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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

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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 172, *Optics and Photonics*, Subcommittee SC 3, *Optical materials and components*.

This second edition cancels and replaces the first edition (ISO 17411:2014), which has been technically revised.

The main changes are as follows:

— the PHom method was added;

— the FT-PSI method and the SCI method were added;

— the linear change of the refractive index is described as an evaluation target.

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

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

1 Scope

This document specifies the measuring method for the homogeneity of the refractive index of optical glasses by laser interferometry to cope with the grades from ISO 10110-18 and ISO 12123.

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

3 Terms and definitions

For the purposes of this document, the following terms and definitions 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/

3.1
homogeneity of the refractive index
peak to valley (PV) of the refractive index variation within the predetermined area in a single test part

3.2
index-matching liquid
transparent liquid with the refractive index which is equivalent or approximate to the refractive index of a test part at the wavelength of the laser to be used and the measurement temperature

3.3
oil-on plate
plane plate, used for flatness correction, obtained by polishing an optical glass, which is attached to a test part by using an *index-matching liquid* (3.2) (where the index matching liquid is sometimes called "oil") as an intermediate liquid

3.4
peak to valley of wavefront
PV value of wavefront
W_{PV}
maximum minus the minimum value of the wavefront in the observation range, as observed by the interferometer when light passes through the test part under test once

Note 1 to entry: W_{PV} is analogous to the peak to valley of f_{WD} in ISO 14999-4[3].

4 Principle

The peak to valley of wavefront, W_{PV}, of a light beam that transmitted through a test object with sufficient flatness is measured using a laser interferometer, and the homogeneity of the refractive index of the test part is obtained.

One of the following methods may be used:

a) Transmission method.

The transmission method is the preferred method for polished parts with plane parallel optical surfaces (e.g. optical windows) to avoid contamination with index matching liquid. One disadvantage of this method is that wavefront deformations caused by surface deformation of the test part influence the resulting PV value of wavefront, W_{PV}, and cannot be separated from the wavefront deformations caused by refractive index inhomogeneity.

b) PHom method.

The PHom method is the preferred method for covering a broad range of materials with different refractive indices, leads to high trueness and precision results for refractive index homogeneity, therefore should be used for high homogeneous material (refractive index difference ≤ 2 × 10^{-6}).

c) Oil–on plate method.

The oil-on plate method needs lower effort for test part preparation and measurement setup, but each type of glass needs its own index-matching liquid.

By minimizing error factors (e.g. temperature stabilization, preparation of refractive index matching liquid) and improving the skill of the metrologist, the same trueness and precision as the PHom method can be achieved.

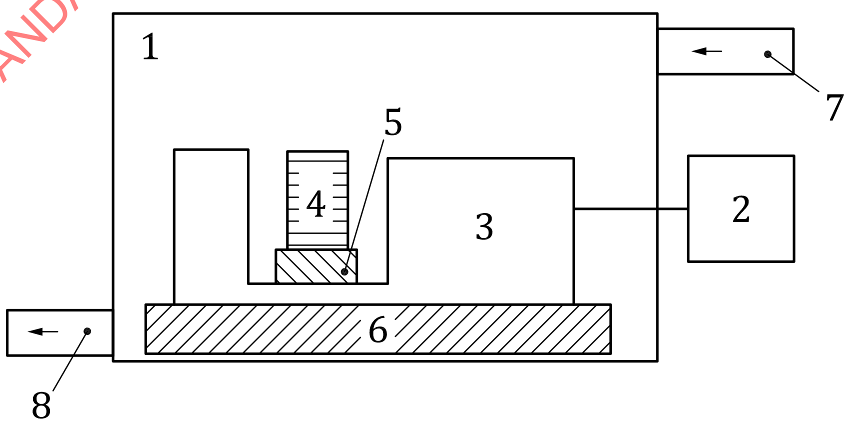
d) FT-PSI method and SCI method.

With the Fourier Transform Phase Shifting Interferometry (FT-PSI method[4]) and the spectrally controlled interferometry (SCI method[5][6]) it is possible to observe the linear change component of the refractive index (see Annex G).

