
**Optics and photonics — Effective
numerical aperture of laser lenses —
Definition and verification procedure**

*Optique et photonique — Ouverture numérique efficace des lentilles
laser — Définition et procédure de vérification*

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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Lenses are used in the field of laser beam forming, typically for collimation of divergent radiation or for focusing collimated radiation to obtain very small spots. A distinction is made between rotational symmetric lenses on one hand and cylindrical lenses, which provide optical power only in one direction, on the other hand.

Two crucial quality characteristics can be defined for such lenses: the trivial demand that the lenses should not clip the laser beam during propagation and the more sophisticated requirement, that they should not significantly increase the beam propagation factor of a traversing beam.

If the divergence angle of the beam before or after the lens is large, the geometric form of the surfaces of the lens needs to be carefully designed to an aspherical or acylindrical form to fulfill the second requirement. The desired form of the surfaces depends on the intended use of the lens and the wavelength of the laser radiation.

In fabrication and application of such lenses the following problems may arise, even in combination:

- in fabrication of the lens the optimum surface form has not been reproduced;
- the lens is applied to a laser beam with a different wavelength than the design wavelength.

Non-well designed or non-well produced lenses or lenses applied to beams with wavelength for which the lens has not been designed may still be useful as long as the involved divergence angles are small enough.

To account for this, an effective numerical aperture is defined here as the sine of half of the maximum divergence angle a laser beam may have before the lens, when it collimates the beam, or after the lens, when it focuses the beam, to ensure that the aberrations introduced by the lens to the beam at the given wavelength is acceptable.

This definition is in close relationship to ISO 11146-1, which is important in the field of laser beam characterization. It provides the decisive parameter in the field of laser beam forming. Furthermore, it is related to a fairly simple verification procedure, which can be applied by manufacturers of laser lenses as well as users with acceptable effort.

Optics and photonics — Effective numerical aperture of laser lenses — Definition and verification procedure

1 Scope

This document covers terms, definitions, and a verification procedure to characterize the ability of laser lenses to collimate divergent laser beams and to focus collimated laser to small spot sizes. The aim of this document is to give users reliable information on the applicability of laser lenses in the field of beam forming.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 11146-1, *Lasers and laser-related equipment — Test methods for laser beam widths, divergence angles and beam propagation ratios — Part 1: Stigmatic and simple astigmatic beams*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at <https://www.iso.org/obp>

— IEC Electropedia: available at <https://www.electropedia.org/>

NOTE Within this document, the terms power density and energy density are used in units of areal densities. According to the common understanding in the fields of optics, photonics and laser technology, the term power density is generally perceived in unit of areal density. In this document, the term energy density also follows this specification. In text books, this power density is also denoted as irradiance and this energy density as fluence.

3.1

beam diameter

$d_u(z)$

<encircled power (energy)> diameter of a circular aperture in a plane perpendicular to the beam axis that contains u % of the total beam power (energy)

Note 1 to entry: For clarity, the term “beam diameter” is always used in combination with the symbol and its appropriate subscript: d_u or d_σ .

[SOURCE: ISO 11145:2018, 3.3.1]

3.2

beam diameter

$d_\sigma(z)$

<second moment of power (energy) density distribution function> diameter defined by using the second moment of the power (energy) density distribution function

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

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

$$\sigma^2(z) = \frac{\iint \left((x - \bar{x}(z))^2 + (y - \bar{y}(z))^2 \right) \cdot E(x, y, z) \cdot dx dy}{\iint E(x, y, z) \cdot dx dy}$$

where the first moments give the coordinates of the beam centroid $[\bar{x}(z), \bar{y}(z)]$

Note 1 to entry: For clarity, the term “beam diameter” is always used in combination with the symbol and its appropriate subscript: d_u or d_σ .

[SOURCE: ISO 11145:2018, 3.3.2]

**3.3
beam widths**

$d_{x,u}(z), d_{y,u}(z)$

<slit transmitted power (energy)> width of the smallest slit aligned with the x or y transverse axes of the power (energy) density distribution function, transmitting u % of the total beam power (energy) along x or y

Note 1 to entry: For circular Gaussian beams, $d_{x,95,4}$ and $d_{y,95,4}$ both equal $d_{86,5}$.

Note 2 to entry: For clarity, the term “beam width” is always used in combination with the symbol and its appropriate subscripts: $d_{\sigma x}, d_{\sigma y}$ or $d_{x,u}, d_{y,u}$.

