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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

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This document was prepared by Technical Committee ISO/TC 172, *Optics and Photonics*, Subcomittee SC 9, *Laser and electro-optical systems*.

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

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

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:

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

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

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_R, 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 Θ_u, Θ_{xu}, Θ_{yu}, Θ_σ, $\Theta_{\sigma x}$, $\Theta_{\sigma y}$ 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.

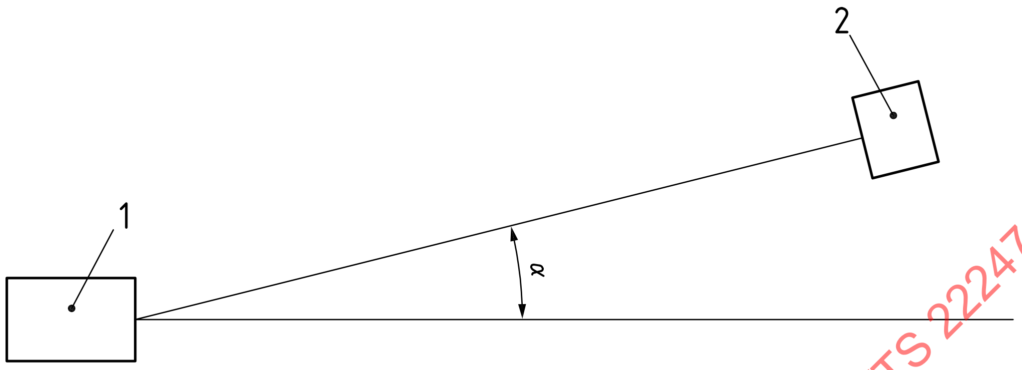
For the goniometric measurement a power (energy) detector has to be moved along a semicircle which has to be centered with the waist (virtual source point) of the laser beam. The radius of the semicircle shall be larger than ten times the (estimated) Rayleigh length of the laser beam (for simple-astigmatic 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).

By moving the detector along the semicircle the power (energy) shall be measured as a function of the angle between the optical axis and the connection line from the center of the semicircle to the detector. The angle range containing 95 % of the complete power (the remaining 5 % equally distributed to both sides of the range) is considered as the full divergence angle in the plane of the semicircle.

For simple-astigmatic beams this measurement has to be performed for both principal axes.



Key

1 laser

2 detector

α angle between the optical axis and the connection line from the center of the semicircle to the detector

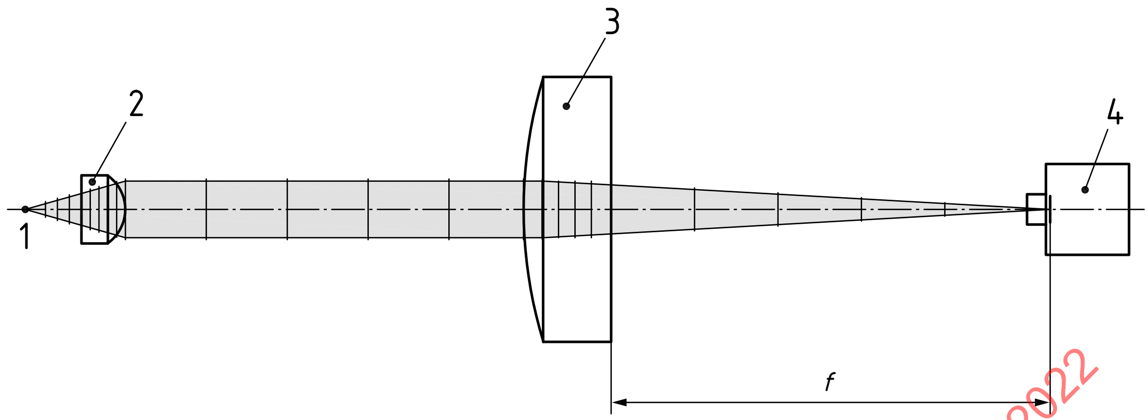
Figure 1 — Principle of a goniometric measurement

9 Verification of the effective numerical aperture of rotational symmetric laser lenses based on the beam propagation ratio

If a simple-astigmatic laser beam is used for this measurement, its astigmatic beam waist separation shall be negligible, i.e. it shall be at least ten times smaller than the smaller of the two Rayleigh lengths along both principal directions.