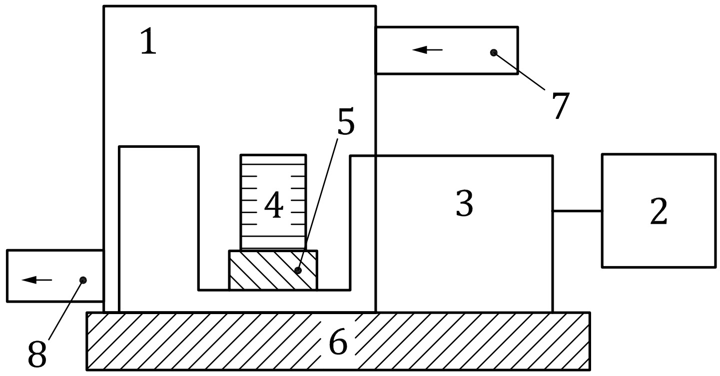
5 Measuring apparatus

5.1 General

Examples for a measuring apparatus are shown in Figure 1. More details are specified in 5.2 to 5.6.



a) First example of composition of measuring apparatus



b) Second example of composition of measuring apparatus

Key

1 thermostatic chamber
2 interferogram analysis device
3 laser interferometer
4 test object composition set (test part, oil-on plate and device to hold them)
5 biaxial adjustment platform (for PHom, FT-PSI and SCI method)
6 vibration isolation table
7 conditioned air inlet
8 ventilation outlet

Figure 1 — Examples 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 light beam 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 W_{PV} from an interferogram.

5.4 Thermostatic chamber

The thermostatic chamber to be used shall be capable of maintaining the interferometer and the test object at a certain temperature. The temperature of the atmospheric conditions shall be between 20 °C and 25 °C depending on the purpose of testing. The temperature fluctuation range (spatial and during measurement time) should be smaller than 0,4 °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 test object composition. It should be provided for performing high trueness and precision measurements.

5.6 Biaxial adjustment platform

The biaxial adjustment platform shall be used for the PHom method. The PHom method requires alignment of the reflected light beam on the front and back surfaces of the test object. At this time, the pan/tilt angle of the test object is adjusted by this equipment. Not required unless measurement is performed by the PHom, FT-PSI and SCI method.

6 Preparation of test part

6.1 General

The test part shall comprise at least two parallel surfaces (the end surfaces), and its thickness (height) direction shall be the direction of observation (which is the direction of the optical axis of the beam pass of an interferometer). The thickness in the direction of observation shall be sufficient to obtain precise and true measured values.

6.2 Transmission method

Both end surfaces (the surfaces orthogonal to the optical axis) of a test part shall be polished flat to a flatness of smaller than 32 nm PV (λ/20 where λ is the laser wavelength). Poor flatness leads to measurement error as described in Annex D. In the event that the required flatness cannot be achieved, either PHom (see 6.3), oil-on plate (see 6.4), or FT-PSI/SCI (see 6.5) methods are recommended instead.

6.3 PHom method

Both end surfaces (the surfaces orthogonal to the optical axis) of a test part shall be polished flat to a flatness of smaller than 1 900 nm PV (3 waves PV).

A small wedge angle between the end surfaces is required to avoid interferences between reflected wavefront from these end surfaces (e.g. 0,10° ± 0,05° valid for test part diameter up to 350 mm and thickness up to 230 mm).

For more information on the PHom-Method see Annex F.

6.4 Oil-on plate method

Both end surfaces (the surfaces orthogonal to the optical axis) of a test part shall be fine ground and flat to a flatness of smaller than 20 000 nm PV. To achieve results of higher precision and trueness, better flatness might be useful. More details see Annex C.

6.5 FT-PSI and SCI method

These two methods can use test parts that are polished plane parallel plates (see Annex G). They are essential when it is necessary to observe the linear change of the refractive index. In this case, the degree of parallelism on shall be such that interference fringes on the front surface reflection, back surface reflection and transmitted wavefront of the observation area can be observed simultaneously. The flatness is the same as the test parts of the PHom method (see 6.3).

7 Operation

The operation shall be performed as follows:

a) Remove dirt from the test part surfaces and oil-on plates, if used.

b) Install the test object in the interferometer so that the predetermined area of the test object fits within the beam pass of the interferometer. When using oil-on plates, attach the oil-on plates to the test part with the index-matching liquid inserted between the test part surfaces and the oil-on plates. While doing this step, do not allow air bubbles to form in the index-matching liquid.

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

d) Adjust the interferometer optics to minimise the number of interference fringes and remove the tilt element of the interference fringes. To avoid common path interference effects inside the test object (in case the test object end surfaces are of good parallelism), the test object shall be tilted with respect to the light beam. An appropriate tilt angle depends on details of test object and interferometer and is often in the order of magnitude of 0,1°. After the adjustment, perform the measurement.

e) Obtain the W_{PV} of the light beam, which is transmitted through the test object measuring system from the interferogram.

