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Lasers and laser-related equipment — Test methods for determination of the shape of a laser beam wavefront —

Part 1:
Terminology and fundamental aspects

Lasers et équipements associés aux lasers — Méthodes d'essai pour la détermination de la forme du front d'onde du faisceau laser —

Partie 1: Terminologie et aspects fondamentaux

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Foreword

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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 15367-1 was prepared by Technical Committee ISO/TC 172, *Optics and optical instruments*, Subcommittee SC 9, *Electro-optical systems*.

ISO 15367 consists of the following parts, under the general title *Lasers and laser-related equipment — Test methods for determination of the shape of a laser beam wavefront*:

— *Part 1: Terminology and fundamental aspects*

— *Part 2: Hartmann-Shack sensors*

Introduction

It is important, when designing, operating or maintaining a laser system, to be able to ensure repeatability, predict the propagation behaviour of the laser beam and to assess the safety hazards. There are four sets of parameters that could be measured for the characterization of a laser beam:

— power (energy) density distribution (ISO 13694);

— beam width, divergence angle and beam propagation factor (ISO 11146);

— phase distribution (ISO 15367);

— spatial beam coherence.

This part of ISO 15367 defines the terminology and symbols to be used when making reference to or measuring the phase distribution in a transverse plane of a laser beam. It specifies the procedures required for the measurement of

— the azimuth of the principal planes of the phase distribution;

— the magnitude of astigmatic aberrations;

— evaluation of the wavefront aberration function and the RMS wavefront deformation.

A useful technique for qualitative assessment of a beam is visual inspection of the fringe pattern in interferograms or an isometric view of a wavefront surface. However, more quantitative methods are needed for quality assurance and transfer of process technology. The measurement techniques indicated in this part of ISO 15367 allow numerical analysis of the phase distribution in a propagating beam and can provide recordable quantitative results.

While it is quite possible to ascribe other conventional aberrations (e.g. coma or spherical aberration) as well as astigmatism to a laser beam, these are not commonly used. Departure of the wavefront of a beam from some ideal surface is a more common indication of quality. On the other hand, rotational asymmetry has a much wider range of effects in a laser beam than is usually associated with astigmatism imposed on a beam of optical radiation by conventional optical systems. For this reason, various forms and characteristics of astigmatism in beams are now defined in detail.

The provisions of this part of ISO 15367 allow a test report to be commissioned with measurements or analysis of a selection of beam characteristics. Measurements of astigmatism are important to system designers who wish to specify optical elements for the correction of astigmatic beams. The measurement techniques defined in this part of ISO 15367 can also be used to assess any residual astigmatism after the addition of corrective elements and to aid with alignment.

A major application of phase distribution measurements comes with the possibility of combining those measurements with a simultaneous measurement of the power (energy) density distribution (ISO 13694) at the same location in the path of a beam. Digital processing of the data can reveal much more detailed characteristics of the propagating beam than can measurements of the power (energy) envelope resulting from calculation of the beam propagation ratio (ISO 11146). The more detailed information can be important to assessors of laser damage and safety hazards as well as process development engineers when it is necessary to know the power (energy) density distribution at the process interaction point.

Lasers and laser-related equipment — Test methods for determination of the shape of a laser beam wavefront —

Part 1: **Terminology and fundamental aspects**

1 Scope

This part of ISO 15367 specifies methods for the measurement of the topography of the wavefront of a laser beam by measurement and interpretation of the spatial distribution of the phase of that wavefront across a plane approximately perpendicular to its direction of propagation. Requirements are given for the measurement and analysis of phase distribution data to provide quantitative wavefront parameters and their uncertainty in a test report.

The methods described in this part of ISO 15367 are applicable to the testing and characterization of a wide range of beam types from both continuous wave and pulsed lasers. Definitions of parameters describing wavefront deformations are given together with methods for the determination of those parameters from phase distribution measurements.

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 9334, *Optics and optical instruments — Optical transfer function — Definitions and mathematical relationships*

ISO 10110-5, *Optics and optical instruments — Preparation of drawings for optical elements and systems — Part 5: Surface form tolerances*

ISO 11145, *Optics and optical instruments — Laser and laser-related equipment — Vocabulary and symbols*

ISO 11146, *Lasers and laser-related equipment — Test methods for laser beam parameters — Beam widths, divergence angle and beam propagation factor*

ISO 13694, *Optics and optical instruments — Lasers and laser-related equipment — Test methods for laser beam power (energy) density distribution*

ISO 15367-2, *Lasers and laser related equipment — Test methods for determination of the shape of a laser beam wavefront — Part 2: Hartmann-Shack sensors*

IEC 60825, (All parts), *Safety of Laser Products*

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

3 Terms and definitions

For the purposes of this document, the definitions given in ISO 9334, ISO 10110-5, ISO 11145, ISO 11146, ISO 13694 and IEC 61040 as well as the following apply.

3.1 General definitions

3.1.1
average wavefront shape
$w(x,y;z_m)$
continuous surface $w(x,y)$ that is normal to the time average direction of energy propagation in the electromagnetic field at the measurement plane $z = z_m$

NOTE 1 In the case of highly coherent radiation, the continuous surface $w(x,y)$ is a surface of constant phase. The phase distribution $\Phi(x,y)$ is then related to the wavefront distribution according to

$$\Phi(x,y) = \frac{2\pi}{\lambda} \cdot w(x,y)$$

where λ is the mean wavelength of the light.

NOTE 2 A continuous surface does not always exist.

3.1.2
wavefront surface
continuous surface $w(x,y)$ that minimizes the power density weighted deviations of the direction of its normal vectors to the direction of the energy flow vectors in the measurement plane

NOTE $w(x,y)$ is the surface that minimizes the expression

$$\iint E(x,y,z_m) \left| \hat{\vec{P}}_\perp(x,y,z_m) - \vec{\nabla}_\perp w(x,y,z_m) \right|^2 \mathrm{d}x\mathrm{d}y$$

where

$\hat{\vec{P}}_\perp(x,y,z) = \dfrac{\hat{\vec{P}}_\perp(x,y,z_m)}{E(x,y,z_m)}$ is the normalized transverse Poynting vector;

$\vec{\nabla}_\perp = \begin{pmatrix} \partial x \\ \partial y \end{pmatrix}$ is the transverse, two-dimensional gradient or Nabla operator.