The laser lens under investigation is inserted into the divergent probe laser beam having the right orientation (front side, back side) according to the manufacturers instructions. The beam axis and the optical axis shall be approximately coaxial. By moving the laser lens along the optical axis a coarse collimation is done. By moving the laser lens transversal to the optical axis the beam axis of the collimated beam is adjusted coaxial to the optical axis of the system.

An auxiliary lens with a long focal length is inserted in the collimated beam, such that beam axis after this lens is still coaxial to the optical axis. Then a spatially resolving detector (e.g. CCD camera) is placed in the focal plane of this lens as shown in Figure 2. For the auxiliary lens and the detector the requirements of ISO 11146-1 apply.



Key

1 laser

2 test specimen (laser lens)

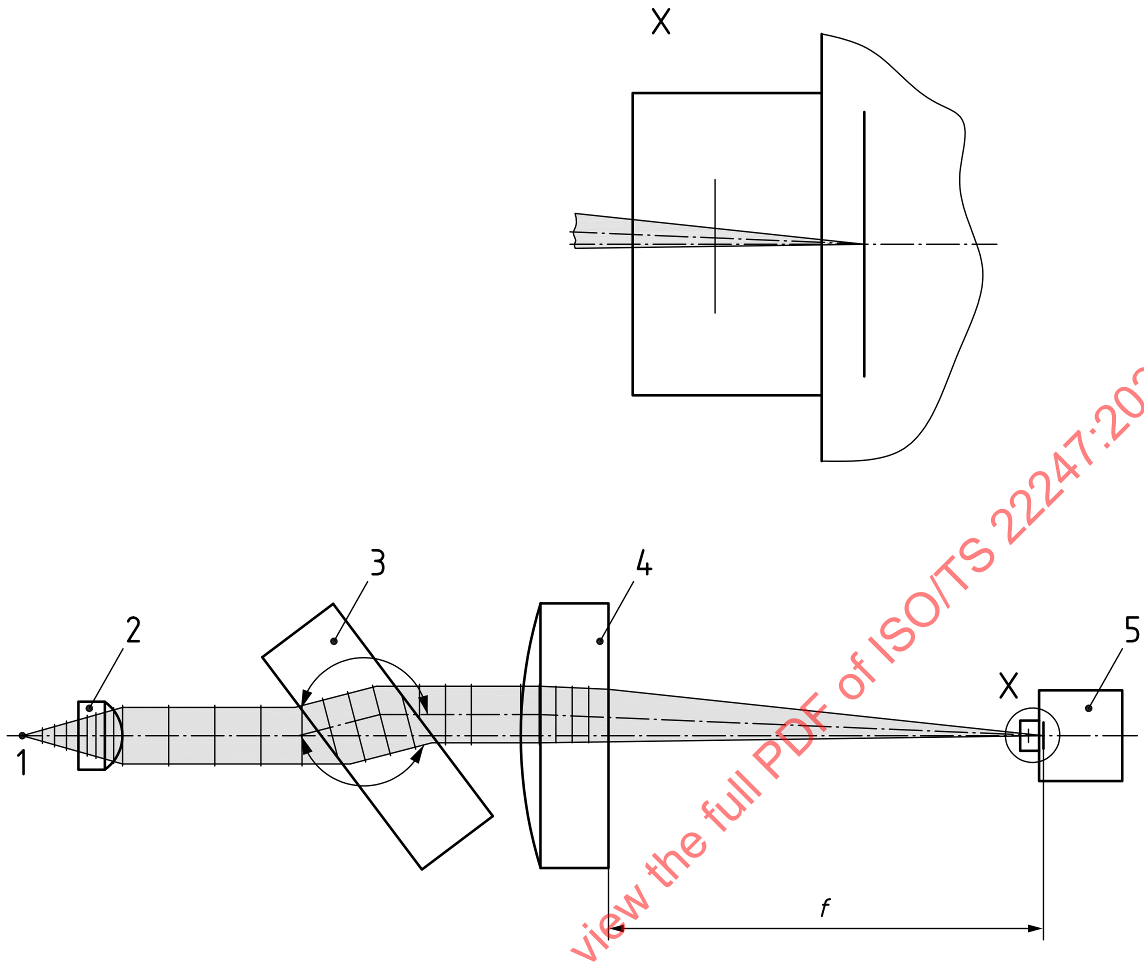
3 auxiliary lens

4 detector

f focal length of auxiliary lens

Figure 2 — Schematic drawing of the setup

NOTE A plane-parallel glass substrate can be used as an auxiliary tool to find to the correct position of the spatially resolving detector. This substrate can be temporarily inserted in the collimated beam in front of the auxiliary lens. By rotating the substrate around an axis orthogonal to the beam axis the collimated beam will be transversally shifted without changing its direction (see Figure 3). The correct position of the detector is characterized by a non-moving beam profile when rotating the substrate. After this test the substrate will be removed.



Key

1	laser
