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

Part 2:
Shack-Hartmann sensors

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

Partie 2: Senseurs Shack-Hartmann

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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 15367-2 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, 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: Shack-Hartmann sensors*

Introduction

Characterization of the beam propagation behaviour is necessary in many areas of both laser system development and industrial laser applications. For example, the design of resonator or beam delivery optics strongly relies on detailed and quantitative information over the directional distribution of the emitted radiation. On-line recording of the laser beam wavefront can also accomplish an optimization of the beam focusability in combination with adaptive optics. Other relevant areas are the monitoring and possible reduction of thermal lensing effects, on-line resonator adjustment, laser safety considerations, or “at wavelength” testing of optics including Zernike analysis.

There are four sets of parameters that are relevant for the laser beam propagation:

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

— beam widths, divergence angles and beam propagation ratios (ISO 11146-1 and ISO 11146-2);

— wavefront (phase) distribution (ISO 15367-1 and this part of ISO 15367);

— spatial beam coherence (no current standard available).

In general, a complete characterization requires the knowledge of the mutual coherence function or spectral density function, at least in one transverse plane. Although the determination of those distributions is possible, the experimental effort is large and commercial instruments capable of measuring these quantities are still not available. Hence, the scope of this standard does not extend to such a universal beam description but is limited to the measurement of the wavefront, which is equivalent to the phase distribution in case of spatially coherent beams. As a consequence, an exact prediction of beam propagation is achievable only in the limiting case of high lateral coherence.

A number of phase or wavefront gradient measuring instruments are capable of determining the wavefront or phase distribution. These include, but are not limited to, the lateral 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, from which the two-dimensional phase distribution can be reconstructed.

In this document, only Hartmann and Shack-Hartmann wavefront sensors are considered in detail, as they are able to measure the wavefront of both fully coherent and partially coherent beams. A considerable number of such instruments are commercially available.

The main advantages of the Hartmann technique are

— wide dynamic range,

— high optical efficiency,

— suitability for partially coherent beams,

— no requirement of spectral purity,

— no ambiguity with respect to 2π increment in phase angle,

— wavefronts can be acquired/analysed in a single measurement.

Instruments which are capable of direct phase or wavefront measurement, as, e.g. self-referencing interferometers, are outside the scope of this part of ISO 15367.

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

Part 2: Shack-Hartmann sensors

1 Scope

This part of ISO 15367 specifies methods for measurement and evaluation of the wavefront distribution function in a transverse plane of a laser beam utilizing Hartmann or Shack-Hartmann wavefront sensors. This part of ISO 15367 is applicable to fully coherent, partially coherent and general astigmatic laser beams, both for pulsed and continuous operation.

Furthermore, reliable numerical methods for both zonal and modal reconstruction of the two-dimensional wavefront distribution together with their uncertainty are described. The knowledge of the wavefront distribution enables the determination of several wavefront parameters that are defined in ISO 15367-1.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

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

ISO 15367-1:2003, *Lasers and laser-related equipment — Test methods for determination of the shape of a laser beam wavefront — Part 1: Terminology and fundamental aspects*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11145 and ISO 15367-1 as well as the following apply.

3.1
array element spacing
d_x, d_y
distance between the centres of adjacent pinholes or lenslets in x and y direction

3.2
sub-aperture screen to detector spacing
L_{H}
spacing of the sub-aperture screen (lenslet array or Hartmann screen) to the detector array

NOTE For Shack-Hartmann sensors this is often set to the lenslet focal length.

3.3
lenslet focal length
f
focal length of the lenslets for a Shack-Hartmann sensor

3.4
sub-aperture width
d_s
aperture width of the pinholes of a Hartmann screen or lenslets of a Shack-Hartmann array, respectively

3.5
angular dynamic range
β_max
maximum usable angular range of Hartmann or Shack-Hartmann sensors

NOTE For square apertures, the angular dynamic range is given by

$$\beta_\mathrm{max} = \frac{d_x}{2L_\mathrm{H}} - \frac{\lambda}{d_x}$$

3.6
wavefront measurement repeatability
$w_\mathrm{r,rms}$
root-mean-square (r.m.s.) difference between single subsequent measurements $w_n(x, y)$ of the same wavefront and the average wavefront $\bar{w}(x, y)$

$$w_\mathrm{r,rms} = \frac{1}{k}\sum_{n=1}^{k}\sqrt{\frac{\sum_x\sum_y E_n(x,y)\left[w_n(x,y)-\bar{w}(x,y)\right]^2}{\sum_x\sum_y E_n(x,y)} - \left(\frac{\sum_x\sum_y E_n(x,y)\left[w_n(x,y)-\bar{w}(x,y)\right]}{\sum_x\sum_y E_n(x,y)}\right)^2}$$

where

n is the number of the measurement;

k is the number of samples taken;

$$\bar{w}(x,y) = \frac{\sum_{n=1}^{k} E_n(x,y)\times w_n(x,y)}{\sum_{n=1}^{k} E_n(x,y)}$$

