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Optics and photonics — Microlens arrays —

Part 2:
Test methods for wavefront aberrations

Optique et photonique — Réseaux de microlentilles —

Partie 2: Méthodes d'essai pour les aberrations du front d'onde

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Foreword

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This document was prepared by Technical Committee ISO/TC 172, *Optics and Photonics*, Subcommittee SC 9, *Laser and electro-optical systems*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 123, *Lasers and photonics,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This second edition cancels and replaces the first edition (ISO 14880-2:2006), which has been technically revised.

The main changes are as follows:

— text for Annex E was revised;

— Figure E.1 was replaced;

— references and numbering confirmed.

A list of all parts in the ISO 14880 series can be found on the ISO website.

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

Examples of applications of microlens arrays include three-dimensional displays, coupling optics associated with arrayed optical radiation sources and photo-detectors, enhanced optics for liquid crystal displays, and optical parallel processor elements.

The market in microlens arrays has generated a need for agreement on basic terminology and test methods for defining microlens arrays. Standard terminology and clear definitions are needed not only to promote applications but also to encourage scientists and engineers to exchange ideas and new concepts based on common understanding.

Microlenses are used as single lenses and also in arrays of two or more lenses. The characteristics of the lenses are fundamentally evaluated with a single lens. Therefore, it is important that the basic characteristic of a single lens can be evaluated. However, if a large number of lenses is formed on a single substrate, the measurement of the whole array will incur a lot of time and cost. Furthermore, methods for measuring lens shapes are essential as a production tool.

Characteristic parameters are defined and examples of applications given in ISO 14880-1. It has been completed by a set of three other International Standards, i.e. ISO 14880-2, ISO 14880-3 and ISO 14880-4.

This document specifies methods for measuring wavefront quality. Wavefront quality is the basic performance characteristic of a microlens. Characteristics other than wavefront aberrations are specified in ISO 14880-3, ISO 14880-4 .

ISO/TR 14880-5 guides the user in selecting the appropriate measurement method from the ISO 14880 series of standards.

Optics and photonics — Microlens arrays —

Part 2:
Test methods for wavefront aberrations

1 Scope

This document specifies methods for testing wavefront aberrations for microlenses within microlens arrays. It is applicable to microlens arrays with very small lenses formed inside or on one or more surfaces of a common substrate.

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 14880-1, *Optics and photonics — Microlens arrays — Part 1: Vocabulary*

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 14880-1 apply.

ISO and IEC maintain terminology 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/

3.2 Symbols and abbreviated terms

Table 1 lists associated symbols, abbreviated terms and units of measurement used in this document.

Table 1 — Symbols, abbreviated terms and units of measure

Symbol	Unit	Term
Φ	µm	wavefront aberration
Φ_{P-V}	µm	peak-to-valley value of wavefront aberration
Φ_{rms}	µm	root-mean-square value of wavefront aberration
λ	µm	wavelength
Θ	degree (°)	acceptance angle
NA	none	numerical aperture

NOTE The wavefront aberration, peak-to-valley values of wavefront aberration and root-mean-square values of wavefront aberration are often expressed in units of ”λ” based on the results of interferometer measurements. Wavefront aberration is expressed in multiples of ”λ” (wavelength (µm)) of the laser light source used in the interferometer.

4 Apparatus

The test system consists of a source of optical radiation, a collimator lens, a method of limiting the measurement aperture, a sample holding apparatus, imaging optics, an image sensor and a system for analysing interference patterns[4][5][7][8][12][15][25].

4.1 Standard optical radiation source.

A source of optical radiation shall be used, which is suitable for the testing of wavefront aberrations of microlenses. The aberrations of the wavefront incident on the test equipment shall have a rms deviation less than or equal to $\lambda/20$, at the wavelength of operation, over an area corresponding to the effective aperture of the microlens to be tested. For information on calculating rms values refer to ISO 14999-4:2015, 3.1.3.

Properties of the source to be specified include centre wavelength, half-width of the spectrum, the type of optical radiation source, states of polarization (randomly polarized optical radiation, linearly polarized optical radiation, circularly polarized optical radiation, etc.), radiance angle (in mrad), spot size or beam waist parameters. Otherwise, the specification of the radiation source shall be described in the test report. ISO 12005 deals with a method for determining the polarization state of a laser beam[11].

NOTE 1 He-Ne gas lasers are sometimes used. Other gas lasers, solid-state lasers, semiconductor lasers (LD), and light emitting diodes (LED) are also used.

NOTE 2 LDs and LEDs are used with beam-shaping optics where necessary.

4.2 Standard lens (reference lens).

Where a standard lens is used as a reference or for generating an ideal spherical wave, the wavefront aberrations of the standard lens shall be smaller by at least one order of magnitude compared to that of the lens to be tested or shall be less than $\lambda/20$ rms deviation.

The objective lens of an optical microscope used as the standard lens shall be specified with the effective numerical aperture. The following shall be given:

— effective aperture;

— focal length at the wavelength of operation.

The test geometry for the measurement of wavefront aberrations is restricted to the case with lens conjugates ∞/f.

4.3 Collimator.

The collimator optics shall have a numerical aperture greater than the maximum numerical aperture of the test sample sufficient to avoid effects due to diffraction. The wavefront aberrations should be less than the Maréchal criterion value and/or the Strehl definition value (both $\lambda/14$: $0{,}07\lambda$ rms). It is however recommended that they are less than $\lambda/20$ at the operational wavelength.

Otherwise the specification used should be described in the test report.

4.4 Beam reduction optical system.

A telescopic system consisting of two positive lenses in an afocal arrangement is used to adapt the beam cross-section to the array detector. The ratio of the focal lengths gives the reduction factor. It is recommended that the wavefront aberrations are less than $\lambda/20$ at the operational wavelength.

NOTE The diameter of the lens area to be evaluated can be selected with an effective aperture defined by software to avoid additional diffraction at a physical aperture.

4.5 Aperture stop.

A physical stop is placed in the optical radiation beam of the test equipment to limit the diameter of the optical radiation beam incident on the lens to be tested. Alternatively, the stop may be defined by truncation software during evaluation.

5 Test principle

The wavefront aberrations of the test microlens shall be determined with an interferometer or another wavefront test device as described in the Annexes. When small-diameter Gaussian beams are used, care should be taken because geometrical optical theory does not apply to the propagation of such beams. The detector surface shall be conjugate with the entrance or exit pupil of the test microlens. An aperture is used to analyse the data for the wave aberrations[13][14][16][17][18].

The test method shall be chosen to suit the application. Single-pass applications require testing using single-pass interferometers[13].