2	test specimen (laser lens)
3	plane parallel plate
4	auxiliary lens
5	detector
f	focal length of auxiliary lens

Figure 3 — Proposed method to determine the correct detector position

The extension of the beam profile in the focal plane of the auxiliary lens is proportional to the residual divergence behind the lens under investigation.

Having the detector correctly placed in the focal plane fine adjustment of the laser lens under investigation is done by moving it along all three spatial directions and by rotating it around two axes, both orthogonal to the beam axis (shown in Figure 4) trying to minimize the residual divergence and thus the extension of the beam profile measured by the spatially resolving detector. In case of a stigmatic beam the extension is defined by the beam diameter $d_{86,5}$. In case of a simple-astigmatic beam the beam widths d_{x95} and d_{y95} are used and the beam width along the direction of the principal axis of the larger initial divergence is minimized.

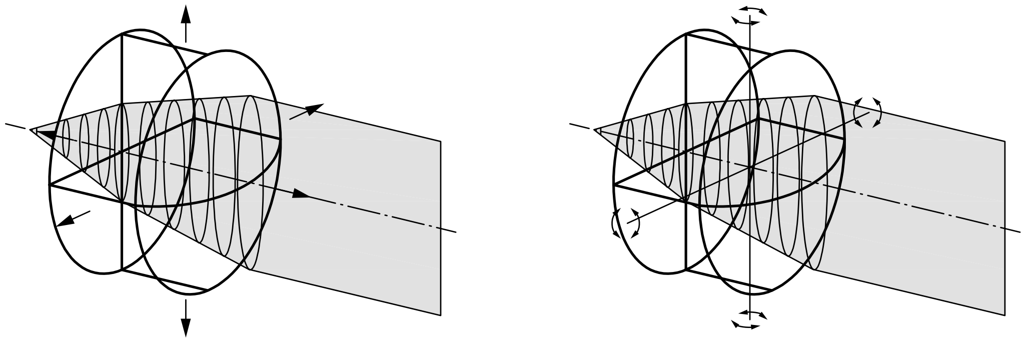


Figure 4 — Degrees of freedom for fine adjustment of the laser lens: three positional degrees of freedom and two rotational degrees of freedom

After this fine adjustment of the laser lens under investigation the beam propagation ratio M^2 is measured by moving the detector along the optical axis according to ISO 11146-1 (see Figure 5). In contrast to ISO 11146-1 the beam diameters and beam widths defined by the second order moments are replaced by the power content based counterparts $d_{86,5}$, d_{x95}, and d_{y95} given in 3.1, 3.3, 3.6, 3.7, and 3.10.

