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Optics and photonics — Microlens arrays —

Part 3:

Test methods for optical properties other than wavefront aberrations

Optique et photonique — Réseaux de microlentilles —

Partie 3: Méthode d'essai pour les propriétés optiques autres que les aberrations du front d'onde

Reference number
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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 14880-3 was prepared by Technical Committee ISO/TC 172, *Optics and photonics*, Subcommittee SC 9, *Electro-optical systems*.

ISO 14880 consists of the following parts, under the general title *Optics and photonics — Microlens arrays*:

- *Part 1: Vocabulary*
- *Part 2: Test methods for wavefront aberrations*
- *Part 3: Test methods for optical properties other than wavefront aberrations*
- *Part 4: Test methods for geometrical properties*

Introduction

This part of 14880 specifies methods of testing optical properties, other than wavefront aberrations, of microlens arrays. Examples of applications for microlens arrays include three-dimensional displays, coupling optics associated with arrayed light sources and photo-detectors, enhanced optics for liquid crystal displays, and optical parallel processor elements.

The testing of microlenses is in principle similar to testing any other lens. The same parameters need to be measured and the same techniques used. However, in many cases the measurement of very small lenses presents practical problems which make it difficult to use the standard equipment that is available for testing normal size lenses.

The market in microlens arrays has generated a need for agreement on basic terminology and test methods. 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.

This part of 14880 contributes to the purpose of the series of ISO 14880 standards which is to improve the compatibility and interchangeability of lens arrays from different suppliers and to enhance development of the technology using microlens arrays.

The measurement of focal length is described in the body of this part of ISO 14880 and the use of an alternative technique, interferometry, is described in Annex A.

Measurement of the focal length of an array of microlenses, using a confocal technique, is described in Annex B.

Coupling efficiency and imaging quality are discussed in Annex C.

Measurement of the focal spot positions of an array of microlenses in parallel, using the Shack-Hartmann technique, is described in Annex D.

Optics and photonics — Microlens arrays —

Part 3:
Test methods for optical properties other than wavefront aberrations

1 Scope

This part of ISO 14880 specifies methods for testing optical properties, other than wavefront aberrations, of microlenses in microlens arrays. It is applicable to microlens arrays with very small lenses formed on one or more surfaces of a common substrate and to graded index microlenses.

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

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

3 Terms and definitions

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

4 Substrate test

The optical quality of the substrate contributes to the quality of the focal positions defined by the microlenses and shall be quantified in accordance with ISO 10110-5.

5 Microscope test method

5.1 Principle

The basic principle is to locate, by optical means, the surface of the microlens under test. The effective back (front) focal length is determined by measuring the axial displacement necessary to locate the focal position.

5.2 Measurement arrangement and test equipment

5.2.1 General

The testing of microlenses is similar in principle to testing larger lenses. In many cases however, the measurement of very small lenses presents practical problems which make it difficult to use standard equipment. In general, two optical techniques can be used. One is based on microscopy, the other is based on interferometry.

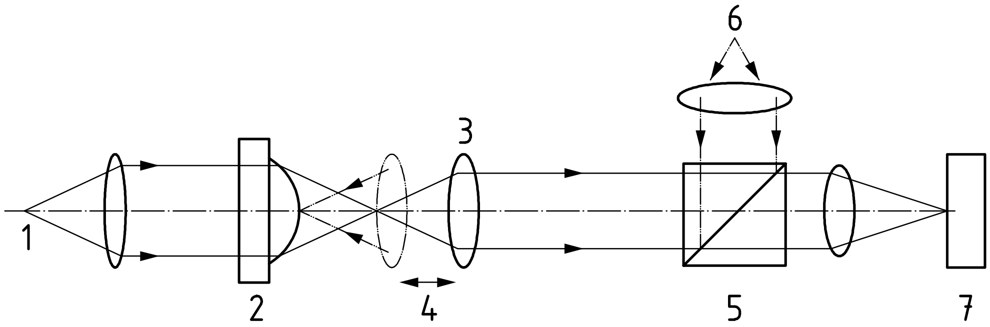
The first technique uses a microscope to locate, by focusing, the vertex of the microlens. The effective back (front) focal length is deduced from a measurement of the displacement necessary to refocus the microscope on the image of a distant source as shown in Figure 1.