NOTE Interferometers often use laser sources for the interferometric test. Dielectric boundaries between lenses contribute to unwanted reflections, stray light and spurious fringe patterns. This can cause severe problems if a double-pass arrangement using reflected optical radiation is chosen, such as when Fizeau or Twyman-Green interferometers are used.

Arrangements using transmitted optical radiation are less affected by spurious fringes than reflection type interferometers. It is preferable to use interferometers of the Mach-Zehnder or lateral shearing type or Shack-Hartmann arrangements in transmitted optical radiation. For the measurement of wave aberrations a single-pass geometry in transmitted optical radiation will often be the first choice for reducing spurious reflections.

6 Measurement arrangements

6.1 Measurement arrangement for single microlenses

Interferometers or wavefront detectors shall be used to measure the transmitted wavefront of the microlens under test. Single-path interferometers such as Mach-Zehnder, lateral shearing or double-pass interferometers such as Fizeau, Twyman-Green, and Shack-Hartmann wavefront detectors can be used for testing as shown in Annexes B to D.

The requirements for the measurement shall be defined. Typical criteria for choosing a specific method are

— required uncertainty of measurement,

— required properties to be measured,

— flexibility of the measurement,

— costs, and

— spot test on one lens or complete measurement.

For more details see ISO/TR 14999-2.

6.2 Measurement arrangements for microlens arrays

Interferometers or wavefront detectors shall be used to measure simultaneously whole arrays or parts of them in the transmitted radiation. Typical test arrangements are described in Annexes E and F.

NOTE While the testing of single lenses selected from an array can be carried out by illuminating with a spherical wave this is in general not possible with array tests. In that case, illuminating with plane wave is more suitable or special provisions using diffractive array wavefront shaping elements have to be used[13].

6.3 Geometrical alignment of the sample

Usually the microlens being tested and its coupling optics shall be set or adjusted into coaxial alignment with the wavefront measuring instruments. Optical alignment instruments and/or devices are commercially available for this purpose.

The sample can be mounted on a stage such as an air-chuck, which has two or three directions of freedom for adjustment.

6.4 Preparation

The test equipment shall be maintained in a temperature-controlled environment and not exposed to vibration so as to obtain consistent results. The use of an optical table is recommended.

The optical surfaces to be tested shall be clean. Uncoated glass surfaces may be safely cleaned with alcohol and cotton wool. The cotton wool should be soaked in a very small amount of solvent before touching the surface and wiped only once across it before being discarded. This minimizes the chances of scratching the surface. Dust may be removed using a clean camel-hair brush or filtered compressed air.

Coated optical surfaces such as antireflection surfaces should be treated with great care and not cleaned unless absolutely necessary. They may be dusted using filtered compressed air.

Guidance should be sought on the correct use of solvents, cotton wool or other wiping materials.

7 Procedure

Measurement requirements and typical methods for measuring the wavefront aberration of individual lenses are described in the Annexes A to D.

Examples for measurements of wavefront aberrations of microlens arrays are described in the Annexes E and F.

8 Evaluation

The wavefront aberration can be calculated from the interferogram[12][16] or from other wavefront measuring systems described in Annexes A to F. From the wavefront aberrations of spherical lenses with circular apertures primary Zernike coefficients can be derived with a prescribed software aperture.

NOTE 1 Typical wavefront aberrations described by Zernike coefficients are

— spherical aberration,

— astigmatism, and

— coma.

NOTE 2 For other lens aperture shapes (such as rectangular), see ISO/TR 14999-2.

The measured wavefront aberrations of samples shall be evaluated and quoted, for example, as peak-to-valley or root-mean-square values. ISO 14999-4 gives definitions of these terms relating to optical measurements.

Care should be taken to interpret peak-to-valley values because they are influenced by spurious values. It is recommended to use multiple times (at least three times) the rms figure instead.

9 Uncertainty of measurement

The wavefront aberrations of a sample are measured by a wavefront test system, which may introduce some aberration of its own. The uncertainty of measurement can be improved by subtracting the system aberrations[9][10].

10 Test report

The test results shall be recorded and shall include the following information if applicable:

a) general information:

1) test has been performed in accordance with ISO 14880-2:2024;

2) date of test;

3) name and address of test organization;

4) name of individual performing the test;

b) information concerning the tested lens:

1) lens type;

2) manufacturer;

3) manufacturer’s model;

4) serial number;

c) test conditions (environmental conditions):

1) temperature;

2) relative humidity;

d) information concerning testing and evaluation:

1) test method used;

2) optical system used;

3) irradiation:

i) source type,

ii) wavelength,

iii) FWHM (full width at half maximum) of optical radiation spectrum,

iv) polarization status,

v) irradiance angle,

vi) spot size;

4) detector;

5) aperture;

e) test results:

1) peak-to-valley value of wavefront aberration $\Phi_{\text{P-V}}$;

2) root-mean-square value of wavefront aberration Φ_{rms};

3) Zernike polynomials or other polynomial coefficients.

Annex A
(informative)

Measurement requirements for test methods for microlenses

The test for wave aberrations of microlenses shall be performed in transmitted optical radiation and in a single-pass arrangement, an interferometer like a Mach-Zehnder interferometer, a lateral shearing interferometer, or a Shack-Hartmann wavefront sensor. A single-pass test arrangement is required for sharp imaging of the lens aperture onto the detector or sensor array and to avoid the strong disturbances due to spurious reflections. Such reflections can occur in a double-pass arrangement like a Fizeau or a Twyman-Green interferometer. In a double-pass geometry the lens under test will deliver two images of the lens aperture one being out of focus causing diffraction effects like edge ringing in the rim region of the lens under test. Such effects can be avoided by using a single-pass arrangement because all reflections from lens surfaces in the auxiliary optical system in the forward direction are negligible, being reflected twice at antireflection coated surfaces. In addition, due to sharp imaging of the lens aperture, there are no ambiguities concerning the definition of the wave aberrations.

The test device shall not introduce aberrations of its own. In a Mach-Zehnder geometry, where the test sample is put into one arm of the interferometer and the reference arm delivers a plane wavefront, the beam splitting/combining optical elements are traversed by plane waves only. Spherical waves would produce spherical aberration or other aberrations for non-symmetric beam splitters. Similar requirements are also applicable for a Shack-Hartmann sensor although no beam splitters are used in this case.

In the case of lateral shearing interferometers, it is necessary to keep the design of the shearing device symmetric and as simple as possible (see for example the shearing interferometer based on two-phase gratings in a series arrangement [array tests]) in order to avoid additional measurement errors.