3.1.3
phase
Φ
fraction of a wave period that has elapsed relative to that at a nominated origin

NOTE Phase is expressed in radians, modulo 2π.

3.1.4
measurement plane
z_m
axial location along the beam axis of the transverse plane in which the wavefront shape/surface is measured

3.1.5
mechanical axes
x, *y*, *z*
orthogonal transverse axes defined by the construction axes of the laser or the measuring system

NOTE The origin of the mechanical axis system should be identified and be coincident with some accessible and obvious location on the beam axis, be it a manufacturer's specification on the laser or reproducible location on the measuring instrument. The orientation of the transverse axes can be those associated with the laser or the vertical and horizontal axes in the measurement environment.

3.1.6
principal planes of wavefront shape/surface propagation
x'z and *y'z*
planes containing the principal axes of the wavefront and the beam axis

NOTE The principal planes of wavefront propagation will not necessarily coincide with the *xz* and *yz* planes of the laboratory system.

3.1.7
wavefront shape/surface co-ordinate system
x', *y'*, *z*
co-ordinate system used as reference axes for denoting the orientation of the principal axes of the astigmatic wavefront shape/surface relative to the mechanical axes of the measuring environment

NOTE The *x'*, *y'* and *z* axes define the orthogonal space directions of wavefront shape/surface in the beam axis system. The *x'* and *y'* axes are transverse to the beam and define the transverse plane. The origin of the *z*-axis is in a mechanical reference *xy* plane defined either by the manufacturer of the laser (e.g. the front of the laser enclosure) or by the measuring system. A schematic diagram of the axes system is shown in Figure 1.

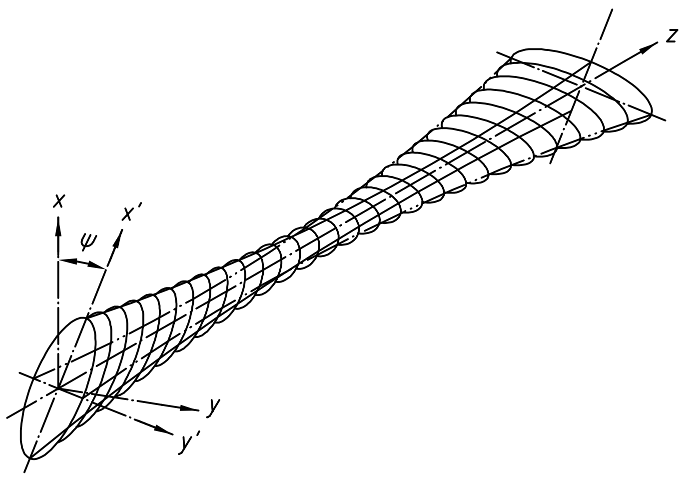


Figure 1 — The co-ordinate system of an astigmatic wavefront relative to the mechanical axes

3.1.8
wavefront azimuth angle
Ψ
angle between the principal planes of the wavefront shape/surface and the mechanical axes

See Figure 1.

3.2 Definitions associated with power (energy) density distribution

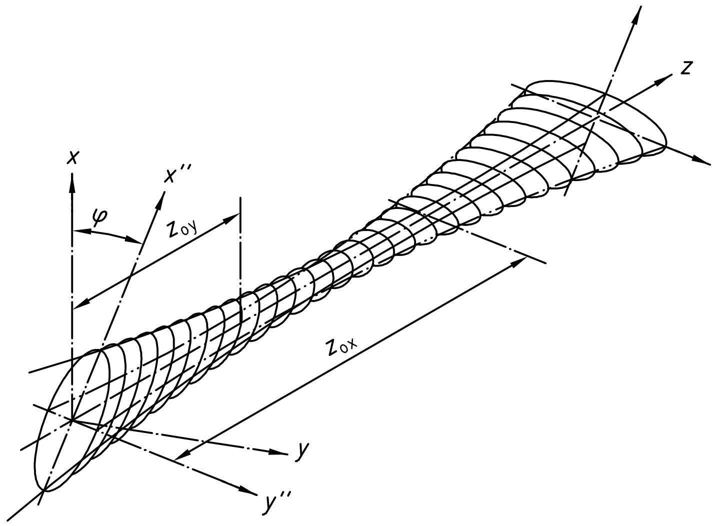
3.2.1
power (energy) density distribution co-ordinate system
x'', y'', z
co-ordinate system used as reference axes for denoting the orientation of the principal axes of the astigmatic power (energy) density distribution relative to the mechanical axes of the measuring environment

NOTE The defining parameters of the power (energy) density distribution of a simple astigmatic beam are shown in Figure 2. Means for the evaluation of the major and minor beam widths and their azimuth angle are contained in ISO 11146.

3.2.2
power (energy) density distribution azimuth angle
$\varphi(z)$
angle between the principal planes of propagation of the power (energy) density distribution and the mechanical axes

See Figure 2.

NOTE 1 For simple astigmatic beams, φ remains constant.



NOTE 2 The waist locations z_{0x} and z_{0y} are shown for both the beam axes

Figure 2 — Co-ordinates of the beam axis system for the power (energy) density distribution

3.3 Definitions associated with astigmatism

3.3.1
astigmatism
property of a laser beam having non-circular power (energy) density profiles in most planes under free space propagation or having a phase twist

NOTE An outline description of astigmatic properties and the requirement to extend their descriptions beyond those used conventionally to describe astigmatic properties of optical elements is contained in Annex A.

3.3.2
simple astigmatism
property of the beam in which the transverse power (energy) density distribution does not possess rotational symmetry but whose principal planes of wavefront shape/surface and power (energy) density distribution are orthogonal and fixed in space, whose azimuth angles are equal ($\varphi = \psi$)

See Figures 1 and 2.