A focusing aid in the microscope such as a split-field focusing graticule enables the featureless vertex of a microlens to be more readily located when viewing with reflected light. For focal length measurements the distant point source may be the emitting tip of an optical fibre or an illuminated test graticule. Tests may be performed with white light or monochromatic illumination.

The second technique uses wavefront sensing to locate the test surface or the centre of curvature. The location test may be carried out with the help of one of the following devices:

- Fizeau interferometer,
- Twyman-Green interferometer,
- lateral shearing interferometer, or
- Shack-Hartmann device.

These are more fully described in ISO 14880-2 and ISO/TR 14999-1. One advantage of interferometry is that for strongly aberrated lenses, the variation in focal length with aperture radius can be readily deduced from the interference patterns. A disadvantage is that tests are restricted to the wavelength of the interferometer light source.



Key

1 distant point source
2 substrate and microlens producing focussed spot
3 microscope objective
4 axial adjustment of microscope to locate lens surface and focus
5 beamsplitter
6 source for focus location on lens surface
7 charge-coupled device (CCD) camera

Figure 1 — A collimated source and microscope used to measure the effective back or front focal length of a microlens

Clauses 5 to 9 concentrate on the microscope technique while an interferometric technique is described in Annex A and a Shack-Hartmann technique in Annex D.

The confocal measurement of the effective focal lengths of lens arrays is described in Annex B.

5.2.2 Test system

5.2.2.1 General

The test system consists of a microscope fitted with displacement transducers, suitable light source, test object, microscope video camera, monitor and image analyser (line intensity scan).

5.2.2.2 Microscope

A microscope fitted with a focusing aid such as a split-image rangefinder is required to enable focus settings to be made on a featureless surface such as the vertex of the microlens surface. The mechanical design shall allow the distant point source or test graticule to be placed below the stage carrying the test lens. Ideally, the test lens should be supported with no additional optical component such as a glass plate between it and the distant point source or test graticule. The displacement of the test surface relative to the microscope objective is measured with a calibrated displacement transducer.

The numerical aperture (NA) of the microscope objective shall be larger than the numerical aperture of the test lens at the focal point.

5.2.2.3 Light source

A light source emitting radiation in the band of wavelengths or at a specific wavelength required for the test shall be used. The properties of the light source shall be described in the experimental results report.

White light can be provided by a quartz-halogen lamp in combination with a suitable aperture stop. Narrow band filters can be used where a restricted range of wavelengths is required. A laser can be used for monochromatic illumination and higher intensities.

5.2.2.4 Test objects

The distant point source can be approximated using the emitting tip of an optical fibre. The distant point source shall be placed on axis with the lens and at an effectively large distance to enable the focal length to be determined.

Alternatively, the object may be a graticule. This enables the optical properties at particular spatial frequencies and field angles to be studied.

The detection of the focus spot may be susceptible to undersampling by the detector array.

The distant point source or test graticule used shall be described in the documentation of the test report.

5.2.2.5 Image display

If the image generated by the microscope is relayed by a video camera to a video display, an electronic intensity display can be used to assist in locating the position of best focus. The intensity of the image at the detector shall be adjusted to maintain a linear response from the detector system.

5.2.2.6 Standard surfaces

A microlens of known focal length at a defined wavelength shall be used as a calibration artefact to verify the performance of the measurement system.

A step height artefact, for example two thin glass plates held together in optical contact to provide a step of known height, shall be used to verify the performance of the displacement measurement system.

5.3 Preparation

For consistent results the test equipment shall be maintained in a temperature-controlled environment, preferably at 20°C and not exposed to vibration.

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 the optical surface 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 and cleaning materials.

