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# Optics and photonics — Optical materials and components — Test method for homogeneity of optical glasses by laser interferometry

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# Optics and photonics — Optical materials and components — Test method for homogeneity of optical glasses by laser interferometry

*Optique et photonique — Matériaux et composants optiques — Méthode d'essai d'homogénéité des verres optiques par interférométrie laser*

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# Foreword

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The committee responsible for this document is ISO/TC 172, *Optics and photonics*, Subcommittee SC 3, *Optical materials and components*.

# Optics and photonics — Optical materials and components — Test method for homogeneity of optical glasses by laser interferometry

## 1 Scope

This International Standard specifies the measuring method for the homogeneity of the refractive index of optical glasses by laser interferometry.

## 2 Normative references

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

ISO 80000-1, *Quantities and units — Part 1: General*

## 3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

**3.1**
**homogeneity of the refractive index**
maximum of the refractive index variations excluding linear changes among refractive index variations within the predetermined area in a single glass sample

**3.2**
**index-matching liquid**
transparent liquid with the refractive index which is equivalent or approximate to the refractive index of a glass sample at the wavelength of the laser to be used

**3.3**
**flatness correction plate**
plane-parallel plate obtained by polishing an optical glass with high homogeneity to a high degree of accuracy, e.g. 1/20 of a laser wavelength, which is stuck to a sample by using an index-matching liquid as an intermediate liquid, for the purpose of correcting the flatness of the sample

**3.4**
**PV value of wavefront**
difference between the maximum and the minimum deviations of the wavefront, observed when light transmits through a sample once with an interferometer from the approximated plane

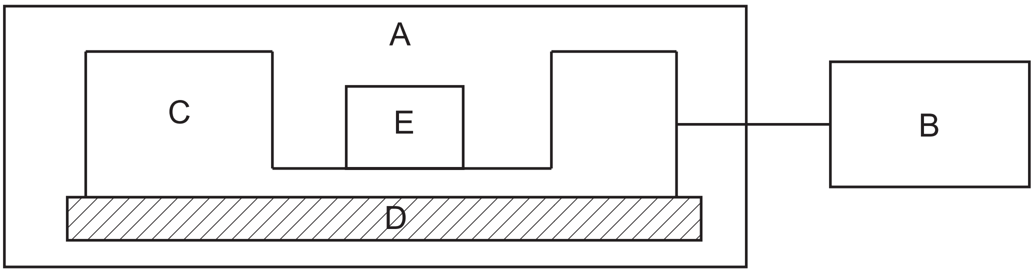
## 4 Principle

The PV value of wavefront of a luminous flux that transmitted through a sample with sufficient flatness is measured using a laser interferometer, and the homogeneity of the refractive index of the sample is obtained.

# 5 Measuring apparatus

## 5.1 General

The measuring apparatus shall be as shown in Figure 1 and as specified in 5.2 to 5.5.



**Key**

| | |
|---|---|
| A | thermostatic chamber |
| B | interferogram analysis device |
| C | laser interferometer |
| D | vibration isolation device |
| E | sample |

**Figure 1 — Example of composition of measuring apparatus**

## 5.2 Laser interferometer

The laser interferometer to be used shall have a laser as a light source and an optical system in which the wavefront of a luminous flux forms a plane. Examples of such interferometers are given in Annex A.

## 5.3 Interferogram analysis device

The interferogram analysis device to be used shall be capable of obtaining the PV value of wavefront from an interferogram.

## 5.4 Thermostatic chamber

The thermostatic chamber to be used shall be capable of maintaining the interferometer and the sample at a certain temperature. The temperature of the standard atmospheric conditions shall be 20 °C, 22 °C, 23 °C, or 25 °C depending on the purpose of testing. The tolerance of the temperatures of the standard atmospheric conditions should be ±0,2 °C. See Annex B.

## 5.5 Vibration isolation device

The vibration isolation device to be used shall be capable of eliminating the effect of vibration from the outside to the interferometer and the sample system. It should be provided for performing high accuracy measurements.

# 6 Preparation of sample

The sample shall be cylindrical or prismatic, and its thickness (height) direction shall be the direction of observation (which is the direction of the optical axis of the luminous flux of an interferometer). The thickness in the direction of observation shall be sufficient to obtain an accurate measured value.

Both end faces (the faces vertical to the optical axis) of a sample shall be polished so that the flatness of not more than 1/20 of a laser wavelength (when the wavelength is 632,8 nm, approximately 0,032 μm) is obtained.