3.3.3
general astigmatism
property of a laser beam having non-circular power (energy) density distributions in most planes and where the orientation of the principal axes of power (energy) density distributions changes during propagation

NOTE For coherent general astigmatic beams, the azimuth angles of the power (energy) density distribution and wavefront differ in any plane.

3.3.4
astigmatic waist separation
Δz_{a}
axial distance between the beam waist locations in the orthogonal principal planes of a beam possessing simple astigmatism

NOTE Astigmatic waist separation is also known as astigmatic difference.

3.3.5
astigmatic wavefront curvature
$C_{x'}, C_{y'}$
values of the maximum and minimum orthogonal curvature of the wavefront of a beam at a specified location.

NOTE 1 Curvature is the reciprocal of the radius of curvature.

NOTE 2 The difference between the two radii of curvature becomes essentially identical with both the astigmatic focal difference and astigmatic waist separations when measurements are made in the farfield of the laser beam.

3.4 Definitions related to the characteristics and topography of the wavefront.

3.4.1
measured wavefront
$w_{\text{m}}(x, y)$
surface resulting from analysis of the measured phase distribution data

3.4.2
corrected wavefront
$w_{\text{c}}(x, y)$
theoretical surface derived by removing the effects of the average linear trend in the x- and y-direction (average tilt and average tip) from the measured wavefront

NOTE The analytic definition can be summarized as:

$$w_{\text{c}}(x,y) = w_{\text{m}}(x,y) - x\overline{\beta}_x - y\overline{\beta}_y$$

3.4.3
approximating spherical surface
s(x, y)
spherical surface $s(x,y)=a(x^2+y^2)$ that minimizes the irradiance (energy) weighted deviation of its normal vectors to the direction of the energy flow vectors in the measurements plane

NOTE The expression to be minimized is

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x,y,z)\left[\left(2ax-\hat{P}_x\right)^2+\left(2ay-\hat{P}_y\right)^2\right]\mathrm{d}x\,\mathrm{d}y$$

where $\hat{P}_x$ and $\hat{P}_y$ are the components of the normalized transverse Poynting vector.

3.4.4
approximating paraboloid surface
c(x, y)
paraboloid surface $c(x,y)=Ax^2+By^2+Cxy$ that minimizes the irradiance (energy) weighted deviation of its normal vectors to the direction of the energy flow vectors in the measurements plane

NOTE 1 The expression to be minimized is

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E(x,y,z)\left[\left(2Ax+2Cy-\hat{P}_x\right)^2+\left(2By+2Cx-\hat{P}_y\right)^2\right]\mathrm{d}x\,\mathrm{d}y$$

where $\hat{P}_x$ and $\hat{P}_y$ are the components of the normalized transverse Poynting vector.

NOTE 2 The best fitting parameters A, B and C can be used to retrieve the wavefront azimuthal angle Ψ and the two orthogonal radii of wavefront curvature R_1 and R_2 from:

$$\Psi=\frac{1}{2}\arctan\left(\frac{C}{B-A}\right)$$

$$R_1=\frac{k}{2}\frac{1}{A\cos^2\Psi+B\sin^2\Psi+2C\sin\Psi\cos\Psi}$$

$$R_2=\frac{k}{2}\frac{1}{A\sin^2\Psi+B\cos^2\Psi-2C\sin\Psi\cos\Psi}$$

3.4.5
defocus
R_{ss}
radius of curvature of approximating spherical surface

3.4.6
wavefront aberration function
$w_{AF}(x, y)$
theoretical surface given by the difference between the corrected wavefront and the approximating spherical or approximating paraboloid surface

NOTE The analytic expression is

$$w_{AF}(x,y)=w_c(x,y)-s(x,y)$$

3.4.7
weighted RMS deformation
irradiance weighted RMS wavefront error
w_{RMS}
root-mean-square value of the power (energy) distribution weighted difference between the local values of the wavefront aberration function and its average value

NOTE $$w_{\mathrm{RMS}} = \sqrt{\frac{\sum_x \sum_y E(x,y)\left[w_{\mathrm{AF}}(x,y) - \overline{w}_{\mathrm{AF}}\right]^2}{\sum_x \sum_y E(x,y)}}$$ where $$\overline{w}_{\mathrm{AF}} = \frac{\int E(x,y) w_{\mathrm{AF}}(x,y)\,\mathrm{d}x\mathrm{d}y}{\int E(x,y)\,\mathrm{d}x\mathrm{d}y}$$

3.5 Definitions related to wavefront gradient measurements

3.5.1
tilt
tilt about the y-axis
β_x
local gradient of the wavefront in the x-direction

NOTE Tilt is given by $\beta_x = \frac{\partial w}{\partial x}$

3.5.2
average tilt
$\overline{\beta}_x$
irradiance (energy) weighted average value of tilt

NOTE The average tilt is calculated using

$$\overline{\beta}_x = \frac{\int E(x,y)\beta_x(x,y)\,\mathrm{d}x\mathrm{d}y}{\int E(x,y)\,\mathrm{d}x\mathrm{d}y}$$

3.5.3
tip
tilt about x-axis
β_y
local gradient of the wavefront in the y-direction

NOTE Tilt is given by $\beta_y = \frac{\partial w}{\partial y}$

3.5.4
average tip
$\overline{\beta}_y$
irradiance (energy) weighted average value of tip

NOTE The average tip is calculated using

$$\overline{\beta}_y = \frac{\int E(x,y)\beta_y(x,y)\,\mathrm{d}x\mathrm{d}y}{\int E(x,y)\,\mathrm{d}x\mathrm{d}y}$$

3.5.5
wavefront gradient
$\nabla w(x, y)$
vector sum of the tip and tilt

NOTE The wavefront gradient is given by

$$\nabla w(x,y) = \frac{\partial w(x,y)}{\partial x} i + \frac{\partial w(x,y)}{\partial y} j$$

where i and j are the unit vectors in the x- and y-direction, respectively.