Since microlens diameters range from a few micrometres to a few millimetres, it is necessary to provide a means for changing the magnification by at least two orders of magnitude. This is in order to fill the aperture of the array photo-detector, typically a CCD-or CMOS array, to obtain sufficient lateral resolution so that strongly deformed wavefronts can also be tested without violating the sampling theorem. Due to the great span of magnifications in combination with the requirement of a plane wave interferometer, the imaging microscope shall be incorporated into the test arm for high magnification ratios commonly obtained with short working distances of the imaging microscope objective. If the imaging objective is to be used outside the interferometer structure, special objective designs are necessary to enable high magnification ratios in combination with long working distances. Two alternative solutions will be discussed in some detail to demonstrate Mach-Zehnder interferometers for the testing of wavefront aberrations. The imaging microscope will preferably be of the telescopic type in order to maintain in the test arm plane waves at the beam combiner.

The change of magnification requires special measures to adapt the beam splitting ratio between the two arms of the interferometer to obtain sufficient contrast in the interference fringes. A good choice for this is a polarizing splitting unit consisting of a polarizing beam splitter in combination with two quarter-wave plates (QWP), one in each arm of the interferometer and a half-wave plate (HWP) in front of the beam splitting unit for rotating the polarization vector.

It is also necessary to provide means for varying the mean intensity independently from the splitting ratio to avoid saturating the photo-detector and producing incorrect measuring results due to non-linear distortion of the signal.

The measurement of wave aberrations requires the irradiation of the test lens from the rear by a spherical wavefront produced by a high-quality microscope objective having a numerical aperture exceeding that of the lens under test. This objective shall have a Strehl definition above 90 % ($\simeq\lambda/20$) to simplify the test procedure and reduce the need for calibrations in many test situations.

For the characterization of small numerical aperture lenses, it is also advisable to provide plane wave irradiation of the sample. Plane wave irradiation enables the measurement of the focal length of the lens. Plane wave irradiation can be used for the determination of the focal length for high aperture lenses in the central resolved interference fringe field. For this purpose, the software has to provide for a central data selection mask of known lateral dimensions. A simple calibration of the scaling factor with the help of a commercial micrometre delivers the absolute diameter of the mask in micrometres.

In Annexes B and C, two alternative solutions for interferometric approaches are given which fulfil the main part or all of the above defined measuring requirements.

Annex B
(informative)

Microlens test Methods 1 and 2 using Mach-Zehnder interferometer systems

B.1 Measurement arrangement and test equipment

Methods 1 and 2 describe Mach-Zehnder interferometer systems, which mainly use plane waves and deviate from plane waves only to measure and to image the wavefront aberrations of the microlens on the array detector. Imaging is by means of a specially designed micro-objective outside the interferometer structure and having a very long working distance.

B.2 Measurement

B.2.1 Method 1

Elements are aligned coaxially. These elements include the radiation source, the beam expander, the aperture stop, the illuminating microscope objective, a reference lens or a microlens under test, plane mirrors, beam splitters, an imaging lens and an image sensor (see Figure B.1). The reference lens and the microlens shall be adjusted in such a manner as to generate minimal aberrations[19][20][21].

Figure B.1 shows a phase shifting interferometer based on a Mach-Zehnder geometry using Mirrors 1 and 2 and beam splitter and beam combiner. A parallel beam emitted from a laser source is expanded by a beam expander and is stopped down by means of an aperture stop in front of the interferometer. The beam is then divided into two beams using a beam splitter. The test arm beam illuminates a beam shaping objective which generates a spherical wavefront to illuminate the microlens under test, or a reference lens being free from aberrations but having the same size. The microlens or the reference lens is positioned confocally producing a nominally plane wavefront in the exit pupil of the lens under test. This wavefront is superimposed on the plane reference wave, resulting in an optical interference pattern. An imaging objective in the exit of the interferometer images the lens aperture sharply onto the photo-detector with a suitable scaling factor to utilise a large part of the photosensitive area of the array detector thus providing sufficient data samples for the characterization of the lens aberrations. The physical aperture stop in front of the interferometer shall be positioned on the optical axis at a distance from the illuminating objective of the test arm so that a sharp image of this stop coincides with the lens aperture under test.

The evaluation of the wave aberrations is made by reading several phase-shifted interference patterns into the on-line computer memory and performing an a posteriori evaluation.

In a first step, the wavefront aberrations of the reference lens together with the aberrations generated by the interferometer are measured and shall be denoted as Φ_0 .

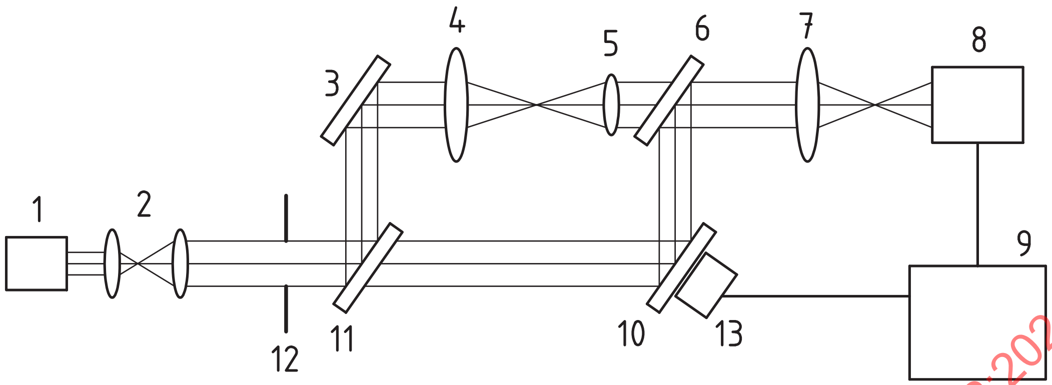
In a second step, the microlens to be tested is placed in the interferometer. The wavefront aberrations of the microlens under test shall be denoted as Φ . These aberrations result from the difference of the data Φ_1 minus the wave aberrations Φ_0 measured in conjunction with the reference lens, as given by Formula (A.1):

$$\Phi = \Phi_1 - \Phi_0 \qquad \text{(A.1)}$$

It is important to use an illuminating microscope objective with an effective NA larger than that of the microlens being tested.

In the configurations shown in Figure B.1, it is possible to put an aperture at the pupil position of the reference lens or that of the microlens under test, or nearby.

The aperture defines the diameter of the test area of the reference lens or the microlens under test. It is also possible to define the test area of the reference lens and of the microlens under test by placing the aperture at the image sensor position or by generating the aperture using software.