When the above-mentioned precision polishing is not performed, flatness correction plates shall be stuck to the sample using an index-matching liquid as an intermediate liquid, to be supplied for measurement. An example of using flatness correction plates is given in Annex C. In this case, the refractive index of the index-matching liquid should conform to that of the sample so that the measurement of homogeneity is not affected. The difference of refractive indices between index-matching liquid and the sample should be approximately 0,005 or less. See Annex B.

Furthermore, in order to bond the flatness correction plates to the sample stably using the refractive index-matching liquid, the flatness of the sample should be approximately 20 μm or less. See Annex D.

## 7 Operation

The operation shall be performed as follows.

a) Remove dirt from the sample surfaces and correction plates, if used.

b) Install the sample in the interferometer so that the predetermined area of the sample fits within the luminous flux of the interferometer. When using flatness correction plates, stick the flatness correction plates to the sample with the index-matching liquid inserted between the sample surfaces and the flatness correction plates. While doing this, do not allow air bubbles in the intermediate liquid.

c) Leave the installed sample to stand until its temperature has returned to the temperature of the measurement environment as given in 5.4. When using flatness correction plates, allow the installed sample with plates to stand until the thickness of the layer of the refractive index-matching liquid between the matched surfaces no longer changes.

d) Adjust the optical system of the interferometer so that the number of interference fringes of an interferogram becomes appropriate, and then perform the measurement.

e) Obtain the PV value of wavefront of the luminous flux which transmitted through the sample measuring system from the interferogram.

## 8 Measurement

The measurement shall be performed as follows.

a) The measurement should be performed twice or more by repeating the series of operations described in Clause 7(d) and Clause 7(e). When the average is taken as a measured value, it should be stated in the test report.

b) The wavefront irregularities of the optical system of the interferometer and the wavefront irregularities due to the homogeneity of the refractive index and the flatness of a flatness correction plate contribute errors to the test results. Therefore, for the wavefront of the luminous flux which transmitted through the sample, these errors should be corrected, and the PV value of wavefront should be obtained from the wavefront after correction. An example of the measurement of the PV value of wavefront is given in Annex E.

## 9 Calculation

The calculation of the test result shall be performed as follows.

a) The homogeneity of the refractive index shall be calculated according to Formula (1).

$$\Delta n = \frac{P_V \cdot \lambda}{t} \tag{1}$$

where

$\Delta n$ is the homogeneity of the refractive index;

$P_V$ is the PV value of wavefront (wavelength unit);

$\lambda$ is the wavelength of laser (mm);

$t$ is the thickness of sample (mm).

b) For reporting, the homogeneity of the refractive index shall be rounded to two significant figures in accordance with ISO 80000-1. However, when it is less than $10^{-6}$, it shall be rounded to one significant figure.

EXAMPLE An example of a calculation is shown below.

$P_V$ is 0,049 ($\lambda$);

$\lambda$ is $632{,}8 \times 10^{-6}$ (mm);

$t$ is 41 mm.

The Formula (2) is given

$$\begin{aligned} \Delta n &= \frac{P_V \cdot \lambda}{t} \\ &= \frac{0{,}049 \times 632{,}8 \times 10^{-6}}{41} \\ &= 0{,}756 \times 10^{-6} \left(\text{Since it is less than } 10^{-6}\text{, it is rounded to one significant figure.}\right) \end{aligned} \tag{2}$$

$$\Delta n = 8 \times 10^{-7}$$

## 10 Test report

For the measurement result, the following items shall be reported:

a) measurement date (year/month/day);

b) measuring location;

c) measuring apparatus, type of interferometer and wavelength of laser;

d) name of the measurer;

e) temperature of measurement;

f) thickness, shape and measurement area of sample;

g) method of sample measuring system (whether or not the sample was used with the flatness correction plates);

h) whether or not correction was performed for the wavefront irregularities of the optical system of the interferometer or wavefront irregularities due to the inhomogeneity of the refractive index and flatness of the flatness correction plate;

i) value of homogeneity of the refractive index (in the case of reporting the average, the number of measurements performed);

j) furthermore, a representative photograph of interference fringes of a sample should be attached where possible;

k) other special conditions to be noted.