3.7
wavefront measurement accuracy
$w_\mathrm{a,rms}$
average of the r.m.s. difference between a reference wavefront w_r and the tilt-corrected wavefront $w_{\mathrm{tc},n}$ after various amounts of tilt θ_n have been applied to the reference wavefront

$$w_\mathrm{a,rms} = \frac{1}{k}\sum_{n=1}^{k}\sqrt{\frac{\sum_x\sum_y E_n(x,y)\left[w_{\mathrm{tc},n}(x,y)-w_\mathrm{r}(x,y)\right]^2}{\sum_x\sum_y E_n(x,y)}}$$

where

n is the nth measurement of the wavefront with tilt $\theta_{x,n}$ and $\theta_{y,n}$ applied;

k is the number of samples taken;

$w_{\mathrm{tc},n}$ is the tilt-corrected wavefront as follows:

$$w_{\mathrm{tc},n}(x,y) = w_n(x,y) - \theta_{x,n}x - \theta_{y,n}y$$

NOTE See also ISO 15367-1:2003, 3.4.7.

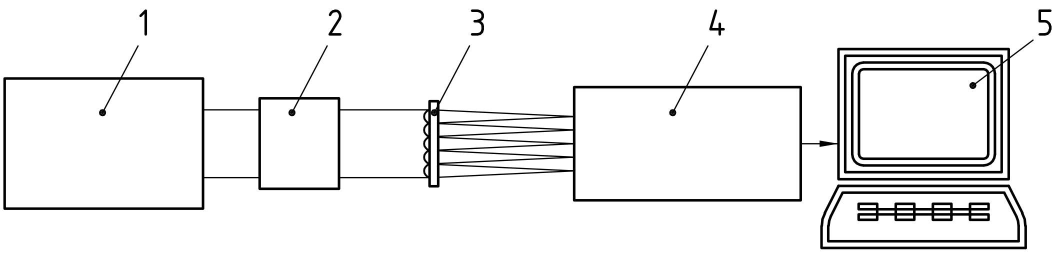
4 Symbols and units

Table 1 — Symbols and units

Symbol	Parameter	Units	Defined in
$E(x, y)$, $H(x, y)$	power (energy) density distribution	W/cm^2, J/cm^2	ISO 13694
x, y, z	mechanical axes (Cartesian coordinates)	mm	ISO 15367-1:2003, 3.1.5
z	beam axis	mm	ISO 15367-1:2003, 3.1.5
λ	wavelength	nm	
z_{m}	location of measurement plane	mm	ISO 15367-1:2003, 3.1.4
$w(x, y)$	average wavefront shape	nm	ISO 15367-1:2003, 3.1.1
$\Phi(x, y)$	phase distribution	rad	ISO 15367-1:2003, 3.1.1, Note 1
$w_{\mathrm{c}}(x, y)$	corrected wavefront	nm	ISO 15367-1:2003, 3.4.2
$s(x, y)$	approximating spherical surface	—	ISO 15367-1:2003, 3.4.3
R_{ss}	defocus or radius of best sphere	mm	ISO 15367-1:2003, 3.4.5
$w_{\mathrm{AF}}(x, y)$	wavefront aberration function	nm	ISO 15367-1:2003, 3.4.6
w_{PV}	wavefront irregularity	nm	
w_{rms}	weighted r.m.s. deformation	nm	ISO 15367-1:2003, 3.4.7
d_x, d_y	array element spacing	mm	3.1
L_{H}	sub-aperture screen to detector spacing	mm	3.2
f	lenslet focal length	mm	3.3
d_{p}	spot size	µm	
d_{s}	sub-aperture width	µm	3.4
β_{max}	angular dynamic range	mrad	3.5
$(x_{\mathrm{c}}, y_{\mathrm{c}})_{ij}$	beam centroid coordinates in sub-aperture ij i.e. the first order moments of the power density distribution in sub-aperture ij	mm	ISO 11146-1
$(x_{\mathrm{r}}, y_{\mathrm{r}})_{ij}$	reference beam coordinates in sub-aperture ij	mm	
$(\beta_x, \beta_y)_{ij}$	local wavefront gradient components (tilt, tip)	—	ISO 15367-1:2003, 3.5.1, 3.5.3
$w_{\mathrm{r,rms}}$	wavefront measurement repeatability	nm	3.6
$w_{\mathrm{a,rms}}$	wavefront measurement accuracy	nm	3.7
$\boldsymbol{B}$	geometry matrix in wavefront reconstruction algorithms	—	
$\boldsymbol{C}$	covariance matrix	—	