If a simple-astigmatic laser beam is used only the beam propagation ratio M^2 along the direction of the principal axis with the larger divergence is measured.

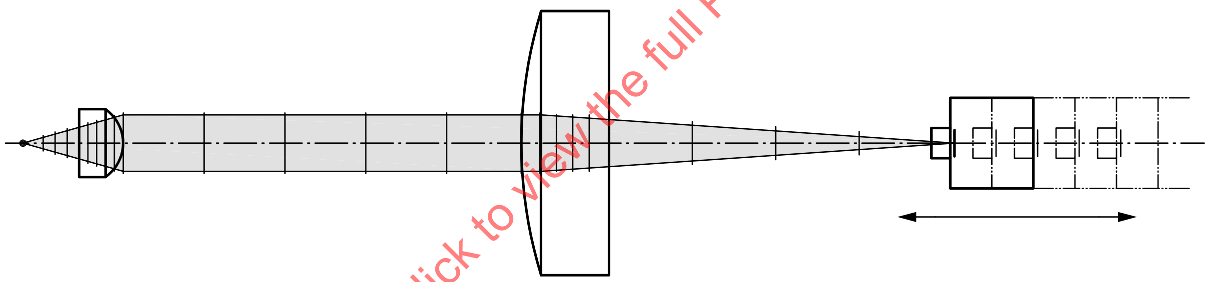


Figure 5 — Acquisition of a beam caustic for the determination of the beam propagation ratio M^2 according to ISO 11146-1

If the measured beam propagation ration M^2 has been increased (compared to the initial high divergent probe beam) by less than 0,5, then the sine of half of the initial divergence angle is a proven lower limit for the effective numerical aperture of the laser lens under investigation at the wavelength of the probe laser beam.

10 Verification of the effective numerical aperture of rotational symmetric laser lenses based on the residual divergence

In this shorter variant of the procedure the measurement of the beam propagation ratio is dispensed. Instead, it relies solely on the residual divergence of the beam collimated by the laser lens under investigation.

It is performed in the same way as the full procedure given in Clause 9 and including the step of fine adjusting the laser lens under investigation. The minimum reachable residual divergence is then used as the criterion for the verification of the effective numerical aperture.

Assuming collimation of the initial high divergent probe beam without any aberrations will result in the following theoretical limit of the residual divergence angle after collimation:

$$\theta_{\text{res,theo}} = \frac{1}{f_{\text{coll}}} M^2 \frac{4\lambda}{\pi} \frac{1}{\theta}$$

where

M^2 is the beam propagation ratio of the initial probe beam;

λ is the wavelength of the beam;

θ is the divergence angle of the initial probe beam ($\theta_{86,5}$, respectively θ_{x95} or θ_{y95});

f_{coll} is the effective focal length of the laser lens under investigation at the wavelength of the beam.

NOTE It can be necessary to experimentally determine the effective focal length of the laser lens under investigation at the wavelength of the beam. If the focal length of the auxiliary lens is known with sufficient precision, the focal length of the laser lens under investigation can be determined by transversely shifting the beam source or the laser lens under investigation and measuring the resulting shift of the beam profile in the focal plane of the auxiliary lens (see Figure 6).

$$f_{\text{coll}} = f \frac{\Delta_{\text{cam}}}{\Delta}$$

where

f is the focal length of the auxiliary lens;

Δ is the transverse displacement of the source or of the laser lens under investigation;

Δ_{cam} is the resulting displacement of the beam profile in the focal plane of the auxiliary lens.