3.5.6
phase gradient
$\nabla \Phi(x, y)$
local slope of the phase distribution surface, being the product of the wavefront gradient and the wave number $2\pi/\lambda$

4 Test methods

4.1 Laser types

Test methods can be devised for measuring the phase distributions of a wide range of pulsed or continuous laser beams. Interferometry principles can be applied to beams covering the full wavelength spectrum for which detectors and optical materials are available, provided that the coherence is sufficient for detectable levels of interference. Phase gradient measurement techniques can be used with both coherent and incoherent beams.

Measurements are most conveniently performed on collimated beams or those with low divergence. Lasers that emit a widely diverging beam are usually provided with optical elements that will nearly collimate the laser beam. Such a laser can be tested with the provided element or that element can be replaced with a test lens with known characteristics.

Any modification to the laser beam from the original manufactured product shall be recorded in the test report.

4.2 Safety

Potential hazards associated with the use of laser beams shall be assessed. The provisions of international safety codes and standards shall be observed (IEC 60825, all parts). It should be recognized that general-purpose phase measuring instruments may not have been constructed to accommodate laser beams of the power (energy) being investigated. This possibility shall be examined and any enhanced safety precautions shall be recorded in the test report.

4.3 Test environment

Measures shall be taken to reduce the uncertainty of measurement to a level where the combined effects of sources of degradation can influence those measurements by no more than 10 % of the target uncertainty in the quantity under investigation. Steps shall be taken to ensure that

— the temperature of the environment is sufficiently stable to avoid influencing the wavefront shape/surface of the sampled beam;

— all equipment has reached its operating temperature;

— extraneous stray reflections and scattered radiation are attenuated;

- dust is extracted from the beam path and all optical surfaces are clean;
- electronic noise and electromagnetic contamination is minimized by shielding or design;
- mechanical and acoustic isolation of both the laser and phase-measuring system is provided;
- the atmospheric environment is controlled to remove draughts or contaminating vapours that might absorb sufficient power (energy) to cause turbulence or thermal degradation of the beam quality.

4.4 Beam modification

4.4.1 Sampling

It may be necessary to extract a sample of the test beam in order to perform in-process beam quality assessment or simply to attenuate the beam to a power (energy) level acceptable to the measurement instrumentation. In this case, optical aberrations including thermal distortion, scattering and stray reflections from the sampling technique employed shall not be allowed to influence the wavefront shape/surface of the sampled beam by more than 10 % of the target uncertainty in the quantity under investigation.

The physical and optical details of the beam sampling/attenuating elements used shall be recorded in the test report.

4.4.2 Beam manipulating optics

When the lateral dimensions or divergence of the beam are not compatible with the aperture or capability of the measuring instrument, optical elements shall be used to convert the beam parameters into a more suitable match. When beam forming or other optical manipulating systems are used they shall

- be designed with low-aberration, high quality components;
- use optical materials appropriate to the wavelength;
- be of a quality such that generation of diffraction fringes and other degrading effects due to inhomogeneity in the bulk optical materials or coating quality is prevented;
- be subject to close visual inspection for scratches and surface imperfections that could degrade the quality of the beam under test;
- be used in an environment with low levels of dust and vibration;
- be mounted in a manner that minimizes distortion due to stress or birefringence;
- be capable of handling the beam power (energy) with negligible thermal distortion;
- be aligned with the axis of the laser beam.

The total permissible degradation introduced by the forming optics shall be such that they will not influence the propagation invariant beam parameters by more than 10 % of the target uncertainty. Particular attention shall be given to the alignment procedures, especially in the case of high quality beams.

So that the properties of the original laser beam can be estimated, all physical and optical details of forming optics introduced into the beam between the laser and the wavefront measuring instrument shall be recorded in the test report.

4.5 Detector system

Examination of the images formed by instruments designed for the measurement of phase distribution requires a two-dimensional detector array or scanning system with high spatial resolution and low optical and electronic noise. The uncertainty in the measurements is directly related to the spatial resolution of the system and to the signal-to-noise ratio.

The provisions of IEC 61040 apply to the radiation detector system. In addition, the following points shall be recorded in the test report:

a) the saturation level, signal-to-noise ratio and the linearity of the detector system to the input laser power (energy) shall be determined from manufacturer's data or by measurement at the wavelength of the laser to be characterized. Any wavelength dependency, non-linearity or non-uniformity of the detector, locally or across its aperture, shall be minimized or compensated by use of a recorded calibration procedure;

b) the damage threshold [power (energy) linear/areal density] of the detector surface shall be ascertained for the exposure duration of the test to ensure that it is not exceeded by the power (energy) density of the laser beam;

c) when using a scanning device to measure an image, care shall be taken to confirm that the laser output is spatially and temporally stable during the scanning period;

d) when measuring pulsed laser beams, the trigger time delay and sampling interval shall be measured and recorded;

e) care shall be taken when introducing optical elements into the path of the beam to ensure that no significant degradation of the beam characteristics is introduced. Sources of possible degradation include the fringes originating from the protective windows of CCD arrays.

The data from the detector shall be recorded. The resolution, linearity and dynamic range of the converter shall be selected to match the demands of both the detector and analysis systems. These properties shall be recorded on the test report.

4.6 Wavefront measuring instruments

4.6.1 The technologies

There are two main technologies that can be applied to the measurement of a wavefront. Interferometry is used to observe a coherent wavefront whereas deflectometry is not necessarily dependent on coherence or the presence of an uninterrupted single wavefront. An outline of the two technologies is given in 4.6.2 and 4.6.3 but a detailed description of the measurement protocol and analysis for each procedure is presented in ISO 15367-2.

4.6.2 Wavefront gradient measuring instruments

There are a number of phase- or wavefront-gradient measuring instruments that can be used to determine the wavefront or phase distribution of the beam. These include, but are not limited to, the shearing interferometer, the Hartmann and Shack-Hartmann wavefront sensor, and the Moiré deflectometer. In these instruments, the gradients (of either wavefront or phase) are measured in appropriate (preferably orthogonal) axes.