8 Measurement

8.1 General

The measurement shall be performed as follows.

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

The wavefront irregularities of the optical system of the interferometer, the wavefront irregularities due to the homogeneity of the refractive index and the flatness of an oil-on plate contribute errors to the test results. Therefore, to obtain the wavefront of the light beam, which is transmitted through the test object, these errors should be corrected, and the W_{PV} should be obtained from the wavefront after correction. An example of the measurement of the W_{PV} is given in Annex E.

8.2 Transmission method

Two measurements shall be performed.

a) Transmitted wavefront measurement of the test part according to Clause 7.

b) Empty cavity measurement to capture the irregularities of the measurement system.

Correction of irregularities of the optical system of the interferometer can be obtained by subtracting the empty cavity measurement from the test part measurement.

One empty cavity measurement may be used to correct the irregularities for several transmittance measurements of test parts.

8.3 PHom method

Four measurements shall be performed.

a) The front surface of the test part shall be set orthogonal to the optical axis and the reflected wavefront has to be measured in accordance with Clause 7.

a) The rear surface of the test part shall be set perpendicular to the light beam and the reflected wavefront has to be measured in accordance with Clause 7.

d) The transmitted wavefront measurement of the test part shall be performed in accordance with Clause 7.

e) The empty cavity measurement shall be performed to capture the irregularities of the measurement system.

Correction of irregularities of the optical system of the interferometer will be obtained by wavefront calculation in accordance with Annex F.

8.4 Oil-on plate method

Two measurements shall be performed:

a) Attach the test part and the oil-on plates with index matching oil in accordance with Annex C together and perform a transmittance measurement in accordance with Clause 7.

b) Attach only the oil-on plates with index matching liquid in accordance with Annex C together and perform a transmittance measurement to capture the irregularities of the measurement and oil-on plate system.

For correction of irregularities of the optical system of the interferometer and of oil-on plates, see C.2

If several test parts of the same glass type are measured in accordance with 8.4 a), a single measurement according to 8.4 b) may be used to correct the irregularities of all the measurements.

8.5 FT-PSI method and SCI method

Four measurements shall be performed.

For FT-PSI and SCI methods, the respective measurement methods shall be as described in Annex G.

9 Calculation

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

a) The homogeneity of the refractive index shall be calculated by the following Formula (1).

$$\Delta n_{PV} = \frac{W_{PV} \cdot \lambda}{t} \tag{1}$$

where

Δn_{PV} is the homogeneity of the refractive index of the test part;

W_{PV} is the W_{PV} (wave);

NOTE The W_{PV} is dimensionless. The “wave” here is a name for convenience, not a unit name.

λ is the wavelength of laser (m);

t is the thickness of the test piece (m).

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 smaller than 1×10^{-6}, it shall be rounded to one significant figure.

An example of a calculation is shown in Formula (2). Here

W_{PV} is 0,049 (wave);

λ is $632,8 \times 10^{-9}$ (m);

t is 0,041 (m).

Then

$$
\begin{aligned}
\Delta n_{\mathrm{PV}} &= \frac{W_{\mathrm{PV}} \cdot \lambda}{t} \\
&= \frac{0{,}049 \times 632{,}8 \times 10^{-9}}{0{,}041} \\
&= 8 \times 10^{-7}
\end{aligned}
\qquad (2)
$$

NOTE Since the result is smaller than 10^{-6}, "$0{,}756 \times 10^{-6}$" is rounded to one significant figure, "8×10^{-7}".

10 Test report

10.1 Requirements

For the measurement result, the following items a) to j) shall be reported:

a) measurement date (YYYY-MM-DD);

b) a reference to this document, i.e. ISO 17411:2022;

c) measuring location;

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

e) name of the metrologist;

f) thickness, dimension and material of the test part and measurement area;

g) method of test part measuring system (whether or not the test part was used with the oil-on 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 oil-on plate;

i) value of homogeneity of the refractive index;

j) wavefront aberration elements to be removed during data analysis. For example, piston, tilt, focus, etc. In particular, in a method in which a linear change in refractive index (tilt component) cannot be measured, it shall be stated that this element has been removed.