6 Procedure

6.1 General

Clean the surface of the lens and substrate to be tested.

6.2 Measurement of effective back or front focal length

Standard instrument calibration procedures should be carried out periodically and the calibration uncertainty estimated [4].

Verify the performance of the test system by measuring, as described below, the effective back (front) focal length of the standard spherical surface and comparing the result with the known value.

The microscope is focused on the surface of the microlens and then displaced to focus on the image of a graticule or a point source placed at infinity. The best focus position for this image may be located using a camera, and vidicon display with line scan to determine the displacement position at which the peak intensity in the image is greatest. The spatial resolution of the camera system shall be sufficient to resolve the image. The axial displacement is measured using the displacement transducer.

6.3 Measurement of chromatic aberration

In general, microlenses are relatively simple and are not corrected for chromatic aberration. The focal length will vary with wavelength of illumination.

With conventional lenses, a ray is deviated by refraction at the interface between two optical media with distinctly different refractive indices. The magnitude of the paraxial focal length for a single spherical surface of radius R is given by

$$f = R/[n_1(\lambda) - n_2(\lambda)] \tag{1}$$

where n_1 and n_2 are the refractive indices of the two media before and after the interface at a wavelength λ. The chromatic aberration of the lens is determined by the dispersion characteristics of the two media, $n_1(\lambda)$ and $n_2(\lambda)$.

The conventional way of characterizing the dispersion of optical materials is by the Abbe number ν, the definition of which includes values for the refractive index of the material at three wavelengths. For example 480 nm, 546 nm and 644 nm for the Abbe number ν_e at the green mercury e-line (546 nm).

$$\nu_e = (n_{546} - 1)/ (n_{480} - n_{644}) \tag{2}$$

The Abbe number usually ranges between 20 and 60. Materials with higher Abbe numbers exhibit less chromatic dispersion than materials with lower Abbe numbers.

The Abbe number of the microlens material may be determined by measuring the focal length of the lens at the appropriate wavelengths and combining Equations (1) and (2), namely

$$\nu_{\text{eff}} = (1/f_{546})/(1/f_{480} - 1/f_{644}) \tag{3}$$

Various Abbe numbers may be defined depending on the choice of wavelengths. It may be more practical to use laser sources and define the Abbe number at those wavelengths.

The focal length of a lens is measured as described in 6.2 using monochromatic illumination. The measurement is then repeated using monochromatic illumination of different wavelengths to derive the chromatic aberration which is defined as

$$\Delta S_z = S_z(\lambda_1) - S_z(\lambda_2) \tag{4}$$

where

$S_z(\lambda)$	is the axial focus position;
λ_1 and λ_2	are the illumination wavelengths with $\lambda_1 > \lambda_2$.

The values obtained relate to the performance of the lens in practice and consideration may have to be given to the dispersion of the substrate.

This method involves measuring small changes of focal length with wavelength and it is important to measure the focal length as accurately as possible to reduce the uncertainty in the value for the Abbe number.

6.4 Measurement of the uniformity of the focal spot positions

Microlens arrays are often used for wavefront measurement such as the Shack-Hartmann test. The lateral shift of the focal spot position from the optical axis represents the angle of the local tilt of the wavefront under test. Therefore reliable data of the uniformity of a microlens array (due to the regular arrangement and the coordinates of the lens aperture centre positions of each individual lenslet of the array) are essential for an accurate wavefront measurement.

The disparity of focal spot position shifts of lenslets of an array determines the uniformity of the array.

The test set-up is described in Annex D.

7 Results and uncertainties

The mean value of a set of measured values for focal length should be calculated and recorded. The variance of the set of measured values should be analysed statistically and the unbiased estimate of the standard deviation evaluated. This is to ascertain the Type A contribution to the expanded uncertainty (see Reference [4]).

Typical sources of uncertainty are included in Table 1.