4.6.3 Self-referencing interferometers

Unlike many instrument designs suitable for testing optical components, the interferometer that is used for the examination of laser beams supplies a reference beam derived from the laser beam itself. Details of these self-referencing or common path interferometers are to be found in many texts on the subject [1][2]. They include radial shearing interferometers as well as the point diffraction design. Since they have a common equal path design, they are significantly less susceptible to vibration than the conventional unequal path designs. Furthermore, they can tolerate a short temporal coherence length and appropriate designs can be used for the examination of very short laser pulses.

A radial shearing Sagnac interferometer with large shear produces fringes that closely approximate the contours of equal phase across a wavefront. A similar result is produced by a Smartt point-diffraction interferometer.

Phase shifting is a procedure that can be used with interferometers [1] to reduce the uncertainty and effects of noise in wavefront measurements. In these instruments, the optical path difference between the interfering wavefronts is varied and multiple samples of the fringe pattern recorded as a function of the variation of the OPD. Subsequent algebraic analysis can reveal the shape of the original wavefront provided it does not vary significantly between the samples. In the case of pulsed lasers or beams of unstable quality or pointing, the arising uncertainty could render the measurements invalid.

Use of interferometers for the measurement of the phase distribution in laser beams shall be guided by the general advice and precautions that are being drafted in ISO 14999[3].

5 Test and measurement procedures

5.1 Alignment

The sampled laser beam and its forming optics shall be adjusted into co-axial alignment with the wavefront measuring instruments. Optical alignment instruments and devices are generally available for this purpose.

The sensitivity of the overall system to misalignment shall be assessed with the objective of evaluating the uncertainty of measurements caused by this source of error.

5.2 Calibration

5.2.1 Transverse spatial calibration

The relationship between the transverse location of points in the measurement plane and analysed wavefront characteristics shall be determined with the aid of fiducial points, markers or apertures placed in the measurement plane. Subsequent inspection of the phase distribution records of a test beam shall be undertaken to provide a calibration record as well as assist in estimating the uncertainty in transverse position measurements.

5.2.2 Tilt and defocus calibration

Absolute calibration of the relationship between the tilt and defocus contributions to the derived shape of a wavefront shall be determined with the aid of well characterized optical elements inserted into a high quality beam that is subsequently analysed with the phase measurement system. Comparison of the derived wavefront properties before and after insertion of a wedge prism or thin lens can provide calibration and an estimate of the associated uncertainties.

5.3 Visual inspection of automated data analysis

The efficiency of acquisition and analysis of the two-dimensional wavefront function is greatly improved by the use of digital processing hardware and software. Extensive noise filtering, smoothing and fitting techniques can be applied to ease the collection and analysis of significant amounts of data for statistical analysis. This route will reduce the uncertainty of measurement. However, it is possible that optical noise from dust, scratches or other sources of interference with the test beam will confuse and lead to errors from automatic analysis systems. The possibility of erroneous analysis will be reduced by inspection of the two-dimensional displays of unprocessed data.

Interferogram fringes, Hartmann patterns or other basic displays shall be subjected to visual inspection by personnel experienced in the field before the results of automatic analysis are accepted.

5.4 Measurement procedures

The tests shall be made under the conditions (if any) specified by the manufacturer of the laser. The wavefront measuring instrument shall be positioned with the measurement plane at a known and recorded location along the test beam axis.

The phase distribution in the beam under test shall be scanned, measured and recorded. In order to assess the uncertainty due to pointing/mode instability of the subject beam, the process shall be repeated for a statistically significant number (~100) of times within an appropriate timescale. The scan time and delay between scans shall be recorded in the test report. Each scan shall be analysed to reveal the measured wavefront. The derived wavefronts shall be stored for subsequent analysis.

If a value for the weighted RMS wavefront deformation is required, the power (energy) density distribution shall be measured in accordance with ISO 13694.

6 Analysis of wavefront quality

6.1 Polynomial representation of wavefronts

Analysis and interpretation of a discrete digitized wavefront can be simplified by using least-squares fitting techniques to derive the coefficients of suitable polynomials that will define an approximating surface. This technique can be used to derive a continuous representation of the test wavefront provided that it does not possess sharp local deformations.

There are many types of polynomial functions, see [1][3][4][5] and ISO 15367-2, that can be used to assist in the analysis and processing of wavefront data. There are functions associated with the names of Zernike, Laguerre, Hermite and Legendre and others. Care is needed in the selection and fitting methods used with the functions as well as any conclusions drawn. For this reason, the polynomial method used to fit an analytically described surface to a measured wavefront shall be identified in the test report.

6.2 Computation of wavefront quality

6.2.1 Removal of tilt effects

The corrected wavefront values shall be determined by estimating the angle and azimuth of tilt then subtracting its effect from the measured wavefront values. Care shall be exercised in the modification of the measured wavefront if the correction involves the subtraction of terms of a fitted polynomial; e.g., Zernike polynomials are not orthogonal over non-circular apertures. In this case, only the terms representing tilt and defocus shall be fitted. Adding other terms to the fit will change the fit coefficients for the terms of interest.

When any special orthogonalization or other processing technique is used to modify the measured wavefront, its description shall be outlined in the test report.

Once the terms representing tilt have been identified, the analytically determined corrections can be subtracted from the measured wavefront data at each grid point of the array in order to determine the corrected wavefront.

6.2.2 Determination of wavefront azimuth angle

The wavefront azimuth angle shall be computed using the first moment (mean), second moment (standard deviation) and cross moments of the corrected wavefront function.

6.2.3 Determination of astigmatic state

One condition for a state of simple astigmatism is the invariance of the wavefront azimuth angle with distance along the beam axis. This test shall be applied by measurement of the phase azimuth angle at a minimum of five axial locations over a range of two Rayleigh lengths.

If the variation in the wavefront azimuth angle is monotonic with distance and any variation exceeds 10°, the beam shall be classified as general astigmatic.

6.2.4 Determination of astigmatic wavefront curvatures

The procedures for determining the maximum and minimum wavefront curvatures shall be:

— measure the wavefront in the far-field of the laser beam;

— determine the wavefront azimuth angle;

— apply numerical methods to transpose the wavefront to coincide with the wavefront distribution co-ordinate system by rotating the axes through the wavefront azimuth angle;

— calculate the values R_1 and R_2 in accordance with 3.4.4;

— determine the wavefront curvatures $C_{x'}$ and $C_{y'}$ as the inverse of R_1 and R_2.