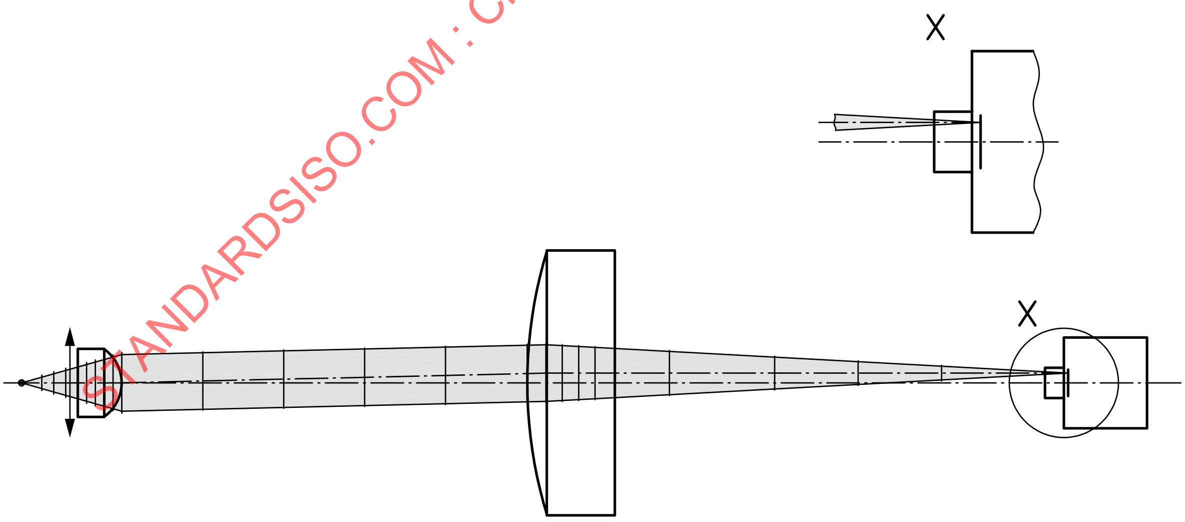


Figure 6 — Setup to determine focal length of laser lens under investigation

The actual residual divergence angle is obtained by the ratio of the beam width d_{meas} in the focal plane of the auxiliary lens to its focal length f:

$$\theta_{res,meas} = \frac{d_{meas}}{f}$$

where d_{meas} is given by d_{86} respectively d_{x95} or d_{y95}.

The sine of half of the initial divergence angle is a proven lower limit for the effective numerical aperture of the lens at the wavelength of the laser beam if the actual residual divercence angle doesn’t exceed the theoretical limit by more than a certain amount. The following condition shall be met:

$$\theta_{res,meas} - \theta_{res,theo} < 0{,}5 \frac{4\lambda}{\pi} \frac{1}{f_{coll}} \frac{1}{\theta}$$

11 Verification of the effective numerical aperture of cylindrical laser lenses

The verification procedure is basically the same as for rotationally symmetric lens given in the previous Clauses 9 and 10.

If a simple-astigmatic laser beam is used, it shall be orientated in such a way that the direction of the higher divergent principal axis is parallel to the working direction of the laser lens under investigation. Determination of diameters, divergence angles and beam propagation ratios is always done along this direction, too.

NOTE The divergence angle of the probe beam along the non-working direction of the laser lens under investigation can result in beam profile widths larger than the detector size along this direction as shown in Figure 7. This is unoffending since only beam widths along the working direction of the lens are required.