10.2 Optional

It may also contain:

a) temperature of measurement;

b) a representative photograph of interference fringes of the test object where possible;

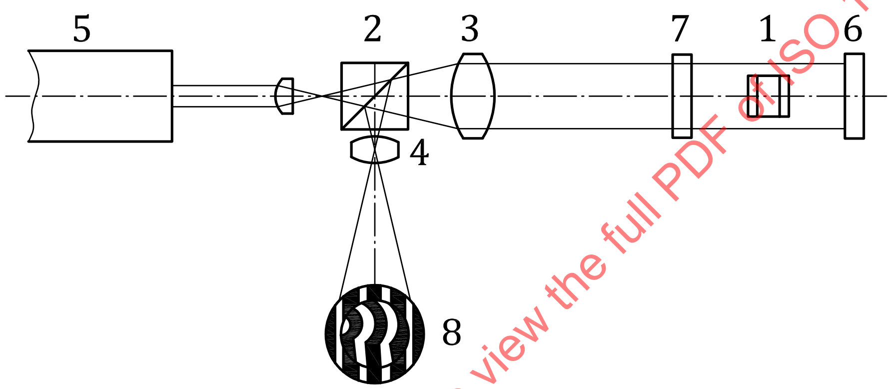
c) other special conditions to be noted.

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, 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 light beam transmits through the test object twice, and Figure A.3 shows an interferometer of the type in which a light beam transmits through the test object once.

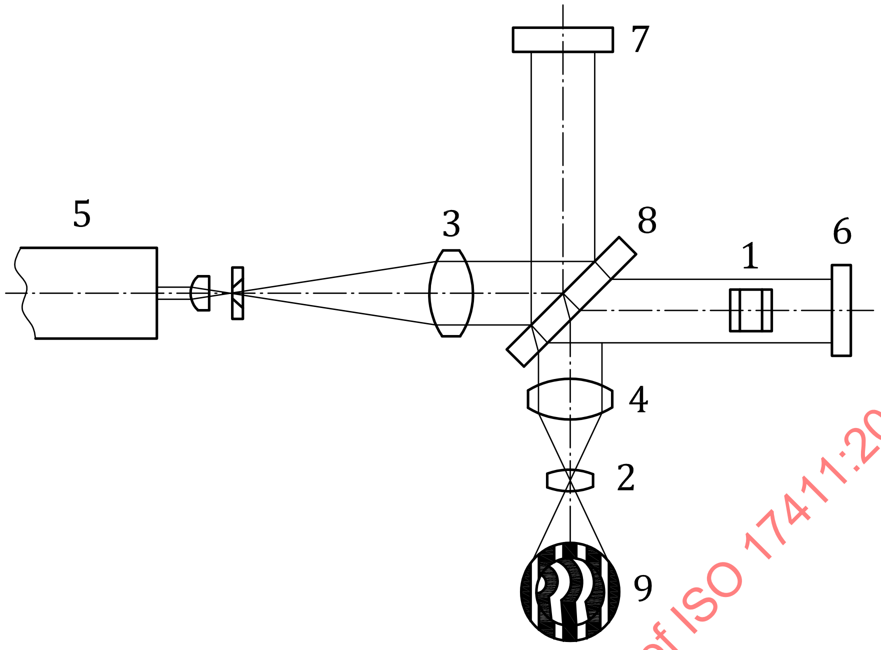


Key

1 test object
2 beam splitter
3 collimating lens
4 imaging lens
5 light source
6 reflective reference flat (RF)
7 transmissive reference flat (TF)
8 interference fringes

Figure A.1 — Fizeau interferometer

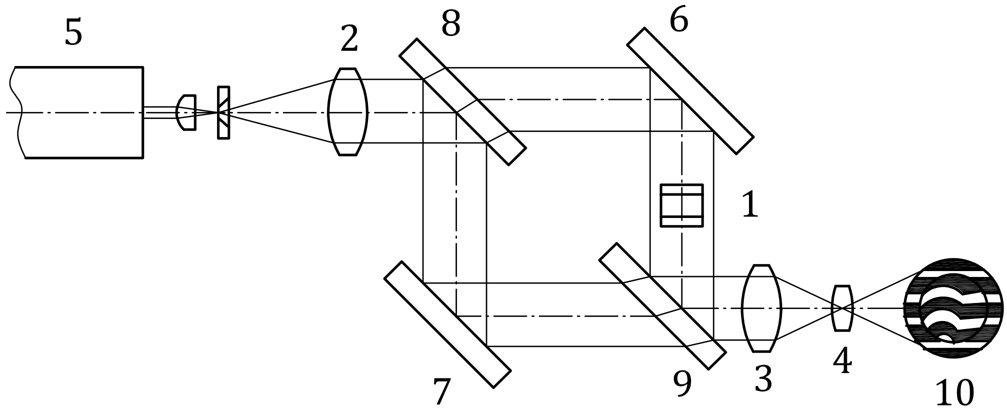
In a Fizeau interferometer as shown in Figure A.1, the reference plane for the wavefront is the exit side of the TF.