6.2.5 Estimation of approximating spherical surface

The location of the centre of curvature and calculation of the radius of curvature of the best-fit spherical surface to the corrected wavefront values shall be made with least-squares-fitting techniques.

6.2.6 Determination of wavefront aberration function

The wavefront aberration function w_{AF} (x, y) shall be derived by subtracting the approximating spherical surface from the corrected wavefront. This shall be performed at each location point (x, y) in the measurement plane by geometric subtraction of the radius of the sphere from the distance between the point and the centre of the sphere.

6.2.7 Determination of weighted RMS wavefront deformation

The weighted RMS wavefront deformation w_{RMS} shall be calculated by using the power (energy) density distribution and the wavefront aberration function w_{AF}. The value of the wavefront function for discrete data is weighted by the power (energy) density so that

$$w_{RMS} = \sqrt{\frac{\sum_x \sum_y E(x,y)\left[w_{AF}(x,y) - \bar{w}_{AF}\right]^2}{\sum_x \sum_y E(x,y)}}$$

NOTE 1 Evaluation of the weighted RMS wavefront deformation requires measurement of the power (energy) density distribution, $E(x, y)$.

NOTE 2 Visual inspection shall take place to ensure that the resulting value is not dominated by diffraction from localized surface blemishes or scratches on supplementary optical elements in the analysis equipment.

7 Uncertainty

7.1 Requirements for uncertainty estimation

The recording of any of the measurements described in this part of ISO 15367 shall consist of the estimated value of the measurand together with an estimate of the combined standard uncertainty or expanded uncertainty [6]. There shall also be a statement of the coverage factor or level of confidence that can reasonably be attributed to the estimated uncertainty range [6]. The procedures necessary for estimating both the statistical (Type A) and non-statistical (Type B) sources of uncertainty shall be applied and combined to provide a unified result. All potential sources of uncertainty shall be considered and an estimate of their individual impact on the final uncertainty shall be made. Only when an individual source of uncertainty has been shown to make a negligible contribution (< 20 %) to the final figure, future measurements with that measuring system can ignore that particular source of uncertainty.

7.2 Sources of uncertainty

7.2.1 Uncertainty in data acquisition

Many of the sources of uncertainty in data acquisition are associated with the digitizing camera (CCD) and the analogue to digital signal converter (ADC). Timing jitter in the camera drive circuitry will lead to an effective uncertainty in pixel position. This effect combined with non-linearity in spatial location and signal amplification will give rise to uncertainties in estimating the interference fringe centres or Hartmann screen spot centroids.

The quantization effect of an 8-bit ADC will contribute a small potential uncertainty to location measurements if the full dynamic range is used. This will not generally be the case and a 10-bit ADC might be necessary to reduce uncertainty to an acceptable level.

7.2.2 Uncertainty due to environmental effects

Power (energy) fluctuations from the laser beam source can cause uncertainty both in fringe/spot location and polynomial coefficient estimates. Calculations of the mean and standard deviations of the results of a number of samples can be used to reduce cumulative uncertainties but slow systematic variations could lead to errors. Under these circumstances, the variations shall be monitored by a supplementary sensor. Detected variations shall be used either to correct the original measurements or, preferably, provide correction feedback to the laser.

On the other hand, variations in measured parameters could be caused by environmental effects such as vibration, turbulence or temperature variations. The precautions described in 4.3 shall be taken to ensure that uncertainties from this source are reduced to the specified level.

7.2.3 Uncertainty due to optical and mechanical defects

A major source of uncertainty can be the interference fringes at the measurement plane caused by spurious reflections and scattering from scratches, coatings and other defects in the optical components along the beam path. The presence of the extraneous fringes will introduce systematic and non-random uncertainties into the measurement. Scrupulous cleaning of components and provision of baffles can be used to reduce the unwanted effects. In the case of long pulse or continuous working beams, the effect of the coherent optical noise can be averaged by introducing a moving diffuser into the optical train.

Calibration of the phase measuring equipment shall be undertaken to reduce systematic Type B uncertainties. The process could involve use of a certified plane reference surface or other correction techniques [1] to produce a beam of known waveform. Measurement of that beam by wavefront mapping will reveal the instrument error. Storage of the reference error in the computer will permit subtraction from future measurements. The nature and stability of the wavefront mapping instrument will dictate arising uncertainty and the need for re-calibration.

Periodic measurement of a reference beam shall be made to identify the necessary re-calibration regime for the measuring equipment.

8 Test report

Measurements shall be performed in conformance with the requirements of ISO 15367-2.

Information concerning the test method, analysis, evaluation, measured values and uncertainties shall be recorded in the form indicated in ISO 15367-2.

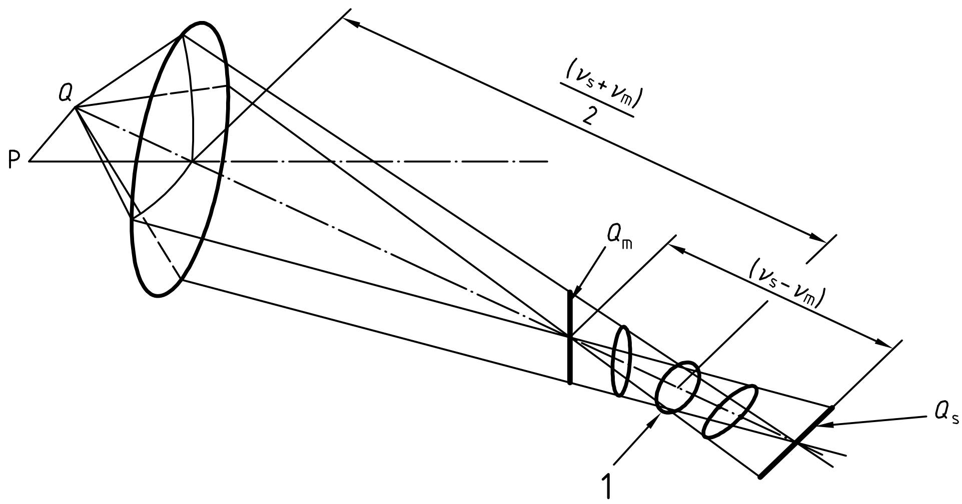
Annex A
(informative)