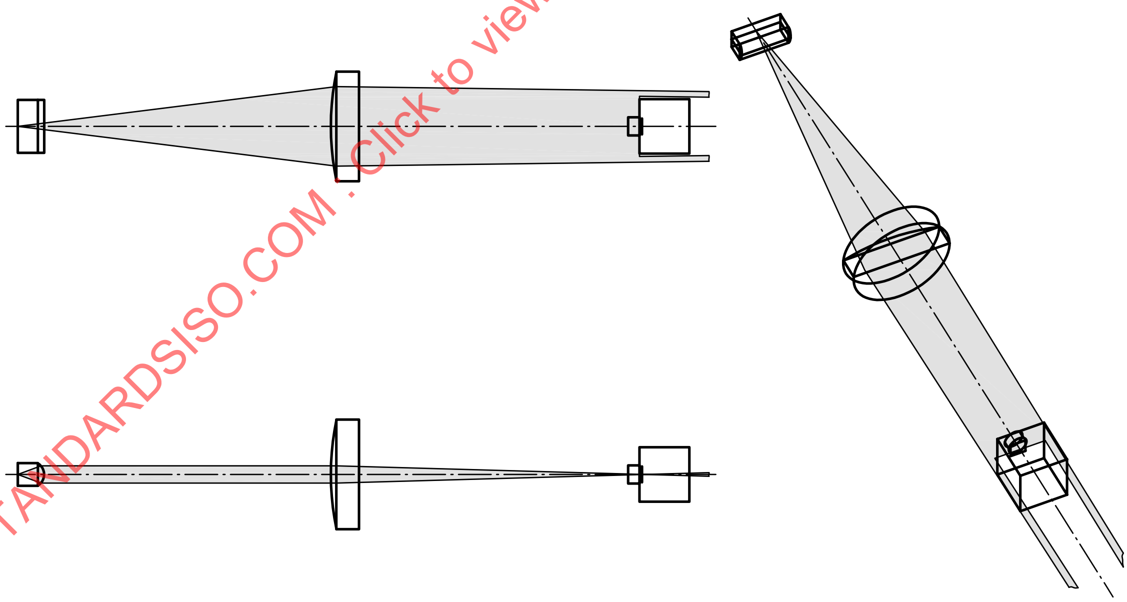
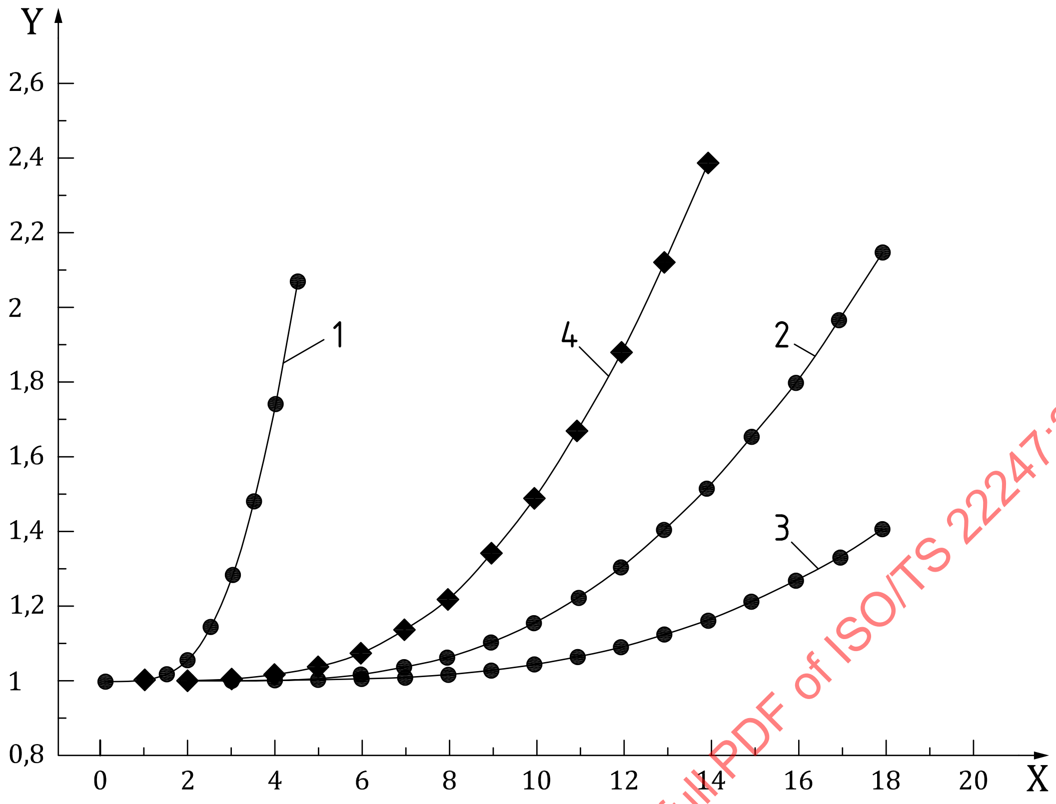