Key

1	test object
2	imaging lens
3, 4	collimating lens
5	light source
6, 7	plane mirror
8	beam splitter
9	interference fringes

Figure A.2 — Twyman-Green interferometer



Key

1 test object

2, 3 collimating lens

4 imaging lens

5 light source

6, 7 plane mirror

8, 9 beam splitter

10 interference fringes

Figure A.3 — Mach-Zehnder interferometer

When a test object is put into the path of one beam of these interferometers, light travels through the test object, and the wavefront irregularities (phase difference) are generated according to the difference of refractive indices within the test object. When this light is superimposed on the other beam of which the wavefront is uniform, an 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 other surfaces in the test set-up that are not in common path, including the test object end surfaces.

Lasers are the most efficient coherent light sources theoretically in a single wavelength (i.e. a narrow wavelength in practice). 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 test object 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 test object 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 test object time enough to reach thermal equilibrium in the interferometer environment.

For homogeneity measurements of high precision and trueness temperature stability in the interferometer chamber and for the test object should be better than the values given in Table B.1.

Table B.1 — Maximum admissible temperature variation in test parts to be measured for different homogeneity conditions with double pass interferometer

Homogeneity to be measured	Thermo-optical coefficient G[a] of the test part			
	5×10^{-6}/K	10×10^{-6}/K	15×10^{-6}/K	20×10^{-6}/K
	Maximum admissible temperature variation K			
10×10^{-6}	1,00	0,50	0,33	0,25
4×10^{-6}	0,40	0,20	0,13	0,10
2×10^{-6}	0,20	0,10	0,07	0,05
1×10^{-6}	0,10	0,05	0,03	0,03

[a] 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 measured wavefront distortion due to refractive index homogeneity in the test part measured with a double pass interferometer is given by Formula (B.1):

$$\Delta W_{\mathrm{H}} = 2 \cdot \Delta n_{\mathrm{PV}} \cdot t \tag{B.1}$$

where

ΔW_{H} is the measured wavefront distortion (m);

Δn_{PV} is the homogeneity of the refractive index in the test part;

t is the test part thickness (m).

The measured wavefront distortion due to thermal gradients in the test part is given by Formula (B.2):

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

where

ΔW_{Th} is the measured wavefront distortion due to thermal gradients in the test part (m);

G is the thermo-optical coefficient (K^{-1});

ΔT is the temperature variation within the test part (peak to valley).

The thermo-optical coefficient G is defined by Formula (B.3):

$$G = (n_{abs} - n_{air})\alpha + \frac{\Delta n_{abs}}{\Delta T} \tag{B.3}$$

where

n_{abs} is the absolute refractive index of the test part;

n_{air} is the refractive index of the ambient air, calculated e.g. using Edlén's or Ciddor's formula (See Reference [7] and [8]);

α is the coefficient of thermal linear expansion (K^{-1});

$\frac{\Delta n_{abs}}{\Delta T}$ is the temperature coefficient of absolute refractive index (K^{-1}).

G is a value combining two optical effects of the test part caused by the temperature change. These two effects are

a) the change in the optical path length due to thermal expansion (depending on expansion coefficient and refractive index difference between the test part and the ambient air), and

b) the change in optical path length due to the temperature coefficient of the absolute refractive index.

By requiring that

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

It follows that

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

Most optical glasses have thermo-optical coefficients G between 5 and $10 \times 10^{-6}\ K^{-1}$. High index dense flint glasses lie higher up to almost $20 \times 10^{-6}\ K^{-1}$. Extreme low index low dispersion fluorophosphate glass types lie below $5 \times 10^{-6}\ K^{-1}$ or even close to 0.

An example for calculating the thermo-optical coefficient, G, of an often-used glass type is shown below.