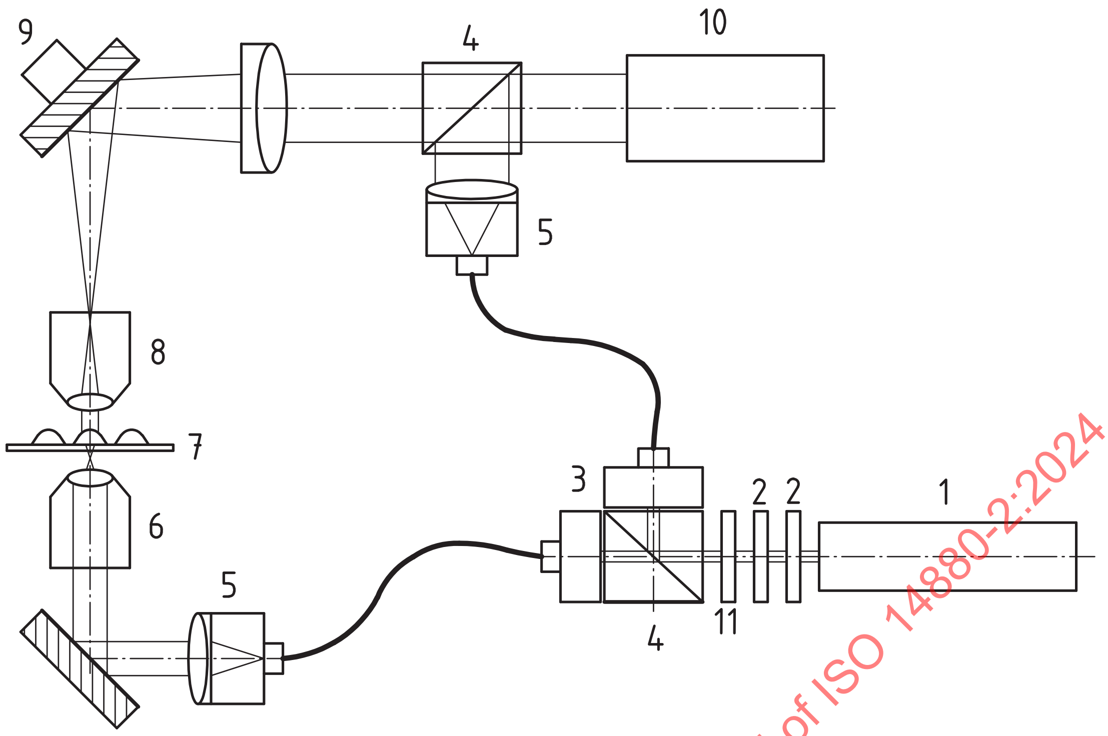
Key

1 light source (laser light source)
2 beam expander
3 mirror 1
4 beam shaping objective
5 reference lens or microlens under test
6 beam combiner
7 imaging lens
8 image sensor array (CCD, CMOS)
9 image processor
10 mirror 2
11 beam splitter
12 aperture stop
13 piezoelectric transducer (PZT)

Figure B.1 — Phase shift interferometer based on Mach-Zehnder interferometer

B.2.2 Method 2

Method 2 describes an alternative and more flexible solution of an interferometer based on a strongly modified Mach-Zehnder geometry using flexible single mode fibres in both arms of the interferometer[22].



Key

1 light source (laser light source)
2 polarizer
3 fibre coupler
4 beam splitter
5 beam expander
6 illumination micro objective 20×
7 microlens under test
8 imaging micro objective 5×; 10×; 20×; 50×
9 mirror mounted on a piezoelectric transducer
10 image sensor array (CCD, CMOS)
11 half-wave plate (HWP)

Figure B.2 — Mach-Zehnder interferometer based on a beam splitting unit using single mode polarization maintaining fibres and an imaging microscope incorporated into the test arm of the interferometer

For the illumination of the interferometer a He-Ne laser or a laser diode source is used (see Figure B.2). The polarization-based beam-splitting unit allows for the independent adjustment of the mean intensity by rotating a polarizer and of the splitting ratio between the object and the reference beam by turning a HWP in front of a polarizing beam-splitting cube. The polarized beams are fed to single mode fibres and each output is expanded to a plane wave. The reference wave is combined with the object wave with the help of a non-polarizing beam splitter. The polarization of the reference beam is matched with that of the object beam by rotating the end of the fibre accordingly. For the irradiation of the lens to be tested there are two alternatives:

a) spherical wave irradiation for the determination of wave aberrations;

b) plane wave irradiation realized by removing the micro-objective in front of the lens to be tested.

With a) a high-quality microscope objective with a sufficient working distance is used to transform the incoming plane wave into an ideal spherical wave which enables the measurement of the wave aberrations for ∞/*f*-conjugates. Plane wave irradiation geometry is chosen for the measurement of weak lenses and in general for phase objects giving the whole phase retardation due to the test sample. With b) there is the possibility for the determination of the effective focal length from the measured phase distribution in a reduced field around the vertex of the lens under test.

The lens array is placed on a *xy*-stage. The microlens under test is sharply imaged onto the photo-detector array using a microscope consisting of a microscope objective and a tube lens forming an afocal setup. The detector array is positioned in the focal plane of the tube lens. Since the set of microscope objectives given in Figure B.2 is designed for the same working distance, it is necessary to take special measures to avoid systematic errors when changing the magnification. In order to keep the imaging afocal, if the microscope objective is changed the tube lens together with the beam combining group and the detector are shifted axially as a unit maintaining plane wave irradiation for the beam combining cube. In this way the risk of aberrations introduced by incorrect adjustments is minimized.

NOTE Tube lenses take the collimated light from an infinity-corrected microscope objective and focus it onto a camera.

The interferometer shown in Figure B.2 is equipped with a polarizing beam-splitting unit allowing for the independent variation of the splitting ratio and the mean intensity as it was required above. Due to the fibre coupling between the beam splitter group and the rest of the interferometer it could be built into a commercial microscope having the advantage of all the means of adjustment of such instruments.

Figures B.3 to B.5 show the field of view for the different adjustments possible in the case of the interferometer shown in Figure B.2. A measuring result for the wave aberrations of a spherical microlens is given in Figure B.6.