Figure 7 — Optical setup for the verification of the effective numerical aperture of cylindrical lenses

When testing cylindrical laser lenses an additional complication may occur: the divergence of the probe beam along the non-working direction of the laser lens under investigtion may increase the residual divergence of the collimated beam along the working direction of the laser lens, even if its surface shape is perfect. This is caused by skew radiation portions and cannot by blamed to the laser lens under investigation. This effect starts at divergence angles of approximately 2° for focal lengths around 10 mm and approximately 6° at focal length around 1 mm (see Figure 8).



Key

X lat. div [°]

Y vert. M^2

1 f = 10 mm, vert. angle = 40°

2 f = 1,0 mm, vert. angle = 40°

3 f = 0,5 mm, vert. angle = 40°

4 f = 1,0 mm, vert. angle = 55°

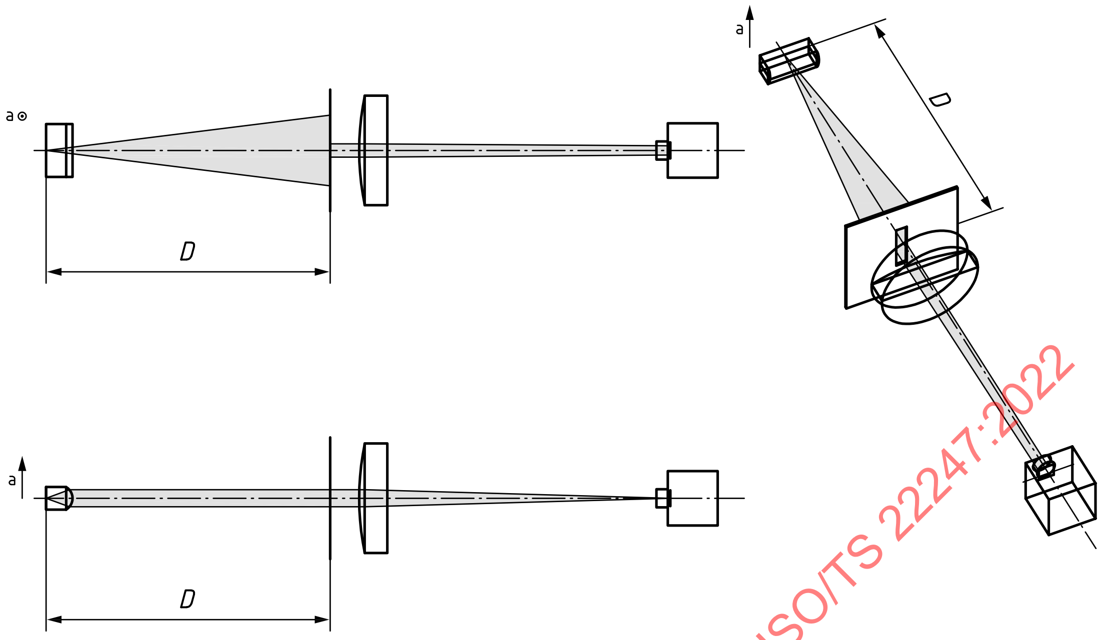
NOTE FAC (fast axis collimation) lens with NA = 0,8.

Figure 8 — Simulation the increase of the beam parameter product caused by the divergence in the non-working direction of the collimating cylindrical lens, given for different focal lengths

To distinguish the effect of real aberrations (due to non-perfect surfaces) from the effect caused by skew radiation portions, it is necessary to use beam sources with divergence angles less than 1,5° along the non-working direction of the laser lens or, if this is not possible, to remove the disturbing radiation portions by an additional aperture in the optical setup.