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

α	$7{,}1 \times 10^{-6}\ K^{-1}$	coefficient of thermal linear expansion for the temperature interval -30 °C to +70 °C;
$\frac{\Delta n_{abs}}{\Delta T}$	$1{,}4 \times 10^{-6}\ K^{-1}$	temperature coefficient of absolute refractive index at 632,8 nm wavelength for the temperature interval +20 °C to +40 °C;
n_{abs}	1,518 22	absolute refractive index of the test part at 632,8 nm wavelength and 20 °C;
n_{air}	1,000 27	refractive index of the air at 632,8 nm wavelength, 20 °C temperature, 101,325 kPa barometric pressure and 50 % relative humidity.

Using Formula (B.3), the result for the thermo-optical coefficient G is given by Formula (B.6):

$$G = 5{,}1 \times 10^{-6}\ \mathrm{K}^{-1} \tag{B.6}$$

Annex C
(normative)

Measurement using oil-on plate method

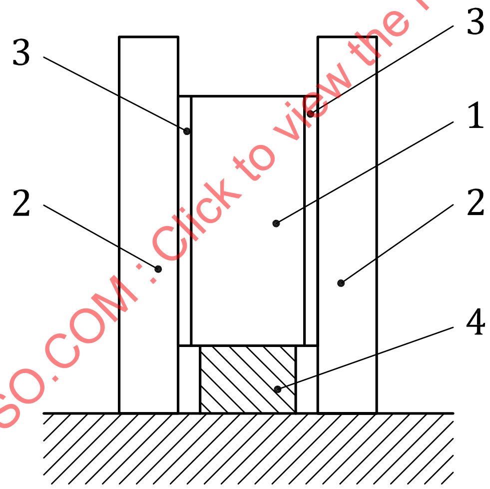
C.1 General

Oil-on plates should be used when both end surfaces (the surfaces orthogonal to the optical axis) of a test part are not precisely polished to obtain the flatness (not more than 1/20 of the laser wavelength) specified in Clause 6.

Using this method, high flatness of the test part is unnecessary if the refractive index of the index-matching liquid is close to refractive index of the test part.

As shown in Figure C.1, the oil-on plates are attached to the end surfaces of a test part using a refractive index-matching liquid, and this whole unit is taken as the test object. The index matching liquid is required for correcting the flatness of the test part.

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



Key

1 test part

2 oil-on plate

3 index-matching liquid

4 stand

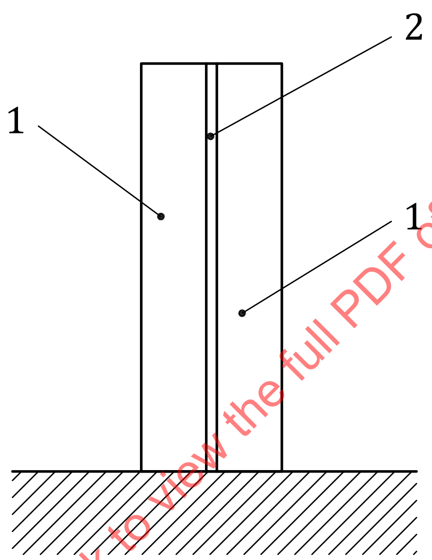
Figure C.1 — Bonding of test part with oil-on plates

C.2 Method for removing system irregularities

A measuring method for removing wavefront irregularities of the optical system of the interferometer and wavefront irregularities due to homogeneity and flatness of the oil-on plates is described below in C.2.

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 improve the measurement precision and trueness.

First, as shown in Figure C.2, attach only the two oil-on 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 oil-on plates. Next, as shown in Figure C.1, attach the oil-on plates to the test part, and install this in the interferometer to perform the measurement. Obtain the wavefront irregularities due to only the test part by subtracting wavefront irregularities of the whole interferometer that were recorded and saved in advance by the computer from wavefront irregularities when the test part was inserted, and thereby obtain the homogeneity of the test part. Sufficient care should be taken not to change the positional relationship between the two oil-on plates when bonded or installed in the interferometer.



Key

1 oil-on plate

2 index-matching liquid

Figure C.2 — Bonding of oil-on plates

C.3 Requirements for the oil-on plates

The homogeneity of the transmitted wave front of the pair of the oil-on plates shall be better than $\lambda/10$ (preferred $\lambda/20$) of the laser wavelength λ.

The surface flatness of an oil-on plate that comes into contact with the test part shall be better than $\lambda/10$ (preferred $\lambda/20$) of the laser wavelength λ.

To prevent common path interference inside the oil-on plate, a wedge angle of about 0,1° shall be provided between the facing surfaces.