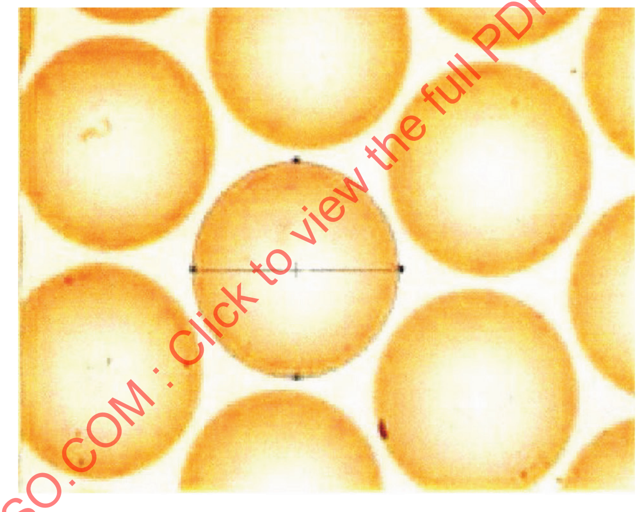
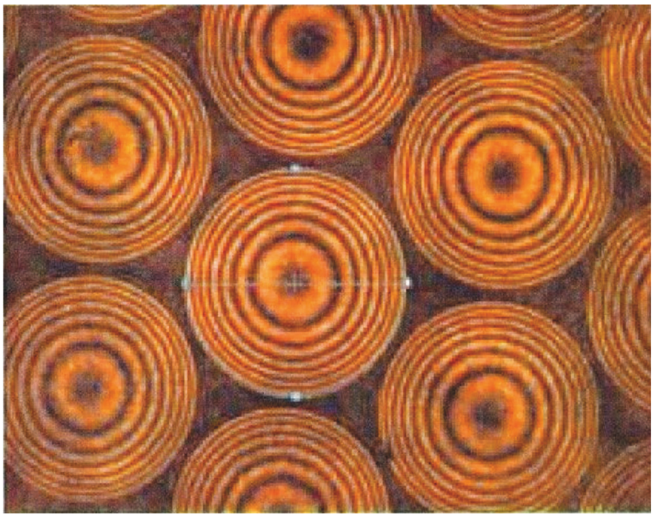


Figure B.3 — White light irradiation for positioning of mask

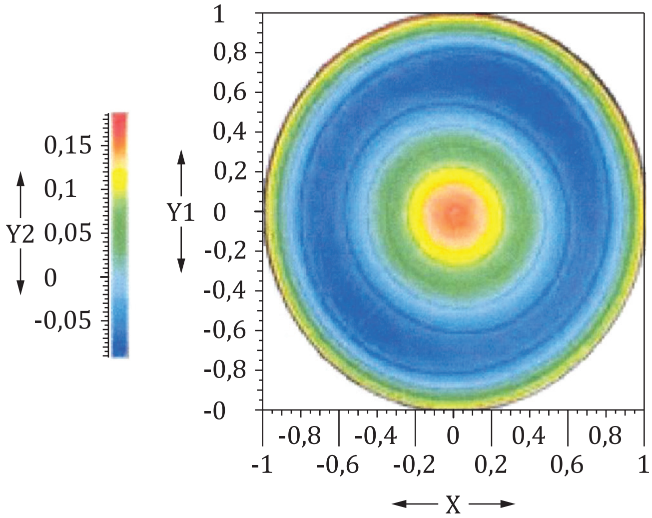


The lens is selected with a mask indicating the field of interest.

Figure B.4 — Plane wave irradiation of the lens array plane

The interference fringes give a clear indication of spherical aberration.

Figure B.5 — Field of view with spherical wave irradiation



Key

X normalized radius (*x*-direction)

Y1 normalized radius (*y*-direction)

Y2 phase/lambda

Figure B.6 — Wavefront aberrations given as Zernike fit

Annex C
(informative)

Microlens test Methods 3 and 4 using a lateral shearing interferometer system

C.1 Measurement arrangement and test equipment

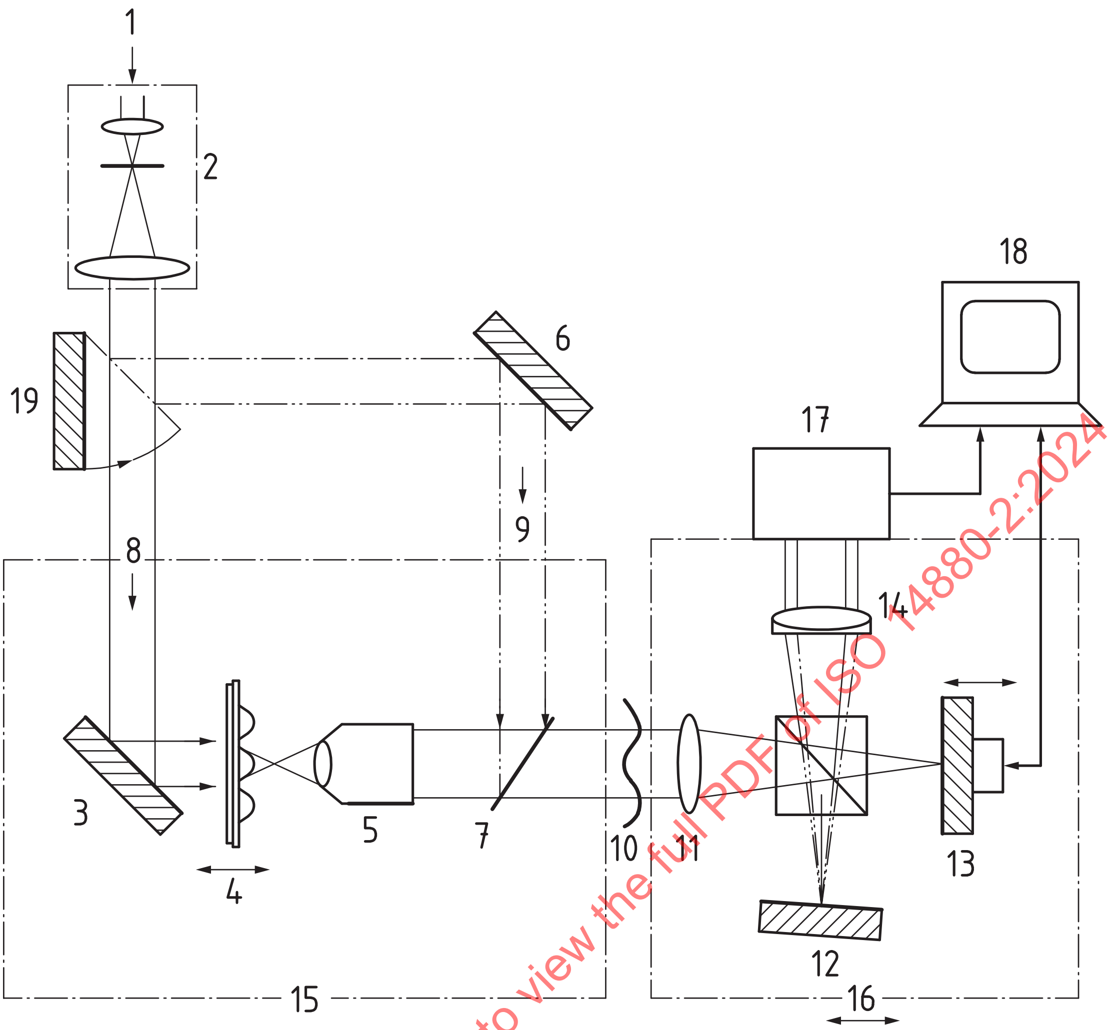
Method 3[23] uses a lateral shearing interferometer system which measures wavefront aberrations of microlenses via the measurement of the partial derivatives of the wavefront in two orthogonal directions and an a posteriori integration of the two data fields resulting in the wave aberrations.