The finite size (along the non-working direction) of the spatial resolving detector itself may act as such an aperture. If the size of the detector (e.g. the CCD chip) is smaller than 0,05 times the focal length of the auxiliary lens, portions of the initial beam propagating with an angle larger than 1,5° (in the non-working direction of the laser lens) do not contribute to the beam profile acquired by the detector in the setup shown in Figure 7.

Another possibility is to insert a slit diaphragm in the beam as shown in Figure 9.



Key

D distance between beam waist and slit diaphragm

a The arrow indicates the working direction of the lens.

Figure 9 — A slit diaphragm might be used to cut of undesirable radiation contributions

To cut off higher divergent and only higher divergent radiation contributions the distance *D* of the slit diaphragm to the beam waist of the divergent beam shall be larger than the five times the Rayleigh length (along the non-working direction of the lens). To sufficiently cut off the higher divergent contributions the width of the slit shall be smaller than 0,05 times the distance of the slit to the beam waist.

12 Long cylindrical laser lenses

12.1 General

For long cylindrical laser lenses the effective numerical aperture may depend on the position along the non-working direction of the lens. Hence, the verification procedure has to be performed at multiple, equidistant positions. This can be done sequentially or parallel.

The effective numerical aperture of such a long cylindrical laser lens is proven, if it is proven at each position. The number and pitch of the test positions shall be stated in the test report.

12.2 Sequential procedure

In the sequential procedure all measurement positions are examined consecutively, typically by shifting the long cylindrical laser lens as shown in Figure 10. At each measurement position the fine adjustment of collimation shall be repeated.

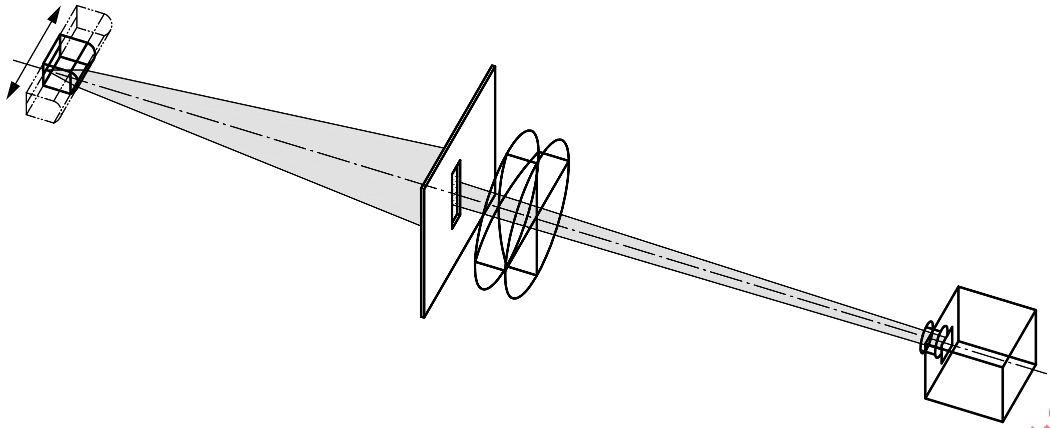


Figure 10 — Sequential procedure to verify the effective numerical aperture at different measurement positions on the same lens

12.3 Parallel procedure

In the parallel procedure the laser lens under investigation is simultaneously exposed at multiple positions by an array of laser beams. Each member of such an array shall fulfill the requirements of Clause 6 on permitted beam sources. The divergence angles of the individual members of the beam array (along the working direction of the laser lens) shall not differ more than 10 % from each other. The beam propagation ratios shall differ less than 20 %.

Beam sources with such properties could be laser diode bars.

The individual members of the beam array shall not overlap on the spatially resolving detector since evaluation of beam widths (along the working direction of the lens) shall be done separately for each beam.

A possible optical system to achieve this by inserting an additional long-focal-length cylindrical lens is shown in Figure 11. The working direction of the lens is orthogonal to the working direction of the laser lens under investigation. The axial position is chosen in order to approximately collimate all the individual members of the beam array.