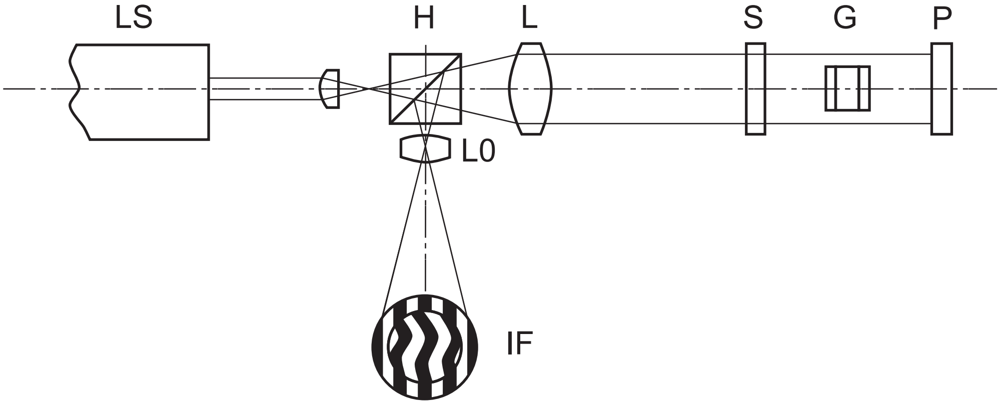
# Annex A

## (informative)

## Laser interferometer

The laser interferometer is a device that generates interference fringes by splitting the parallel rays with uniform wavefronts into two with a semi-transparent plane mirror (beam splitter), and after making each ray pass through difference paths, shifts the wavefronts slightly and then superimposes them again.

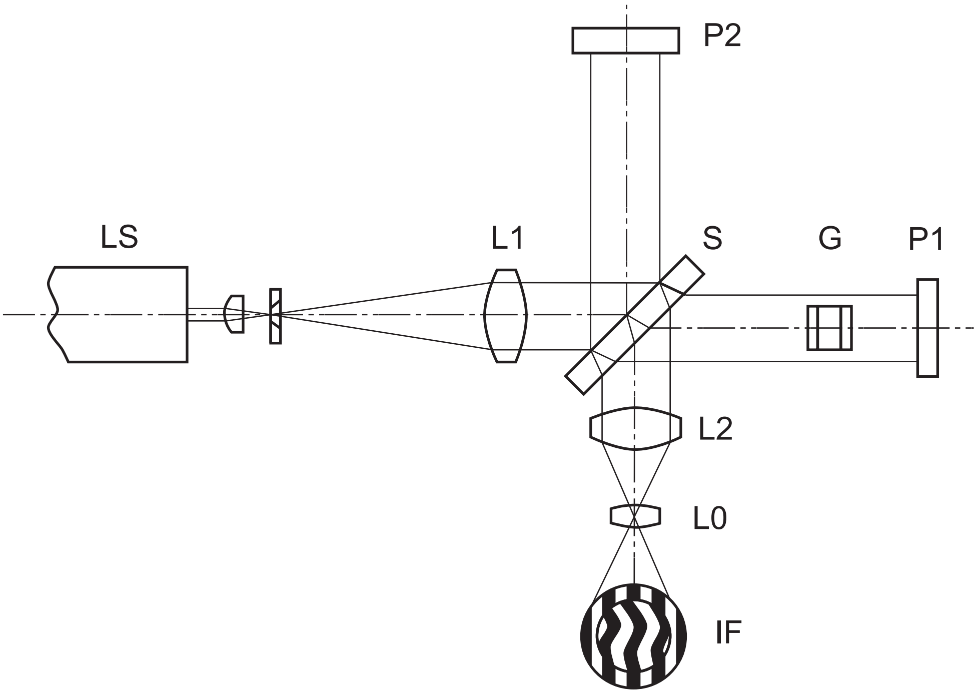
As examples of devices suitable for the homogeneity measurement of glass, three types of interferometers are shown below. Figures A.1 and A.2 show interferometers of the type in which a luminous flux transmits through the sample twice, and Figure A.3 shows interferometer of the type in which a luminous flux transmits through the sample once.