C.2 Measurement

C.2.1 Method 3

Figure C.1 shows a lateral shearing interferometer. With this configuration, the beam expander expands a parallel beam emitted from the source of optical radiation. The parallel beam is then transmitted to the microlens under test which transforms the spherical wavefront emerging from the microlens into a plane wavefront by means of a high-quality microscope objective having a sufficient numerical aperture. The outgoing nominally plane wavefront carries the wave aberrations of the lens under test. An auxiliary objective focuses the wavefront onto the end mirrors of a Michelson interferometer. By tilting one (or both in opposite directions) of the mirrors the emerging wavefronts from an identical auxiliary objective are laterally sheared with respect to each other[23][24].

If the axial distances of the components of the whole set-up are properly chosen the lens aperture is sharply imaged on the detecting array providing a shearing interferogram for instance in the X-direction. Tilting the mirror of the Michelson around the orthogonal axis an interferogram in the Y-direction is formed. The phase distributions are measured by means of phase shifting techniques. The necessary phase shifts are produced by moving one of the mirrors axially with the help of a piezoelectric transducer (PZT) device. The integration of the two shear images enables the determination of the wave aberrations. The same set-up has also a reflected ray facility to measure the position of the vertex of the microlens enabling the determination of the effective focal length by moving the micro-objective between the cat's eye and the focus position with a stage having a length measuring facility.



Key

1 light source (laser light source)
2 beam expander
3 mirror
4 microlenses under test
5 microscope objective 20 × 0,65
6 mirror
7 beam splitter
8 transmitted optical radiation
9 reflected optical radiation
10 aberrant plane wave
11 auxiliary lens
12 mirror 1, tiltable
13 mirror 2, on piezoelectric transducer (PZT)
14 sheared apertures
15 illumination setup
16 shearing setup
17 image sensor array (CCD, CMOS)
18 PC
19 tiltable mirror

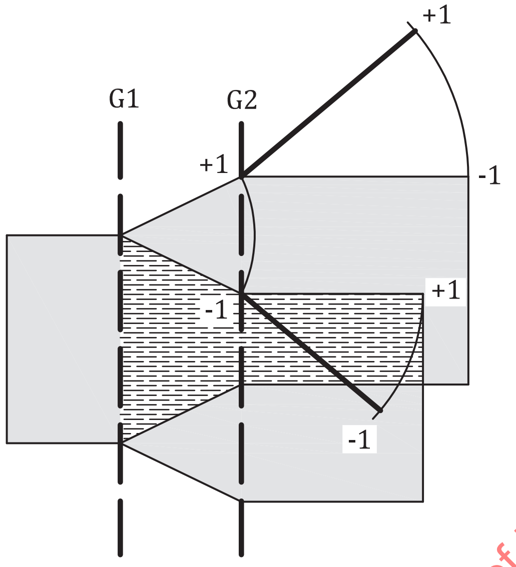
NOTE The incoming wavefront is focused on the mirror with the help of a well corrected small numerical aperture objective. The impact of the beam splitting cube onto the wavefront aberrations is taken into account in the design of the auxiliary objective.

Figure C.1 — Lateral shearing interferometer based on a Michelson-setup where the lateral shear is produced by tilting one of the mirrors

C.2.2 Method 4

NOTE See Reference [24] for details.

Method 4 relies on the use of two diffractive beam splitters (see Figure C.2 for the physical principle of the diffraction based shearing device) for providing the shear. In this case, the shear is directly applied to plane waves coming from the combination of the microlens plus a compensating microscope objective (see Figure C.3 for a set-up enabling the measurement of the wave aberrations of a microlens).

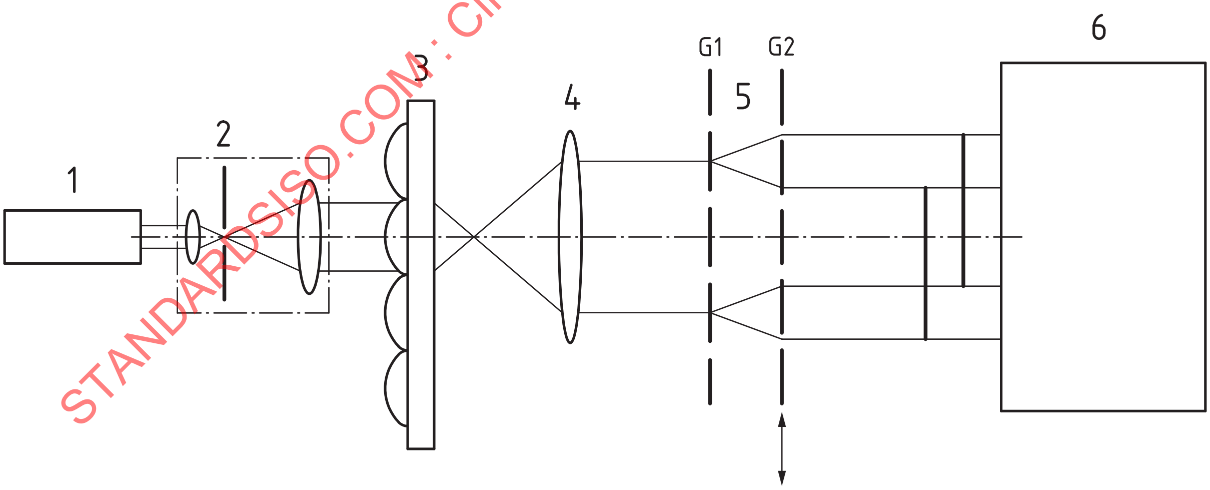


Key

G1	grating 1
G2	grating 2
+1, −1	order of diffracted beam

NOTE The binary phase grooves provide a phase shift of π, enabling the zero diffraction order to be suppressed.