Table 1 — Uncertainty considerations

Origin	Type	Uncertainty limit
Focal length measurement	A	Calculated from a set of, typically nine, measurements
Calibration	A/B	Varies with instrument and method of calibration

Optimum measurement conditions can be selected by monitoring the temperature and relative humidity values during the measurements, and always giving the apparatus time to reach room temperature. The Abbe offset error is minimized by arranging for the displacement transducer to measure as close as possible to the optical axis.

8 Coupling efficiency, imaging quality

Microlenses are often used to collimate light from a small source such as a laser diode, to focus light to a small aperture or to couple light into a fibre. In other applications, microlenses are used to generate small images of an object. Therefore remarks regarding the coupling efficiency and the imaging quality of microlens arrays are described for information in Annex C.

9 Test report

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

a) General information:

    1) test has been performed according to ISO 14880-3:2006;
    2) date of calibration, calibration procedure and calibration uncertainty assessment;
    3) date of test;
    4) name and address of test organization;
    5) accreditation (if relevant);
    6) name of individual performing the test.

b) Information about the lens under test:

    1) lens type;
    2) manufacturer;
    3) manufacturer’s model;
    4) serial number.

c) Environmental test conditions:

    1) temperature;
    2) relative humidity.

d) Information concerning testing and evaluation:
    1) test method used;
    2) optical system used;
    3) light source:
        i) source type,
        ii) wavelength;
    4) displacement transducer used.

e) Test results:
    1) effective back focal length;
    2) effective front focal length;
    3) focal spot position shifts ΔS_x and ΔS_y;
    4) chromatic aberration: ΔS_z;
    5) uncertainty table.

Annex A
(informative)

Measurements with wavefront measuring systems

A.1 Interferometer measurement principle

A variety of methods exist for measuring the focal length of lenses[5]. Back (front) focal length may be measured using an interferometer to help locate the vertex of the lens surface and to find the best focus position and using a linear displacement transducer for length measurement. One of the following devices could be used for this purpose:

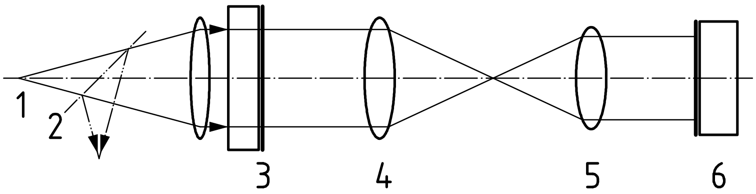
- Fizeau interferometer;
- Twyman-Green interferometer;
- lateral shearing interferometer, or
- Shack-Hartmann device.

Use of a Fizeau interferometer is described here as an example. A collimated beam from a coherent light source is partially reflected from a plane reference surface to generate a reference wavefront. The transmitted light is focused to a spot by a high quality lens and this spot is used to probe the position of the lens surface and the focal point. Interference patterns are monitored to determine the two locations.

NOTE For strongly aberrated microlenses, the effective focal length as defined in ISO 14880-1 may differ significantly from values based on wavefront deviation criteria.

A.2 Measurement arrangement and test equipment

The Fizeau interferometer is shown in Figure A.1.



Key

1 coherent light source and collimator
2 beamsplitter
3 reference plane
4 high quality microscope objective
5 microlens under test
6 optical flat

Figure A.1 — Fizeau interferometer

In principle, interferometers available for testing conventional sized lenses, particularly those of the Fizeau type, may appear to be suitable for measurements with microlenses. In practice, problems may arise from stray reflections from secondary surfaces in close proximity to the surface under test. The relatively high magnification involved may lead to difficulties in focusing on the test surfaces of the microlens. Interferometers specially designed for microsurfaces overcome these problems [6]. Position the optical flat as close as possible to the microlens under test to minimize aperture diffraction errors and focus the lens array onto the detector array.