**Key**

| | |
|---|---|
| G | glass sample |
| H | beam splitter |
| L | collimating lens |
| L0 | imaging lens |
| LS | light source |
| P | plane mirror |
| S | beam splitter |
| IF | interference fringes |

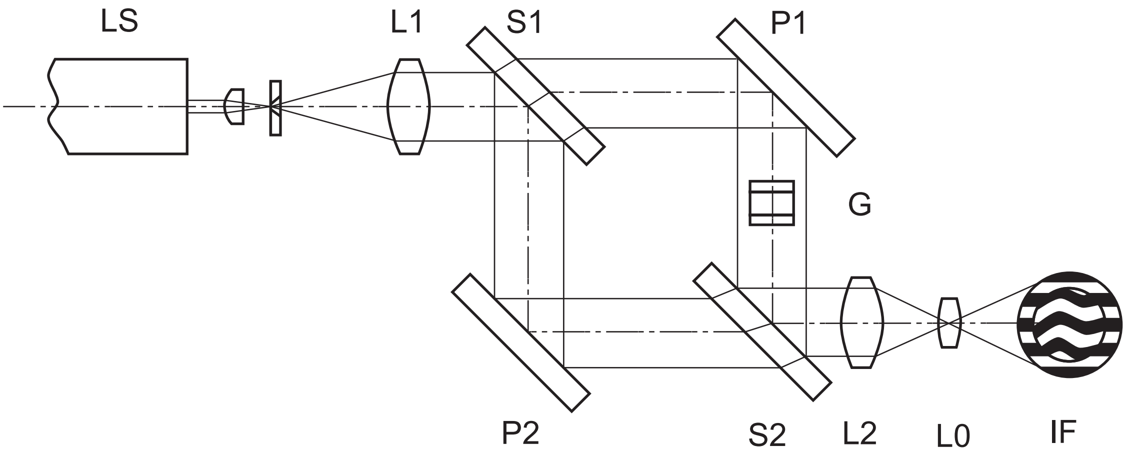
**Figure A.1 — Fizeau interferometer**



**Key**

| | |
|---|---|
| G | glass sample |
| L0 | imaging lens |
| L1, L2 | collimating lens |
| LS | light source |
| P1, P2 | plane mirror |
| S | beam splitter |
| IF | interference fringes |

**Figure A.2 — Twyman-Green interferometer**



**Key**

| | |
|---|---|
| G | glass sample |
| L1, L2 | collimating lens |
| L0 | imaging lens |
| LS | light source |
| P1, P2 | plane mirror |
| S1, S2 | beam splitter |
| IF | interference fringes |

**Figure A.3 — Mach-Zehnder interferometer**

When a glass sample is put into the path of one beam of these interferometers, light travels through the glass, and the wavefront irregularities (phase difference) are generated according to the difference of refractive indices within the glass sample. When this light is superimposed on the other beam of which the wavefront is uniform, interferogram that shows the relative phase difference appears. The phase difference of light is generated due to not only the homogeneity of the refractive index, but also any less than perfect flatness of a sample end face.

A laser is the most efficient coherent light source in a single wavelength. By using this, it is possible to observe interference fringes of which the contrast is good, irrespective of the optical path difference.

# Annex B
(informative)

# Temperature stability for homogeneity measurements

Thermal gradients within the sample and within the optical components of the interferometer lead to wavefront distortion because of their refractive indices' dependence on temperature. In the wavefront registered by the interferometer, it is not possible to separate the influences of thermal gradients from the wavefront distortion caused by the refractive index variation within the sample and the quantity to be measured. Thermal gradients should be kept low by operating the interferometer in a temperature stabilized chamber and by giving the sample time enough to reach thermal equilibrium in the interferometer environment.

For high accuracy homogeneity, measurements temperature stability in the interferometer chamber and for the sample should be better than the values given in Table B.1.

**Table B.1 — Maximum admissible temperature variation in optical glass samples to be measured for different homogeneity conditions with double pass interferometer**

Dimension in degrees Celsius[a]

| Homogeneity to be measured | For optical glass types with thermo-optical coefficient *G*[b] | | | |
|---|---|---|---|---|
| | $5 \times 10^{-6}$ /°C | $10 \times 10^{-6}$ /°C | $15 \times 10^{-6}$ /°C | $20 \times 10^{-6}$ /°C |
| $10 \times 10^{-6}$ | 1,00 | 0,50 | 0,33 | 0,25 |
| $4 \times 10^{-6}$ | 0,40 | 0,20 | 0,13 | 0,10 |
| $2 \times 10^{-6}$ | 0,20 | 0,10 | 0,07 | 0,05 |
| $1 \times 10^{-6}$ | 0,10 | 0,05 | 0,03 | 0,03 |

[a] Admissible temperature variations are given in degrees Celsius.