Figure C.2 — Shearing interferometer on the basis of a series arrangement of two Ronchi-phase gratings



Key

1 light source (laser light source)
2 beam expander
3 microlens array under test
4 microscope objective
5 shearing interferometer

6 image sensor array (CCD, CMOS)

G1 grating 1

G2 grating 2

Figure C.3 — Shearing interferometer set-up for testing microlenses with respect to wave aberrations on the basis of a diffractive shearing unit being symmetric and free from aberration contributing elements

Shearing interferometers provide the partial derivatives (or more exactly, the difference of wavefront aberrations between laterally sheared copies of the wavefront under test). Therefore, it is necessary to measure the derivatives in two dimensions (see Figure C.4 as an example) in order to be able to calculate the wave aberrations a posteriori by fitting suitable polynomials to the data. For this integration, it is necessary to know the lateral shear amount and the lateral metric in order to obtain reliable data for the wavefront aberrations. The diffractive shearing set-up has some very essential advantages:

a) it provides a symmetric shear around the optical axis;

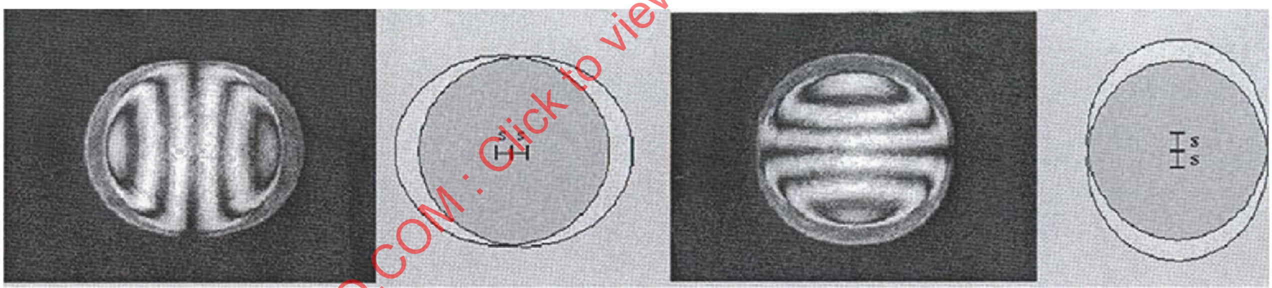
b) it is extremely stable and easy to integrate into an optical set-up;

c) it can be rotated as a whole by 90° to obtain the two orthogonal derivatives;

d) the shear can be adjusted simply by varying the distance of the gratings;

e) the phase can very easily be shifted by a translation of one of the gratings in relation to the other perpendicular to the grooves of the gratings;

f) due to the simple design with two plane parallel glass plates having binary relief structures on one side, the contribution of the interferometer components to the aberrations can be kept $<\lambda/20$ using standard manufacturing methods for the phase gratings.



Key

s lateral shear

NOTE Since the shearing unit is rather compact and common path-type the two orthogonal shears can be adjusted by rotating the grating combination through 90°.

Figure C.4 — Shearing interferograms produced with the help of a diffractive shearing interferometer at a wavelength of 1,32 µm in *x*-direction (left) and *y*-directions (right)

Annex D
(informative)

Microlens test Method 5 using a Shack-Hartmann sensor system

D.1 Measurement arrangement and test equipment

Wavefront aberrations of a microlens can also be measured using a Shack-Hartmann wavefront sensor system[6].

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 and a higher efficiency of radiation collection. The power (energy) density distribution behind the array is recorded by a position sensitive detector, most commonly a CCD or CMOS sensor array. The detector signals can be acquired by a computerized data acquisition and analysis system. (See also ISO 15367-2.)

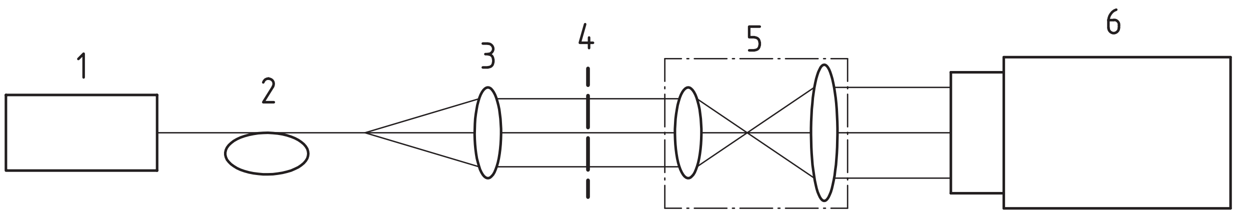
D.2 Measurement

Figure D.1 shows the layout used to measure the wavefront aberrations with a Shack-Hartmann wavefront sensor. The elements are aligned co-axially. These elements include an optical radiation source, optical fibre, collimating lenses, the microlens being tested, a beam expander, and a wavefront sensor along with an appropriate image processor (not shown).

At first a reference file is created with the wavefront sensor using the layout in Figure D.1. The output of optical radiation from an optical fibre is collimated and sent through a microscope, the output of which is incidence on a wavefront sensor. This reference contains information on the combined effect of the optics used for the beam expander. The aberrations of the reference wavefront will be subtracted from the subsequent microlens measurements.

Next, there are two possibilities for measuring the actual microlens depending on the power of the microlens. For a “slower” microlens (where the NA of the microlens is less than the NA of the fibre), the layout in Figure D.2 can be used to measure the aberrations. In this case, a microlens is placed at the imaging plane just preceding the beam expander and the position of the fibre is adjusted to collimate the beam through the microlens. The aberrations of the microlens are automatically measured with respect to the reference measurement taken with the set-up in Figure D.1 (the aberrations of the beam expander optics are subtracted out in the reference file).

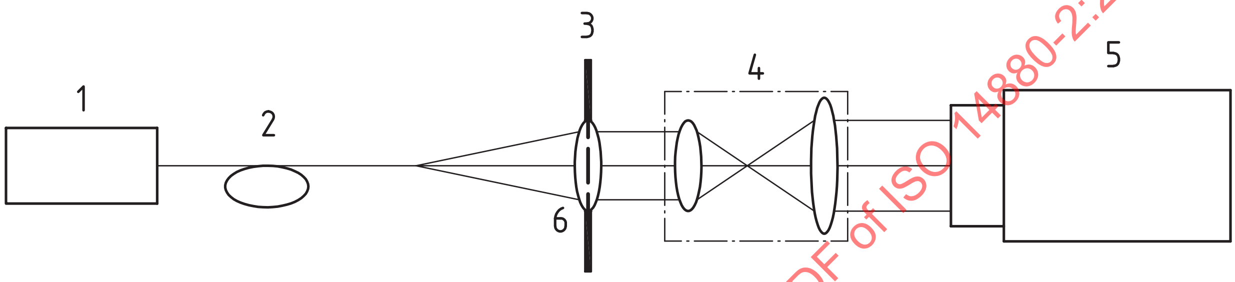
For a “faster” microlens (where the NA of the microlens is larger than the NA of the fibre), the layout in Figure D.3 is used. In this case, a slower lens is used to collimate optical radiation from the fibre through a fast refocusing lens (at least as fast as the microlens being tested), which is then incident upon the microlens to be tested. Again the aberrations of the microlens are measured with respect to the reference file.