C.4 Requirements for test part flatness and index matching liquid

The obtainable precision and trueness of the oil-on plate method depends strongly on the combination of

— the difference of the refractive indices between the index matching liquid and the test part;

— the flatness of the test part.

The wavefront change at a surface is expressed by $W_G \cdot \Delta n_S$, where Δn_S is the difference of the refractive indices between the refractive index-matching liquid and the test part. Then, W_G and Δn_S should satisfy the following Formula (C.1):

$$m \cdot \Delta n_S \cdot W_G \leq W_K \tag{C.1}$$

where

m	is the is the number of times a light beam transmits through the surface of a test object;
Δn_S	is the difference of the refractive indices between the index-matching liquid and the test part;
W_G	is the wavefront of the surface flatness of the test part (wave);
W_K	is the wavefront of the individual error of each interferometer (wave).

When $W_K = \lambda/10$, the maximum permissible difference of refractive indices between refractive index-matching liquid and test part is shown in Table C.1.

Table C.1 — Maximum difference of refractive indices between refractive index-matching liquid and test part

Number of times a light beam transmits through the test object	Flatness, W_G					
	30λ	20λ	10λ	5λ	λ	$0{,}5\lambda$
	Maximum permissible refractive index difference for $W_K = \lambda/10$					
Once	0,001 7	0,002 5	0,005 0	0,010 0	0,050 0	0,100 0
Twice	0,000 8	0,001 3	0,002 5	0,005 0	0,025 0	0,050 0

From the above discussion follows, that by using a well-matched index-matching liquid and very flat surfaces, the error caused by the flatness is mitigated and the measurement precision and trueness are improved. The error of the PV value caused by flatness ΔW_{PV} is calculated according to Formula (C.2):

$$\Delta W_{PV} \leq 2 \cdot W_G \cdot \Delta n_S \tag{C.2}$$

C.5 Preparation of the index matching liquid

As the refractive index matching liquid, various liquids, a mixture of two or more kinds of liquids, and a liquid in which a solid is dissolved are used. Table C.2 shows examples of substances are used as the material during preparation.

Table C.2 — General refractive-index matching liquids

Reagent	n_d **or** n_D (20 °C)
Liquid paraffin	1,47
Cedar oil	1,51
1,1,2,2-tetrabromoethane	1,63
1-bromonapthalene	1,66
Diiodomethane	1,74
Saturated sulfur solution in diiodomethane	1,78

It is important that the index of refraction of the liquid is the same as the refraction index of the test part

— at the laser wavelength of the interferometer, and

— at the measurement temperature (temperature in the thermostatic chamber).

C.6 Measurement error due to the refractive index preparation error of the refractive index matching liquid

As mentioned before, the difference in refractive index between the test part and the refractive index matching liquid (i.e. preparation error) in combination with the flatness deviation of the test part causes measurement errors.

The formula for calculating the homogeneity measurement error is as follows Formula (C.3):

$$\varepsilon_{\max} = \frac{\Delta l_{\text{gap}} \times \Delta n_{\text{s}}}{t} \quad \text{(C.3)}$$

where

$\varepsilon_{\max}$	is the maximum value of homogeneity measurement error that occurs;
Δl_{gap}	is the sum of the flatness of the two side planes of the test part (m);
Δn_{s}	is the refractive index difference between test part and refractive index matching liquid;
t	is the test part thickness (m).

NOTE In this calculation, the flatness of the surface of the oil-on plate in contact with the test part is sufficiently small (see C.3) that the influence can be neglected.

For the calculation examples below, the flatness of the test part is assumed to be 3 µm (Table C.3) and 20 µm (Table C.4) respectively on each side. When this is sandwiched between oil-on plates from both sides, the sum of the flatness on both is up to 6 µm and 40 µm respectively. Based on these assumptions, the measurement errors have been calculated for several combinations of test part thickness and refractive index differences between test part and refractive index matching liquid. The calculation results are shown in Table C.3 respectively Table C.4 below.