[SOURCE: ISO 11145:2018, 3.5.1]

**3.4
beam widths**

$d_{\sigma x}(z), d_{\sigma y}(z)$

<second moment of power (energy) density distribution function> width defined by using the second moment of the power (energy) density distribution function along x or y

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

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

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

$$\sigma_x^2(z) = \frac{\iint (x - \bar{x}(z))^2 \cdot E(x, y, z) \cdot dx dy}{\iint E(x, y, z) \cdot dx dy}$$

$$\sigma_y^2(z) = \frac{\iint (y - \bar{y}(z))^2 \cdot E(x, y, z) \cdot dx dy}{\iint E(x, y, z) \cdot dx dy}$$

where $(x - \bar{x}(z))$ and $(y - \bar{y}(z))$ are the distances from the current point's coordinates to the beam centroid $(\bar{x}(z), \bar{y}(z))$

Note 1 to entry: For clarity, the term “beam width” is always used in combination with the symbol and its appropriate subscripts: $d_{\sigma x}, d_{\sigma y}$ or $d_{x,u}, d_{y,u}$.

[SOURCE: ISO 11145:2018, 3.5.2]

**3.5
beam waist**

portion of a beam where the beam diameter or beam width has a local minimum

[SOURCE: ISO 11145:2018, 3.7.1]

3.6**beam waist diameter** $d_{0,u}$

<encircled power (energy)> diameter d_u of the beam at the location of the beam waist

[SOURCE: ISO 11145:2018, 3.7.4, modified — Note 1 to entry was deleted.]

3.7**beam waist width** $d_{x0,u}$, $d_{y0,u}$

<slit transmitted power (energy)> beam widths $d_{x,u}$ and $d_{y,u}$ at the locations of the beam waists in the x and y directions, respectively

[SOURCE: ISO 11145:2018, 3.7.8, modified — Note 1 to entry was deleted.]

3.8**beam waist location** z_{0x} , z_{0y} , z_0

location where the beam widths or the beam diameters reach their minimum values along the beam axis

[SOURCE: ISO 11145:2018, 3.7.2, modified — Note 1 to entry was deleted.]

3.9**astigmatic beam waist separation** Δz_a

axial distance between the beam waist locations in the orthogonal principal planes of a beam possessing simple astigmatism

[SOURCE: ISO 11145:2018, 3.7.3, modified — Note 1 to entry was deleted.]

3.10**divergence angle** θ_u , $\theta_{x,u}$, $\theta_{y,u}$

<encircled, slit transmitted power (energy)> full angle formed by the asymptotic cone of the envelope formed by the increasing beam diameter (width)

[SOURCE: ISO 11145:2018, 3.8.1, modified — Notes 1 to 4 to entry and the example were deleted.]

3.11**divergence angle** θ_σ , $\theta_{\sigma x}$, $\theta_{\sigma y}$

<second moment of power (energy) density distribution function> full angle formed by the asymptotic cone of the envelope formed by the increasing beam diameter (width)

[SOURCE: ISO 11145:2018, 3.8.2, modified — Notes 1 to 3 to entry were deleted.]

3.12**Rayleigh length** z_{Rz} , z_{Rx} , z_{Ry}

distance from the beam waist in the direction of propagation for which the diameter and beam width are equal to $\sqrt{2}$ times their respective values at the beam waist

[SOURCE: ISO 11145:2018, 3.9.1, modified — Notes 1 and 2 to entry were deleted.]

3.13 beam propagation ratio

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

Note 1 to entry: In contrast to ISO 11145:2018, 3.10.2, in this document the beam propagation ratio is not defined by the second order moments based definitions of beam diameter, beam width, and divergence angles, but instead by the power content based counterparts given in 3.2, 3.4, and 3.11 of this document and ISO 11145:2018, 3.7.5 and 3.7.9.

3.14 residual divergence angle

angle of divergence $\theta_u, \theta_{xu}, \theta_{yu}, \theta_\sigma, \theta_{\sigma x}, \theta_{\sigma y}$ of a divergent laser beam after collimation by a laser lens

3.15 effective numerical aperture

NA_{eff}
sine of half of the maximum divergence angle, which a nearly diffraction limited beam can have before it is truncated by the finite geometry of the lens or its beam propagation ratio along the collimating direction of the lenses is increased by more than 0,5 due to aberrations

Note 1 to entry: The effective numerical aperture is always less or equal to the geometrical aperture of the lens.

4 Coordinate systems

The coordinate system is defined according to ISO 11146-1.

The laser beam propagates along the z-axis. In case of simple astigmatic laser beams the x- and y-axis are aligned parallel to the principal axes of the beam.