[b] The thermo-optical coefficient, *G*, is a glass type specific value.

The limit values for temperature stability in Table B.1 come from the following consideration.

The wavefront distortion due to refractive index homogeneity in the sample measured with a double pass interferometer is

$$\Delta W_H = 2 \cdot \Delta n \cdot d \tag{B.1}$$

where

$\Delta n$ is the refractive index variation in the sample (peak-to-valley);

$d$ is the sample thickness.

The wavefront distortion due to thermal gradients in the sample is

$$\Delta W_{Th} = 2 \cdot d \cdot G \cdot \Delta T \tag{B.2}$$

where

$\Delta T$ is the temperature variation within the sample (peak-to-valley).

The thermo-optical coefficient *G* is defined by

$$G=\left[(n-1)\alpha+\frac{dn}{dT}\right] \tag{B.3}$$

By requiring that

$$\Delta W_{Th}<\frac{1}{2}\Delta W_{H} \tag{B.4}$$

It follows that

$$\Delta T<\frac{\Delta n}{2\cdot G} \tag{B.5}$$

By far, most optical glasses have thermo-optical coefficients *G* between 5 and 10 × $10^{-6}$ /°C. High index dense flint glasses lie higher up to almost 20 × $10^{-6}$ /°C. Extreme low index low dispersion fluorophosphates glass types lie below 5 × $10^{-6}$ /°C or even close to 0. The glass type N-BK7, which is very frequently used for high homogeneity applications, has a thermo-optical coefficient of 6,7 × $10^{-6}$ /°C.

For the calculation of *G,* the following quantities have been used:

| | |
|---|---|
| $n_e$ | is the refractive index at the e-line 546 nm; |
| $\alpha$ | is the coefficient of thermal expansion valid for the temperature interval −30 °C to +70 °C; |
| $dn/dT$ | is the refractive index change with temperature relative to air at the spectral e-line for the temperature interval +20 °C to +40 °C. |

EXAMPLE An example for calculating the thermo-optical coefficient, *G,* is shown below.

Glass type is N-BK7.

| | |
|---|---|
| $\alpha$ | 7,1 × $10^{-6}$ /°C |
| $dn/dT$ | 3,0 × $10^{-6}$ /°C |
| $n_e$ | 1,51872 |
| $G$ | 6,68 × $10^{-6}$ /°C |

# Annex C
## (informative)

# Measuring method using flatness correction plates

Flatness correction plates should be used when both end faces (the faces vertical to the optical axis) of a sample glass are not precisely polished to obtain the flatness (not more than 1/20 of the laser wavelength) specified in Clause 6.

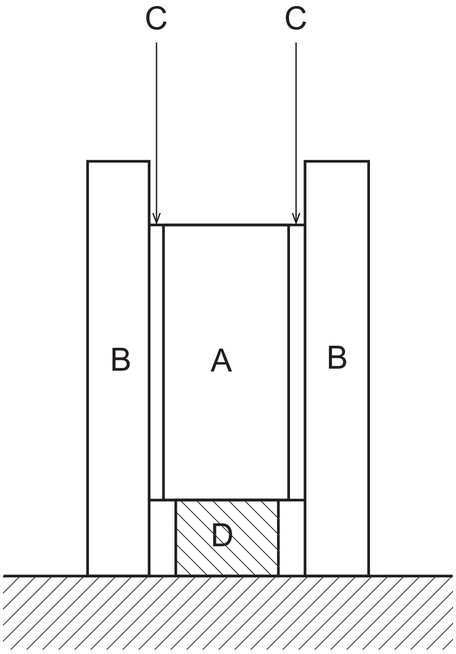
Examples of usages of correction plates are shown below.

EXAMPLE 1 When both end faces of the sample are not precisely polished.

As shown in Figure C.1, the correction plates are stuck to the end faces of a sample using a refractive index-matching liquid, and this whole unit is taken as the sample measuring system.

Sufficient attention should be paid to matters such as temperature change or the amount of refractive index-matching liquid, so that the correction plates are free from distortion when being bonded.

When one side of a sample is precisely polished, only one correction plate is used.



