ISO/TR 11146-3.

NOTE 2 In ISO 11146-1, the three spatial second order moments are defined as σ_x^2, σ_y^2 and σ_{xy}^2. In this part of ISO 11146 and ISO/TR 11146-3, the angular brackets are used to emphasize the coordinates of the moments. This means that $\sigma_x^2 = \langle x^2 \rangle$, $\sigma_y^2 = \langle y^2 \rangle$ and $\sigma_{xy}^2 = \langle xy \rangle$.

NOTE 3 Three angular moments $\langle \Theta_x^2 \rangle$, $\langle \Theta_y^2 \rangle$ and $\langle \Theta_x \Theta_y \rangle$ are independent of z. The other seven second order moments are, in general, functions of z.

3.7
spatial second order moments of the Wigner distribution
$\langle x^2 \rangle, \langle y^2 \rangle, \langle xy \rangle$

subset of the second order moments, which can be directly obtained from measured power density distribution by

$$\langle x^2 \rangle (z) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)(x - \langle x \rangle)^2 \mathrm{d}x \; \mathrm{d}y}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z) \mathrm{d}x \; \mathrm{d}y} \tag{4}$$

$$\langle y^2 \rangle (z) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)(y - \langle y \rangle)^2 \mathrm{d}x \; \mathrm{d}y}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z) \mathrm{d}x \; \mathrm{d}y} \tag{5}$$

and

$$\langle xy \rangle (z) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z)(x - \langle x \rangle)(y - \langle y \rangle) \mathrm{d}x \; \mathrm{d}y}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E(x,y,z) \mathrm{d}x \; \mathrm{d}y} \tag{6}$$

3.8
beam matrix
P
symmetric and positive definite 4×4 matrix containing all ten second order moments of the Wigner distribution and its elements and given by

$$\boldsymbol{P} = \begin{bmatrix} \langle x^2 \rangle & \langle xy \rangle & \langle x\Theta_x \rangle & \langle x\Theta_y \rangle \\ \langle xy \rangle & \langle y^2 \rangle & \langle y\Theta_x \rangle & \langle y\Theta_y \rangle \\ \langle x\Theta_x \rangle & \langle y\Theta_x \rangle & \langle \Theta_x^2 \rangle & \langle \Theta_x\Theta_y \rangle \\ \langle x\Theta_y \rangle & \langle y\Theta_y \rangle & \langle \Theta_x\Theta_y \rangle & \langle \Theta_y^2 \rangle \end{bmatrix} \tag{7}$$

3.9
effective beam propagation ratio
M_{eff}^2
invariant quantity related to the focusability of a general astigmatic beam, defined as:

$$M_{\text{eff}}^2 = \frac{4\pi}{\lambda}\left[\det(\boldsymbol{P})\right]^{\frac{1}{4}} \quad (8)$$

where det ($\boldsymbol{P}$) is the determinant of matrix $\boldsymbol{P}$

NOTE 1 The effective beam propagation ratio M_{eff}^2 is an invariant related to the overall beam spread or the near and far field localization of the beam.

NOTE 2 For simple astigmatic beams, the effective beam propagation ratio is the geometric mean of the beam propagation ratios of the principal axes of the beam: $M_{\text{eff}}^2 = \sqrt{M_x^2 \times M_y^2}$. For stigmatic beams $M_{\text{eff}}^2 = M^2$.

3.10
intrinsic astigmatism

a

degree of how close to a stigmatic beam the general astigmatic beam can be transformed by using lenses and free spaces

$$a = \frac{8\pi^2}{\lambda^2}\left(\left(\langle x^2\rangle\langle\Theta_x^2\rangle - \langle x\Theta_x\rangle^2\right) + \left(\langle y^2\rangle\langle\Theta_y^2\rangle - \langle y\Theta_y\rangle^2\right) + 2\left(\langle xy\rangle\langle\Theta_x\Theta_y\rangle - \langle x\Theta_y\rangle\langle y\Theta_x\rangle\right)\right) - \left(M_{\text{eff}}^2\right)^2 \geqslant 0 \quad (9)$$

NOTE Beams are classified according to their intrinsic astigmatism a, which is an invariant quantity. A beam with $a = 0$ is called intrinsic stigmatic, a beam with $a > 0$ is called intrinsic astigmatic. For simple astigmatic beams $a = (1/2)\left(M_x^2 - M_y^2\right)^2$. More details are given in ISO/TR 11146-3.

3.11
twist parameter

t

parameter related to the rotational properties of the phase front of a beam, and also to the orbital angular momentum carried by the beam

$$t = \langle x\Theta_y\rangle - \langle y\Theta_x\rangle \quad (10)$$

NOTE The twist parameter is invariant under propagation through free space and spherical lenses. It might be altered under propagation through cylindrical lenses.

3.12
principal axes of a power density distribution

axes of the maximum and minimum beam extent based on the centred second order moments of the power density distribution in a cross-section of the beam

[ISO 11146-1:2005]

NOTE The axes of maximum and minimum extent are always perpendicular to each other.

3.13
orientation of a power density distribution

φ

angle between the x–axis of the laboratory system and that of the principal axis of the power density distribution which is closer to the x–axis

[ISO 11146-1:2005]

NOTE From this definition it follows that $-\frac{\pi}{4} < \varphi < \frac{\pi}{4}$ for $|\varphi| \neq \pi/4$; if $\varphi = \pm\pi/4$, φ is defined as the angle between the x– axis and the major principal axis of the power density distribution.

3.14
beam widths
$d_{\sigma x}, d_{\sigma y}$
extent of a power density distribution in a cross-section of the beam at an axial location z along that principal axis which is closer to the x- or y-axis of the laboratory coordinate system, respectively, based on the centred second order moments of the power density distribution

NOTE If the principal axes make the angle $\pi/4$ with the x– and y-axes of the laboratory coordinate system, then $d_{\sigma x}$ is by convention the larger beam width.

[ISO 11146-1:2005]

4 Coordinate system

The x–, y– and z–axes define the orthogonal space directions in the laboratory axes system and shall be specified by the user. The z–axis shall approximately coincide with the direction of the beam. The x– and y–axes are transverse axes, usually horizontal and vertical, respectively. The origin of the z-axis is in a reference x–y plane defined by the manufacturer, e.g. the front of the laser enclosure.

5 Test principles

5.1 General

The following test principles are valid for general astigmatic beams. For stigmatic and simple astigmatic beams ISO 11146-1 may be applied.

5.2 Spatial second order moments of the Wigner distribution

Spatial second order moments are obtained by acquisition of power density distributions by means of spatially resolving detectors, correcting the measured profiles and calculating the first and second order moments.

5.3 Second order moments of the Wigner distribution

For the determination of all ten second order moments two different measurement set-ups are required.

Eight of the ten second order moments and the sum $\left(\left\langle x\Theta_y\right\rangle + \left\langle y\Theta_x\right\rangle\right)$ are obtained by acquisition of power density distributions along the propagation axis z in different planes near the generalized waist position, calculating the three spatial second order moments of each measured power density profile and fitting three independent parabolas to them.

The difference $\left(\left\langle x\Theta_y\right\rangle - \left\langle y\Theta_x\right\rangle\right)$ is obtained from the spatial moments of a power density distribution acquired behind a cylindrical lens.

5.4 Derived quantities

The effective beam propagation ratio M^2_{eff}, the intrinsic astigmatism a, and the twist parameter t are obtained from the second order moments of the Wigner distribution according to the Equations (8) to (10).