Astigmatism and laser beams

A.1 Introduction

The need for re-defining the terms used for quantifying astigmatism in a measurement standard is best justified by examining one of the major reasons for measuring the degree of astigmatism in a laser beam. A number of lasers suffer from output beams that have power density distributions that are strongly non-circular. This means that the waist width and divergence in the two principal planes of the beam are significantly different from each other. In addition, the location of the orthogonal waists can differ. This effect is equivalent to the conventional view of axially separated line foci observed when examining the off-axis focusing behaviour of optical components (see Figure A.1).

A number of applications of lasers require that the beam be collimated. When the beam does not possess circular symmetry (i.e. is not stigmatic), the collimating lens must have anamorphic properties. If the correction is not perfect, the near collimated beam will have some residual astigmatism. Measurement or the degree of residual astigmatism using conventional concepts may lead to erroneous conclusions. This is because the corrective procedures will need to know the maximum and minimum radii of curvature of the wavefront of the beam at a position close to the exit pupil of the original collimating lens.



Key

1 diameter

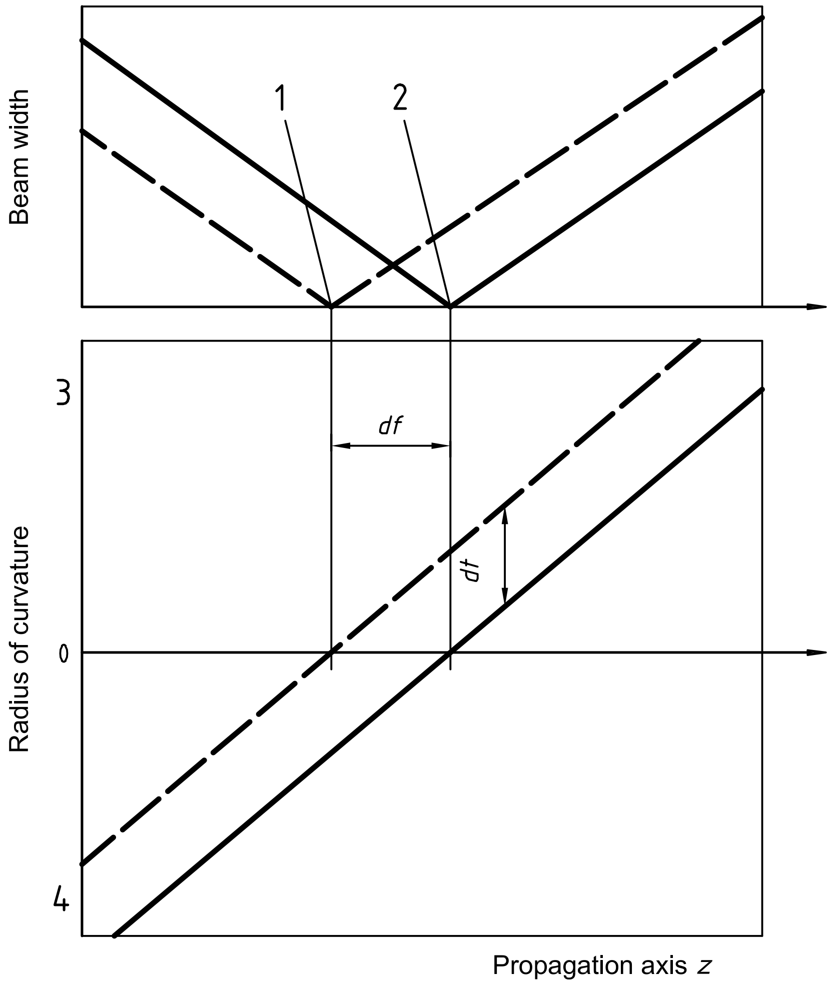
Figure A.1 — Circle of least confusion
(see [7])

A.2 Conventional concepts

The conventional numerical value of astigmatism is simply the distance along the chief ray between the “line focus” formed by sagittal rays and the orthogonal line focus formed by the tangential or meridional rays.

Naturally, the distance between the line foci can be measured by using equipment that can display the transverse distribution of the irradiance in the beam. The location of the line foci can then be determined directly. Determination of the maximum and minimum radii of curvature in the wavefront at a specific location can then be estimated by the conventional view that the radius of curvature of the wavefront is the distance between that wavefront and the appropriate line focus (see Figure A.2).

If these measurements and method of interpretation were to be performed on the near-collimated beam from the laser, the conclusions would be in error.



Key

1 tangential line focus

2 sagittal line focus

3 convex

4 concave

NOTE 1 Difference in radii of curvature is equal to the separation of the foci wherever they are measured.

NOTE 2 The values of the width and radii around the two orthogonal line foci are shown together with the deduction of the differences in radii from the separation of the foci.