**Key**

| | |
|---|---|
| A | sample |
| B | flatness correction plate |
| C | index-matching liquid |
| D | stand |

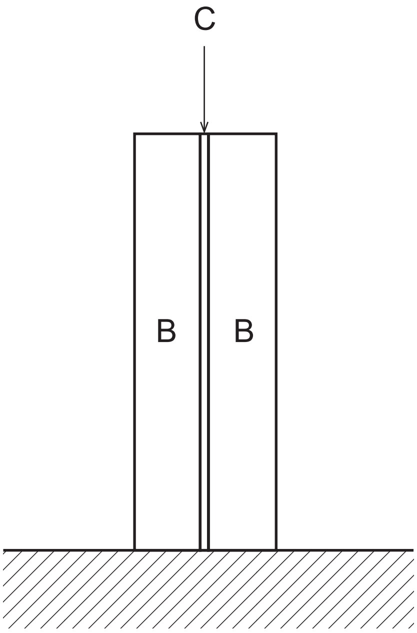
**Figure C.1 — Bonding of sample with flatness correction plates**

EXAMPLE 2 Measuring method for removing wavefront irregularities of optical system of interferometer and wavefront irregularities due to homogeneity and flatness of correction plate.

When the automatic analysis device using a computer can be used as an interferogram analysis device, the following procedure can be performed in order to increase the measurement accuracy.

First, as shown in Figure C.2, stick only the two correction plates together by using the refractive index-matching liquid, and install this in the interferometer to perform the measurement. Have the computer record and save the wavefront irregularities of the whole interferometer including wavefront irregularities due to the correction plates. Next, as shown in Figure C.1, stick the correction plates to the sample, and install this in the interferometer to perform the measurement. Obtain the wavefront irregularities due to only the sample by subtracting wavefront irregularities of the whole interferometer that were recorded and saved in advance by the computer from wavefront irregularities when the sample was inserted, and thereby obtain the homogeneity of the sample. Sufficient care should be taken not to change the positional relationship between the two correction plates when bonded or installed in the interferometer.

Sufficient attention should also be paid to matters such as temperature change or the amount of refractive index-matching liquid, so that the correction plates are free from distortion when being bonded.



**Key**

| | |
|---|---|
| B | flatness correction plate |
| C | index-matching liquid |

Figure C.2 — Bonding of flatness correction plates

# Annex D
(informative)

# Flatness of the sample

In the interferometer, a difference between a change caused by the flatness of the sample and a change caused by the refractive index distribution of the sample cannot be separated. For an accurate measurement, a change caused by the flatness of the sample should be controlled to within the error range of the interferometer at least. In the interferometer of the type in which a luminous flux transmits through the sample once, e.g. Mach-Zehnder interferometer, a luminous flux transmits through the face of a sample twice. Then, in the interferometer of the type in which a luminous flux transmits through the sample twice, e.g. Fizeau interferometer and Twyman-Green interferometer, a luminous flux transmits through the face of a sample four times.

The flatness of the sample $W_S$ is as follows.

$$m\left(n_G - 1\right) W_S \leq W_K \tag{D.1}$$

where

$n_G$ is the refractive index of the sample;

$W_S$ is the flatness of the sample;

$W_K$ is the individual error of each interferometer;

$m$ is the number of times a luminous flux transmits through the face of a sample.

where

$m$=2 when a luminous flux transmits through the sample once, e.g. in a Mach-Zehnder interferometer;

$m$=4 when a luminous flux transmits through the sample twice, e.g. in a Fizeau interferometer and Twyman-Green interferometer.

When $W_K = \lambda/10$ and $n_G = 1{,}5$, the maximum permissible flatness is shown in Table D.1, where $\lambda$ is the wavelength of laser.

**Table D.1 — Maximum permissible flatness**

| Number of times a luminous flux transmits through the sample | Permissible flatness |
|---|---|
| Once | $\lambda/10$ |
| Twice | $\lambda/20$ |

When it is difficult to polish many samples at high accuracy, a flatness correction plate is used. Using this method, high flatness of the sample is unnecessary if the refractive index of the index-matching liquid is close to refractive index of the sample. Wavefront change at a face is expressed by $W_S \cdot n_S$, where $\Delta n_S$

is the difference of the refractive indices between the refractive index-matching liquid and the sample. Then, $W_S$ and $\Delta n_S$ should satisfy the following formula.

$$m \cdot \Delta n_S \cdot W_S \leq W_K$$

where

$\Delta n_S$ is the difference of the refractive indices between the index-matching liquid and the sample.

When $W_K = \lambda/10$, maximum permissible difference of refractive indices between refractive index-matching liquid and sample is shown in Table D.2.