A.3 Measurement of effective back or front focal length

To measure focal length, the microlens under test is positioned on-axis so as to collimate the diverging beam. A high quality plane mirror or optical flat is used to reflect the light back through the system where it combines with the reference wavefront to form an interference pattern. It is advisable to first align the plane mirror without the microlens and microscope objective in place by tilting the plane mirror until the interference pattern is nulled, that is the intensity is uniformly distributed. The microscope objective and microlens are then inserted and the axial position of the microlens is adjusted until the interference pattern is again nulled. Alternatively, a small tilt may be introduced between the two wavefronts to generate a pattern of interference bands and the setting is made by adjusting the axial position of the microlens until the bands are straight, parallel and equidistant.

The lens under test is then moved axially until the probe beam is focused on the lens surface. In this position, the light is partially reflected in the cat's eye configuration back to the interferometer to form a pattern of bands. The lens position is adjusted until the bands are either nominally straight or nulled.

Focal length measurements are deduced from the axial displacements of the test lens between the positions discussed above. Such measurements may be conveniently made with a laser length measuring interferometer.

NOTE In practice, totally straight interference bands will rarely be obtained. The effect of aberrations in the lens under test will be to introduce bending of the interference bands that will vary over the field. Residual aberrations in the test system can also be apparent especially when using the cat’s eye configuration which inverts one wavefront with respect to the other.

Annex B
(normative)

Confocal measurement of effective back or front focal length of lens array

B.1 Measurement principle

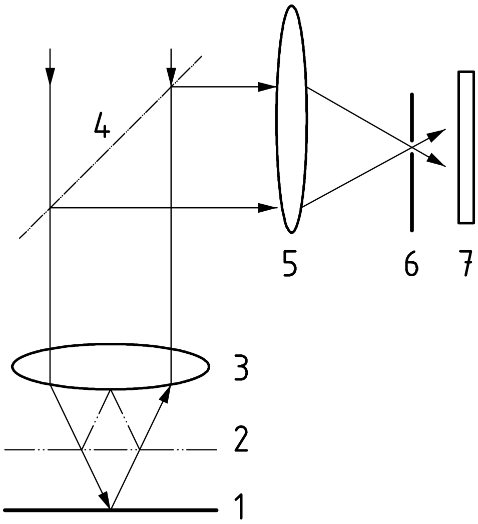
The effective back (front) focal length of multiple lenses in the array can be measured using the confocal principle with light focused by a single lens as shown in Figure B.1.

A plane mirror surface in Position A should be located by focusing light to the surface where it is reflected in the cat's eye configuration. Light reflected back through the lens is reflected at a beam-splitter and focused to a pinhole. Light transmitted by the pinhole is detected electronically.

When the mirror surface is positioned at the focal point of the microlens, the light reflected back through the pinhole is at a maximum. If the distance from the lens to the mirror surface is reduced, a position is found at Position B where the intensity of light transmitted by the pinhole reaches a secondary maximum. In this position, light is reflected from the lens surface in the cat's eye configuration.

The distance between the two positions is one half of the effective focal length of the microlens.

By replacing the lens with a microlens array the mean effective focal length of the array can be measured.



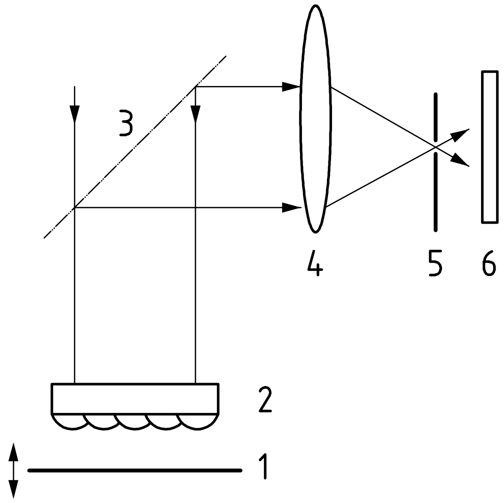
Key

1 mirror surface Position A
2 mirror surface Position B
3 microlens
4 beamsplitter
5 focusing lens
6 pinhole
7 detector

Figure B.1 — Measurement of the effective focal length of a microlens array

B.2 Measurement system for microlens array

A confocal optical system and a plane mirror on an adjustable stage equipped with a displacement transducer is required as shown in Figure B.2. The mirror is positioned close to the focal plane of the lens array and the axial position adjusted until maximum light is transmitted by the pinhole. The detector array, for example a CCD, enables the spatial distribution of bundles of rays from each microlens aperture to be monitored. The axial position of the mirror is scanned and the position that corresponds to maximum intensity at the CCD for each lens element is recorded.