Figure A.2 — Idealized view of the variation of beam width and radius of curvature of the wavefront around a line focus

A.3 The Astigmatic Laser Beam

The width d_S of a laser beam in one of its principal planes can be written as:

$$d_S = d_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \quad \text{where} \quad z_R = \frac{\pi}{M^2 4 \lambda} d_0^2$$

where

z_R is the Rayleigh length;

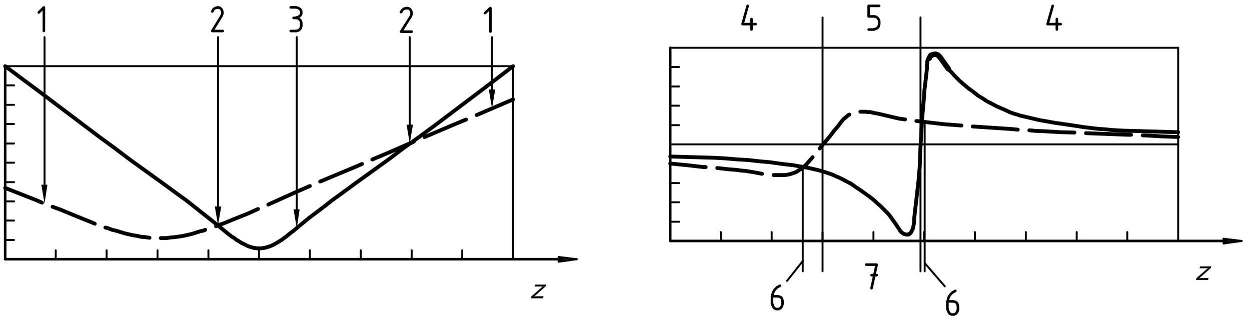
d_0 is the beam waist width;

M^2 is the beam propagation ratio.

The radius of curvature of the wavefront is described by:

$$R_S = \frac{z_R^2}{z} + z$$

The wavefront curvature, defined as the inverse of the radius of curvature, together with the beam width, is shown in Figure A.3 for the two orthogonal projections of a beam.



a) **Beam width** b) **Wavefront curvature**

Key

1 elliptic beam X-axis major

2 circular

3 elliptic beam Y-axis major

4 elliptical fringes

5 saddle fringes, opposite curvatures

6 spherical wavefront

7 cylindrical wavefront

NOTE The values are given for width and curvature in the two principal planes of propagation. The separation of the waists are clearly evident in the beam width diagram.

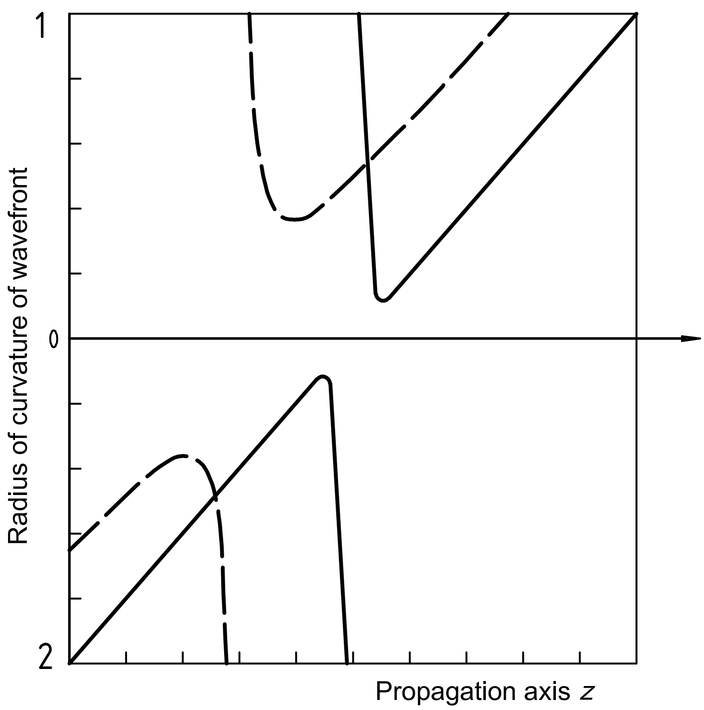
Figure A.3 — Beam width and curvature in a simple astigmatic laser beam as a function of propagation distance z

Examination of the various regions of Figure A.3 reveals some interesting facts. The existence of the two "line foci" is evident from the location of separated minima of the beam widths. These are the two beam waists.

At a distance far away from the beam waists, the diagram reveals the astigmatic or elliptic irradiance profiles and elliptic fringes or wavefront contours in the beam. The curves also show that in most cases (but not all), there will be locations in the beam path where the widths are equal and there is a circular irradiance profile. However, at those locations, the wavefront curvatures are still unequal and the beam still displays astigmatism.

The graphs representing the curvature of the wavefront cross each other at two locations. This means that at those locations, the wavefront is spherical. At two further locations, one of the two wavefront curvatures becomes zero while the orthogonal curvature is still finite. This means that, at those locations, the wavefront is cylindrical. In between the latter two locations, the curvatures will have an opposite sign and the wavefront exhibit a saddle shape.

Figure A.3 reveals the complex behaviour of a laser beam wavefront near the orthogonal waist. A graph of the radius of curvature of the wavefront (Figure A.4) highlights this behaviour. When this graph is compared with the equivalent curves in Figure A.2, it is evident that in the region around the beam waists, the correlation between the separation of the waists and the wavefront curvature is not a simple one-to-one relationship. However, at distances greater than approximately five Rayleigh lengths from the waists, the conventional relationship can be resumed.



Key

1 convex

2 concave

Figure A.4 — Orthogonal radii of curvature of a simple astigmatic laser beam in the axial region around the beam waists

A.4 The three measures of astigmatism

As far as the design of correcting collimation lenses is concerned, the most relevant measurements of astigmatism in the laser beam are the values of the maximum and minimum radii of curvature of the wavefront at the location of the lens. For this reason, a formal definition is given for astigmatic wavefront curvatures. Naturally, these methods are best made by direct measurement of the shape of the wavefront.

The conventional view of astigmatism is widely accepted and generally understood. This position should be maintained. It is perfectly valid to measure the position of “line foci” and use these values to estimate the radii of curvature of the wavefront at locations along the beam path that are far removed from those line foci. However, since it is possible to measure the locations of line foci by measuring the position of those foci re-imaged by a transfer lens, it is important to record such measurements in a way that will allow the user to recognize the source and to avoid using incorrect procedures for the estimation of wavefront curvatures. In order to preserve the conventional approach to measurements of astigmatism, the definition of astigmatic focal difference is used.

If astigmatism measurements are to be made or used in the near field of a laser beam (within ± 5 Rayleigh lengths) of the beam waists, then those waists should be located using the standard techniques defined in ISO 11146. In this case, in order to differentiate explicitly from measurements taken in the far field, the distance between those waists should be referred to as the astigmatic waist separation.

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