Key

1	light source (laser light source)	4	imaging plane
2	fibre	5	beam expander
3	collimating lens	6	shack-hartmann sensor

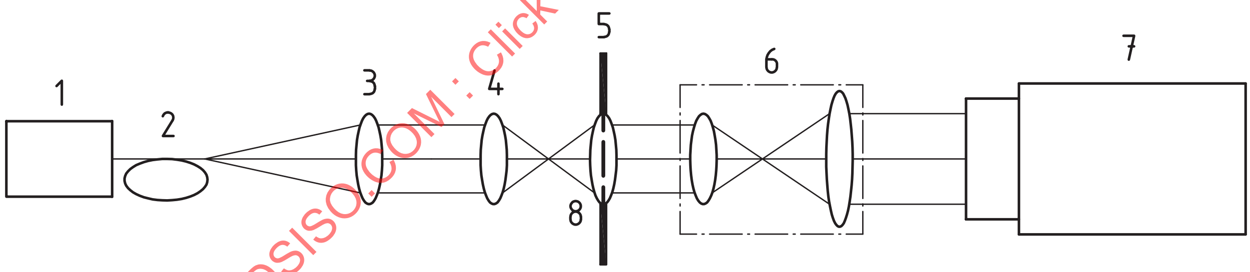
Figure D.1 — Layout for reference measurement



Key

1	light source (laser light source)	4	beam expander
2	fibre	5	shack-hartmann sensor
3	aperture	6	slower microlens to be tested

Figure D.2 — Layout for measurement of a "slow" microlens



Key

1	light source (laser light source)	5	aperture
2	fibre	6	beam expander
3	collimating lens	7	shack-hartmann sensor
4	refocusing lens	8	fast microlens to be tested

Figure D.3 — Layout for measurement of a "fast" microlens

Annex E
(informative)

Microlens array test Method 1 using a Twyman-Green interferometer system

E.1 Measurement arrangement and test equipment

Array test Method 1 uses a Twyman-Green interferometer system to measure the wavefront aberrations of a microlens array.

E.2 Measurement

Figure E.1 shows a Twyman-Green design of interferometer adapted for microlens array wavefront measurement. It uses polarised laser illumination together with half-wave and quarter-wave plates to control the efficiency of transmission and reflection at the polarising beam splitter and to suppress the stray reflections.

The interferometer is illuminated by an expanded and collimated beam which is incident on a polarizing beam splitter via a half-wave plate. The half-wave plate allows the wavefront polarisation to be aligned with beam splitter surfaces. The beam is divided into two and one beam is reflected to the reference arm. This contains a plane reference mirror, mounted on a piezoelectric transducer (PZT) which enables precise changes in the optical path length to be introduced. After reflection at the mirror the beam once again traverses the quarter-wave plate and the modified polarisation state allows for efficient transmission of the reference beam via the cube beam splitter to the output arm.

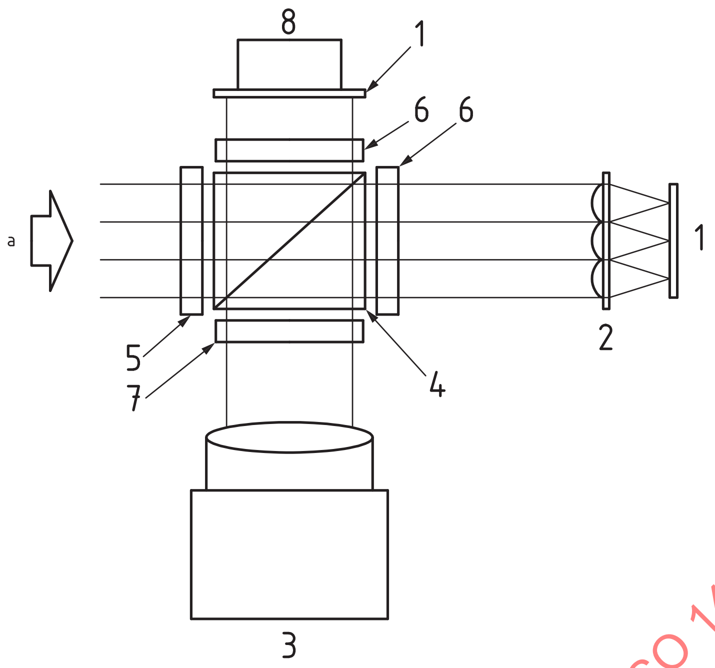
The beam that is initially transmitted by the cube beam splitter illuminates the microlens array under test. This generates an array of spots which are focused onto another plane mirror. The axial position of this mirror is adjusted to achieve the cat's-eye position whereby the individual beams are reflected back through the same microlenses. Note that each small beam is now inverted. This limits the range of aberrations that can be measured.

Once again, a quarter-wave plate is used in double pass to rotate the polarisation state and the cat's-eye reflected beams in the test arm are reflected at the cube beam splitter to combine with the reference beam that is transmitted at the beam splitter. A polarising filter is used to clean up the wavefronts which generate an interference fringe pattern, relayed to an image sensor by an imaging lens. The pattern can be phase-shifted by applying a voltage to a piezoelectric transducer (PZT) to displace the reference mirror and the patterns can be analysed by special software or assessed by eye.

This measurement approach reveals the even wavefront aberrations of each microlens being tested, combined with the aberrations of the interferometer including the reference plane errors. The method for subtracting system aberrations from the microlens array data is similar to that described in the previous section at D.2.

There are limitations on the aberrations that can be measured this way. Only the even components of the wavefront aberrations can be measured. This means that spherical aberration is measured correctly but not, for example, coma. The reason for this is the inversion of the wavefronts from the individual microlenses, after the cat's eye reflections of the beams focused at the plane mirror.

Elements are aligned coaxially. These elements include the optical radiation source, beam expander, aperture stop, first- and second- standard lenses, microlens array under test, mirrors, imaging lens, and an image sensor. The effects of stray reflections arising at normal incidence surfaces are minimised by the use of optical waveplates to control the polarisation states of the illumination.



Key

1 plane mirror
2 microlens array under test
3 image sensor
4 polarising beamsplitter
5 half-wave plate
6 quarter-wave plate
7 polarising filter
8 piezoelectric transducer (PZT)
a Polarized laser illumination.

Figure E.1 — Twyman-Green interferometer for microlens array wavefront measurement