Key

1 mirror positioned at microlens array focal plane
2 microlens array
3 beamsplitter
4 focusing lens
5 pinhole
6 detector array

Figure B.2 — Measurement of the effective back or front focal length of a microlens array

Annex C
(informative)

Coupling efficiency, imaging quality

C.1 Coupling efficiency

Microlenses are often used to collimate light from a small source such as a laser diode, to focus light to a small aperture or to couple light into a fibre. Coupling efficiency is usually expressed as the ratio of the input power to the power transferred and is an important factor in optical communication networks that use optical fibres to transmit signals. The efficiency of coupling will depend on the size of the focused spot and this is a function of the numerical aperture subtended by the focused wavefront, the wavefront aberrations and the wavelength of illumination. It will also depend on the input characteristics of the fibre. In order to obtain a high coupling efficiency, it is necessary to match the wavefield and the fibre mode [7].

When the focused spot departs from the ideal point spread function the energy is spread over a larger area and it is useful to quantify the ratio of peak focal intensities in the aberrated spot to the ideal point spread function in the absence of aberrations [8]. This is defined as the Strehl ratio and can be approximated by the geometrical Strehl ratio defined as

$$S = \mathrm{e}^{-(2\pi\sigma)^2}$$

where σ is the root-mean-square deviation of the wavefront in wavelengths.

Wavefront aberrations are readily measured using interferometry as described in ISO 14880-2 and modern wavefront analysis software usually offers an option to calculate the Strehl ratio from the interferogram.

C.2 Imaging quality

Microlenses are sometimes used to generate small images of an object, for example in three-dimensional or novel imaging systems. The quality of the images can be quantified by using a test chart as an object and examining the small images with a microscope. Factors such as resolution can be tested this way. Another useful factor is the modulation transfer function (MTF). This can be measured with special apparatus in which a small slit is used as the test object and a Fourier analysis is carried out on the image formed by one microlens. MTF can also be calculated from the wavefront analysis carried out by interferometry as described in ISO 14880-2. MTF measurements are described in ISO 15529 [3].

Annex D
(normative)

Measurement of the uniformity of the focal spot positions of a microlens array

D.1 Measurement principle

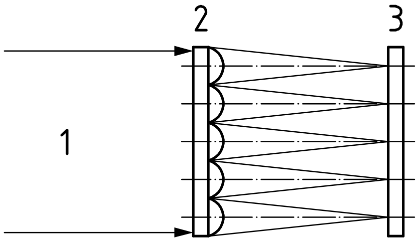
The focal spot position shift is obtained by comparing the coordinates of the focal spot position with the coordinates of the aperture centre position.

The focal spot position shift of each lenslet (as defined in ISO 14880-1) within a microlens array is obtained in parallel by illuminating the array with a reference plane wave in a Shack-Hartmann test setup.

The quality of the reference plane wave has to be tested, e.g. by shearing interferometry.

D.2 Measurement arrangement and test equipment

The Shack-Hartmann measurement arrangement is shown in Figure D.1.



Key

1 reference plane wave
2 microlens array under test
3 detector array

Figure D.1 — Measurement of the uniformity of the focal spot positions

D.3 Measurement of the uniformity of the focal spot positions

The detector is positioned in the effective back focal plane of the microlens array. The coordinates of each focal spot are recorded.

The coordinates of the focal spot positions are compared with those of the aperture centre positions in order to obtain the focal spot position shifts ΔS_x and ΔS_y of each lenslet within the array.

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