5 Short description of the verification procedure

For the verification procedure a divergent probe laser beam source with known divergence angle and beam propagation ratio is required. Simple-astigmatic laser beams with equal divergence angles in both principal directions shall have a beam propagation ratio M^2 of less than 1,5 along at least one principal direction. Simple-astigmatic laser beams with non-equal divergence angles shall have a beam propagation ratio M^2 below 1,5 along the principal axis having the larger divergence angle.

The divergent laser beam is collimated by the laser lens under investigation. If a cylindrical laser lens is under investigation, the laser beam shall be orientated such, that the higher divergent principal direction is parallel to the working direction of the lens.

In the following the probe laser beam before collimation by the laser lens under investigation will be called the initial beam. Its divergence will be called the initial divergence and its beam parameters the initial beam parameters.

In the preferred version of the verification procedure the beam propagation ratio M^2 of the collimated beam in the principal direction with higher initial divergence or in working direction of the collimating lens will be measured according to ISO 11146-1. If the initial beam propagation ratio has been increased due to the collimation by the laser lens under investigation by less than absolute 0,5, then the sine of half the divergence angle of the divergent laser beam is considered a proven lower limit of the effective numerical aperture of the lens at the wavelength of the laser beam.

In another version of the verification procedure only the residual divergence after collimation in the principal direction with higher initial divergence or in working direction of the collimating laser lens will be measured and compared to a theoretical residual divergence, calculated from the initial divergence angle and the initial beam propagation factor before collimation and the focal length of the laser lens under investigation. If the measured residual divergence angle differs from the theoretical one less than a limit, which again depends on the initial divergence angle and the focal length of the

laser lens, then the sine of half the divergence angle of the initial laser beam is considered to be a proven lower limit of the effective numerical aperture of the laser lens at the wavelength of the laser beam.

6 Permitted beam sources

For the verification procedure high-divergent, nearly diffraction limited probe laser beams are required. These laser beams shall be stigmatic or simple-astigmatic, according to the definitions of ISO 11146-1. Pseudo-stigmatic, pseudo-simple-astigmatic or general-astigmatic beams are not allowed.

For stigmatic laser beams a beam propagation ratio M^2 of less than 1,5 shall be proven.

For simple-astigmatic laser beams a beam propagation ratio M^2 of less than 1,5 shall be proven for the higher divergent principal direction.

The divergence angle of the laser beam (in case of simple-astigmatic laser beams: the larger divergence angle) determines the maximum effective numerical aperture that can be proven by the verification procedure.

High-divergent laser beams of this kind might be emitted by diode lasers or single-mode fibers. It is allowed to increase the divergence of the initial laser beam by means of optical components to meet the requirements of the effective numerical aperture to be proven, as long as the final laser beam satisfies the requirements given in this clause.

7 Measurement of the beam propagation ratio of the initial probe laser beam (before collimation)

The determination of the beam propagation ratio of the initial, high-divergent probe beam shall be performed according to the specifications of ISO 11146-1. In contrast to ISO 11146-1 in this document the beam propagation ratio shall not be defined by the second order moments based definitions of beam diameter, beam width, and divergence angles, but instead by the power content based counterparts given in [3.1](#), [3.3](#), [3.6](#), [3.7](#), and [3.10](#) of this document. For beam diameters and beam widths a power content of 86,5 % and 95 %, respectively, shall be used.

Since the beam propagation ratio of high-divergent laser beams may not be directly obtainable, it might be necessary to collimate the beam to be able to perform the measurement. In this case it is important to use an optical system with proven high numerical aperture, e.g. a suitable microscope lens.

8 Measurement of the divergence angle of the initial laser beam (before collimation)

The determination of the divergence angle of the laser beam should be done by a goniometric measurement. In case of simple-astigmatic beams, the divergence angles in both principal axis have to be measured.

NOTE It is necessary to measure the divergence angle with the goniometric method due to the expectedly high divergence angles of the initial laser beam. These prevent the (indirect) measurement of the divergence angle by measuring the beam diameter in the focal plane of an auxiliary lens as proposed in ISO 11146-1.

For the goniometric measurement a power (energy) detector has to be moved along a semicircle which has to be centered with the waist (virtual source point) of the laser beam. The radius of the semicircle shall be larger than ten times the (estimated) Rayleigh length of the laser beam (for simple-astigmatic beams: the larger of the two Rayleigh lengths along both principal axes) and shall be larger than twenty times the size of the sensitive area of the detector.

The sensitive area of the detector shall be kept orthogonal to the connecting line from the center of the semicircle to the detector.

The plane of the semicircle shall contain the optical axis of the laser beam (beam axis).