5 Test principle of Hartmann and Shack-Hartmann wavefront sensors

The Hartmann principle is based on a subdivision of the beam into a number of beamlets. This is either accomplished by an opaque screen with pinholes placed on a regular grid (Hartmann sensor), or by a lenslet or micro-lens array (Shack-Hartmann sensor), resulting in an average wavefront gradient sampling (see Figure 1) and a better radiation collection efficiency. The power (energy) density distribution behind the array is recorded by a position sensitive detector, most commonly a CCD sensor or an array of quadrant detectors (quadcells). The detector signals can be accumulated by a computerized data acquisition and analysis system.



Key

1 laser

2 attenuator

3 lenslet array

4 position sensitive detector

5 data acquisition and analysis system

Figure 1 — Experimental arrangement for wavefront measurement using Shack-Hartmann technique

The position of the beamlet centroids shall be determined within each sub-aperture, both for the beam under test and a reference source, preferably a collimated laser beam. The displacements of the centroids with respect to the reference represent the local wavefront gradients, from which the wavefront $w(x, y)$ is reconstructed by direct integration or modal fitting techniques (see Clause 8).

The type, manufacturer and model identifier of the instrument used for Hartmann or Shack-Hartmann wavefront measurement, as well as the array size and the lens/hole spacing, shall be recorded in the test report.

6 Measurement arrangement and test procedure

6.1 General

Questions concerning different laser types, laser safety, test environment, beam modification (including sampling/attenuation and beam manipulating optics) as well as general requirements on detectors to be employed for phase gradient measurements are treated in ISO 15367-1.

All details on the beam sampling and attenuating optics shall be recorded in the test report.

6.2 Detector system

The detector system used for Hartmann and Shack-Hartmann wavefront measurements shall consist of two elements:

a) a device for segmentation of the beam under test into ray bundles (sub-aperture screen), for example an array of (refractive or diffractive) lenslets (Shack-Hartmann) or a pinhole array (Hartmann).

b) a position sensitive detector (e.g. a CCD camera) positioned at a distance L_H behind the segmenting array (L_H may be set to f in case of Shack-Hartmann detector, or an appropriate correction may be applied).

The detector area shall be partitioned into sub-apertures corresponding to the segmenting array used for subdivision of the beam. Most commonly, an orthogonal array of lenslets/pinholes with a fixed spacing d_x, d_y (in x-, y-direction, respectively) is employed. In this case the detector array shall be partitioned into $N \times M$ rectangular sub-apertures with a spacing d_x, d_y and indexed (ij).

The angular dynamic range of the wavefront sensor with respect to the wavefront variation is directly related to the ratio of the size of the spots generated on the detector to the size of the sub-apertures. To avoid overlapping, the spot size shall be smaller than the sub-aperture size. According to the local wavefront gradient, the spot of a sub-aperture moves towards the border of its assigned region on the detector. If the spot crosses the border, its position may not be correctly obtained anymore. This effect limits the angular dynamic range of the sensor.

For Shack-Hartmann sensors, the spot size d_p is approximately given by

$$d_p = 2\frac{\lambda f}{d_s} \tag{1}$$

where

f is the focal length of the lenslets;

d_s is the width of the square lenslet apertures;

and where it is assumed that the sub-aperture screen to detector spacing equals the focal length. The displacement Δx of a spot due to a horizontal local wavefront gradient β_x at its corresponding sub-aperture is given by

$$\Delta x = \beta_x \times f \tag{2}$$

The maximum allowed displacement Δx_{max} to prevent the spot from crossing its assigned region is

$$\Delta x_{max} = \frac{1}{2}(d_x - d_p) \tag{3}$$

and the according maximum horizontal wavefront gradient

$$\beta_{x,max} = \frac{d_x}{2f} - \frac{\lambda}{d_s} \tag{4}$$

If the size of the lenslet aperture d_s equals the array element spacing d_x, the maximum horizontal wavefront gradient yields

$$\beta_{x,max} = \frac{d_x}{2f} - \frac{\lambda}{d_x} \tag{5}$$

Thus, to avoid spot overlap, the focal length of the lenslets is required to be less than $d_x^2 / 2\lambda$. To achieve a useful dynamic range and minimize cross talk, the focal length shall be less than $2d_x / 5\lambda$. A smaller focal length will result in a greater angular dynamic range, but may also result in greater measurement uncertainty. For the vertical direction a similar expression holds.