Table C.3 — Estimated homogeneity measurement error from the refractive index matching liquid preparation error and the test section thickness. Δl_{gap} = 6 µm

Δn_{S}	**Test part thickness** m			
	0,02	0,05	0,10	0,20
	Maximum value of homogeneity measurement error ($\times 10^{-6}$)			
0,000 1	0,03	0,01	0,01	0,00
0,000 2	0,06	0,02	0,01	0,01
0,000 5	0,15	0,06	0,03	0,02
0,001 0	0,30	0,12	0,06	0,03
0,002 0	0,60	0,24	0,12	0,06
0,005 0	1,50	0,60	0,30	0,15
0,010 0	3,00	1,20	0,60	0,30

Table C.4 — Estimated error of homogeneity measurement from the refractive index matching liquid preparation error and the test section thickness. Δl_{gap} = 40 µm

Δn_S	Test part thickness m			
	0,02	0,05	0,10	0,20
	Maximum value of homogeneity measurement error (×10^{-6})			
0,000 1	0,20	0,08	0,04	0,02
0,000 2	0,40	0,16	0,08	0,04
0,000 5	1,00	0,40	0,20	0,10
0,001 0	2,00	0,80	0,40	0,20
0,002 0	4,00	1,60	0,80	0,40
0,005 0	10,00	4,00	2,00	1,00
0,010 0	20,00	8,00	4,00	2,00

Annex D
(informative)

Flatness of the test part

In the interferometer, a difference between a change caused by the flatness of the test part and a change caused by the refractive index distribution of the test part cannot be separated. For a precise and true measurement, a change caused by the flatness of the test part should be controlled to within the error range of the interferometer at least. In the interferometer of the type in which a light beam transmits through the test part once, e.g. Mach-Zehnder interferometer, a light beam transmits through a surface of a test part twice. Then, in the interferometer of the type in which a light beam transmits through the test part twice, e.g. Fizeau interferometer and Twyman-Green interferometer, a light beam transmits through a surface of a test part four times.

The flatness of the test part W_G is given by Formula (D.1):

$$m(n_G - 1)W_G \leq W_K \tag{D.1}$$

where

n_G is the refractive index of the test part;

W_G is the wavefront of the flatness of the test part (wave);

W_K is the wavefront of the individual error of each interferometer (wave);

m is the number of times a light beam transmits through the surface of a test part.

where

$m = 2$ when a light beam transmits through the test part once, e.g. in a Mach-Zehnder interferometer;

$m = 4$ when a light beam transmits through the test part 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 λ is the wavelength of the laser.

Table D.1 — Maximum permissible flatness

Number of times a light beam transmits through the test part	Permissible flatness
Once	$\lambda/10$
Twice	$\lambda/20$

In PHom method as well as in FT-PSI and SCI method, the influence of flatness on both sides of the test part can be removed by calculation, so the flatness within the effective measurement diameter should be 3λ or less.

For the oil-on plate method hints to flatness are given in C.4

Annex E
(informative)

Method for obtaining W_{PV}

E.1 Obtaining W_{PV} 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 W_{PV} 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 the wavefront, P_V, according to Formula E.1. 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.

$$W_{PV} = (b_1 + b_2)\frac{f}{a} \tag{E.1}$$

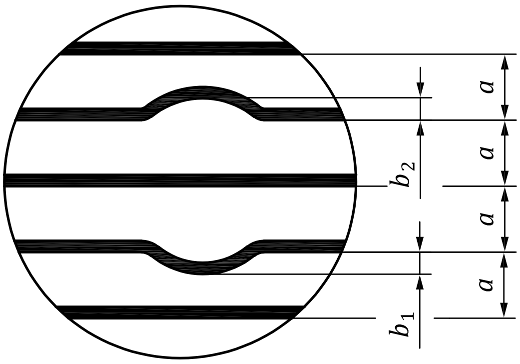
where f is the interferometer scale factor.

b) Here, since the W_{PV} is the value when a light beam transmits through the test object 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 — Interferometer scale factor

Number of times a light beam transmits through the test object	Examples of interferometers	interferometer scale factor
Once	Mach-Zehnder interferometer etc.	1
Twice	Fizeau interferometer, Twyman-Green interferometer, etc.	0,5

c) In order to increase analysis precision and trueness, 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 W_{PV} from bending of interference fringes

E.2 Obtaining W_{PV} by phase measurement method

For this method, reading and analysis of data are processed by a computer. The analysis precision and trueness 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.

By moving the interferometer plane plate (plane mirror or transmission flat) finely or by changing the wavelength of the measurement light source, 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.

When using the method of Clause 4 a) to d), use the least squares method to remove the linear change from this and obtain the W_{PV}. If the correct linear change shall be obtained using the method of G, it need not be removed.

Finally (especially when using a Fizeau-Interferometer), make sure that the W_{PV} becomes the value when a light beam transmits through the test object once.