**Table D.2 — Maximum difference of refractive indices between refractive index-matching liquid and sample**

| **Number of times a luminous flux transmits through the sample** | **Flatness, $W_S$** | | | | | |
|---|---|---|---|---|---|---|
| | $30\lambda$ | $20\lambda$ | $10\lambda$ | $5\lambda$ | $\lambda$ | $0.5\lambda$ |
| Once | 0,0017 | 0,025 | 0,0050 | 0,0100 | 0,0500 | 0,1000 |
| Twice | 0,0008 | 0,0013 | 0,0025 | 0,0050 | 0,0250 | 0,0500 |

From the above discussion, using both high flatness and accurate index-matching liquid, the error caused by the flatness becomes lower and measurement accuracy becomes higher. The error of the PV value caused by flatness $\Delta P_V$ is calculated according to the following formula.

$$\Delta P_V \leq 2 \cdot W_S \cdot \Delta n_S$$

# Annex E
(informative)

# Method for obtaining PV value of wavefront

## E.1 Obtaining PV value of wavefront from bending of interference fringes

For this method, there is a manually operated method and a method using “an automatic interference fringe analysis device” that utilizes a computer. In both methods, the PV value of wavefront is generally obtained by utilizing the position of the dark interference fringes. The manual method is not suitable for performing wavefront correction, which requires the wavefront information of all the area of the interference fringes.

a) As shown in Figure E.1, draw parallel lines at equal intervals along the interference fringes, measure the interval $a$, and the deviations $b_1$ and $b_2$ at the locations in which the deviation between parallel lines and interference fringes is largest. Here, $b_1$ and $b_2$ are the deviations in mutually opposite directions. Then, obtain the PV value of wavefront, $P_V$, according to the following formula. Make sure that the interval and gradient of parallel lines are such that the value $(b_1 + b_2)$ is the minimum. When the automatic interference fringe analysis device is used, perform this adjustment by using the least-squares method.

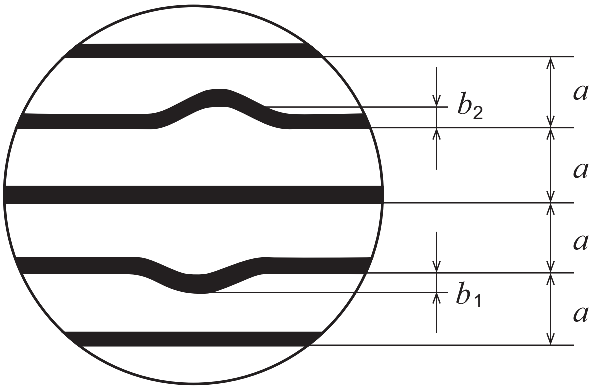
$$P_V = (b_1 + b_2)\frac{f}{a} \qquad \text{(E.1)}$$

b) Here, since the PV value of wavefront is the value when a luminous flux transmits through the sample once, and the value $f$ differs according to the type of interferometer used, the following values given in Table E.1 should be used.

**Table E.1 — Value *f***

| Number of times a luminous flux transmits through the sample | Examples of interferometers | Value *f* |
|---|---|---|
| Once | Mach-Zehnder interferometer etc. | 1 |
| Twice | Fizeau interferometer, Twyman-Green interferometer, etc. | 0,5 |

c) In order to increase analysis accuracy, adjust the fringes so they are at right angles to those shown in Figure E.1, and repeat the procedure in a).



**Key**

| | |
|---|---|
| *a* | distance of regular interval of fringes |
| $b_1$, $b_2$ | distance between the bending top of fringe and regular interval line |

**Figure E.1 — Obtaining PV value of wavefront from bending of interference fringes**

## E.2 Obtaining PV value of wavefront by phase measurement method

For this method, reading and analysis of data are processed by a computer. The analysis accuracy of the phase measurement method is higher than that of the automatic interference fringe analysis device. Therefore, the phase measurement method should be used wherever possible.

Move the plane plate that makes the reference beam of an interferometer (plane mirror or beam splitter) minutely, measure the light intensity change of the whole interference fringes, and obtain the wavefront curve from the wavefront phase relation of each position of interference fringes. Eliminate the linear changes from this using the least-squares method, and obtain the PV value of wavefront from the difference between the maximum and the minimum values of the wavefront. At this time, make sure that the PV value of wavefront becomes the value when a luminous flux transmits through the sample once.

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